Final Geotechnical Summary Report
SR-710 Tunnel Technical Study
Los Angeles County, California

Prepared For:
California Department of Transportation
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Los Angeles, CA 90012

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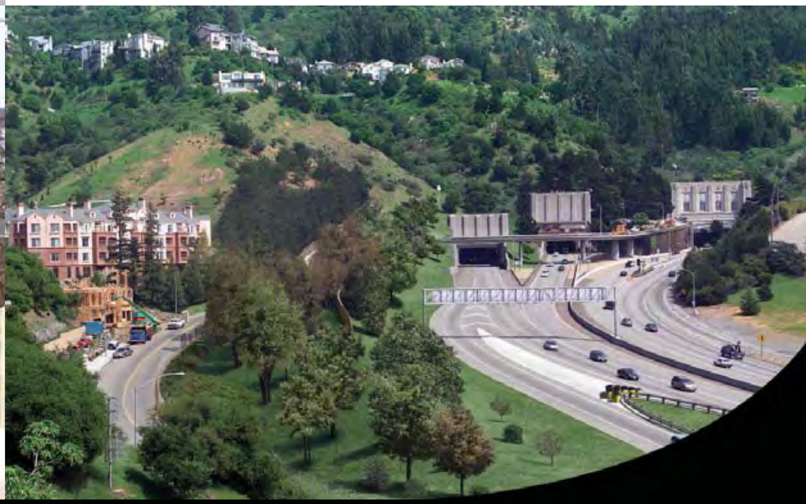
April 2010

Volume I of V



CH2MHILL

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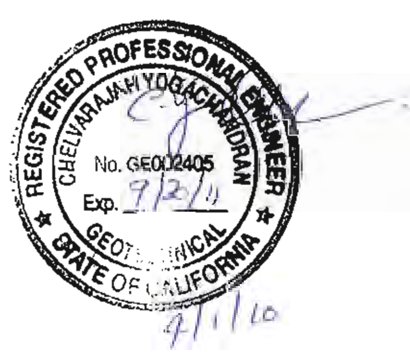

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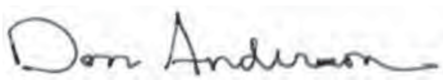

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Acronyms and Abbreviations

µg/L	micrograms per liter
1,1-DCE	1,1-dichloroethene
1,2-DCA	1,2-dichlorethane
1,2-DCE	1,2-dichloroethene
1,2,3-TCP	1,2,3-trichloropropane
APEQFZ	Alquist-Priolo Earthquake Fault Zone
ASTM	American Society for Testing and Materials
ATV	acoustic televiewer
bgs	below ground surface
Cal-OSHA	California Occupational Safety and Health Administration
Caltrans	California Department of Transportation
CCl_4	carbon tetrachloride
CDMG	California Division of Mines and Geology
CDOGR	California Division of Oil and Geothermal Resources
CDWR	California Department of Water Resources
CGS	California Geological Survey
CIP	cast-in-place
cis-1,2-DCE	cis-1,2-dichloroethene
ClO_4	perchlorate
Cr^{6+}	hexachrome
DTSC	Department of Toxic Substances Control
ECIS	East Central Interceptor Sewer
EFZ	earthquake fault zone
EIS	environmental impact study
EPB	earth-pressure balance
EPFT	Elysian Park Fold and Thrust Belt
ESA	Environmental Site Assessment
FHWA	Federal Highway Administration
FS	feasibility study

ft/s	feet per second
g	gravitational acceleration
GPS	global positioning system
GRO	gasoline-range organics
H_2S	hydrogen sulfide
HDPE	high-density polyethylene
I	Interstate
ISA	initial site assessment
km	kilometer
LACDPW	Los Angeles County Department of Public Works
LADPW	Los Angeles Department of Public Works
LEL	lower explosive limit
LOTB	log of test boring
LUST	leaking underground storage tank
M	earthquake magnitude
mg/kg	milligram per kilogram
M_L	earthquake Richter magnitude
M_W	earthquake moment magnitude
MASW	multichannel analyses of surface waves
MCL	maximum contaminant level
Metro	Metropolitan Transportation Authority
mm/yr	millimeters per year
MSGW	Main San Gabriel Watermaster
msl	mean sea level
MTBE	methyl tertiary butyl ether
NATM	New Austrian Tunneling Method
NDMA	n-nitrosodimethylamine
NEIS	Northeast Interceptor Sewer Line
NISZ	Newport-Inglewood Structural Zone
NO_3	nitrate
NOS	North Outfall Sewer
NPL	National Priorities List
OU	Operable Unit

PAH	polyaromatic hydrocarbon
PBA	peak bedrock acceleration
PCB	polychlorinated biphenyl
PCE	tetrachloroethene
PGA	peak ground acceleration
PPE	personal protective equipment
ppm	parts per million
PRP	potentially responsible party
psi	pounds per square inch
RBMB	Raymond Basin Management Board
ReMi	refraction microtremor
RI	remedial investigation
ROD	Record of Decision
RQD	rock quality designation
RWQCB	Regional Water Quality Control Board
SC	Steering Committee
SCAG	Southern California Association of Governments
SCEC	Southern California Earthquake Center
SEM	sequential excavation method
SR	State Route
S-wave	shear wave
TAC	Technical Advisory Committee
TBA	tertiary butyl alcohol
TBM	tunnel boring machine
TCE	trichloroethylene
TPH	total petroleum hydrocarbon
UCS	unconfined compressive strength
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VLBI	very long baseline interferometry
VOC	volatile organic compound

Glossary of Terms

Alluvium. Accumulated material that was transported and deposited at a site by means of flowing water, such as a stream or river.

Anticline. An upward-curving (convex) fold in rock that resembles an arch. The central part contains the oldest section of rock.

Aquiclude. A body of ground that will absorb water slowly but will not transmit it fast enough to supply a well or spring.

Aquifer. A permeable formation that stores and transmits groundwater in sufficient quantity to supply wells.

Aquitard. Semipervious layer above or below an aquifer.

ATV. Acoustic televiewer measurement, which provides high-resolution oriented images of the borehole walls in "pseudo-color."

Bar. Unit of measure of hydrostatic pressure equal to approximately one atmosphere or 33.5 feet of head.

Basement Complex Rocks. Undifferentiated rocks, commonly igneous and metamorphic, that underlie younger rocks, commonly sedimentary, in a given area.

Bedrock. Earth materials below the surface soil deposits. Bedrock is typically harder and stronger than the surface soil.

Caliper measurements. Measurements that evaluate the size and shape of a borehole.

Contamination plume. A three-dimensional zone of groundwater and/or soil contamination.

Epoch. One subdivision of a geologic period, often chosen to correspond to a stratigraphic series. Also used for a division of time corresponding to a paleomagnetic interval.

Fault. A zone in the earth along which one side has moved relative to the other. Sudden movements on faults cause earthquakes.

Fernando Formation. Bedrock generally consisting of layers or beds of claystone, siltstone, and mudstone with some sandstone and conglomerate

Foliation. Aligned layers of minerals characteristic of some metamorphic rocks. Foliation forms in metamorphic rocks when pressure and heat change the shape, size or orientation of existing minerals or changes the minerals creating a parallel rock fabric.

Formation. A distinctive body of rock. Geologists name formations after the localities where they were first studied, or where they are especially well exposed.

Fracture. Any break in rock along which no significant movement has occurred.

Geologic structure. The geometric relationship of bedrock formations, faults, folds, and fractures.

Graben. A down-dropped block bounded by normal faults.

Groundwater Table. The surface of a body of groundwater that is continuous over a significant area.

Hydraulic conductivity. A measure of the permeability of a rock or soil; the volume of flow through a unit surface area in unit time with unit hydraulic pressure difference as the driving force.

Igneous. Pertains to rock formed when molten rock (magma) cools and solidifies (crystallizes).

In situ testing. Testing at natural or original location/place.

Joint. A narrow fracture in rock along which there has been no significant movement of either side. Joints commonly form in parallel sets.

Lineament. Linear topographic features or alignments of vegetation. Lineaments could be the surface expression of faults.

Metamorphic rock. Bedrock that has been altered by the earth's internal heat and/or pressure.

NEIS. North East Interceptor Sewer. Sewer tunnel constructed in Los Angeles that was completed in 2005.

Normal Fault. A fault in which the hanging-wall block moved down relative to the foot-wall block.

Outcrop. A segment of bedrock that appears at the earth's surface.

Packer Tests. An in situ test method to evaluate the hydraulic conductivity of a bedrock formation.

Perched Groundwater. A localized body of groundwater that is situated atop an impermeable layer.

Permeability. A measure of the ability of a material (typically, a rock or unconsolidated material) to transmit fluids.

Piezometers. A partly slotted pipe installed in the ground to monitor groundwater levels.

Physiography. A description of the physical nature of natural features.

Pressuremeter tests. An in situ test performed inside a borehole to estimate modulus and limit pressure of the bedrock.

Puente Formation. Bedrock generally consisting of layers or beds of claystone, siltstone, diatomaceous siltstone, mudstone, shale, and sandstone.

Rock Mass. Rock as it occurs in situ, including both the rock material and its structural discontinuities.

Rock Quality Designation. An index that relates to the degree of fracturing in a rock mass as observed in a core sample. Recorded as a percentage (sum of intact core pieces greater than 4 inches in length/total length of the core run, in inches).

Sedimentary rock. A rock formed by the accumulation and cementation of mineral grains transported by wind, water, or ice to the site of deposition or chemically precipitated at the depositional site.

Seismic reflection testing. A test using seismic waves produced by mechanical vibration or blasting, to measure seismic velocity directly under the wave generator.

Seismicity. The worldwide or local distribution of earthquakes in space and time; a general term for the number of earthquakes in a unit of time.

Shear. A break in rock with limited continuity at which displacement has occurred.

Slip. Movement of an active fault.

Stratigraphy. The science of the description, correlation, and classification of strata including the interpretation of the depositional environments of those strata.

Superfund site. Superfund is the common name for the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), a United States federal law designed to clean up abandoned hazardous waste sites.

Surface wave testing. Measuring surface waves generated by dynamic sources, such as hammers, weight drops, electromechanical shakers, vibroseis, and bulldozers, to evaluate the properties of subsurface material.

Syncline. A downward-curving (concave) fold in rock that resembles the letter "U." The central part contains the youngest section of rock.

Topanga Formation. Bedrock generally consisting of siltstone, mudstone, sandstone, and conglomerate with local volcanic intrusions.

Tuff. A rock composed of volcanic ash.

Weathering. The set of all processes that decay and break up bedrock—a combination of physical fracturing and chemical decomposition.

Executive Summary

Introduction

The California Department of Transportation (Caltrans) and the Los Angeles County Metropolitan Transportation Authority (Metro) have proposed tunnels for extending State Route (SR) 710 within the area shown in Figure 1-1. The intent of this extension is to alleviate traffic congestion within the area, with a secondary benefit of improving air quality. In 2006, Metro performed a feasibility assessment of a tunnel to connect SR-710 at Valley Boulevard to Interstate (I) 210. In 2008, Caltrans retained a team led by CH2M HILL to evaluate the geologic conditions within the study area shown in Figure 1-1. This Geotechnical Summary Report presents the results of the 2008 study.

Caltrans Geotechnical Services and the CH2M HILL team jointly conducted the study, including planning of the exploration program, conducting field exploration, and evaluation of geotechnical data. CH2M HILL, Earth Mechanics, Inc. (EMI), Jacobs Associates (JA), and ILF comprise the CH2M HILL team.

Based on requests from local communities, Congressman Adam Schiff, District 29, introduced legislation mandating that a route-neutral approach be used for the SR-710 Tunnel Technical Study. Route-neutral means that all routes receive equal attention and no route for the tunnel is favored over another. It also requires that all practical routes for extending SR-710 be considered. As part of the route-neutral concept, Caltrans, along with the CH2M HILL team, identified five study zones as shown in Figure 1-2, representing the potential corridors for extending SR-710. The study area has been defined as the area bound by I-10 to the south, SR-2 to the west, I-210 to the north, and I-605 to the east.

The purpose of this geotechnical study is to determine the geologic, groundwater, and seismic conditions within the selected study zones to identify factors that affect the geotechnical feasibility of designing and constructing a tunnel. In addition, this information provides a basis for a comparison of the study zones with respect to tunneling.

For this study, the invert (bottom) of the tunnel along most of the zones is assumed to be about 200 feet below ground surface (bgs), except for the ends of the zones where the roadway would have to connect to existing freeways at the ground surface, and the diameter of the tunnel is assumed to be about 50 feet. Our understanding is that a detailed evaluation of the tunnel profile and tunnel configuration will be made during the environmental documentation phase in the future.

The following subsections of this Executive Summary provide a synopsis of the work that was carried out for this study.

Data Collection and Review

This task involved a comprehensive compilation and review of reports and publications from public and private files regarding the surface and subsurface conditions in the five zones. This collection and review task was performed to establish background information for the zones and to guide development of the field exploration program conducted for this phase of the study.

Data were compiled from public agencies including Caltrans, the United States Geological Survey (USGS), the California Geological Survey (CGS), the Southern California Earthquake Center (SCEC), the California Division of Oil and Geothermal Resources (CDOGR), the City of Los Angeles, the Los Angeles County Department of Public Works - Geotechnical and Materials Engineering Division (LACDPW), the California Department of Water Resources (CDWR), the Main San Gabriel Watermaster (MSGW), the Raymond Basin Management Board (RBMB), and the Dibblee Foundation. In addition, unpublished reports by other consultants were reviewed.

Historical and recent aerial photographs were examined to identify linear topographic and vegetation alignments that could be the surface expression of earthquake faults. Black and white photographs within the Fairchild Collection at Whittier College were the principal photographs utilized for the lineament analysis. Additional details regarding data collection and review are provided in Section 2 of this report.

Field Exploration Program

Field explorations were conducted to provide additional data for characterizing geologic and groundwater conditions within the tunnel study zones. Exploratory borings and geophysical surveys were completed to determine the characteristics of soil/rock units and to estimate the limits of the anticipated geologic formations within the study area.

The field investigation program included core borings, geological reconnaissance, and geophysical surveys. The locations of the borings and geophysical surveys were selected based on the site reconnaissance and review of available geotechnical and geological information. Twenty-five core borings, 17 seismic reflection lines, and 78 multichannel analysis of surface wave (MASW) tests were performed to characterize subsurface conditions. Table ES-1 presents a summary of the exploration program, including the previous borings available in each zone.

TABLE ES-1
Exploration Summary

Zone	Number of Previous Borings Available	Number of Borings in Current Study	Number of Seismic Reflection Lines	Number of Surface Wave Lines	Approximate Length of Zone (miles)
1	74	7	4	20	5.0 to 5.5
2	61	5	3	12	5.0 to 5.5
3	40	12	6	24	4.5 to 5.0
4	34	1	2	10	6.0 to 7.5
5	77	0	2	12	9.5 to 11.0

Caltrans Geotechnical Services and CH2M HILL completed the core borings. Caltrans completed 13 borings, and the remaining borings were completed by the CH2M HILL team. Representative samples of soil and rock core were obtained from each of the borings. Selected samples of soil and rock were tested in a laboratory to determine the properties of the different geologic materials encountered during this study. After completion of the drilling, all but three of the borings were converted to piezometers for monitoring groundwater levels.

In situ testing and downhole logging were completed in selected borings to determine the physical characteristics and engineering properties of the in-place soil/rock units. These tests/surveys included pressuremeter tests, caliper tests, acoustic televiewer (ATV), downhole compression and shear-wave velocity measurements, natural gamma, resistivity or conductivity logging, and packer tests. Additional details regarding the field exploration program are provided in Section 3 of this report.

Regional Geology, Faulting, and Seismicity

The SR-710 study area encompasses portions of the San Gabriel Valley, the southern San Rafael Hills, the Elysian Hills, and the Repetto Hills (Figure 4-1). These areas are within a transition zone between the northwest-southeast-trending Peninsular Ranges physiographic province to the south and the east-west-trending Transverse Ranges province to the north. A detailed description of the regional geology is presented in Section 4 of this report.

The study area is underlain by Quaternary-age alluvium (less than approximately 2 million years old), Tertiary-age sedimentary rocks (approximately 2 to 16 million years old), and ancient crystalline basement complex rocks (igneous and metamorphic rocks older than about 120 million years). Table ES-2 presents a generalized stratigraphic column of the geologic units within the study area.

TABLE ES-2
Study-Specific Stratigraphic Column

Geologic Unit/ Formation Name	Map Symbol	Geologic Epoch (Period)	Approximate Age (Years)	Generalized Description
Young Alluvium	Qa, Qg, Qal	Holocene (Quaternary)	0 to 11,000	Sand and gravel with scattered cobbles and boulders and layers/lenses of silt and clay; stream and fan deposits. Poorly defined, lenticular, discontinuous bedding.
Old Alluvium	Qae, Qalo, Qoa, Qof, Qt, Qvoa	Pleistocene (Quaternary)	11,000 to 2 million	Sand and gravel with scattered cobbles and boulders and layers/lenses of silt and clay stream and fan deposits. Poorly defined, lenticular, discontinuous bedding.
Fernando	Tfcg, Tfss, Tfsl, Tfs, Tfr	Pliocene (Tertiary)	2 to 5 million	Predominantly claystone, siltstone and mudstone, with some sandstone and conglomerate. Massive, marine deposits.

TABLE ES-2
Study-Specific Stratigraphic Column

Geologic Unit/ Formation Name	Map Symbol	Geologic Epoch (Period)	Approximate Age (Years)	Generalized Description
Puente (includes Monterey, Modelo, and Unnamed Shale)	Tpsl, Tpsh, Tpds, Tpss, Tpun, Tmy, Tmss, Tmsh, Tmlv	Late Miocene (Tertiary)	5 to 11 million	Claystone, siltstone, diatomaceous siltstone, mudstone, shale, and sandstone. Laminated to thinly bedded, locally thickly bedded. Marine deposits.
Topanga	Ttss, Ttcg, Ttsl, Ttqdc, Ttsc, Ttqdb	Middle Miocene (Tertiary)	11 to 16 million	Siltstone, mudstone, sandstone, and conglomerate, with local volcanic intrusions. Thinly to thickly bedded, marine deposits.
Basement Complex Rocks	Wqd, Wqg	Cretaceous and Pre Cretaceous	120 to 160+ million	Crystalline igneous rocks (diorite, quartz diorite, monzonite, foliated igneous rocks) and layered metamorphic rocks (gneiss).

Southern California is seismically active and crossed by a number of faults capable of producing significant earthquakes. Strong ground shaking is expected in the study area due to the regional seismicity. In addition, several active, potentially active, and inactive faults cross the study area. The active faults identified in the study area include the Raymond fault and the Alhambra Wash fault. The Raymond fault crosses Zones 2, 3, and 4 and is considered to be the most significant fault. The Alhambra Wash fault is projected to cross Zones 4 and 5. Potentially active faults in the study area are the Eagle Rock and San Rafael faults. Additional details regarding the regional geology, faulting, and seismicity are provided in Section 4 of this report.

Groundwater Conditions

Results of the literature reviews determined that Zones 1 through 5 straddle five separate groundwater basins of the South Coast Hydrologic Region:

- The Los Angeles River portion of Zone 1 located north of SR-110 and the broad valley located along Eagle Rock Boulevard (westernmost portion of Zone 2) are part of the San Fernando Valley Groundwater Basin.
- The portion of the Los Angeles River located south of SR-110, the Arroyo Seco, and all other drainages located in the eastern portions of Zones 1 and 2 and in the southwestern portion of Zone 3 are parts of the Coastal Plain of the Los Angeles Groundwater Basin – Central Sub-basin. A portion of Eagle Rock Basin is located in the northwest region of Zone 2.
- Zone 3 straddles three separate groundwater basins—the Central Sub-basin in the southwest, the San Gabriel Valley Groundwater Basin in the southeast, and the Raymond Groundwater Basin in the north.

- Zone 4 is located within two groundwater basins—the San Gabriel Valley Groundwater Basin in the south and the Raymond Groundwater Basin in the north.
- Zone 5 is located entirely within the San Gabriel Valley Groundwater Basin.

Groundwater levels vary considerably across the study area and occur as deep aquifers and as shallow perched zones. Several of the faults within the study area act as groundwater barriers with different levels on either side of the fault. A major part of the alluvium is an aquifer, and there will be a potential for inflows into tunnel excavations unless control measures are implemented. The underlying rock formations contain groundwater but are not aquifers. However, isolated bodies of groundwater might be encountered within faulted and/or fractured zones in the rock. Impact to groundwater should be kept minimal during tunnel construction and operation. Additional details regarding groundwater conditions are provided in Section 5 of this report.

Hazardous Materials

Hazardous materials present within the study zones are likely sources of soil and groundwater contamination. The potential for hazardous materials within the zones was evaluated using information from the Initial Site Assessments (ISAs) and an Environmental Site Assessment (ESA) performed for the study area.

The ISAs and the ESA identified several sites within the five study zones that have soil and groundwater contamination issues (see Figure 6-1).

The most significant contamination issues are the existence of the two National Priorities List (NPL) sites located within Zones 1, 4, and 5. These two NPL sites (also known as Superfund sites) are the San Fernando Valley Superfund Site (Zone 1) and the San Gabriel Valley Superfund Sites (Zones 4 and 5). The sites have known groundwater contamination.

Most of the groundwater contamination is due to chlorinated volatile organic compounds that are the result of past industrial activities in the area. Therefore, the potential of encountering the contaminated groundwater should be considered in tunnel design, and contamination containment should be part of the construction method.

In addition to the above NPL sites, a large number of small soil and groundwater contamination sites are identified in each zone. These sites are expected to be less important than the NPL sites for tunnel design and construction because of the small size of most sites and the depth of the tunnel. Additional details about hazardous materials are provided in Section 6 of this report.

Description of Zone Geologic Conditions

A summary of the geologic conditions determined for each zone in this preliminary evaluation is presented below. Additional details about the geologic conditions within Zones 1 through 5 are provided in Sections 7 through 11 of this report, respectively.

Zone 1 Geologic Conditions

Based on the results of this evaluation, the key geologic factors for this zone in terms of tunnel design and construction considerations (Plate 5) are:

- Subsurface conditions in most of this zone are fairly uniform, consisting mainly of weak sedimentary rocks of the Puente Formation. Typically, the formation in this zone consists mostly of sandstone, siltstone, and shale. Locally, there is a potential for encountering alluvium (or soil) near the northwestern and southeastern portions of the zone and beneath the Los Angeles River.
- Generally, the rock mass is only slightly fractured. Several inactive faults will likely be encountered; however, no active faults are mapped within this zone.
- Most of the rock is considered weak to moderately weak, although there is a potential for stronger cemented layers and concretions within the Puente Formation.
- The groundwater table within the alluvium is shallow (approximately 20 to 50 feet bgs) in parts of this zone. The rock mass is not expected to transmit large quantities of groundwater into the tunnel, except for possibly beneath the Los Angeles River and within isolated fractured zones. In this area, recharge from the river could lead to higher sustained groundwater inflows. High groundwater inflows are also expected in the saturated alluvium at the northwestern and southeastern portions of the zone.
- The water-bearing alluvial materials along the Los Angeles River in Zone 1 are considered to be susceptible to liquefaction in areas where groundwater is near the ground surface and loose, cohesionless soils occur.
- One Superfund site is located in the zone, which could be a source of contaminated soil and groundwater in the tunnel. This concern applies mainly to the northwestern portion of the zone.
- There is a relatively high potential of encountering naturally occurring gas (methane and/or hydrogen sulfide) in this zone because it is underlain by Puente Formation.

Zone 2 Geologic Conditions

Based on the results of this evaluation, the key geologic factors for this zone in terms of tunnel design and construction considerations (Plate 6) are:

- Subsurface conditions in this zone are fairly uniform, consisting mainly of weak sedimentary rocks of the Puente and Topanga Formations. The Puente Formation includes sandstone, siltstone, and shale and is found in the southeastern portion of the zone. Siltstone and sandstone of the Topanga Formation are expected in the northeastern portion (Plate 6). In addition, depending on the location of the tunnel, sandstones and conglomerates of the Fernando Formation may be encountered. Locally, alluvium (or soil) is expected near the northwestern and southeastern portions of the zone.

- Generally, the rock mass is slightly to moderately fractured. Several inactive faults will be encountered in this zone (Plate 1). The active Raymond fault crosses the zone at the northwestern end. The Raymond fault is capable of generating earthquakes in the range of earthquake moment magnitude (M_W) 6 to 6.7 and producing displacement of about 2 to 4 feet.
- Most of the rock is considered weak to moderately weak, although there is a potential for strongly cemented layers and/or concretions in the Puente and Topanga Formations. Additionally, cobbles and boulders can be expected in the northern portion of this zone, within the Topanga and Fernando Formation conglomerate and the alluvium.
- The Raymond fault is a groundwater barrier, and significant variations in groundwater levels can be expected on either side of the fault. Groundwater is shallow in alluvial valleys (approximately 20 feet bgs), but it is believed to be perched on top of bedrock. The rock mass generally has low permeability and, therefore, is not expected to transmit large quantities of groundwater into the tunnel.
- Some localized soil and groundwater contamination associated with two gas stations could result in hazardous materials being encountered in the northwestern end.
- Alluvial materials within the drainages that cross Zone 2 have been identified as potentially susceptible to liquefaction in areas where loose, cohesionless soils are below the groundwater table.
- There is a relatively high potential of encountering naturally occurring gas (methane and/or hydrogen sulfide) in this zone because a significant portion of the zone is underlain by Puente Formation.

Zone 3 Geologic Conditions

Based on the results of this evaluation, the key geologic factors for this zone in terms of tunnel design and construction considerations (Plate 7) are:

- Subsurface conditions in this zone vary at tunnel depth, including unconsolidated soil deposits (alluvium), weak sedimentary rocks (Puente, Fernando, and Topanga Formations), and strong igneous and metamorphic basement complex rocks (Wilson Quartz Diorite).
- Rock strength varies widely in this zone from the sedimentary rocks (which are very weak to weak) to the higher-strength igneous and metamorphic rocks. There is a potential for strongly cemented layers and/or concretions in the Puente and Topanga Formations. Additionally, cobbles and boulders can be expected in the northern portion of this zone within the Topanga Formation conglomerate and within the alluvium.
- The Raymond fault and San Rafael fault are groundwater barriers. Depth to groundwater varies from as shallow as 50 feet bgs near the Raymond fault to more than 100 feet in both the northern and the southern parts of the zone. Groundwater elevations vary by more than 100 feet on opposite sides of the San Rafael fault. Rock formations are not expected to transmit large quantities of groundwater into the tunnel. However, groundwater inflows are expected when tunneling in the saturated alluvium.

- There is one active, two potentially active, and several inactive faults in this zone. The Raymond fault is active and is capable of generating earthquakes in the range of M_W 6 to 6.7 and of producing displacement at the tunnel level of about 2 to 4 feet. The activity of the San Rafael and Eagle Rock faults are unknown; potentially active and inactive faults may act as groundwater barriers.
- Alluvial materials within the drainages that cross Zone 3 have been identified as potentially susceptible to liquefaction in areas where groundwater-saturated, loose, cohesionless soils are present.
- Two sites with minor soil contamination are located at the northern limits of this zone.
- There is a moderate potential of encountering naturally occurring gas (methane and/or hydrogen sulfide) in this zone because the southern portion of the zone is underlain by Puente Formation.

Zone 4 Geologic Conditions

Based on the results of this evaluation, the key geologic factors for this zone in terms of tunnel design and construction considerations (Plate 8) are:

- Subsurface conditions are fairly uniform in this zone at tunnel depth and consist mainly of Old Alluvium with a limited amount of sedimentary rocks (Fernando and Puente Formations) near the southern end of the zone. The majority of the tunnel is expected to be in the Old Alluvium. The Old Alluvium is generally expected to consist of uncemented coarse sand and gravel interbedded with sand, silt, and clay. The Fernando Formation is expected to consist of siltstone and claystone. The Puente Formation is expected to be composed of clayey siltstone and silty claystone (commonly called mudstone), as well as some sandstone.
- The Old Alluvium exhibits the strength characteristics of a soil with low cohesion (i.e., low undrained shear strength). Cobbles and boulders can be expected in the Old Alluvium. The Fernando and Puente Formations are expected to be moderately weak to weak rock. Strong cemented layers and concretions may be encountered locally in the Puente Formation.
- The active Raymond fault and Alhambra Wash fault cross this zone and could cause ground rupture during a large earthquake. Several inactive faults within the Tertiary-age rocks cross the southwestern portion of this zone.
- Most of the tunnel in this zone would be at or below the water table. Depth to groundwater varies; however, it could be as shallow as 100 feet below grade. The Raymond fault is a groundwater barrier. Historically, groundwater is shallowest on the north side of this fault. Groundwater inflows could occur while tunneling below the groundwater table in the saturated alluvium.
- Some of the alluvial materials within Zone 4 have been identified as potentially susceptible to liquefaction in areas where groundwater-saturated, loose, cohesionless soils are present.

- One Superfund site is located approximately at the southwestern end of this zone. The United States Environmental Protection Agency (USEPA) is currently evaluating the extent of the contamination and will subsequently complete a Record of Decision (ROD). Six other sites with various levels of soil contamination are also present in this zone close enough to impact the tunnel. Most of these sites are located in the vicinity of the northern end.
- There is a low potential for encountering naturally occurring gas in this zone due to the limited portion of the tunnel in the Puente Formation.

Zone 5 Geologic Conditions

Based on the results of this evaluation, the key geologic factors for this zone in terms of tunnel design and construction considerations (Plate 9) are:

- Subsurface conditions are fairly uniform in this zone at tunnel depth and consist mainly of Old Alluvium with a limited amount of sedimentary rocks (Fernando and Puente Formations) near the southern end of the zone. The Old Alluvium is generally expected to consist of uncemented, coarse sand and gravel interbedded with sand, silt, and clay. The Fernando Formation is expected to consist of siltstone and claystone. The Puente Formation is expected to be composed of clayey siltstone and silty claystone (commonly called mudstone), as well as some sandstone.
- The Old Alluvium exhibits the strength characteristics of a soil with low cohesion (i.e., low undrained shear strength). The Fernando and Puente Formations are expected to be moderately weak to weak rock. Cobbles and boulders can be expected in the Old Alluvium. Strong cemented layers and concretions may be encountered in the Puente Formation.
- The Alhambra Wash fault is considered active and projects into this zone. The inactive Workman Hill fault projects toward the western portion of the zone.
- Most of the tunnel in this zone would be at or below the groundwater table. Depth to groundwater varies with groundwater at surface grade in some locations. Groundwater inflows could occur when tunneling below the groundwater table in alluvium.
- The perennial Rio Hondo and San Gabriel River, as well as recharge lakes and deep (greater than 150 feet) gravel quarries, are located in the eastern portion of this zone.
- As a result of the shallow historically highest groundwater level, and, based on the composition of the shallow alluvial materials that occur along the eastern portion of Zone 5, potentially liquefiable conditions have been identified in general for the eastern half of the zone.
- One Superfund site is located in the south-central portion of the zone, which could be a source of soil and groundwater contamination in this zone. Seven other sites with various levels of soil and groundwater contamination are also present in this zone. Most of these sites are located near the eastern or central portion of Zone 5.
- There is a low potential for encountering naturally occurring gas in this zone due to the limited portion of the tunnel in the Puente Formation.

Geotechnical Considerations for Tunnel Design and Construction

Information collected during this study was interpreted relative to tunnel design and construction within each of the zones. Zones with similar geology/geotechnical conditions were grouped to provide similar tunnel design and construction considerations. Results of these reviews are summarized as follows:

Geologic Conditions in Zones 1 and 2

Tunnel excavations in Zones 1 and 2 will likely be in the Fernando, Puente, and Topanga Formations, depending on the location of the tunnel through the study zones. These formations consist of sedimentary rocks that have similar characteristics. There is some inherent variability within these formations, such as occasional cemented layers and concretions within the sandstone.

Tunnel excavation in Zones 1 and 2 is feasible given the tunnel technology currently available, such as the tunnel boring machines (TBMs) used for the Northeast Interceptor Sewer Line (NEIS) project. Several other tunnels have been successfully constructed through these or similar formations in the Los Angeles area. The uniformity of geological conditions in Zones 1 and 2 will simplify construction planning. The potential impact of the cemented layers and concretions will need to be addressed in the selection/design of tunnel excavation equipment. These layers may reduce tunnel advance rates; however, properly designed tunneling equipment can successfully excavate these formations.

Geologic Conditions in Zone 3

Variable geologic conditions are anticipated within Zone 3. Alluvium (soil), low-strength rock, and high-strength rock are all expected to be encountered in this zone. The bedrock material is expected to consist of the weak rocks of the Fernando, Puente, and Topanga Formations, as well as stronger basement complex rocks and limited amounts of volcanic rocks. Strong cemented layers or concretions may be present in the sedimentary rock formations; cobbles and boulders may be encountered in the alluvium and conglomerate of the Topanga Formation in the northern portion of the zone.

A tunnel through Zone 3 will encounter varied geologic conditions, including several geologic formations with a wide range of strength and other physical properties. The basement complex rocks in the northern part of the alignment are stronger rocks that would likely require greater effort to excavate than the sedimentary rocks previously discussed.

Although Zone 3 exhibits the most variable geology of all the zones, excavation of a tunnel in this zone could be done with specialized tunneling machines adaptable to the expected range of anticipated geologic conditions or by using a flexible approach that allows methods to be changed to suit the geology. Due to the variability, the TBM could have a cutterhead with tools that could be changed to excavate either soil or rock. In addition, pressurized-face excavation methods would likely need to be used for face stability in the alluvium and fractured or crushed rock zones.

Geologic Conditions in Zones 4 and 5

Zones 4 and 5 consist mostly of alluvium with some weak sedimentary rocks of the Fernando and Puente Formations near the southern and western ends, respectively. There is some inherent variability within these formations, such as scattered cemented layers and concretions within the sandstone. The majority of the proposed tunnels in each of the zones will be excavated through the alluvium. The alluvium is generally expected to be uncemented, coarse sand and gravel interbedded with sand, silt, and clay with potential for cobbles and boulders.

Tunneling through alluvium involves a greater potential loss of ground at the tunnel face and surface settlement than tunneling through rock. Alluvium is the main formation in Zones 4 and 5. It is expected that the majority of the soil at tunnel depth will be saturated, which increases the potential for instability and surface settlement. Specialized TBMs with positive face control, using earth-pressure balance (EPB) or slurry methods, can control ground loss and surface settlement. The design of specialized TBMs and tunnel operations become more complex as the groundwater head increases. Tunneling machines for Zones 4 and 5 would need to be designed for the saturated alluvium, which contains cobbles and boulders, as well as the sedimentary rock at the southern (Zone 4) and western (Zone 5) portions of these zones.

Active and Inactive Faults

There are steeply dipping, inactive faults in all five zones. Tunneling across these faults is expected to include excavation in fractured rock, clay gouge, and variable groundwater conditions. The groundwater head can vary considerably across a fault if it is acting as a groundwater barrier. Therefore, the potential for groundwater inflows could be expected to vary dramatically across a fault zone. Fault zones are typically less than about 50 feet wide, but much wider zones with multiple branches (about 1,000 feet) are not uncommon. Additionally, a tunnel crossing a fault could encounter a wider zone of faulting if the tunnel were to cross the trend of the fault obliquely. A properly designed TBM can normally excavate these fault crossings without major difficulty, although the rate of excavation is normally less than the rate in better quality rock.

Depending on the location of a potential tunnel, the active Raymond fault may cross Zone 2 (if the tunnel is located within the northwest end of Zone 2) and may cross a potential tunnel in Zones 3 and 4. Similarly, the tunnel may cross the Alhambra Wash fault in Zones 4 and 5. Special considerations will need to be made for excavating through a fault and lining a tunnel in an active fault zone. An oversized tunnel could be excavated in the fault zone to accommodate fault offset (see Section 12.0). Such oversize excavations are typically employed through fault zones to accommodate offsets during fault rupture.

Additionally, tunnels through faults with clayey fault gouge can encounter squeezing conditions. Special provisions will be required to advance a TBM through the clayey zone. The tunnel will need to be designed to accommodate the expected fault displacements.

Contaminated Soil and Groundwater

The Superfund sites in Zones 1, 4, and 5 have the potential to impact tunnel construction and muck-disposal operations. In particular, plumes of contaminated groundwater and soil could be encountered during tunnel excavation. Although the severity of the hazardous conditions might be less in a tunnel than on the ground surface, handling hazardous materials in the confinement of a tunnel could be challenging. The contaminated soil, water, and vapors must be controlled to protect the workers and avoid contaminating adjacent areas. The contaminated soil and water must be handled properly and be transported to appropriate disposal sites.

Naturally Occurring Gas

Naturally occurring gas could be encountered in any of the formations discussed above; however, based on experience with other tunnels in Los Angeles, naturally occurring gas is most likely to be encountered within the Puente Formation. This formation is present in all five zones in different proportions. Appropriate precautions will be necessary in accordance with California Occupational Safety and Health Administration requirements for dealing with naturally occurring gasses during tunnel excavation.

Comparison of Zones

Key ground characteristics for tunneling, such as subsurface conditions, groundwater, contamination, faulting, and seismicity, and potential for gassy conditions, were compared between each zone and are summarized in Table ES-3. A more detailed comparison of the zones is provided in Section 13 of this report.

TABLE ES-3
Comparison of Zones

Zone	Approximate Length of Zone (miles)	Number of Geologic Formations	Predominant Geologic Formation(s)	Percent of Zone in each Formation	Number of Reported/ Mapped Faults	Number of Active Faults Crossing Zone	Potential for Gassy Conditions[a]	Percent of Zone under Superfund Sites
1	5.0 to 5.5	2	Puente Alluvium	80 to 90 10 to 20	5	0	H	5 to 10
2	5.0 to 5.5	4	Puente Topanga Fernando Alluvium	70 to 80 10 to 15 5 to 10 5 to 10	7	1 (NW end)	H	0
3	4.5 to 5.0	5	Topanga Alluvium Puente Fernando Diorite	30 to 40 10 to 20 20 to 30 5 to 10 10 to 20	7	1[b]	M	0
4	6.0 to 7.5	3	Alluvium Fernando Puente	70 to 80 10 to 15 10 to 15	5	2	L	5 to 15
5	9.5 to 11.0	3	Alluvium Fernando Puente	75 to 85 10 to 15 5 to 10	3	1	L	5 to 30

Notes:
[a] H-High, M-Moderate, L-Low
[b] Two potentially active faults cross Zone 3

A comparison of these geotechnical conditions was performed to identify the significance of each condition per zone. Each geotechnical condition has been categorized as design-, construction-, or operation-related. This classification is independent of the how significant the issue is; however, the classification assists in identifying the phase or phases of the project that each condition pertains to most. The results of this comparison analysis are provided in Section 13.8 of this report, and a memorandum regarding a detailed comparison of these conditions is presented in Attachment 1.

It should be recognized that these geotechnical conditions are routinely encountered in tunnel design, construction, and operation and can be successfully addressed, as discussed in Section 12 of this report. Preliminary concepts to mitigate these geotechnical conditions are described in Sections 7 through 11 of this report. A memorandum regarding detailed descriptions of the mitigation concepts is presented in Attachment 2.

Concluding Remarks

Information in this report provides a preliminary summary of geotechnical conditions within the five zones being considered for the SR-710 tunnel. Sections in this report contain detailed information about the geology, faults, seismicity, groundwater, contaminated materials, and potential for gassy conditions within each zone. This information provides a basis for evaluating the geotechnical feasibility of tunneling within each of the zones.

Based on the information collected and reviewed as part of the current geotechnical study, tunneling is considered to be geotechnically feasible in all five zones. Geotechnical feasibility implies that it is possible to construct a tunnel in the geologic formations expected, including the geotechnical conditions associated with these formations using currently available tunneling technologies. Section 12 discusses several tunnel projects and the construction technologies available for conditions similar to those present within the zones under consideration for this study.

SECTION 1
Introduction

1.1 Study Description

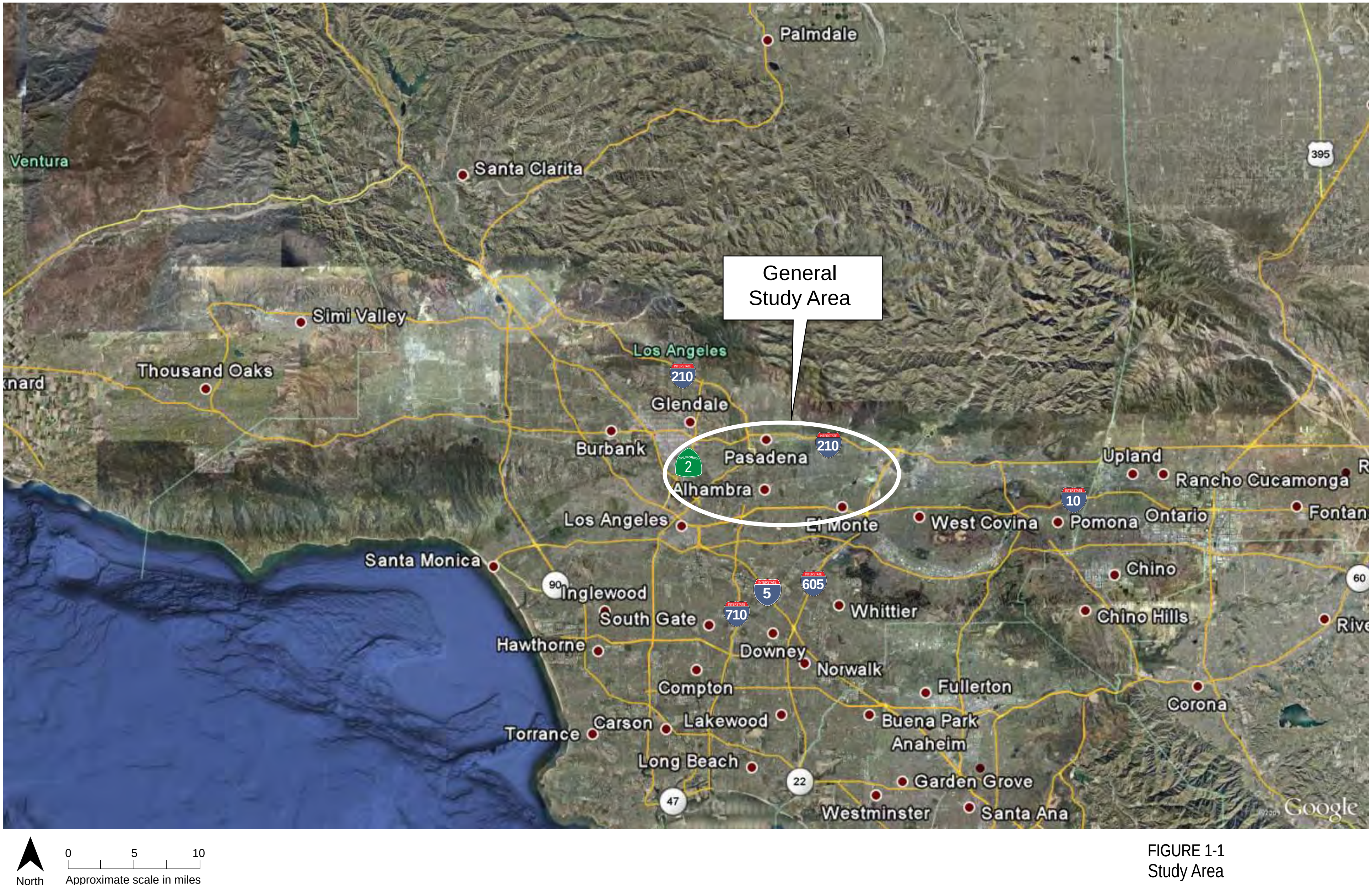
The California Department of Transportation (Caltrans) retained CH2M HILL to provide engineering support for the extension of State Route (SR) 710 from its existing terminus at Valley Boulevard. CH2M HILL teamed with Earth Mechanics, Inc. (EMI), Jacobs Associates (JA), and ILF to provide engineering services for this study. The engineering services included geotechnical, geological, seismic, and hydrogeological investigations for the proposed extension. Caltrans Geotechnical Services and the CH2M HILL team jointly conducted the study, including planning of the exploration program, conducting field exploration, and evaluation of geotechnical data. Caltrans and Los Angeles County Metropolitan Transportation Authority (Metro) will use the results of this study during future evaluations of the technical, operational, and financial feasibility of the project, and during the potential environmental study phase of the project.

The extension of the SR-710 project has been in the planning stages for over 40 years. A surface freeway was proposed in the past, but it received mixed reactions from the stakeholders. In an effort to move the project forward, Caltrans and Metro proposed a tunnel for the extension. In 2006, Metro performed a feasibility assessment (PBI, 2006) to evaluate the option of connecting SR-710 at Valley Boulevard to I-210 in Pasadena. This CH2M HILL study is an extension of the Metro assessment, focusing on the geotechnical aspects of the project.

Based on requests from local communities, Congressman Adam Schiff, District 29, introduced legislation mandating that a route-neutral approach be used for the SR-710 Tunnel Technical Study. A route-neutral approach means that no one route for the tunnel is favored over another. All practicable routes for extending SR-710 are being considered based on factual data. As part of the route-neutral concept, the study area has been defined as the area bound by I-10 to the south, SR-2 to the west, I-210 to north, and I-605 to the east, as shown in Figure 1-1. The CH2M HILL team has been requested to evaluate the subsurface conditions on all practical routes for extending SR-710 within the study area. Caltrans Geotechnical Services and the CH2M HILL team identified the five study zones shown in Figure 1-2 as the basis for this geotechnical study.

1.2 Background

State Route 710 serves as a major north-south link in the Los Angeles County transportation network. This freeway is an extensively traveled facility in Los Angeles County. Metro, in conjunction with Caltrans, is in the process of widening SR-710 from the Port of Los Angeles to SR-60 to lessen the congestion within this area. Currently, SR-710 terminates at Valley Boulevard, and the traffic coming off SR-710 continues on local streets within the cities of Alhambra, South Pasadena, and Los Angeles causing major traffic congestion. The following subsections describe planning studies, as well as advisory and steering committee input, that served as a basis for this SR-710 Tunnel Technical Study.



Aerial image © Google Earth, 2010. Annotation by CH2M HILL, 2010.

FIGURE 1-1
Study Area
SR-710 Tunnel Technical Study

CH2MHILL

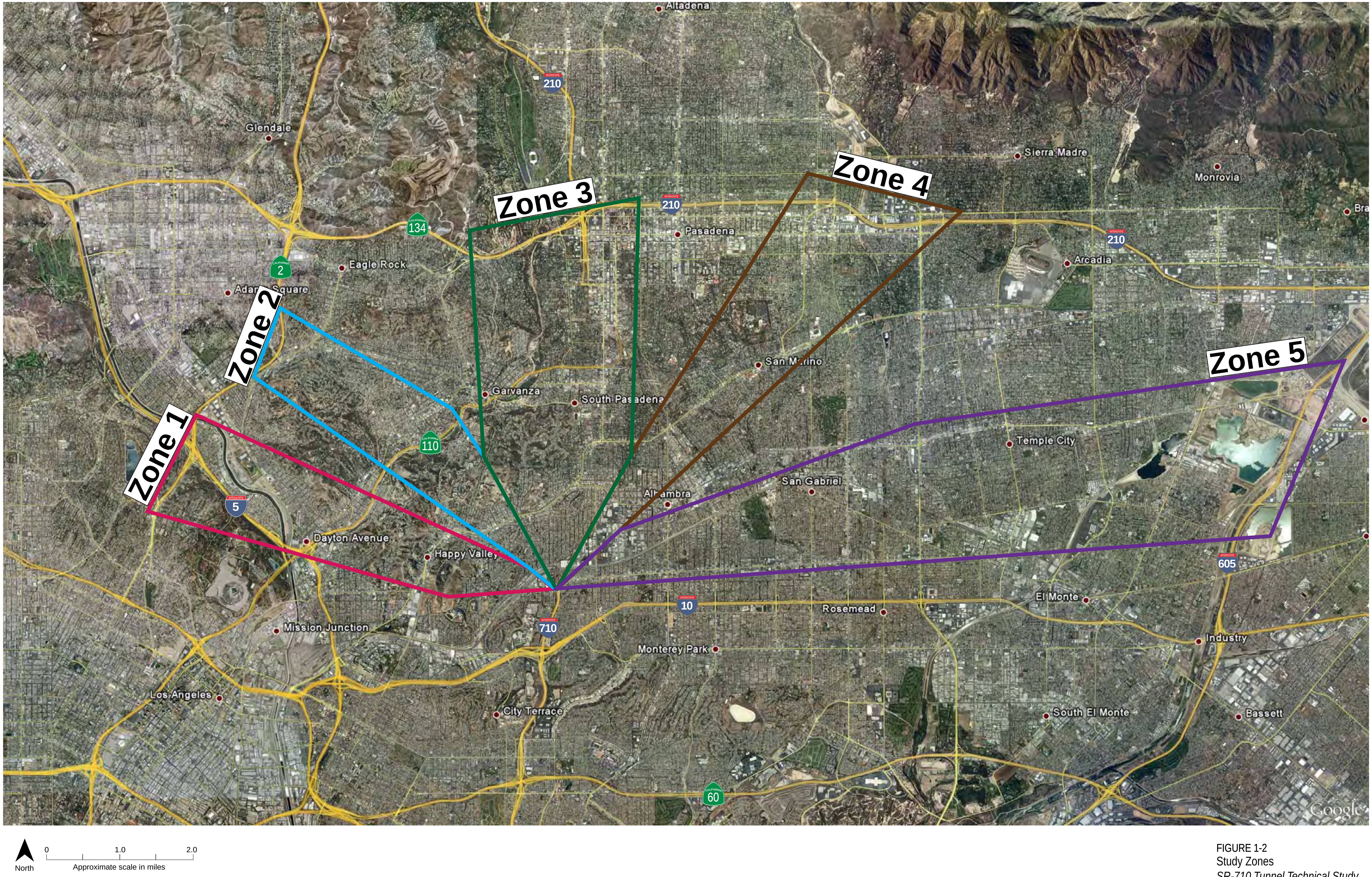


FIGURE 1-2
Study Zones
SR-710 Tunnel Technical Study

1.2.1 Previous Caltrans Evaluations

Caltrans has been studying concepts to extend the freeway to relieve traffic congestion and to improve the regional air quality within the general area. In 1992, Caltrans and the Federal Highway Administration (FHWA) prepared the *SR-710 Final Environmental Impact Statement* (EIS), which addressed the SR-710 "gap" closure using an at-grade solution. In 1996, Caltrans produced the *Route 710, Model Evaluation of the City of South Pasadena's Multi – Mode Low Build Proposal*, which described general trends of expected traffic reductions on major city streets related to a freeway gap closure. In 1998, the Record of Decision was obtained, which described the Meridian Variation Alternative as the preferred alternative. In 1998, Caltrans District 7 produced *Questions and Answers and Preliminary Design Plans* for the project, which discussed environmental issues, benefits and adverse impacts, and costs/funding related to the then-proposed gap closure.

1.2.2 Metro Feasibility Assessment

In 2006, Metro completed the feasibility assessment of extending SR-710 from Valley Boulevard to I-210 using a tunnel (PBI, 2006). Three tunnel alignments were considered extending from the north end of existing SR-710 in south Alhambra to existing I-210 in Pasadena. The assessment concluded that the tunnel concept is feasible to complete the freeway, and no fatal flaws were identified. The scope of the 2006 Metro assessment included technical, operational, and financial feasibility in addition to geotechnical feasibility.

1.2.3 Zone-Specific Route-Neutral Evaluation

Subsequent to the completion of the Metro feasibility assessment, Caltrans was requested by stakeholders to perform additional geotechnical exploration across a wider area to evaluate subsurface conditions. The study documented in this report is in response to that request.

To follow a route-neutral concept on the evaluation of geotechnical conditions along the extension of SR-710, five study zones were selected as shown in Figure 1-2. The study zones were selected by both Caltrans and CH2M HILL, after evaluating available data related to subsurface geology. The limits of the study zones are defined with consideration given to anticipated subsurface geology, based on the initial review of the subsurface conditions and on the study team's experience with the geology in the study area. The limits of each zone are described as follows:

Zone 1 – From the terminus of SR-710 at Valley Boulevard, this zone extends westerly and ends near the southern terminus of SR-2. Zone 1 is approximately 5.0 to 5.5 miles long and about 1.5 miles wide at the western end. Zone 1 is located entirely within the city of Los Angeles.

Zone 2 – From the terminus of SR-710 at Valley Boulevard, this zone extends northwesterly and intersects SR-2 near the midpoint between I-5 and SR-134. Zone 2 is approximately 5.0 to 5.5 miles long and about 1 mile wide at the northwestern terminus at SR-2. Zone 2 is located entirely within the city of Los Angeles.

Zone 3 – From the terminus of SR-710 at Valley Boulevard, this study zone extends north and terminates at SR-134 and I-210. Zone 3 is approximately 4.5 to 5.0 miles long and about 2.5 miles wide at the northern terminus. Zone 3 is located within the cities of Los Angeles, Alhambra, South Pasadena, and Pasadena.

Zone 4 – From the terminus of SR-710 at Valley Boulevard, this study zone extends in a northeasterly direction and terminates at I-210 between SR-134 and I-605, approximately 3 miles east from SR-134. Zone 4 is approximately 6.0 to 7.5 miles long and about 2.2 miles wide at its terminus at I-210. Zone 4 is located within the cities of Los Angeles, Alhambra, South Pasadena, Pasadena, San Marino, and East Pasadena.

Zone 5 – From the terminus of SR-710 at Valley Boulevard, this study zone extends easterly and ends at I-605. Zone 5 is approximately 9.5 to 11.0 miles long and about 2.5 miles wide at the eastern terminus. The eastern limit of Zone 5 at I-605 extends roughly from Arrow Highway on the north to midway between Lower Azusa Road and Ramona Boulevard on the south. Zone 5 is north of I-10 and is located within the cities of Los Angeles, Alhambra, San Gabriel, Rosemead, Arcadia, Temple City, El Monte, North El Monte, and Irwindale.

In accordance with the route-neutral approach, a specific alignment for the tunnel in each zone was not selected. The exploration program was developed to determine preliminary subsurface information for any tunnel alignment across the dimensions of each zone. The major focus has been to characterize the materials that would be encountered within these zones, such that the results can be used to evaluate any given tunnel alignment within the study area.

1.2.4 2008 Regional Transportation Planning

The Southern California Association of Governments (SCAG) includes the SR-710 extension as a tunnel in its adopted 2008 Regional Transportation Plan as part of a comprehensive, regional, multi-modal, and multi-billion dollar package of transportation improvements through 2035 that will help achieve the region's long-term goals for mobility and air quality. The voter-approved Measure R sales tax in Los Angeles County includes the SR-710 extension, and Metro's recently adopted Long-Range Transportation Plan includes the SR-710 extension.

1.2.5 Advisory and Steering Committee Participation

Caltrans formed a Technical Advisory Committee (TAC) and Steering Committee (SC) for this study to provide guidance, as needed. The members of this committee were selected to represent the various stakeholders with interest in the completion of this study.

The TAC and SC consist of representatives from Caltrans, Metro, cities, counties, and councils. Caltrans, Metro, and CH2M HILL conducted meetings with both TAC and SC to discuss the selected study zones and the overall scope of work. The scope of work for the geotechnical study along with the study zones were agreed upon by both TAC and SC. The findings and status of the study were presented at several meetings with TAC and SC.

1.3 Purpose of Geotechnical Study

The purpose of the geotechnical study is to evaluate the geologic, groundwater, and seismic conditions along the selected study zones to determine if it is feasible to construct a tunnel through these conditions. In addition, the geologic data interpretation will enable comparison of the key geological factors for tunneling in the zones. The study evaluated the geologic conditions, groundwater conditions, seismicity, faulting, potential for contaminated soil or groundwater, and presence of naturally occurring gas with respect to each of the tunnel study zones.

For the purpose of this study, the invert (bottom) of the tunnel is assumed to be about 200 feet below ground surface (bgs); the diameter of the tunnel is assumed to be about 50 feet. Our understanding is that a detailed evaluation of the tunnel profile and tunnel configuration will be made during the environmental documentation phase in the future.

1.4 Scope of Work

Caltrans Geotechnical Services and CH2M HILL jointly developed the exploration program to evaluate the subsurface conditions. The field exploration provided information on soil, rock, and groundwater conditions anticipated within the selected zones. The exploration program was developed based on available data, such as previously conducted borings, available geologic maps, and fault and seismic data, to provide information necessary for characterization purposes. The team also evaluated existing information from deep well logs and other previously conducted geotechnical investigations to plan the exploration program for this study phase. In situ testing and logging were also performed within the borings.

The approach to selection of the exploration locations was to obtain subsurface information to characterize various materials that were anticipated within the assumed tunnel zone. Borings and/or geophysical testing were performed to obtain the characteristics of the formations within the zones. The geotechnical program that was developed to evaluate the subsurface conditions within the study area includes the following tasks:

- Collect and review available information including previous geotechnical and geological data, geologic and seismic maps, and fault information.
- Summarize relevant information from similar tunneling projects completed in the Los Angeles area, in California, and in the world.
- Review published geologic mappings.
- Study lineaments to confirm published fault interpretations and check for unknown faults.
- Conduct field exploration and laboratory testing programs:
  - Drill 25 borings (one inclined) to depths ranging from 150 to 500 feet.
  - Perform in situ testing and logging consisting of pressuremeter tests, caliper tests, acoustic televiewer (ATV), downhole shear wave velocity measurements, and packer tests.
  - Convert selected borings into groundwater observation points by installing piezometers.
  - Perform 17 seismic reflection lines, 78 multichannel analyses of surface waves (MASW), and refraction microtremor (ReMi) testing.
  - Conduct laboratory testing on selected soil and rock samples for the purpose of characterizing and determining the engineering and excavation properties of material likely to be encountered.

- Evaluate the collected data in conjunction with previously compiled information to characterize the subsurface conditions in each zone.
- Prepare this geotechnical summary report, which contains the findings of the exploration program and a preliminary comparison of zones relative to tunneling conditions.
- Present the findings of the exploration program to TAC, SC, and surrounding communities.

1.5 Report Organization

This geotechnical summary report is organized into five volumes. Volume I includes the 16 sections of the main text, attachments, and geotechnical figures/plates; appendixes are in subsequent volumes as follows:

Volume I

- **Executive Summary** provides a brief summary of key aspects of this report.
- **Sections 1 through 6** summarize the introduction; data collection and review; field investigation; regional geology, faulting, and seismicity; groundwater evaluation; and hazardous materials.
- **Sections 7 through 11** describe site conditions encountered in Zones 1 through 5.
- **Section 12** presents previous tunneling experience.
- **Section 13** provides a comparison of ground conditions for tunneling in each zone.
- **Section 14** presents the summary of findings and conclusions.
- **Section 15** describes limitations of the geotechnical study.
- **Section 16** provides references used in the preparation of this report.
- **Attachment 1** presents a comparison of geotechnical conditions.
- **Attachment 2** presents concepts to address geotechnical conditions.
- **Plates** (geotechnical maps and figures) are provided at the end of the main text in Volume I.

Volume II

- **Appendix A** presents current and previous boring logs and pictures of rock core samples.
- **Appendix B** provides groundwater monitoring data.

Volume III

- **Appendix C** contains geophysical investigation data.

Volume IV

- **Appendix D** provides in situ test results.
- **Appendix E** presents laboratory test results.

Volume V

- **Appendix F** contains the Environmental Screening Assessment (ESA).
- **Appendix G** provides responses to the comments made to the draft version of the report.

SECTION 2

Data Collection and Review

2.1 Literature Search/Review

One of the first steps involved a comprehensive compilation and review of readily available reports and publications from public and private files regarding the surface and subsurface conditions in the five zones and the immediate vicinity. The objective of this task was to gather and assess existing information to develop an initial understanding of the geologic, faulting, hydrogeological, environmental, and geotechnical considerations of each zone.

Data were compiled by acquiring readily available reports and publications from public agencies including:

- United States Geological Survey (USGS)
- California Department of Transportation (Caltrans)
- California Geological Survey (CGS)
- California Division of Oil and Geothermal Resources (CDOGR)
- Southern California Earthquake Center (SCEC)
- City of Los Angeles and the Los Angeles Department of Public Works (LADPW) - Geotechnical and Materials Engineering Division
- Los Angeles County Department of Public Works (LACDPW)
- California Department of Water Resources (CDWR)
- Main San Gabriel Watermaster (MSGW)
- Raymond Basin Management Board (RBMB)
- Dibblee Foundation

In addition, unpublished reports available in company and personal files, and available technical reports issued by other consultants were compiled and reviewed. A complete list of the geologic references compiled and reviewed is presented in the reference section of this report (Section 16). Table 16-1 provides information on the applicability of the compiled references to each of the individual zones under consideration.

Although the review of all the references included in Table 16-1 contributed to the understanding of the geologic, groundwater, and environmental conditions within the five zones, the following sources of data provided some of the most relevant information.

One of the best sources of information on the geological and fault conditions within Zones 1 through 3 is the "Geology of the Elysian Park-Repetto Hills Area," a report published by the CGS (Lamar, 1970). The geologic maps published by the Dibblee Foundation for the Los Angeles, Hollywood, Pasadena, Mount Wilson, El Monte, and Baldwin Park Quadrangles (Dibblee, 1989a, 1989b, 1989c, 1998, and 1999) complemented the understanding of those three zones, as well as Zones 4 and 5.

Key geologic data along portions of Zones 1 through 3 were obtained from the geotechnical investigations for the Metro Pasadena Line (e.g., Law/Crandall, 1993). In addition, the geotechnical investigations and construction of the upper reach of the Northeast Interceptor Sewer (NEIS) Line Tunnel and the Avenue 45 – Arroyo Drive Relief Sewer (Avenue 45 Sewer) contributed significantly to the understanding of the geologic conditions along the portion of the Los Angeles River and Arroyo Seco that is located within Zones 1 and 2, respectively (City of Los Angeles, 2000, 2001, 2006a, and 2006b; and URS 2006). Caltrans as-built logs of test borings (LOTBs) for different freeways in all zones also contributed some key geotechnical data (Caltrans, 1971, 1974a, and 1974b).

The most relevant information on groundwater, alluvium fill thickness, and depth to bedrock for the portions of the San Gabriel and Raymond groundwater basins in Zone 3 through 5 was obtained from the CDWR (1966) and from Geoscience Support Services, Inc. (Geoscience, 2004), respectively. Annual groundwater contour maps for the first basin were available from the MSGW (2006) and for the second basin from the RBMB (2006 and 2007). Finally, historically highest groundwater information for the entire area studied was obtained from the California Division of Mines and Geology (CDMG) (1998a, 1998b, 1998c, 1998d, 1998e, and 1998f).

Several environmental reports prepared by various consultants for the United States Environmental Protection Agency (USEPA) allowed understanding of the lateral and vertical extent and type of groundwater contamination at the San Fernando, Alhambra, and the El Monte Superfund sites (JMMI, 1992; CDM, 1998, 2006, 2008a, and 2008b; GeoSyntec, 2006a and 2006b; and CH2M HILL, 2003, 2006, 2007, and 2009c) located in Zone 1, Zone 4, and Zone 5, respectively.

Information on the location of oil and/or natural gas fields was obtained from the CDOGR (2001).

2.2 Previous Metro Feasibility Assessment

The geotechnical portion of the Metro assessment (PBI, 2006) summarized the geologic and geotechnical conditions along three proposed tunnel alignments extending from the north end of the existing SR-710 in south Alhambra to the existing I-210 in Pasadena, a distance of about 4.5 miles (7.2 kilometers [km]). The geotechnical portion of the 2006 Metro assessment was based on a site reconnaissance and review of existing published data, geologic information, soil and rock boring logs, foundation reports, groundwater data, seismicity data, and pertinent documents from other projects in the area of the Metro assessment. As part of the Metro assessment, three borings were drilled to a depth of 200 feet. The report was regarded as a generalized, preliminary description of the geological and geotechnical conditions likely to be encountered by the then-proposed tunnel, with the understanding that additional site-specific studies would be required for tunnel design and construction specifications. Significant sources of geologic and geotechnical information used in preparation of the Metro assessment were also reviewed in preparation of this study (see Section 16, References). The Metro assessment concluded that construction of the then-proposed tunnel was feasible.

2.3 Fault Lineament Study

Historical and recent aerial photographs of the study area were examined to identify lineaments (linear alignments) of topographic highs and lows, color changes, or linear alignments of vegetation, any of which might represent the surface expression of geologic faults. The Fairchild aerial-photograph collection at Whittier College was the primary source of aerial photographs. The reviewed photographs are summarized in Table 16-2. Additional photographs were color images from the Google® Web site.

The oldest photographs in the Fairchild collection were from 1927; these are among the earliest aerial photographs taken by flying in a systematic overlapping grid with surveyed locations. These photographs are overlapping black-and-white images that can be viewed in three-dimensions. These old photographs are generally more useful for geological analysis than modern photographs because they reveal geological conditions prior to much of the urban development of the region. Part of the study area was developed before these photographs were taken, and locally this development obscures the predevelopment topography.

The photographs listed in Table 16-2 cover most of the study area, including Zones 1 through 5. Due to the high degree of urban development, even in the late 1920s and early 1930s, one cannot be sure that some natural lineaments were not removed by grading or construction; therefore, some natural lineaments could have gone undocumented. However, grading practices prior to the 1950s generally utilized natural topography rather than completely removing it, enabling most of the known active faults in the study area such as the Alhambra Wash, Raymond, and Hollywood faults to be clearly identified on the aerial photographs.

The observed lineaments/faults were plotted on mylar overlays on the photographs and/or on maps. Although the analysis did not reveal any new faults, details on the location, width, and length of known faults were documented much more completely than anything available in the existing scientific literature. Some of the identified lineaments were later verified in the field by geological reconnaissance and seismic reflection surveys. These relationships are discussed in this report, where appropriate for the zones.

2.4 Summary of Data Review

The data collected during the review of available information along with the fault lineament study provided a good understanding of the subsurface conditions within the study area. The data review task provided information related to the geologic, groundwater, and seismic conditions, and soil and groundwater contamination. The information collected through data review, along with data collected from the current exploration, is summarized in Sections 4 through 11.

SECTION 3

Field Investigation

3.1 General

The field investigation program, jointly conducted by Caltrans Geotechnical Services and CH2M HILL team, included rotary-wash core borings, geological reconnaissance, and geophysical surveys. The purpose of the investigation was to characterize the subsurface material and determine the engineering properties of the soil and rock within each zone. The locations of the borings and geophysical surveys were selected based on a review of available geotechnical and geological information. The locations of the borings and the components of the geophysical survey are shown in the Geotechnical Maps (Plates 1 and 2) and Surface Wave Testing Location Maps (Plates 3 and 4). The investigation also incorporated borings previously drilled within the study area by others.

The selection of the number of borings and geophysical testing on each zone was based on the amount of data collected within each zone, the general understanding of the geology within each zone, and expected variation in material type in each zone. Particularly, the borings and geophysical testing focused on collecting information related to different formations expected within the study area to enable us to characterize these formations. The number of borings, along with the geophysical testing, was selected such that adequate information is collected for geotechnical feasibility evaluation. The details of the site reconnaissance/geologic mapping, field investigation, field testing, in situ testing, seismic geophysical testing, and the laboratory testing are presented below. In developing the exploration program, the following factors that influence tunneling were considered:

- Type of material at tunnel level
- Variability of the subsurface conditions within the zone, including whether mixed face conditions are expected
- Groundwater conditions
- Presence of major geologic structures in each zone, such as faults and folds
- Potential for naturally occurring gas
- Potential for contaminated soil, rock, and/or groundwater

In addition to the 25 borings, the exploration program included in situ testing and groundwater monitoring within the borings, and two types of geophysical testing. The in situ testing and groundwater monitoring are described in Section 3.4 of this report. The seismic geophysical testing, which is described in Section 3.5, involved the following two types of seismic geophysical tests:

- Seismic reflection testing to identify the location and orientation of selected active and inactive faults, the contact between alluvium and bedrock, and depth to groundwater.
- The surface-wave seismic method to obtain information on depth of alluvium and the dynamic characteristics of the underlying material.

3.2 Geologic Reconnaissance

Study team members conducted a site reconnaissance within the study area to finalize the boring and geophysical survey locations. The selected locations were photographed to document existing surficial conditions. Limited geologic reconnaissance within the study area was also conducted to verify and refine existing geological data. Due to the urbanized nature of the study area, geologic field reconnaissance was limited to areas with rock outcrops. The geologic field reconnaissance consisted of spot-checking regional geologic maps available for the study area. Geological maps utilized during this study included those published by Lamar (1970), Dibblee (1989a, 1989b, 1989c, 1998, and 1999), Tan (2000a and 2000b), and Yerkes and Campbell (2005). Geotechnical maps covering Zones 1 through 3 are presented in Plate 1; Zones 4 and 5 are covered in Plate 2.

3.3 Field Exploration

3.3.1 Review of Previous Exploration

Subsurface information utilized in the current study is based on the review of previous investigations performed by others within the study area, including the LOTB sheets in the as-built plans of the highway bridge structures within the study area. Review of existing borings provided subsurface information in all five zones and helped to identify data gaps and additional borings needed in this study.

The number of available existing borings in each zone is shown in Table 3-1. Because there were numerous existing borings and subsurface information, only one new boring was drilled in Zone 4 for this investigation. No borings were drilled in Zone 5 because the existing boring coverage is considered to be adequate for characterization at this time. Appendix A.2 presents the previous boring logs and as-built LOTB sheets for the borings referenced in Table A-2, which summarizes the previous borings and as-built LOTB information.

TABLE 3-1
Exploration Summary

Zone	Number of Available Previous Borings	Number of Borings in Current Study	Number of Seismic Reflection Lines	Number of Surface Wave Lines	Approximate Length of Zone (miles)
1	74	7	4	20	5.0 to 5.5
2	61	5	3	12	5.0 to 5.5
3	40	12	6	25	4.5 to 5.0
4	34	1	2	10	6.0 to 7.5
5	77	0	2	12	9.5 to 11.0

3.3.2 Current Exploration

Twenty-five borings were drilled between January 6 and May 1, 2009 using the rotary-wash method for the current exploration program. All borings were drilled vertically, except Boring R-09-Z1B2, which was drilled at an inclination of approximately 60 degrees. The purpose of the inclined boring was to intercept the Elysian Park fault. During the planning phase of the work, several other borings were considered for inclined drilling, but these could not be performed because the inclination would have advanced the borings beneath private properties.

Figure 3-1. Drilling Operation at Boring Location R-09-Z3B12.

The geotechnical drilling program was divided between Caltrans Geotechnical Services and the CH2M HILL team. The Caltrans drilling services from Sacramento, California, drilled 13 borings. Cascade Drilling, Inc. of La Habra, California, drilled 12 borings under subcontract to CH2M HILL. The borings were designated as R-09-ZaBb, where "Za" represents the zone and "Bb" represents the boring number within each zone.

- Seven borings were drilled in Zone 1.
- Five borings were drilled in Zone 2.
- Twelve borings were drilled in Zone 3.
- One boring was drilled in Zone 4.
- No borings were drilled in Zone 5 for this current study.

Because of obstruction to drilling, Boring R-09-Z2B2 was terminated at 282 feet, which is shorter than the planned depth of 400 feet. Inclined Boring R-09-Z1B2 was terminated at 326 feet (inclined depth) due to drilling difficulties; the planned depth of this boring was 525 feet (inclined depth). The boring locations are shown in Plates 1 and 2. Figure 3-1 shows the drilling operation at boring location R-09-Z3B12. Table 3-1 summarizes the exploration program by zone. Also included in this table is the available relevant previous boring information for each zone.

The working area and soil and rock samples collected during this study were screened using a MiniRAE 3000 multi-gas monitor. The readings of the volatile organic compounds (VOCs) are presented in the remarks column of the boring logs (Appendix A.1).

After completion of the drilling, all but three of the borings (R-09-Z2B2, R-09-Z3B4, and R-09-Z1B2) were converted to piezometers to enable determination of groundwater depth. Boring R-09-Z2B2 was not converted to a piezometer because of obstruction to drilling. Inclined Boring R-09-Z1B2 also was not converted to a piezometer. Because of future proposed improvements at this location, Boring R-09-Z3B4 was not converted to a piezometer. These three borings were backfilled with bentonite grout and finished to match the existing surface conditions. Each piezometer was fitted with a locking cap and traffic-rated well box, except boring locations R-09-Z1B8 and R-09-Z3B2, where standpipes were used. The piezometer construction details are provided in Appendix B. The boring locations were surveyed after the completion of the drilling operations.

Rock quality designation (RQD) values provided in the boring logs are based on the sum of intact core pieces that were 4 inches or greater in length between two natural discontinuities. The majority of core samples obtained in this study are soft and weak and commonly do not meet the "sound core" definition for the American Society for Testing and Materials (ASTM) standard RQD method (ASTM D 6032). These RQD values should not be used to evaluate the rock mass quality for soft and weak rock. The RQD values reported for hard rock in Zone 3 are valid for such analysis. However, the density of fracturing (reflected by different RQD percentages) in weak and hard rock may play a significant role in the secondary permeability of those materials and may directly influence the occurrence of groundwater and its flow.

Boring information, including exploration number, ground-surface elevation, exploration depth, and groundwater table elevation are summarized in Table A-1. Drilling and sampling details are provided in Appendix A.1 along with detailed boring logs. Log of test borings are presented in Appendix A.3. Photographs of rock core samples are presented in Appendix A.4.

3.4 Field Testing

The exploration work included downhole (in situ) testing and groundwater monitoring. In situ testing and logging were conducted to investigate the characteristics of the rock mass. Laboratory testing of core specimens characterizes the intact rock material but not the discontinuities of the rock mass. Field and laboratory test information are necessary to develop a complete picture of subsurface conditions. The geophysical survey was performed by Geovision Geophysical Services of Corona, California, and Caltrans Geophysics and Geology Branch. The pressuremeter testing was conducted by In Situ Testing of Snohomish, Washington, and the packer testing was conducted by Cascade Drilling, Inc. of La Habra, California, all under subcontract to CH2M HILL. Groundwater depths were initially measured upon completion of drilling, prior to installation of piezometers.

3.4.1 In Situ Testing and Logging

In situ testing was performed on vertical borings. The in situ tests included downhole geophysical measurements, caliper logging, ATV recordings, pressuremeter testing, and packer testing. The following subsections provide brief descriptions of the tests conducted in the borings. Additional information from these tests, including the results, is provided in Appendices B, C, and D submitted in Volumes II, III, and IV of this document.

3.4.1.1 Downhole Geophysical Testing and Logging

Downhole geophysical testing and logging included caliper logging, seismic velocity measurements, natural-gamma logging, and ATV recordings. The results of this testing and logging were used in combination with core logs to identify rock type, geologic structures, and the engineering properties of the rock mass. Caltrans Geophysics and Geology Branch performed resistivity logging in addition to downhole geophysical testing and logging on borings drilled by Caltrans drilling services. The downhole geophysical tests were performed in accordance with ASTM D 5753, Standard Guide for Planning and Conducting Borehole

Geophysical Logging. Downhole geophysical testing was not performed in inclined Boring R-09-Z1B2 and in Boring R-09-Z2B2. Results of the downhole geophysical tests are provided in Appendix C.1.

3.4.1.2 Pressuremeter Testing

A prebored mono-cell pressuremeter was used to record the response of the loading and unloading of the material being tested. Pressuremeter test results are used to estimate the in situ modulus of the rock mass including a sampling of the discontinuities. Figure 3-2 shows the pressuremeter set up at boring location R-09-Z1B5.

Figure 3-2. Pressuremeter set up at Boring Location R-09-Z1B5.

To characterize each formational material, two to three pressuremeter tests were performed on each formational material. Forty-six pressuremeter tests were performed for the current study to obtain representative in situ measurements for each formation. A summary of pressuremeter tests is provided in Table D-1. Recovery and RQD information is presented in this table to indicate the type of material in which the pressuremeter results were obtained. Results of pressuremeter tests are presented in Appendix D.1.

3.4.1.3 Packer Testing

Permeability of the rocks was measured by packer testing, which involves injecting water under pressure into the rock through the walls of the borehole. A double packer assembly consisting of two packers was lowered into the borehole to the desired testing interval to determine the permeability of the material. The testing interval (packer spacing) was kept generally at 10 feet. Observations of the elapsed time and the volume of water pumped at different pressures were recorded.

Generally, four tests were performed in each boring. Two tests were performed above the anticipated tunnel crown, one test below the tunnel invert, and one test within the anticipated tunnel zone. Packer inflation pressure was adjusted for the depth and the rock type and corresponding geologic structure. A summary of the packer tests is presented in Table D-2 and the results are included in Appendix D.2.

3.4.2 Groundwater Monitoring

At the completion of in situ testing, all but three borings were converted to a piezometer. Inclined boring R-09-Z1B2 was not converted to a piezometer. Vertical Boring R-09-Z2B2 was not converted to a piezometer because of obstruction to drilling. Boring R-09-Z3B4 also was not converted to a piezometer because of planned future proposed improvement at this location. The piezometers were constructed to monitor the depth of the groundwater table over a period of time. Groundwater measurement was taken in the piezometers approximately 2 to 4 months after installation of the piezometers. Because some of the piezometers were not developed, groundwater may not have been stabilized at the time of reading. These piezometers should be developed in future phases of the study for groundwater level measurements. A summary of piezometer installations and groundwater elevations is presented in Table B-1 of Appendix B.

3.5 Seismic Geophysical Testing

Two types of seismic geophysical tests were performed as part of the SR-710 exploration program: (1) seismic reflection testing and (2) MASW and ReMi testing. The objective of the geophysical studies was to characterize subsurface geology, structure, and geotechnical conditions up to a target depth of approximately 300 to 400 feet bgs at various locations within each of the five study zones.

3.5.1 Seismic Reflection Testing

Seismic reflection testing was conducted to collect compressional wave velocity (P-wave) information at locations identified by the CH2M HILL team. P-wave reflection data were acquired along each profile using an IVI™ MiniBuggy vibratory source. Seventeen seismic-reflection tests were performed as part of this study. Typical length of the seismic line was approximately 1,600 to 1,900 feet. One seismic line (Z4-G1) was extended to 3,500 feet to evaluate the Raymond fault zone. Figure 3-3 shows the seismic-reflection testing set up for the SR-710 Tunnel Technical Study. Locations of these lines are shown in Plates 1 and 2. A summary of seismic-reflection testing is presented in Table C-1 in Appendix C.2.

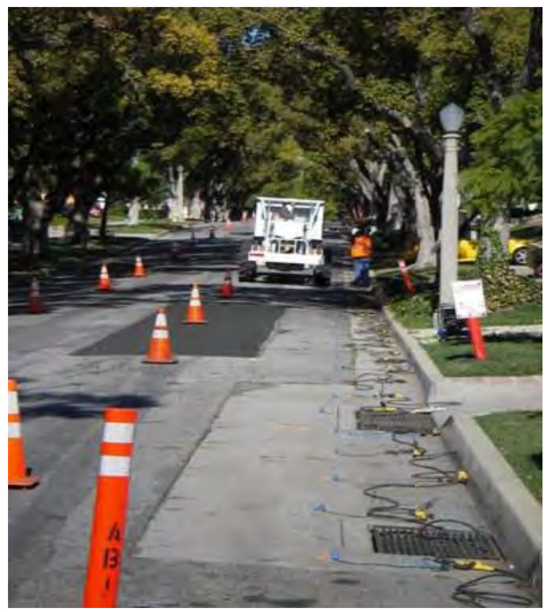


Figure 3-3. Seismic Reflection Testing.

3.5.2 MASW and ReMi Testing

This testing method involved collection of shear-wave velocity data using the MASW and ReMi testing methods. The MASW uses an active source to obtain shear wave (S-wave) velocity data, while the ReMi procedure uses ambient vibration data to collect S-wave velocities. This technique is ideally suited to two-dimensional shear wave imaging, with data collected in a roll-along manner similar to that of the seismic reflection technique. Typical depths of measurement range up to 200 feet.

S-wave data have many potential applications related to site characterization including correlation of seismic properties between boreholes; estimating depth to bedrock (providing there is sufficient contrast in velocity between bedrock and overlying sediments), estimating N-value using empirical correlations between S-wave velocity and N-value, estimation of excavatability or rippability of rock.

Seventy-eight MASW tests were performed for this study. Test locations are provided in Plates 3 and 4. Summary of test locations are presented in Table C-2; the results of the MASW testing are presented in Appendix C.3.

3.6 Laboratory Testing

The properties of the soil and rock within the five zones were estimated on the basis of laboratory testing performed on similar soil and rock as part of other projects, and by conducting laboratory tests collected as part of the SR-710 Tunnel Technical Study. Results of the laboratory tests were used to measure the properties of the soil and intact rock. These properties, in combination with the rock mass properties from in situ testing and logging, are used to estimate the requirements for tunnel design and construction.

3.6.1 Previous Laboratory Test Data

Limited applicable laboratory test results were obtained from previous borings and as-built LOTB sheets. The available laboratory test data were generally performed to confirm the visual classification of the soil and rock at shallow to only moderate depths below the ground surface, and therefore originates from much shallower depths than is of interest for this study. In most cases, the depths of exploration for buildings and bridges are terminated once the formational materials are encountered, and therefore would provide information useful to only the tunnel portal component.

The geotechnical reports prepared for the two tunnel projects (NEIS and Avenue 45 Sewer) within the study area provide laboratory test information on formational material that is relevant to the current study. EMI (2006) summarized laboratory information from the 2006 Metro SR-710 tunnel report specifically relevant to tunnel design. Information from these previous laboratory test results is presented in Appendix E.2.

3.6.2 Current Laboratory Test Results

A laboratory test program was developed to provide data on relevant engineering properties of the soil and rock that exist within the study area. The intent of the testing program was to supplement the limited data that were obtained from previous exploration programs. The focus of the testing was on characterization of soil and rock properties from the likely depth of the tunnel within each zone.

Selected soil and rock samples were tested for classification, moisture content and density, compressibility, strength, rock characteristic, corrosion potential, and petrographic analysis. The CH2M HILL team selected samples for testing based on formational type, rock weathering and hardness, sample depth related to tunnel, and potential portal zone location.

The laboratory tests were performed by the following companies:

- AP Engineering and Testing, Inc., Pomona, California
- Colorado School of Mines, Golden, Colorado
- Earth Mechanics, Inc., Fountain Valley, California
- Geoscience Consultants, Las Vegas, Nevada
- Geo Test Unlimited, Nevada City, California
- Leighton Consulting, Inc., Irvine, California
- Sierra Testing Laboratories, Inc., El Dorado Hills, California
- Spectrum Petrographics, Inc., Vancouver, Washington

All testing was performed in general accordance with the applicable ASTM standards (ASTM, 2008) or California Test Methods (CTMs) (Caltrans, 1990). Figure 3-4 shows a typical triaxial laboratory testing setup. The type of tests performed on the soil and rock samples collected from the borings are summarized in Table 3-2.

The results of the laboratory testing are presented in Appendix E.1. A table at the beginning of Appendix E.1 presents a summary of the index, physical, strength, and corrosion parameters.

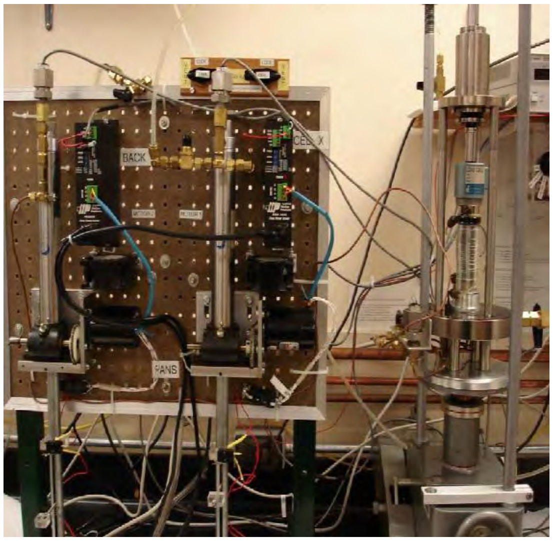


Figure 3-4. Triaxial Laboratory Testing.

TABLE 3-2
Summary of Laboratory Test Methods

Laboratory Test	Test Method
Moisture and Dry Density	ASTM D2937
Moisture Content	ASTM D 2216
Grain Size Distribution	ASTM D422
Atterberg Limits	ASTM D4318
Expansion Index	ASTM D 4829
Consolidation	ASTM D 2435
Direct Shear (Consolidated Drained)	ASTM D3080
Unconsolidated Undrained Triaxial Compressive Strength	ASTM D 2850
Cerchar Abrasivity Index	N/A
Petrographic Thin Section Analysis	N/A
Slake Durability	ASTM D 4645
Point Load Index	ASTM 5731
Elastic Moduli with Compressive Strength	ASTM D7012
Unconsolidated Undrained Triaxial Shear	ASTM D2850
Corrosion Suite (Sulfate, Chloride, pH, Resistivity)	CTM 417, 422 and 532/643

SECTION 4

Regional Geology, Faulting, and Seismicity

4.1 Regional Geology

The regional geology describes the general geological setting and is largely based on existing geological investigations of the study area, supplemented by information collected as part of this exploration program.

4.1.1 Physiography

The SR-710 study area primarily comprises the western San Gabriel Valley, the southern San Rafael Hills, the eastern portion of the Elysian Hills, and the Repetto Hills (as shown in Figure 4-1). These areas are within the transition zone between the northwest-southeast-trending Peninsular Ranges physiographic/geological province on the south and the east-west-trending Transverse Ranges province on the north.

The westernmost part of the SR-710 study area consists of the Elysian Hills at the eastern end of the Santa Monica Mountains (Transverse Ranges). The Repetto Hills consist of a group of small hills and valleys between the Santa Monica Mountains/Elysian Hills and the Puente Hills (Peninsular Ranges) on the southeast. The Repetto Hills include Mount Washington, Monterey Park Hills, and the Montebello Hills, as well as several unnamed hills along the western edge of the San Gabriel Basin. The San Rafael Hills occupy the northwest part of the study area between the Repetto Hills and the Verdugo Hills.

The eastern half of the SR-710 study area is within the San Gabriel Valley and its northwestern counterpart, the Raymond Basin. The San Gabriel Basin is bordered by the Puente Hills and San Jose Hills on the south and east, and by the San Gabriel Mountains on the north.

The San Gabriel Valley is a relatively flat-floored valley between the San Gabriel Mountains on the north, the San Jose Hills on the east, the Puente Hills on the south, and the Repetto/Verdugo/San Rafael hills on the west. The northern margin of the valley is characterized by a series of ancient alluvial fans emanating from the San Gabriel Mountains. The valley floor gently descends southerly from elevations of 700 to 1,000 feet along the northern margin to approximately 300 to 400 feet in the south. The gradual descent is interrupted locally by an arcuate escarpment (ranging from about 10 to 150 feet high) extending from the Monrovia area to the South Pasadena area and westerly into the hills of Glendale and Los Angeles. Associated with this escarpment are closed depressions, springs, reverse-tilted fan surfaces, and small ridges. All of these features are due to fault displacement by the Raymond fault.

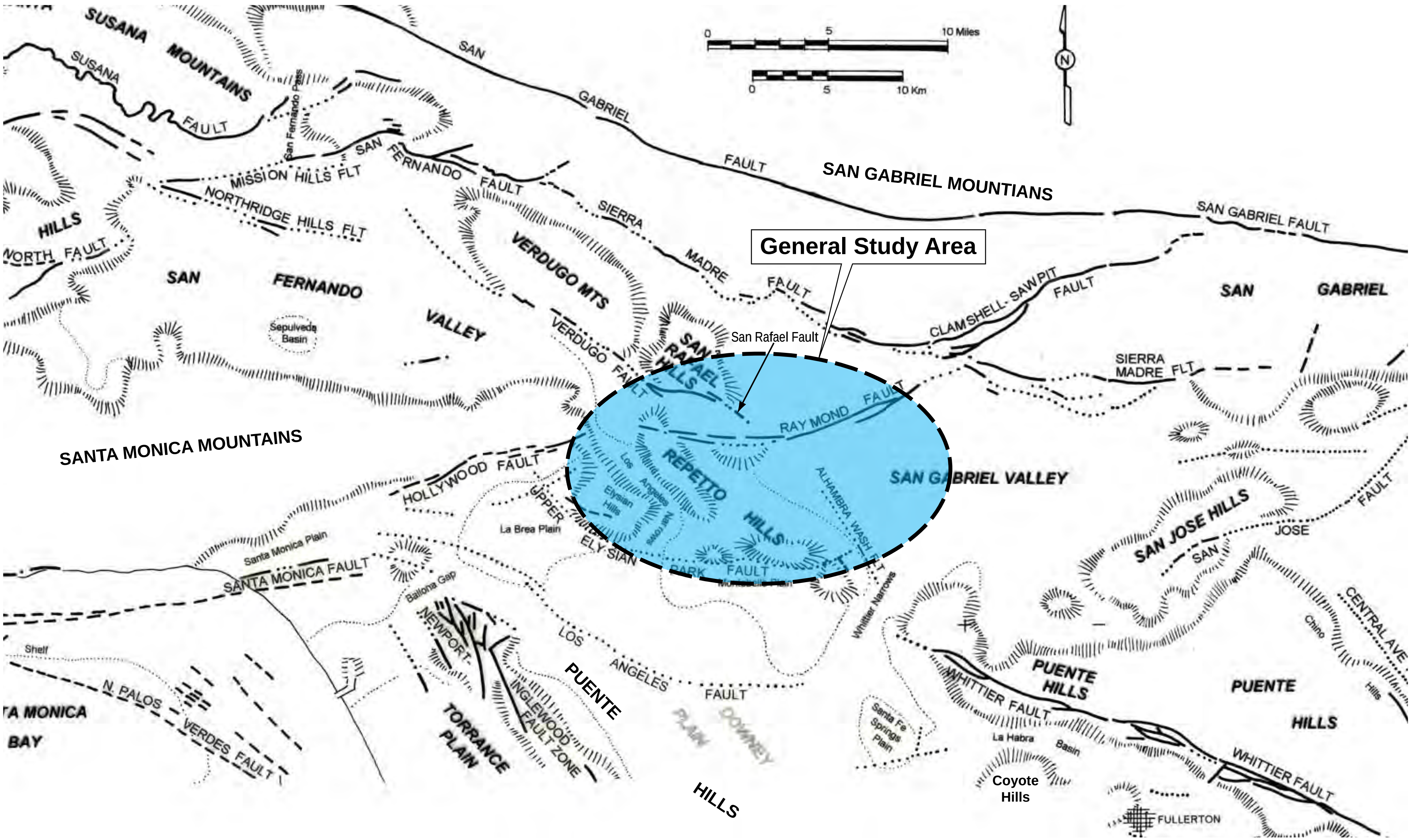


FIGURE 4-1
Map of Major Active Faults and Physiographic Features
SR-710 Tunnel Technical Study

Major drainages in the study area are the Los Angeles River in the west, and the Rio Hondo and San Gabriel River in the east. Smaller intermittent drainages (from west to east) are Arroyo Seco in the Repetto and San Rafael Hills, and the Alhambra/San Pasqual Wash, Rubio Wash, Eaton Wash, Arcadia Wash, and Santa Anita Wash in the western and central parts of the San Gabriel Valley. There are numerous southwest-northeast-trending dry drainages in the Repetto Hills that are remnants (that is, antecedent drainages) of a drainage system that was active during the wetter periods of the Pleistocene ice ages (more than 10,000 years ago).

4.1.2 Stratigraphy

Regional geologic maps (Lamar, 1970; Dibblee, 1989a, 1989b, 1989c, 1998 and 1999; Tan, 2000a and 2000b; Yerkes and Campbell, 2005; Morton and Miller, 2003) confirmed by this study indicate that the SR-710 study area is underlain by nonmarine Quaternary-age (approximately less than 2-million-year-old) alluvium, marine Tertiary-age (approximately 2- to 16-million-year-old) sedimentary rocks, and Cretaceous and Pre-Cretaceous (120 to 160+ million-year-old) crystalline basement complex of igneous and metamorphic rocks (Table 4-1).

TABLE 4-1
Study-Specific Stratigraphic Column

Geologic Unit/ Formation Name	Map Symbol	Geologic Epoch (Period)	Approximate Age (Years)	Generalized Description
Young Alluvium	Qa, Qg, Qal	Holocene (Quaternary)	0-11,000	Sand and gravel with scattered cobbles and boulders and layers/lenses of silt and clay; stream and fan deposits. Poorly defined, lenticular, discontinuous bedding.
Old Alluvium	Qae, Qalo, Qoa, Qof, Qt, Qvoa	Pleistocene (Quaternary)	11,000-2 million	Sand and gravel with scattered cobbles and boulders and layers/lenses of silt and clay; stream and fan deposits. Poorly defined, lenticular, discontinuous bedding.
Fernando	Tfcg, Tfss, Tfsl, Tfs, Tfr	Pliocene (Tertiary)	2-5 million	Predominantly claystone, siltstone and mudstone, with some sandstone and conglomerate. Massive, marine deposits.
Puente (includes Monterey, Modelo, and Unnamed Shale)	Tpsl, Tpsh, Tpds, Tpss, Tpun, Tmy, Tmss, Tmsh, Tmlv	Late Miocene (Tertiary)	5-11 million	Claystone, siltstone, diatomaceous siltstone, mudstone, shale, and sandstone. Laminated to thinly bedded, locally thickly bedded. Marine deposits.
Topanga	Ttss, Ttcg, Ttsl, Ttqdc, Ttsc, Ttqdb	Middle Miocene (Tertiary)	11-16 million	Siltstone, mudstone, sandstone, and conglomerate, with local volcanic intrusions. Thinly to thickly bedded, marine deposits.
Basement Complex Rocks	Wqd, Wqg, Wqm	Cretaceous and Pre Cretaceous	120-160+ million	Crystalline igneous rocks (diorite, quartz diorite, monzonite, foliated igneous rocks) and layered metamorphic rocks (gneiss).

The alluvial deposits are underlain by Tertiary-age sedimentary rocks or basement complex rocks. The Tertiary-age (approximately 2- to 16-million-year-old) rocks crop out in the Elysian, Repetto, and San Rafael hills and underlie the Quaternary deposits in the valleys. These Tertiary-age sedimentary formations consist of the Fernando Formation, Puente Formation, and Topanga Formation. In the northern portion of Zones 3 and 4, the Tertiary-age formations and/or alluvium are underlain by basement complex rocks. These basement complex rocks comprise Cretaceous and pre-Cretaceous-age (approximately 120 to 160-million-year-old) igneous intrusive rocks (diorite, quartz diorite, and quartz monzonite). These igneous rocks commonly have weak metamorphism in the form of aligned dark minerals (foliation). The basement complex rocks contain pre-Cretaceous metamorphic rocks (for example, gneiss). Table 4-1 represents the study-specific generalized stratigraphic column and lists the formations in vertical sequence from youngest to oldest. The following subsections summarize the characteristics of the geologic formations encountered within the study area.

Laboratory test results from current and previous studies (2006 Metro assessment, NEIS tunnel, and East Central Interceptor Sewer [ECIS] tunnel) were reviewed to characterize the strength value of each formational material. In addition to laboratory test results, shear-wave velocity data from downhole instruments, MASW testing and pressuremeter test data were also reviewed to characterize each formation. The results of the unconfined compressive strengths (UCS) for different formational material encountered within the SR-710 study area are presented as a histogram in Figure 4-2. The UCS values are also tabulated in Table 4-2. Laboratory tests were minimal on some of the formational material because of their limited presence in the borings.

TABLE 4-2
Summary of Unconfined Compressive Strength

Geologic Unit	Unconfined Compressive Strength (psi)		
	Minimum	Maximum	Average
Puente Formation	42	15,397	1,717
Topanga Formation	11	8,488	1,431
Fernando Formation	45	451	245
Basement Complex Rocks	35	2,998	684

Alluvial soils typically showed average S-wave velocities below 1,100 feet per second (ft/s), although in some portions, velocities up to 1,600 ft/s were measured. Decomposed and intensely fractured sedimentary bedrock was often found to have S-wave velocity in the alluvial soil range. Intensely to moderately weathered bedrock often had S-wave velocities in the range of 1,100 to 2,000 ft/s. Slightly weathered and fresh bedrock were often found to have S-wave velocities greater than 2,300 ft/s. Therefore, S-wave velocities greater than 1,100 ft/s in the surface wave velocity models were generally associated with bedrock materials. Lower velocities were typically associated with alluvium and sometimes with decomposed bedrock. Summaries of shear wave velocity and pressuremeter data are provided in Tables 4-3 and 4-4, respectively. Table 4-5 summarizes the coefficient of permeability from the packer tests performed on each formation.

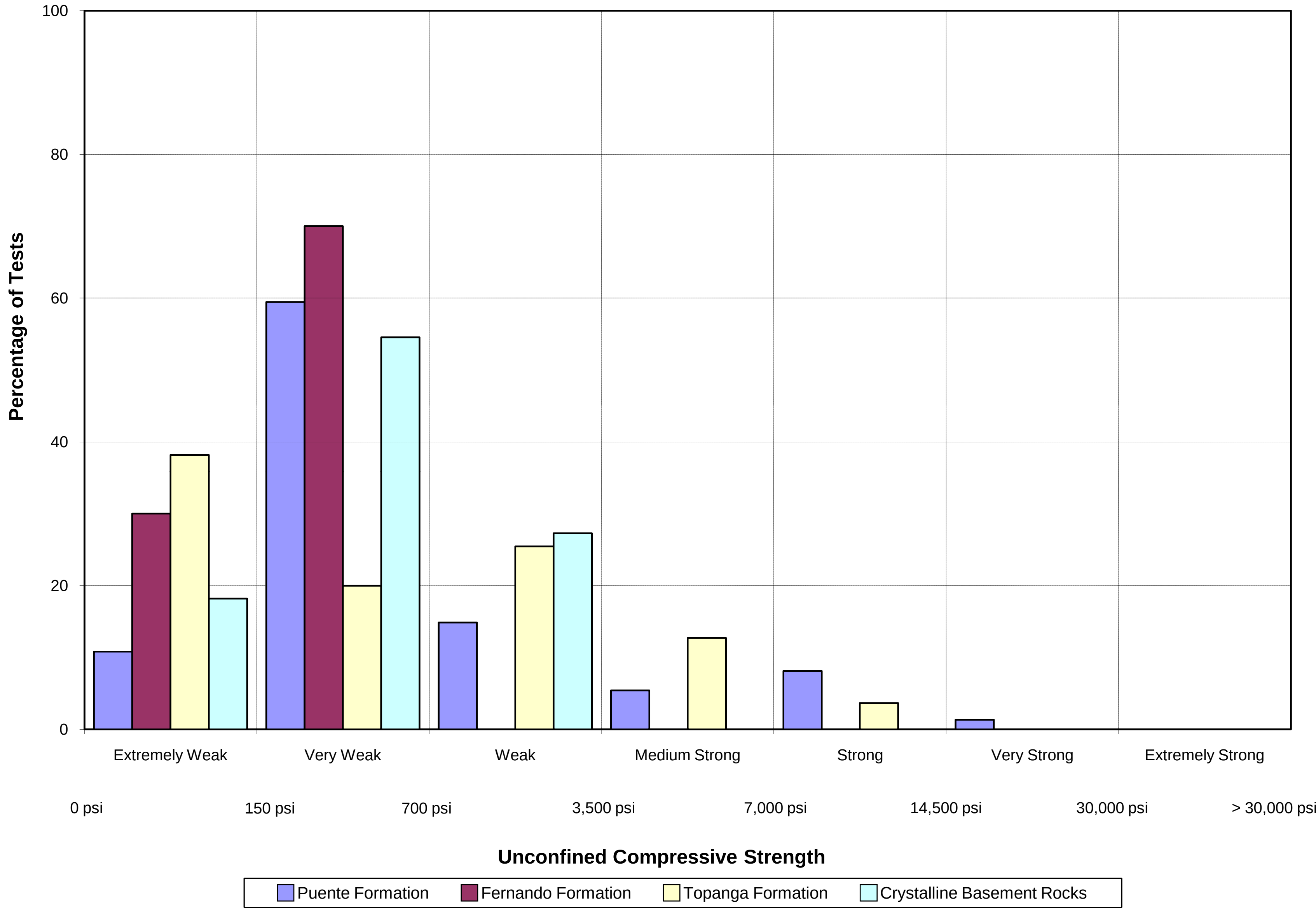


FIGURE 4-2
Unconfined Compressive Strength Histogram
SR-710 Tunnel Technical Study

TABLE 4-3
Summary of Shear Wave Velocity

Geologic Unit	Zone 1			Zone 2			Zone 3			Zone 4		
	Shear Wave Velocity (ft/s)			Shear Wave Velocity (ft/s)			Shear Wave Velocity (ft/s)			Shear Wave Velocity (ft/s)		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Alluvium <50 ft	586	1,608	994	448	1,243	815	449	1,823	1,081	904	1,700	1,242
Alluvium >50 ft	700	1,913	1,095	833	1,390	1,029	583	3,140	1,647	1,022	1,798	1,506
Fernando Formation	-	-	-	-	-	-	877	1,345	1,084	1,022	2,096	1,697
Puente Formation	641	5,126	2,317	982	5,047	2,292	1,334	3,365	2,237	-	-	-
Topanga Formation	-	-	-	666	5,468	2,492	785	6,696	2,928	-	-	-
Basement Complex Rocks	-	-	-	-	-	-	1,600	6,696	3,565	-	-	-

TABLE 4-4
Summary of Pressuremeter Data

Geologic Unit	Shear Strength, Log Method (psi)			Initial Shear Modulus (psi)			Unload/Reload Shear Modulus (psi)		
	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
Fernando Formation	90	350	183	1,600	20,000	11,400	3,600	32,000	14,400
Puente Formation	137	1,280	571	4,000	56,000	25,344	20,000	250,000	107,578
Topanga Formation	40	1,600	396	3,000	69,000	17,888	3,000	450,000	113,750
Basement Complex Rocks	160	800	438	5,500	34,000	21,817	47,000	590,000	246,000

TABLE 4-5
Summary of Packer Test Results

Geologic Unit	Number of Tests	Permeability (ft/sec)	
		Minimum	Maximum
Fernando Formation	7	$2.7X10^{-8}$	$9.1X10^{-8}$
Puente Formation	27	$7.5X10^{-8}$	$7.0X10^{-7}$
Topanga Formation	36	$1.5X10^{-8}$	$1.3X10^{-5}$
Basement Complex Rocks	10	$3.2X10^{-8}$	$4.2X10^{-7}$

4.1.2.1 Quaternary Alluvium

Quaternary alluvial materials are encountered in all of the five zones. The alluvial materials consist of interbedded lenses and/or discontinuous layers of fine-grained soil (clay and silt) and coarse-grained materials (sand and gravel) that generally increase in strength with depth. These materials are generally divided into Young (Qal) and Old Alluvium (Qalo). The Young Alluvium is limited to shallow depths in active drainage channels that currently carry runoff across the area. The Old Alluvium crops out at the surface as alluvial fans and terrace deposits dissected by the active drainage channels. Old alluvial materials underlie Young Alluvium and are observed at deeper depths. Cobble-size rocks are common within the young and Old Alluvium; some boulders also may be scattered throughout the unit.

Figure 4-3 shows alluvial material encountered in boring R-09-Z3B3. The Old Alluvium is slightly more consolidated than the Young Alluvium. Bedding within these deposits is essentially horizontal but is poorly developed, commonly lenticular, and discontinuous. The contact between the alluvial materials and underlying bedrock is expected to be irregular because the alluvium has covered landscapes developed by bedrock erosion. Based on our field exploration program, average shear-wave velocities within the upper 50 feet of the tested alluvium range from 450 to 1,820 ft/s, and from 580 to 3,140 ft/s for tested depths greater than 50 feet.

Figure 4-3. Alluvium. The three cores show a variety of sandy and gravelly alluvium from boring R-09-Z3B3. The core on the left is coarse sand and fine gravel from depths of 130 to 133 feet; the core in the middle is coarse gravel from154 to 159 feet; the core on the right is sand and gravel from 30 to 31 feet.

4.1.2.2 Fernando Formation

The Pliocene-age Fernando Formation consists primarily of low-strength, dark gray to black, massive (unbedded), marine claystone and siltstone. Scattered, locally abundant, and randomly oriented rip-up clasts, in addition to small hard concretions and thin hard layers, occur within the lower portion of this unit. The lower portion grades upward into white-to-brick red, conglomeratic sandstones, conglomerates, and interbedded sandstones, all of which are believed to have been deposited in near-shore marine conditions as a deep marine basin was filled.

The gravel- to cobble-sized rocks of the conglomerate and conglomeratic sandstone consist of hard, well-rounded igneous rocksand up to 40 percent angular fragments of hard sandstone, limestone, and shale similar to the underlying sedimentary rocks in the area. The sandstone is fine-grained, massive, soft, and micaceous with scattered gravel-sized hard-rocks.

Figure 4-4 shows Fernando Formation siltstone encountered in boring R-09-Z4B4. Based on our field exploration program, average shear-wave velocities within the Fernando Formation range from 870 to 2,100 ft/s. Uniaxial compressive strength of Fernando Formation varies from 50 pounds per square inch (psi) to 750 psi. The permeability of the Fernando Formation was measured to be approximately 10^{-7} to 10^{-8} ft/s.

The Fernando Formation overlies the Puente Formation with both conformable and unconformable contacts. According to Lamar (1970), the fine-grained lower and coarse-grained upper units can be over 4,300 and 1,500 feet thick, respectively.

Figure 4-4. Fernando Formation. Core from boring R-09-Z4B4 at a depth of 139 to 144 feet and 233 to 238 feet, showing consistent nature of unbedded siltstone/ mudstone.

4.1.2.3 Puente Formation

The deep-water marine rocks of the late Miocene Puente Formation crop out and/or are anticipated at depth in all of the five zones. Various geologists have assigned different formational names to the same rocks. Such names include Puente, Monterey, Modelo, and Unnamed Shale (Dibblee, 1989a and 1989b; Lamar, 1970; Weber, 1980). These assignments are basically nothing more than nomenclatural preferences of the individuals, but the rocks within the study area largely have similar engineering and tunneling properties. The name Puente Formation, as used by Lamar (1970), is followed throughout this report.

According to the dominant rock type, these rocks are mapped as several members as follows (from older to younger): sandstone (Tpss), shale (Tpsh), diatomaceous siltstone/shale (Tpds), and siltstone (Tpsl) units. The sandstone member (Tpss) consists predominantly of thin to thick bedded fine-grained sandstone and silty sandstone with scattered laminations to thick interbeds of siltstone and shale. Individual beds and intervals of these rocks are friable, weakly cemented, and susceptible to softening in the presence of water, but other beds are strongly cemented. The shale member (Tpsh) consists predominantly of thinly bedded to laminated and fissile shales with thin interbeds to laminations of fine-grained sandstone and siltstones. The diatomaceous siltstone/shale member (Tpds) is represented by thin-bedded to laminated diatomaceous siltstones. Finally, the siltstone member (Tpsl) generally consists of thin-bedded to laminated siltstones with medium to thick interbeds to laminations of fine-grained sandstone. Figure 4-5 shows Puente Formation sandstone and siltstone encountered in borings R-09-Z1B3 and R-09-Z1B6.

The degree of weathering in these rocks decreases with increasing depth from decomposed to fresh. The rocks generally are of low strength with locally hard cemented interbeds and concretions. The observed cemented zones and concretions were generally strong and can be hard to very hard. These cemented zones were not over 3 feet in thickness and are not anticipated to be laterally continuous over long distances. Average shear-wave velocities measured for the Puente Formation range from 640 to 5,130 ft/s. Uniaxial compressive strength of the Puente Formation varies from 50 to 750 psi. Strength of cemented layers and concretions vary from 4,000 to 15,400 psi.

The permeability of the Puente Formation is approximately 10^{-7} to 10^{-8} ft/s. According to Lamar (1970), the thickness of the sandstone, shale, diatomaceous siltstone, and siltstone units in the Repetto Hills are over 800, 300, 950, and 2,700 feet, respectively. The Puente Formation unconformably overlies the Topanga Formation.

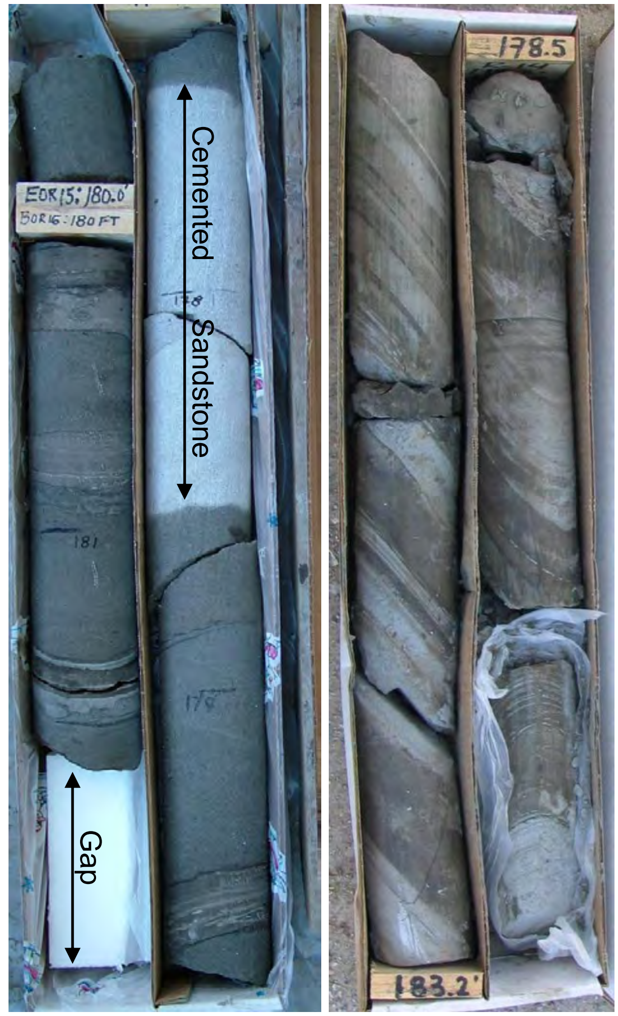


Figure 4-5. Puente Formation. The two cores on the left are from boring R-09-Z1B3 at a depth of 177 to 181 feet and show predominantly thick bedded to thin bedded sandstone with siltstone laminations; the light gray material is hard calcareous-cemented sandstone. The two cores on the right are from boring R-09-Z1B6 at a depth of 178 to 183 feet and show predominantly thin bedded to laminated siltstone and sandstone.

4.1.2.4 Topanga Formation

The middle-Miocene-age Topanga Formation (11 to 16 million years old) occurs as three separate units within Zones 2 and 3 (Lamar, 1970). These units include a lower siltstone member (Ttsl), a middle sandstone member (Ttss), and an upper conglomerate/breccia member (Ttcg). The rocks of the Topanga Formation tend to be coarser-grained north of the Raymond fault.

The siltstone (Ttsl) unit consists of thinly bedded to laminated and fissile siltstones and shales, with fine- to coarse-grained sandstone interbeds that present a rhythmically bedded sequence typical of turbidity current deposits. Figure 4-6 shows the siltstone member (Ttsl) of the Topanga Formation encountered in boring R-09-Z3B7. Hard beds of tuff and tuffaceous sandstones were noted at the upper portion of the unit (Lamar, 1970). At the anticipated tunnel depth, the Topanga Formation might consist of well-bedded, slightly weathered, extremely weak to medium strong, and slightly to moderately fractured rock. The rocks of this unit are commonly very similar to those of the siltstone member of the Puente Formation (Tpsl); some geoscientists, in fact, have mapped them as Puente Formation (Dibblee, 1989b; Weber, 1980).

The sandstone unit (Ttss) consists of well-bedded, medium- to coarse-grained sandstone with thin interbeds and laminations of fine-grained sandstone, siltstone, and/or shale with some conglomerate beds. The sandstone (Ttss) unit at the currently anticipated tunnel depth is slightly weathered to fresh, very soft to moderately soft, friable to low strength, and unfractured to slightly fractured. Individual beds and intervals of these rocks are friable, weakly cemented, and susceptible to softening in the presence of water. Figure 4-6 shows the sandstone member (Ttss) of the Topanga Formation encountered in boring R-09-Z3B7.

Figure 4-6. Topanga Formation. Core on right is conglomerate with sandstone matrix from boring R-09-Z3B6 at a depth of 223 to 226 feet; core in middle is sandstone with siltstone laminations from boring R-09-Z3B7 at a depth of 253 feet; core on left is siltstone/ mudstone from boring R-09-Z3B8 at 258 feet.

The conglomerate/breccia member (Ttcg) generally consists of hard, well-rounded to subangular rock fragments derived from the basement complex of the San Gabriel and Verdugo mountains. Rock fragments of the Topanga Formation are commonly within an uncemented, friable, sandy matrix that allows the hard fragments to be broken out of the matrix with little difficulty. The conglomerate and breccia range from extremely large, house-sized blocks to fine, gravel-sized rock. More commonly, however, the conglomerates consist of rounded, fine gravel and small cobbles in a medium- to coarse-grained friable arkosic sand matrix. Some beds are strongly cemented with calcium carbonate and are hard to very hard and resistant rocks. In addition, this unit includes scattered sandstone beds. Figure 4-6 shows the Topanga Formation conglomeratic member (Ttcg) encountered in boring R-09-Z3B6.

Localized, well-cemented, thin calcareous, and siliceous concretions were encountered scattered through all units of the Topanga Formation. Furthermore, scattered, well-cemented, thin beds and lenses were encountered throughout the formation. The cemented zones, layers, and concretions are generally strong and can be hard to very hard. These hard layers, zones and/or concretions were not observed to be over 3 feet thick and are not anticipated to be laterally continuous over large distances.

Based on our field exploration program, average shear wave velocities within the Topanga Formation range from 660 to 6,700 ft/s. The uniaxial compressive strength of the Topanga Formation varies from 40 to 750 psi. Strength of cemented layers and concretions vary from 3,000 to 11,000 psi. The permeability of the rock within the Topanga Formation was measured to be on the order of 10^{-5} to 10^{-8} ft/s.

4.1.2.5 Basement Complex Rocks

The northern part of Zone 3 consists of the Cretaceous-age basement complex rocks exposed in the San Rafael Hills where it is designated as Wilson diorite or quartz diorite (Dibblee, 1989b; Lamar, 1970). However, these rocks comprise a wide suite of lithologies, including diorite, monzonite, quartz diorite, quartz monzonite, and gneissic diorite. Figure 4-7 shows quartz diorite and metamorphic rocks encountered in boring R-09-Z3B4.

The rock consists primarily of plagioclase feldspars with quartz, hornblende, and biotite. Regardless of the variable lithologies, these rocks have similar engineering properties. Although the rocks are generally hard with strengths as high as 30,000 psi, they are highly fractured. The fracture density is commonly greater than 10 fractures per foot and RQDs are generally zero and rarely greater than 10 percent. The highly fractured nature of the basement rocks makes it difficult to get a sample that will give reliable measurements of rock strength. Based on our field exploration program, average shear-wave velocities within the basement complex rocks range from 1,600 to 6,700 ft/s.

Figure 4-7. Basement Rocks. Igneous and metamorphic rocks from boring R-09-Z3B4. The two cores on right are weathered rocks from a depth of 200 to 205 feet. The two cores on left are fresh rock from 271 to 275 feet.

Although the RQD of the core samples taken from the packer test locations within the basement complex rocks were very poor (typically between 0 and 20 percent), the permeability of the basement rock was measured to be on the order of 10^{-7} to 10^{-8} ft/s. This indicates that the packer test locations were likely disturbed by the presence of mudcake on the borehole walls, thus resulting in low permeability rates as observed during our study. Basement complex rocks were not observed in Zones 1, 2, 4, and 5.

4.1.3 Geologic Structure

The San Gabriel Basin is a large down-warp created by regional north-northeast to south-southwest-directed compressional geological forces that have uplifted the San Gabriel Mountains and folded the rocks in adjacent hills. The Elysian, Repetto, and San Rafael Hills in the western part of the study area are primarily a result of late-Quaternary-age folding and uplift (less than about 500,000 years old). The faults and folds in the hills largely trend southeasterly from the Santa Monica Mountains to the Puente Hills and are commonly referred to as the Elysian Park Fold and Thrust Belt (EPFT) (Davis and Namson, 1998).

Active faults in the SR-710 study area are the Raymond and Alhambra Wash faults. An active fault is defined by the state as a fault that has experienced surface displacement within the Holocene Epoch (roughly the last 11,000 years). The Eagle Rock and San Rafael faults are generally considered to be potentially active. A potentially active fault is defined by the state as a fault that has experienced surface displacement within the Quaternary Period (Hart and Bryant, 2007). There is little compelling evidence that the Eagle Rock or San Rafael faults have been active in Holocene time. Recent trenching investigations across the San Rafael fault did not reveal any displacements within even late Pleistocene-age alluvium.

In addition to any earthquakes on the faults within the study area, large earthquakes on other nearby active faults such as the Hollywood and Sierra Madre faults (Figure 4-1) may impact the study area with strong ground motions (see Section 4.3.2). Such ground motions should be accounted for during design of portals, shafts, and shallow tunnels. Tunnels at greater depths are expected to move simultaneously with the ground during an earthquake, and as such, are expected to perform better than structures at shallower depths. In addition to the surface faults, the study area might be underlain by deep subsurface thrust faults, such as the Upper Elysian Park and the Puente Hills thrust fault system (Figure 4-1). Although these two fault systems may generate shaking strong enough to affect tunnel facilities, the faults are too deep to result in significant deformation at tunnel depths.

4.2 Regional Faulting

The faults of greatest significance to the study are described in detail below. The locations of these faults are shown in Figure 4-1, Plates 1 and 2, and in the representative geologic profiles (Plates 5 through 9). These faults represent earthquake shaking hazards, but only the Raymond and Alhambra Wash faults are identified as Alquist-Priolo Earthquake Fault Zones (APEQFZ), which implies a potential for surface-rupture. Such a designation indicates the fault is well known and its location is well defined. Other potentially active faults may not be identified as APEQFZ simply because their locations are not well defined and/or they have not generated earthquakes in historical time.

4.2.1 Active Faults within Study Area

4.2.1.1 Raymond Fault

One of the major faults in the study area is the Raymond fault. The State of California (CGS) has established an APEQFZ along the Raymond fault from the San Gabriel Mountains in the east to near the intersection of Avenue 50 and York Boulevard on the west. The Raymond fault extends southwesterly from the Sierra Madre fault zone at the base of the San Gabriel Mountains through the communities of Monrovia, Arcadia, San Marino, and Pasadena to the Raymond Hill area of South Pasadena, where the Raymond fault trends more westerly through the communities of South Pasadena, Highland Park, and possibly into Los Angeles (Figure 4-1). Therefore, the Raymond fault crosses the northwestern portion of Zone 2, and all of Zones 3 and 4. The length of the fault is 12 to 15.5 miles long depending upon which interpretation is accepted. The fault forms a gentle arc, convex toward the south across the alluvial deposits of the San Gabriel Valley. The fault is best expressed in the San Marino to South Pasadena area, where it forms a prominent escarpment up to 100 to 150 feet high.

A prominent linear gravity anomaly extending easterly from the southern margin of the Santa Monica Mountains, under the Los Angeles River plain, and into the Repetto Hills indicates that the Hollywood fault may extend easterly into the Repetto Hills, and has led to the interpretation by some that the Hollywood and Raymond faults may be interconnected. However, the westerly continuation of the Raymond fault into the Los Angeles River floodplain is uncertain and the earthquake/rupture histories are somewhat different, (Weaver and Dolan, 2000). Others (e.g. Dolan et al., 1995) have suggested that the Raymond fault may be a tear fault associated with the uplift of the Verdugo Hills. For the purposes of this study, it is assumed that the Raymond and Hollywood faults are independent features. Further evaluation of these faults will be required if the study proceeds to the detailed design stage.

The most recent major surface rupture on the Raymond fault occurred in Holocene time, sometime about 1,000 to 2,000 years ago (Crook et al., 1987; Weaver and Dolan, 2000). The recurrence interval for surface rupturing events may be about 3,300 years (Dolan et al., 2000a; Weaver and Dolan, 2000).

The largest earthquake within this SR-710 study area in historical times was the 1988 Pasadena earthquake with a magnitude (M_L) of 5.0 (M_W of 4.9). This shock was a strike-slip event interpreted by Jones et al. (1990) to have occurred on the Raymond fault.

Most geoscientists consider the Raymond fault to be a left-lateral reverse-oblique fault that dips steeply (approximately 80 degrees) to the north. The fault had long been considered to be a reverse fault due to the 100- to 150-foot-high escarpment that indicated the north side of the fault was uplifted relative to the south side. However, some stream channels appear to be offset laterally (horizontally) by about 1,300 feet, suggesting a lateral vs. vertical ratio of about 13:1. The focal mechanism of the 1988 Pasadena earthquake indicated that the motion of the quake was predominantly left-lateral, with a reverse component of only about one-fifteenth the amount of lateral component. This 15:1 ratio is quite similar to the 13:1 based on surficial data, and together they provide strong evidence that the fault is a left-lateral reverse oblique fault, but primarily a strike-slip feature.

Currently, there is little consensus on the rate of slip. Geological trenching studies across the fault scarp indicate average slip rates between 0.1 and 0.4 millimeters per year (mm/yr) (SCEC, 2009; Dolan et al., 2000a). More recently, the rate of slip has been estimated to be about 1.5 mm/yr, based on regional tectonics (Cao et al., 2003).

The amounts of potential surface displacements on the Raymond fault are poorly known. Buwalda (1940) noted a 4-foot-high scarp at the mouth of Kewan Canyon, but this could have been the result of several displacements. Due to the lack of earthquake history on the Raymond fault, seismic design for the fault must be based on empirical fault/earthquake relationships from worldwide data, such as those of Wells and Coppersmith (1994). The use of the Wells and Coppersmith empirical database to estimate earthquake magnitudes and displacements is the industry standard for seismic design. According to the fault-length/earthquake–magnitude relations of Wells and Coppersmith (1994), and applying the half-length rupture criterion generally used for engineering projects (Albee and Smith, 1966), the fault is capable of generating a maximum earthquake magnitude in the range of 6.1 to 6.5. The maximum earthquake estimated by the CGS (2009) is in the range of M_W equaling 6.0 to 7.0. Caltrans (Merriam and Shantz, 2007) estimates a maximum earthquake of 6.6. Based on a length of 12 miles, a down-dip width of 10 miles, and average slip of 1.6 to 3.3 feet, Weaver and Dolan (2000) estimated a maximum earthquake of M_W 6.7. Assuming rupture of the entire fault, from the San Gabriel Mountains to the Santa Monica Mountains, an M_W 6.7 event would be a worst-case scenario.

Assuming a maximum earthquake of 6.1 to 6.7, the earthquake-magnitude/fault-displacement relationships of Wells and Coppersmith (1994) can be used to estimate likely surface rupture displacement amount per event. Historical earthquakes in the 6.1 to 6.7 magnitude range have generated average displacements of 0.3 to 1.5 feet per event and maximum displacements of 0.8 to 3.4 feet per event. Interestingly, the 3.4-foot estimate is close to the 4-foot-scarp height noted by Buwalda (1940).

4.2.1.2 Alhambra Wash Fault

The Alhambra Wash fault is a short northwest-southeast-trending fault in the southern part of the San Gabriel Valley (Figure 4-1). The surficial expression of the fault is approximately 1.5 miles long extending from I-60 on the southeast to San Gabriel Boulevard on the northwest (CDMG, 1991; Treiman, 1991b). The fault is designated as an APEQFZ and, therefore, is considered to be active. Based on data collected during this study (in particular seismic reflection lines Z4-G2 and Z5-G2, see Appendix C.2), the buried trace of the Alhambra Wash fault likely trends northwest through the western portions of Zones 4 and 5.

Extensive fault trench investigations by Gath et al. (1994), Ehlig (1999), Schell and Hushmand (2002) revealed faults generally dipping to the northeast, with the northeast side down (normal separation). Gath et al. (1994) postulated that the fractures in their trenches were due to three or four fault rupture events in latest Quaternary time with the latest displacement of about 1 to 1.3 feet occurring about 3,000 to 4,000 years ago. Gath et al. (1994) estimated right-lateral, normal oblique slip with a lateral slip rate of about 0.1 to 0.2 mm/yr and a vertical slip rate of about 0.08 mm/yr. Schell and Hushmand (2002) documented two quaternary ruptures, with the last event occurring in Holocene time with about a 1-foot displacement.

Although there is no compelling direct geological evidence, several investigators have considered the fault to continue to the northwest approximately coincident with the Alhambra Wash, which originates in the Raymond Hill region of South Pasadena. Tan (2000b) shows several short, widely scattered fault segments extending northwesterly into the City of Alhambra. Dibblee considers the fault to be an extension of the Workman Hill fault and infers the fault to continue northwesterly well beyond Valley Boulevard into the city of Alhambra. However, Yeats (2004) indicates that there is no oil well data to support such an interpretation and states that the associated geomorphic features do not extend northwest of I-10.

Contours of the historically highest groundwater in the southwest San Gabriel Valley change direction quite abruptly at the northwesterly projection of the Alhambra Wash fault (CDMG, 1998b) suggesting that the fault forms a groundwater barrier in Quaternary-age sediments. The edge of the groundwater barrier extends beyond I-10 approximately to Mission Road in central Alhambra. Seismic reflection lines Z4-G2 and Z5-G2 from this investigation across the fault projection appear to have revealed faults within Quaternary sediments in line with the northwesterly projection of the fault (see Sections 10 and 11 and Plate 2).

The potential for surface displacement on the Alhambra Wash fault is poorly known and, like the Raymond fault, must be based on empirical earthquake relationships. Using worldwide empirical data on earthquake magnitude and fault length as documented by Wells and Coppersmith (1994), the maximum magnitude of an event on the Alhambra Wash fault could be about 6.25. Based on this, potential surface rupture displacement along the Alhambra Wash fault would be expected to be much less than those that would be expected along the Raymond fault discussed above.

4.2.2 Potentially Active Faults Within Study Area

4.2.2.1 Eagle Rock and San Rafael Faults

Existing geological maps (Lamar, 1970; Dibblee, 1989b and 1989c; Yerkes and Campbell, 2005; City of Pasadena, 2002; LAI, 1990) show different locations for the Eagle Rock and San Rafael faults. The principal difference is that Lamar (1970) maps the San Rafael and Eagle Rock faults as separate features. The San Rafael fault extends southeasterly from within the San Rafael Hills to the north edge of Grace Hill, Raymond Hill and the smaller associated knolls, essentially along the same trace as Dibblee's Eagle Rock fault. At the eastern end, Lamar splits the fault into two splays or branches—one extends through the top of Raymond Hill, and the other is a dotted line (that is, a subsurface fault) trending more easterly past Arroyo Parkway and into the hills north of the main trace of the Raymond fault. Lamar maps the Eagle Rock fault to the south of the San Rafael fault within the knolls and projecting south of Raymond Hill (Plate 1). The differences between the fault mapping are not really significant from an earthquake hazard perspective, but the differences might be important for tunneling, in that if there is only one fault (as indicated by Dibblee), the tunnel could pass through faulted rocks in a shorter distance than if there were two separate faults (as indicated by Lamar). Borehole R-09-Z3B3 excavated during this study (Plate 1 and Appendix A.1) encountered a significant zone of fault gouge believed to be the San Rafael fault. The Eagle Rock and San Rafael faults do not extend across the Raymond fault and transect solely Zone 3.

Both the Eagle Rock and San Rafael faults are considered potentially active faults, as defined in Section 4.1.3. According to the Caltrans Seismic Design Criteria (2009) fault database, the Eagle Rock fault is estimated as having a maximum earthquake magnitude of 6.8. Although the San Rafael fault is not well documented, the approximate magnitude of the maximum earthquake can be estimated using worldwide empirical data on earthquake magnitude and fault length data as documented by Wells and Coppersmith (1994). According to these empirical relationships, the maximum magnitude could be about 6.0.

4.2.2.2 Unnamed Fault Zone (Formerly the York Boulevard Fault)

In 1970 Lamar mapped a northwest trending fault along York Boulevard (within Zone 2) and referred to it as the York Boulevard fault. However, subsequent construction of SR-2 produced rock exposures that revealed errors in previously mapped surface geology that was used to infer the presence of the York Boulevard fault. After a subsequent study and evaluation of the newly exposed surface geology along SR-2, Lamar (1975) concluded that his York Boulevard fault is not exposed in that area. As a result, the existence of that fault was later officially rescinded by CDMG (1975). However, Dibblee (1989b) shows a fault along the base of the hills along the south margin of the valley and continues usage of the name York Boulevard fault. Furthermore, drilling in the South Pasadena area (Plate 7) has revealed several anomalous conditions that support the existence of one or more faults along the south side of the valley, approximately parallel to the Raymond fault. In this report, this fault is referred to as the unnamed fault zone.

Seismic-reflection line Z2-G1 (Appendix C.2) near the western end of Zone 2 indicates two faults, one north of York Boulevard and one to the south. These features are in proximity to a groundwater barrier at the nearby Sparkletts plant. All of these features provide compelling evidence for a zone of young faulting within the York Boulevard valley, extending as far west as about Eagle Rock Boulevard. At this time, it is uncertain whether these features represent branches of the Raymond fault, or whether they represent separate faults. The zone of faulting is expected to cross the northwestern portion of Zone 2.

4.2.3 Regional Faults Outside the Study Area

4.2.3.1 Hollywood Fault (Southern Frontal Fault System)

One of the major fault systems in the Los Angeles Basin is along the southern edge of the Santa Monica Mountains separating Mesozoic plutonic rocks from Tertiary and Quaternary sedimentary rocks. The fault system, commonly referred to as the Southern Frontal Fault System of the Transverse Ranges, consists of the Santa Monica, Hollywood, Malibu Coast, and smaller segments such as the Potrero faults (Figure 4-1).

The Santa Monica Mountains rise abruptly to 1,500 to 2,000 feet above the Los Angeles Basin floor and are indicative of a large vertical component of faulting. Earthquake focal mechanisms and local geologic relationships suggest a predominance of reverse faulting with a subordinate left-lateral component. Geodetic data indicate that vertical uplift exceeds the left lateral shift in the Los Angeles area by more than about a 3:1 ratio (Argus et al., 1999).

Investigations for the Metro Rail Red Line drove a tunnel through the Hollywood segment of the fault system and found a major fault zone with the plutonic rocks of the Santa Monica Mountains uplifted and thrust over Quaternary alluvium and colluvium. The fault zone consists of a northerly dipping fault zone about 115 feet wide within a sheared gouge zone approximately 330 feet wide (Guptill et al., 1997).

The great length of the Southern Frontal fault system suggests that the fault is capable of generating a large earthquake (approximately 7.5 magnitude), but the discontinuous nature of faulting suggests that the individual fault segments might behave independently. The shorter segments would not be expected to generate a maximum earthquake as large as 7.0. Dolan et al. (1997) postulated an event of approximately M_w 6.6 for the Hollywood fault. The earthquake recurrence interval is very long and could be approximately a few thousand years. In addition, documented slip rates are less than 1.0 mm/yr, but this estimate suffers from lack of data on the lateral slip (Dolan et al., 1997). The CGS (2009) assumes a slip rate up to about 1.0 mm/yr (+/- 0.5 mm). The Hollywood fault is mapped northwest of Zone 1 and west of Zone 2, as shown in Plate 1.

4.2.3.2 Elysian Park Fold and Thrust Belt

The Elysian Park Fold and Thrust Belt (EPFT) was initially described by Davis et al. (1989) who postulated that the Los Angeles area is underlain by a deep master detachment fault and that most of the uplift in the region is caused by slip along the detachment that results in folding and blind-thrust faulting at bends and kinks in the detachment fault. The detachment/blind-thrust model was initially embraced primarily because the 1987 Whittier earthquake occurred near one of the postulated thrust ramps beneath the EPFT. Subsequent work (for example, Shaw and Suppe, 1996; Oskin et al., 2000; Bullard and Lettis, 1993; Shaw and Shearer, 1999; Shaw et al., 2002) has highly modified the original model, and currently most seismic hazard analyses recognize only the Upper Elysian Park Thrust (shown in Figure 4-1).

Shaw and Suppe (1996) estimated earthquake magnitudes associated with these thrust faults ranging from 6.6 to 7.3, with recurrence intervals in the 340 to 1,000 years range. The CGS, following the lead of Oskin et al. (2000), models the Upper Elysian Park Thrust as a feature about 11 miles (18 kilometers) long and dipping 50 degrees northeasterly with a slip rate estimate of approximately 1.3 ± 0.4 mm/yr. As currently understood, the down-dip projection of the Upper Elysian Park Thrust underlies Zones 1 and 2, roughly the southern half of Zone 3, and likely the western portions of Zones 4 and 5.

Although the EPFT might generate strong ground motion within the study area, it is not considered to be capable of generating surface rupture.

4.2.3.3 Puente Hills Fault System

The Puente Hills Thrust fault system is the name currently given to a series of northerly dipping subsurface thrust faults (blind thrusts) extending approximately 25 to 28 miles (40 to 45 kilometers) along the eastern margin of the Los Angeles Basin (Figure 4-1). Shaw and Shearer (1999) synthesized oil company data and seismicity to interpret three discrete thrust faults underlying the La Brea/Montebello Plain, Santa Fe Springs Plain, and Coyote Hills. These faults are similar to faults previously named the Las Cienegas and Norwalk faults (Wright, 1991; Harding and Tuminas, 1988; Schell, 1997). These faults form an en-echelon arrangement from the northern Los Angeles Basin to the southern part of the Puente Hills (Figure 4-1).

Down-dip projection of the Santa Fe Springs segment of the Puente Hills faults extends to the approximate area of the 1987 Whittier earthquake hypocenter, which Shaw and Shearer (1999) relocated to about 10 miles depth. Subsequent work on the fault system (Shaw et al., 2002) infers that the en-echelon segments of the Puente Hills Thrust are related, and displacements are gradually transferred from one segment to the next. Using empirical data on rupture area, magnitude, and co-seismic displacement, Shaw et al. (2002) estimated a potential for earthquakes of M_W 6.5 to 6.6 for individual segments and a M_W 7.1 for linked ruptures. The recurrence intervals for these events are approximately 400 to 1,320 years for single events and 780 to 2,600 years for magnitude 7.1 events. The most recent seismic hazard model by the Cao et al. (2003) uses a slip rate of 0.7 ±0.4 mm/yr.

The exact geometry and location of the Puente Hills fault system is unclear, the fault system may extend north and underlie all five zones at depth. Although the Puente Hills fault system might generate strong ground motion at the site, it is not considered to be capable of generating surface rupture.

4.3 Regional Seismicity

4.3.1 Historical Seismicity

The study area is located within seismically active Southern California. The present-day seismotectonic stress field in the Los Angeles region is one of north-northeasterly compression. This is indicated by the geologic structures, by earthquake focal-mechanism solutions, and by geodetic measurements (global positioning system [GPS] and very long baseline interferometry [VLBI]). These data suggest crustal shortening of between 5 and 9 mm/yr across the greater Los Angeles area and less than 2.5 mm/yr extension in the east-west direction. About 6 mm/yr occur in the study region, but much of this occurs on the Sierra Madre fault just north of the study area.

Historical epicenter maps show widespread seismicity throughout the region. Although the historical earthquakes occur near known faults, the earthquakes are difficult to directly associate with mapped faults. Part of this difficulty is due to the fact that the basin is underlain by several subsurface thrust faults (blind faults). The largest historical earthquakes in the region were the 1994 Northridge, the 1971 San Fernando, the 1933 Long Beach, the 1987 Whittier, and the 1988 Pasadena earthquakes (Figure 4-8). The 1994 Northridge earthquake had a moment magnitude (M_W) of about 6.7 (M_S 6.8, M_L 6.4), and occurred on a southerly dipping subsurface fault, which was unknown prior to the earthquake. The epicenter of the event was in the center of the San Fernando Valley. The main shock occurred at a depth of about 12 miles (19 kilometers). Earthquake aftershocks clearly defined the rupture surface dipping about 35 degrees southerly from a depth of about 1.2 to 1.9 miles (2 or 3 kilometers) to 14 miles (23 kilometers) (Hauksson et al., 1995).

The 1971 San Fernando earthquake (M_W 6.7, M_S 6.4, M_L 6.4) was of similar size to the 1994 event but involved surface rupture. The 1971 event occurred on a northerly dipping thrust fault that dips from the northern side of the San Fernando Valley to a depth of about 9 miles (15 kilometers) under the San Gabriel Mountains. Several mapped surface faults were involved such as the Sylmar, Tujunga, and Lakeview faults. These faults are commonly considered to be part of the Sierra Madre fault system, which extends northwesterly from the north side of the San Gabriel Valley into the San Fernando Valley and easterly to the Cucamonga fault in the San Bernardino area.

Another major historical earthquake in the Los Angeles region was the 1933 Long Beach event, which had a magnitude of about M_W 6.4 (M_L 6.3). This earthquake did not rupture the surface but is believed to have been associated with the Newport-Inglewood Structural Zone (NISZ), a major strike-slip fault in the Los Angeles Basin (Benioff, 1938). The association was based on abundant ground failures along the NISZ trend (but no unequivocal surface rupture was identified). Reevaluation of the seismicity data by Hauksson and Gross (1991) relocated the 1933 earthquake hypocenter to a depth of about 6 miles (9.6 kilometers) below the Huntington Beach-Newport Beach city boundary.

The 1987 Whittier earthquake (M_L 5.9, M_W 5.9) occurred on the Puente Hills Thrust fault which is a subsurface fault dipping under the Puente Hills to about 10 miles (16 kilometers) beneath the San Gabriel Basin (Shaw and Shearer, 1999). This event did not rupture the ground surface.

Two small but locally significant earthquakes occurred in the Pasadena region in 1988 and 1991 (Figure 4-8). The 1988 earthquake had a magnitude of 5.0 (M_L) (M_W 4.9) and might have occurred on the Raymond fault at a depth of about 10 miles (16 kilometers) (Jones et al., 1990). Focal-mechanism solutions indicate that this event was associated with left-lateral, strike-slip faulting. The 1991 earthquake had a magnitude of 5.8 (M_L) and occurred at a depth of about 7.5 miles (12 kilometers) below the San Gabriel Mountains. The focal mechanism indicated pure thrust faulting. This event is believed by Hauksson (1994) to have occurred on a splay of the Sierra Madre fault zone called the Clamshell-Sawpit fault.

4.3.2 Seismic Ground Shaking

Seismic analysis for highway projects in California generally uses the parameters for ground shaking as defined by Caltrans in terms of its Deterministic Peak Ground Acceleration (PGA) Map (Merriam and Shantz, 2007) and the probabilistic criteria presented in Appendix B of Caltrans Seismic Design Criteria (Caltrans, 2009). PGA contours from the Caltrans 2007 map within the study area are shown in Figure 4-9, as well as the five study zones. The map shows the maximum strength of earthquake shaking expected as a percentage of gravitational acceleration (g).

Review of the 2007 Caltrans map indicates that the faults with the most impact on the seismic design for the study area are the Puente Hills Blind Thrust with some lesser affects from the Raymond, Upper Elysian Park Blind Thrust, and Eagle Rock faults. According to the map, the PGA varies from 0.8 g to 0.9 g in the northern and southern parts of Zone 1, respectively. In Zone 2, the PGA varies from 0.7 g near the northwest corner and 0.8 g near the southern boundary. The PGA in Zone 3 varies from 0.7 g to 0.8 g from north to south, respectively. In Zone 4, the PGA is 0.8 g near the southern end, 0.7 g in the central portion of the zone, and 0.6 g near the northern end. In Zone 5, the PGA is 0.6 g at the northeast corner, 0.7 g in the central portion of the zone, and 0.8 g at the west end.

These PGA values are preliminary and provide a basis for comparison of all five zones. However, Caltrans procedures commonly require several adjustments to these values based on fault type (such as strike slip faults and thrust faults) and for distance from the faults. The final design values will need to consider these additional adjustment parameters.

4.3.3 Other Seismic Hazards

The levels of ground shaking as discussed above are high. The consequences of these ground motions could include the following:

- **Liquefaction of loose, cohesionless soil located in the upper 50 to 75 feet of saturated loose to medium-dense alluvium.** The potential for liquefaction will depend on a combination of the density of the soil, the grain-size distribution, the depth below the ground surface, and the location of the water table. Consequences of liquefaction could include loss in bearing capacity of foundations, lateral flow or spreading of the ground, and post-earthquake settlement. These mechanisms will be of primary importance to the tunnel portal zones.

- **Slope instability or movement of sloping ground.** The potential for instability will depend on the degree of slope, strength of the soil, groundwater location, and level of ground shaking. Consequences of slope instability could include loading to structures located in ground that moves. Again, this effect will be of primary concern for the design of portal structures.

- **Seismic earth pressure loads to buried structures and retaining walls.** These lateral loads will depend on the type of structure or retaining wall, the characteristics of the soil behind the wall or around the structure, and the level of ground shaking. Seismic earth pressures are also primarily a surface loading consideration at tunnel portals.

These seismic hazards are routinely addressed during the design phase. Experience during earthquakes in the Los Angeles area has demonstrated that current design methods are sufficient for handling these types of design issues.

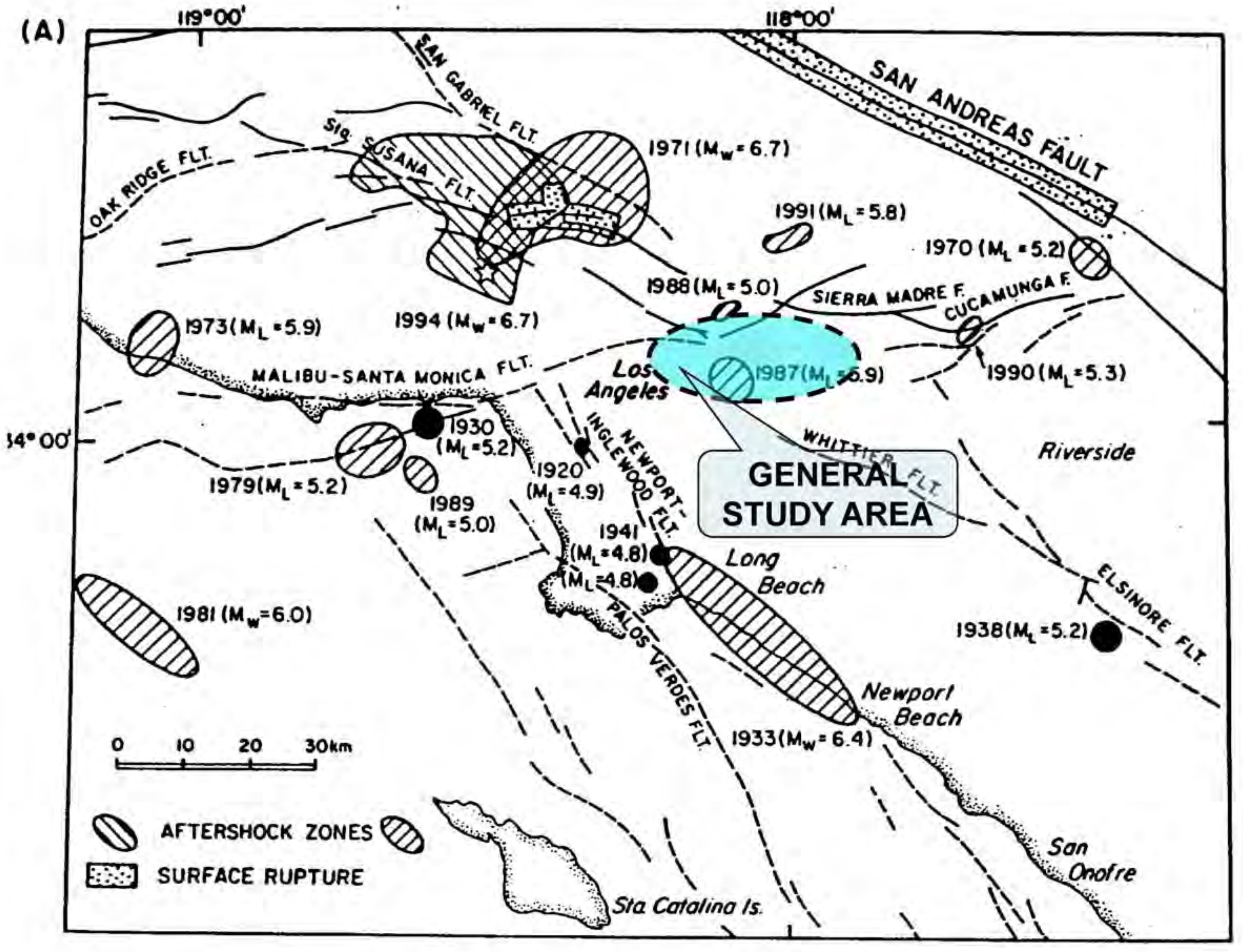
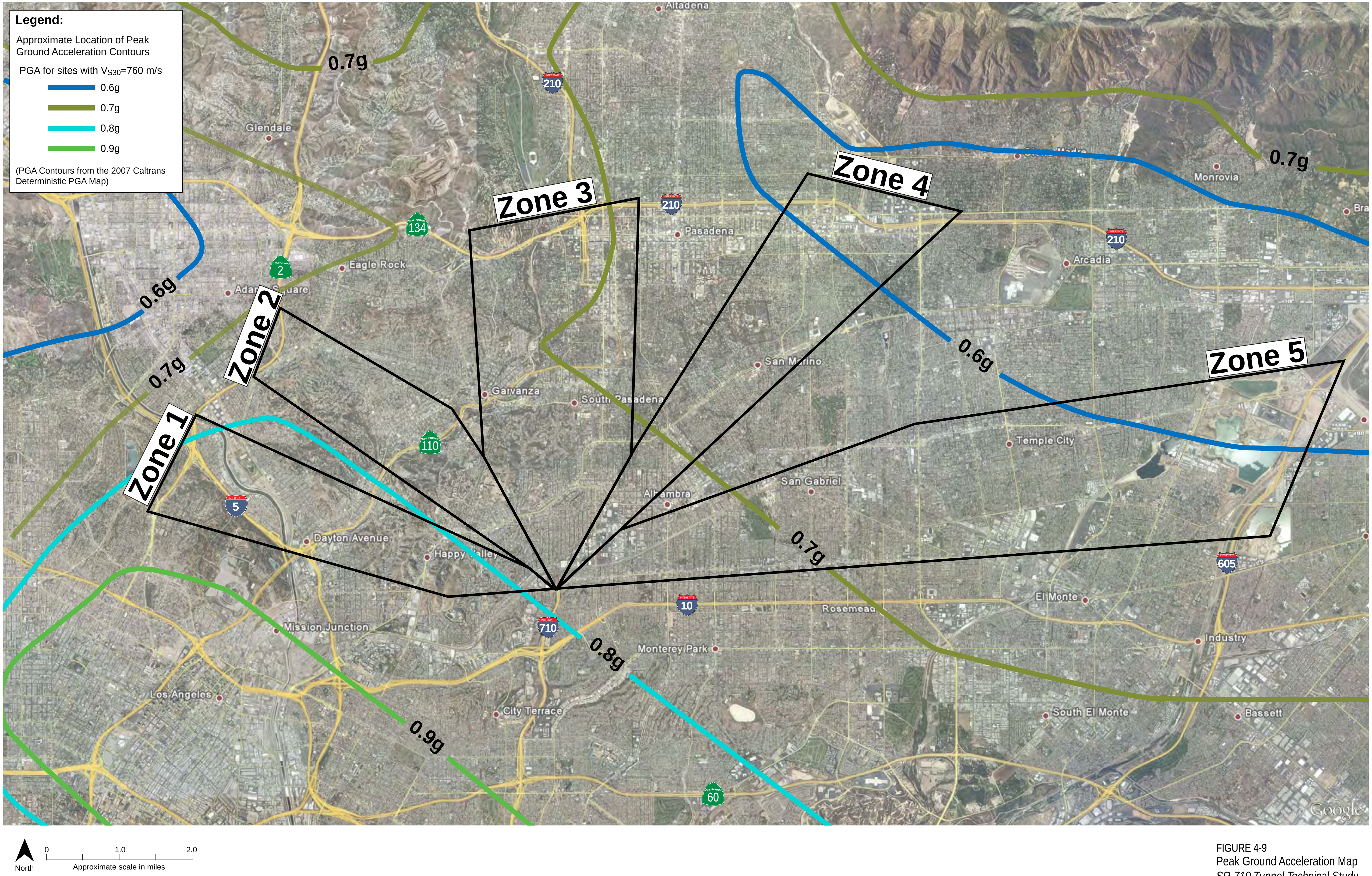


FIGURE 4-8
Regional Seismicity Map
SR-710 Tunnel Technical Study
CH2MHILL



Aerial image © Google Earth, 2010. Annotation by CH2M HILL, 2010.

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FIGURE 4-9
Peak Ground Acceleration Map
SR-710 Tunnel Technical Study

CH2MHILL

SECTION 5

Groundwater Evaluation

5.1 Review of Groundwater Data

Readily available groundwater reports, publications, and/or data were compiled and reviewed from public agencies including the CDWR, the CGS (formerly CDMG), the City of Los Angeles, the LADPW, MSGW, and the RBMB. Also, unpublished reports available in company files and technical reports by other consultants were reviewed. In addition, groundwater information collected from piezometers installed during this study was evaluated to determine the groundwater conditions within the study zones. A complete list of the references compiled and reviewed is presented in Section 16 of this report.

The groundwater conditions for Zone 1 are reported in the following references. As part of their report on geologic aspects of tunneling in the Los Angeles area (Yerkes et al., 1977) provide general groundwater depth information for areas along the Los Angeles River. More specific groundwater monitoring data for the Los Angeles River, for the period of December 1993 to December 2006, are provided as part of the study of the Pollock Area of the San Fernando Superfund site (CH2M HILL, 2007). Approximately seven groundwater monitoring wells have been monitored on a quarterly or annual basis. Groundwater information from seven borings drilled in Zone 1 also was compiled.

Groundwater level data for Zone 2 were obtained from the LACDPW Web site for the northwesternmost portion (LACDPW, 2009). Groundwater data for the Arroyo Seco area were obtained from the City of Los Angeles (2006a and 2006b) and PET (2004). These later sources not only provide groundwater data but also present detailed boring logs and cross sections that interpret the hydrogeologic conditions in that area. Groundwater information also was collected from five borings drilled in this zone.

Groundwater levels for Zones 3, 4, and 5, and the entire San Gabriel and Raymond groundwater basins, were obtained from the MSGW (2006) and the RBMB (2006 and 2007). Geologic, groundwater, environmental and aquifer data for the west and central portions of the San Gabriel basin were obtained from CDM (1998, 2006, 2008a and 2008b), GeoSyntec (2006a and 2006b), CH2M HILL (2003, 2006, and 2009c), and Stetson (2005). Groundwater information for Zone 3 was obtained from 12 borings drilled as part of this study and 3 borings drilled as part of the 2006 Metro Assessment. In particular, the CH2M HILL (2009c) report provides a detailed discussion of the groundwater conditions for the Alhambra area of Zones 3, 4, and 5. These reports not only provide groundwater and environmental data but also present cross sections interpreting the hydrogeologic conditions.

5.2 Site Setting

The five study zones for the SR-710 Tunnel Technical Study are located across several alluvial groundwater basins, which are separated by bedrock upland areas. The study zones are located in the San Fernando, Eagle Rock, Central, Raymond, and San Gabriel groundwater basins. The study zones, groundwater basins, and bedrock upland areas are shown in Figure 5-1.

The groundwater basins contain permeable alluvial materials that can transmit large amounts of groundwater. Groundwater from these basins is a primary source of the water supply for the region. The basins are adjudicated as a result of historical overdraft conditions. A brief description of these basins is provided below (CDWR, 2003).

- The San Fernando Valley Groundwater Basin includes the water-bearing sediments beneath the San Fernando Valley, Tujunga Valley, Browns Canyon, and the alluvial areas surrounding the Verdugo Mountains near La Crescenta and Eagle Rock. The basin is bounded on the north and northwest by the Santa Susana Mountains, on the north and northeast by the San Gabriel Mountains, on the east by the San Rafael Hills, on the south by the Santa Monica Mountains and Chalk Hills, and on the west by the Simi Hills. The water-bearing sediments consist of the lower Pleistocene Saugus Formation (not observed within the study area), and Pleistocene and Holocene alluvium. The groundwater in this basin is mainly unconfined with some confinement within the Saugus Formation in the western part of the basin and in the Sylmar and Eagle Rock areas.
- The Raymond Basin includes the water-bearing sediments bounded by the contact with consolidated basement rocks of the San Gabriel Mountains on the north and the San Rafael Hills on the southwest. The west boundary is delineated by a drainage divide at Pickens Canyon Wash. The southeast boundary is the Raymond fault, which acts as a barrier to groundwater flow southward into the San Gabriel Basin. The water-bearing materials of the Raymond Basin are dominated by unconsolidated Quaternary alluvial gravel, sand, and silt deposited by streams flowing out of the San Gabriel Mountains. Water in the alluvium is typically unconfined.
- The San Gabriel Valley Groundwater Basin includes the water-bearing sediments underlying most of the San Gabriel Valley. This basin is bounded on the north by the Raymond fault and the contact between Quaternary sediments and basement rocks of the San Gabriel Mountains. Exposed consolidated rocks of the Repetto, Merced, and Puente Hills bound the basin on the south and west. The Chino fault and the San Jose fault form the eastern boundary. The water-bearing materials of this basin are dominated by unconsolidated to semi-consolidated alluvium deposited by streams flowing out of the San Gabriel Mountains. These deposits include Pleistocene and Holocene alluvium and the lower Pleistocene San Pedro Formation (not observed within the study area).
- The Central Basin is bounded on the north by a surface divide called the La Brea high, and on the northeast and east by emergent less-permeable Tertiary rocks of the Elysian, Repetto, Merced, and Puente Hills. Throughout the Central Basin, groundwater occurs in Holocene and Pleistocene sediments. The Central Basin is historically divided into forebay and pressure areas. In the study area, the Los Angeles forebay of the Central Basin has unconfined groundwater conditions.

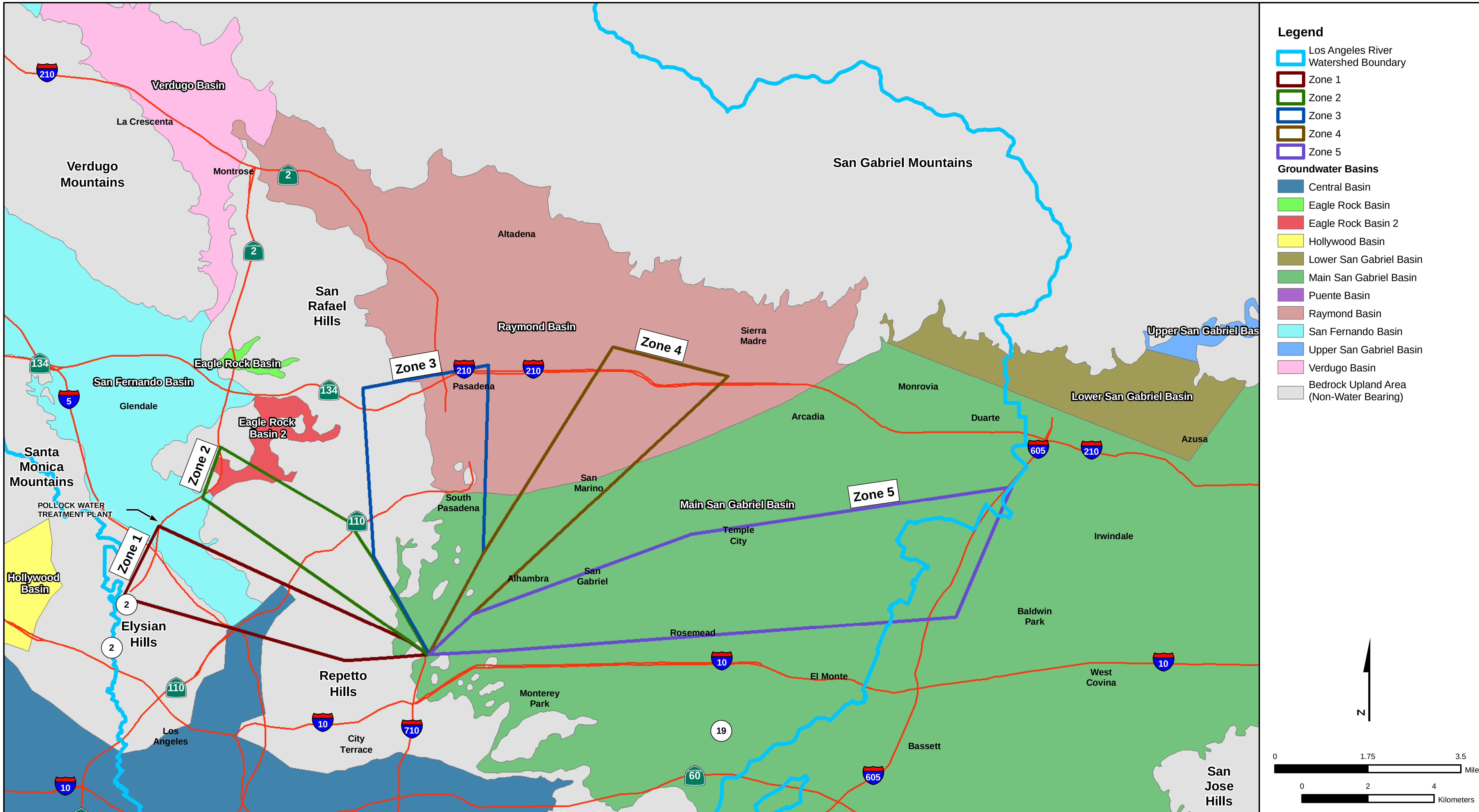

Figure 5-1
Groundwater Basins
SR-710 Tunnel Technical Study
Los Angeles County, California

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5.3 Use of Water Resources

5.3.1 Groundwater

A multitude of groundwater production wells and several groundwater monitoring wells and geotechnical borings have been drilled and/or installed within all the five groundwater basins by the CDWR, City of Los Angeles, LACDPW, USEPA, and different consulting firms. As a result, it is concluded that the Los Angeles River portion of Zone 1, the eastern half of Zone 3, and the entire Zones 4 and 5 are located in active groundwater extraction basins that have constituted a very important local source of groundwater since the foundation of the communities throughout the area.

The unconfined aquifer along the Los Angeles River is being utilized by the LACDPW through wells located at their Pollock Treatment Plant. The Pollock Treatment Plant extracts and treats groundwater for local distribution to water users in the City of Los Angeles. Groundwater is being extracted by LACDPW via a minimum of two active water wells located at the northwestern portion of Zone 2. The very shallow unconfined aquifer along the Arroyo Seco does not appear to be used for water consumption (LACDPW, 2009).

The unconsolidated alluvial sediments of the San Gabriel and the Raymond groundwater basins constitute important groundwater basins in Southern California. The deep aquifers in both groundwater basins have been actively exploited for the last few decades by local communities as a source of groundwater. A multitude of groundwater extraction wells are located throughout the basin and are used by different water management boards and water districts. Bedrock units are generally considered to be non-water bearing. The study zones, groundwater basins, and bedrock upland areas are shown in Figure 5-1.

5.3.2 Surface Water

The five study zones for the SR-710 technical study area located within the Los Angeles River Watershed, which covers over 834 square miles from the eastern portions of Santa Monica Mountains to the San Gabriel River Watershed in the east. The San Gabriel River Watershed covers approximately 640 square miles. The study zones and surface water features are shown in Figure 5-2.

The Los Angeles River flows from its headwaters in the mountains in northwestern Los Angeles County into the San Fernando Valley and eastward to the northern corner of Griffith Park where the channel turns southward through the Los Angeles Narrows before it flows south across the coastal plain to the Pacific Ocean. The Los Angeles River is confined within a concrete and riprap-lined aqueduct in most of the SR-710 tunnel study area; however, small portions are open and allow infiltration into the alluvium underlying the aqueduct. Major tributaries in the study area drain the San Gabriel Mountains and include Arroyo Seco, Compton Creek, and Rio Hondo. There are spreading grounds and open quarries along these tributaries that capture surface water for groundwater recharge.

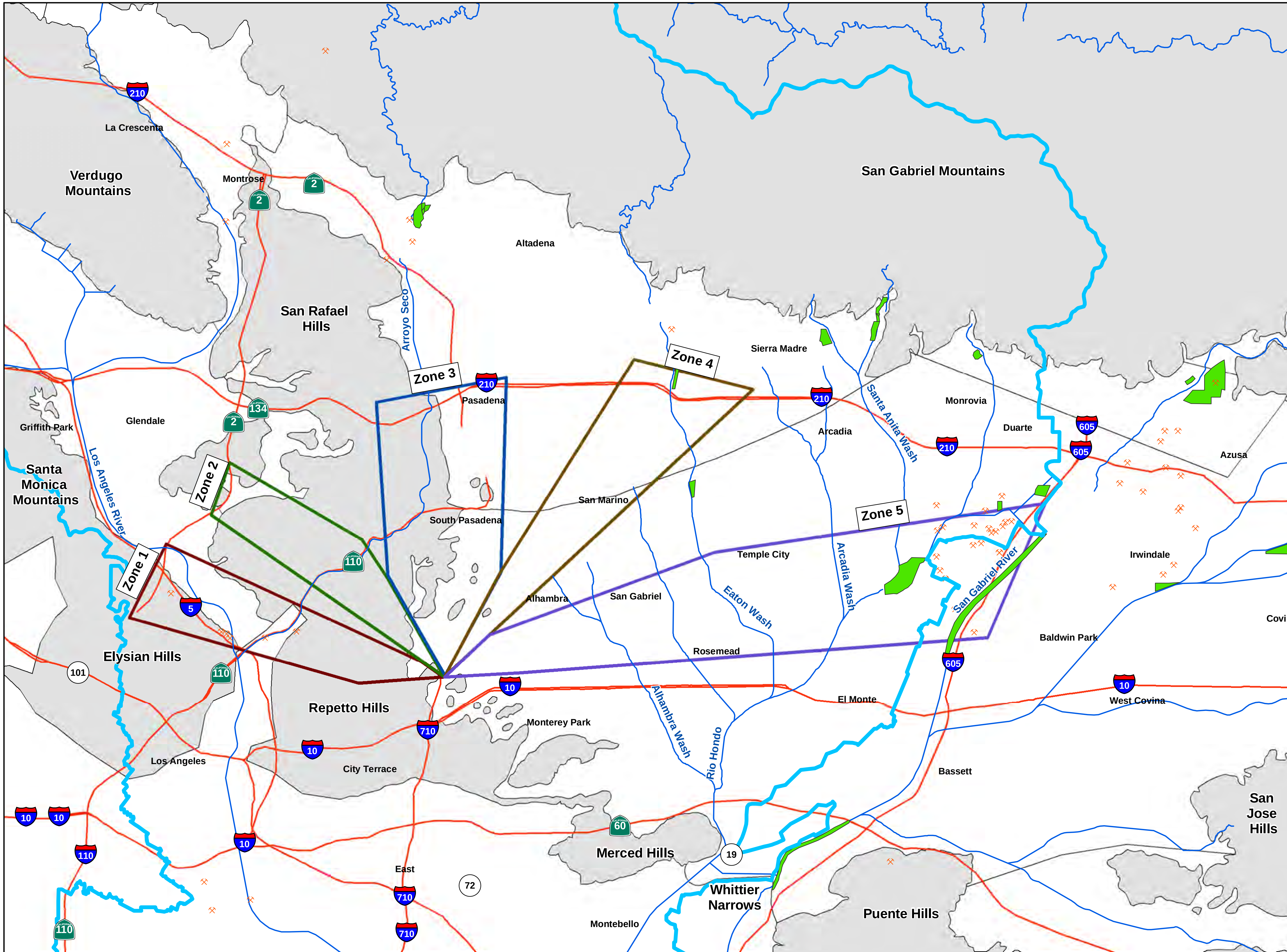

Figure 5-2
Surface Water Features
SR-710 Tunnel Technical Study
Los Angeles County, California

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The San Gabriel River flows from its headwaters in the San Gabriel Mountains southward through the Whittier Narrows before it flows south across the Coastal Plain to the Pacific Ocean. Channel flows pass through different sections in the San Gabriel River, diverting from the riverbed into four different spreading grounds for controlled flow and groundwater recharge above the Whittier Narrows Dam.

Flow in the Los Angeles River, San Gabriel River, and tributary washes occur primarily in the winter months in response to precipitation. These surface water features within the five study zones for the SR-710 tunnel study are ephemeral and partially concrete lined. Surface water recharges the alluvial groundwater basins when storm flows occur mostly by gravity drainage because the water table elevations are below the bottom of the riverbeds and washes. The water within the channels either flows downstream or infiltrates into the subsurface. In general, there is no base flow of groundwater to surface water after storm flows recede because groundwater is below the bottom of these surface water features. Therefore, any lowering of the water table in alluvial areas due to groundwater dewatering from construction or operations and maintenance activities associated with proposed SR-710 tunnel activities likely would not affect the surface water features present in any of the five proposed zones.

5.4 Groundwater Conditions

Zones 1 through 5 straddle five separate groundwater basins of the South Coast Hydrologic Region. Impact to groundwater should be kept minimal during tunnel construction and operation. Tunnel construction technology should be selected to provide minimal impact to the groundwater resources. The groundwater basin and surface water features in each zone are described below.

Zone 1: The eastern portion of Zone 1 is mainly in bedrock of the Repetto Hills with small portions in the Main San Gabriel Groundwater Basin. The western portion of Zone 1 is mainly in the San Fernando and the Central Groundwater Basins. The bedrock is comprised of the lower-permeability Puente Formation. The Los Angeles River and Arroyo Seco are surface water bodies located within Zone 1. The Los Angeles River flows through the western portion of Zone 1; Arroyo Seco flows through the central portion of Zone 1. The Los Angeles River and Arroyo Seco are concrete-lined channels. No springs are known to occur in the upland bedrock areas.

Zone 2: This zone is mainly located in bedrock of the San Rafael Hills. A small portion of Zone 2 is located in the Eagle Rock Groundwater Basin 2, San Fernando, and Main San Gabriel Groundwater Basins. The northwestern portion of Zone 2 is located in the Eagle Rock Groundwater Basin 2 and the San Fernando Groundwater Basin. The southeastern portion of Zone 2 is located in the Main San Gabriel Groundwater Basin. The bedrock is comprised of the lower-permeability Puente and Topanga Formations. Arroyo Seco runs through the central portion of Zone 2. No springs are known to occur in the upland bedrock areas.

Zone 3: The western portion of Zone 3 is located in bedrock of the San Rafael Hills. The eastern portion of Zone 3 is located in the Raymond and Main San Gabriel Groundwater Basins. The bedrock consists of the less permeable Fernando, Puente, and

Topanga Formations. Arroyo Seco runs through the northwestern portion of Zone 3. No springs are known to occur in the upland bedrock areas.

Zone 4: The northern portion of Zone 4 is located within the Raymond Groundwater Basin. The southern portion of Zone 4 is located within the Main San Gabriel Groundwater Basin. Upland bedrock areas do not occur in this zone. Eaton Wash runs through the northeastern portion of Zone 4.

Zone 5: This zone is located in the Main San Gabriel Groundwater Basin. From west to east, surface water features located within Zone 5 include Alhambra Wash, Easton Wash, Arcadia Wash, and Rio Hondo. The San Gabriel River and Santa Fe Flood Control Basin are located in the eastern portion of Zone 5.

5.5 Contaminated Groundwater Conditions

Contaminated groundwater zones occur within the study area. A more-detailed description of groundwater and soil contamination within the individual zones is provided under Section 6 and in Appendix F. Zone-specific descriptions of the groundwater conditions are provided in the Groundwater Conditions subsections of Sections 7 through 11.

SECTION 6

Hazardous Materials

6.1 Review of Data Collected

Hazardous materials concerns within the five study zones (Zones 1 through 5) associated with the SR-710 Tunnel Technical Study were evaluated using information from the three Initial Site Assessments (ISAs) and a limited Environmental Site Assessment (ESA), as listed below. The ISAs were conducted for areas in the vicinity of the 13 geotechnical borings performed by Caltrans in Zones 1, 2, and 3, whereas the limited ESA was conducted for all five study zones. The purpose of these assessments was to identify sites within the five study zones that have potential soil or groundwater contamination that could affect geotechnical work (for example, drilling or tunneling) associated with the SR-710 Tunnel Technical Study. These assessments included reviews of electronic environmental databases, historical reference sources, and regulatory agency databases. Additionally, the ISA's included site reconnaissance of properties in the vicinity of the boring locations.

6.1.1 Records Review Procedures

Results of the ISAs and ESA are summarized in the following study documents. The ISAs provide information specific to the boreholes in the five zones; whereas, the ESA provides overall screening of potential hazardous materials locations for all areas encompassed by Zones 1, 2, 3, 4, and 5. Because the scope of the ESA encompassed all areas within each zone, it is the primary reference used and is of more relevance to the tunneling work.

- CH2M HILL. 2008. *Initial Site Assessment for Proposed Boring Locations Z1-B1, Z1-B8, Z2-B4, Z3-B2, and Z3-B9. SR -710 Tunnel Technical Study*. December.
- CH2M HILL. 2009a. *Initial Site Assessment for Proposed Boring Locations Z1-B3, Z1-B4, Z2-B2, Z2-B3, Z3-B6, Z3-B7, Z3-B8, Z3-B10, and Z3-B11. SR-710 Tunnel Technical Study*. January.
- CH2M HILL. 2009b. *Initial Site Assessment for Proposed Boring Locations Z1-B1 (revised location), Z2-B5, and Z3-B5. SR-710 Tunnel Technical Study*. March.
- CH2M HILL. 2009d. *Environmental Site Assessment for Zones 1, 2, 3, 4, and 5 SR-710 Tunnel Technical Study*. August. (included as Appendix F of this report)

The procedures used during reviews of these sources of information and site reconnaissance are further described below.

6.1.1.1 Electronic Environmental Database Reports

The ISA and the limited ESA used electronic environmental database reports that were generated by Environmental Data Resources, Inc. (EDR) to perform record searches of local, state, and federal databases in accordance with the ASTM E 1527-05 standard of practice guidance. The hazardous materials sites identified in these EDR reports were screened to include only hazardous materials sites that were considered open or active sites by the lead regulatory agencies and sites that had affected the soil or groundwater within Zones 1 through 5.

6.1.1.2 Agency Web Site Databases

The list of hazardous materials sites from the EDR reports considered open sites with impacts to soil or groundwater within Zones 1 through 5 were then further researched on the California Regional Water Quality Control Board (RWQCB) Web site called "Geotracker" or the California Department of Toxic Substances Control (DTSC) Web site called "Envirostor." In most cases, these Web sites provided summary information or electronic reports that detailed investigations that had occurred at the site, such as ongoing groundwater investigations, leaking underground storage tank (LUST) removal reports, or remedial action plans.

These electronic reports generally documented the site conditions, including the contaminants of concern and their respective concentrations (for example, benzene at 1,200 micrograms per liter [µg/L]). This detailed information was then included in the ISAs or the limited ESA and referenced.

6.1.1.3 Historical Reference Documents

Historical aerial photographs, topographical maps, and Sanborn maps were reviewed to assess historical land uses and identify evidence of environmental concerns in the vicinity of the proposed boring locations. Reviews of historical investigation reports and documents obtained from Envirostor and Geotracker were completed for the remaining areas within Zones 1, 2, 3, 4, and 5.

Oil and gas maps were obtained from the California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (CDOGR) to determine whether oil and/or gas wells are present within Zones 1 through 5.

6.1.2 Site Reconnaissance Procedures

As part of the ISAs, a site reconnaissance was performed at the locations of the proposed borings and the properties adjoining the borings to observe the environmental conditions of the sites and determine the current land uses. Observations from the site reconnaissance that could be of an environmental concern were recorded and included in the ISAs as applicable. No site reconnaissance was performed as part of the limited ESA.

6.2 Summary of Hazardous Materials Information

The ISAs and the limited ESA identified several sites within the five study zones that have soil and groundwater contamination issues (shown in Figure 6-1). These contaminated sites have the potential to impact the project during both the geotechnical study and construction phases.

The biggest contamination issues are the existence of the three National Priorities List (NPL) sites within Zones 1, 4, and 5. These three NPL sites (also known as Superfund sites) are the San Fernando Valley Superfund Site (Zone 1) and the San Gabriel Valley Superfund Sites identified as Area 1 (El Monte) and Area 3 (Alhambra) (Zones 4 and 5). The sites have known groundwater contamination issues that are in various stages ranging from assessment to remediation.

Most of the groundwater contamination is due to chlorinated VOCs that are the result of past industrial activities in the area. Contaminated groundwater plumes have been delineated for the San Fernando Valley Superfund Site Area 4 (Pollock Field) in Zone 1 and the San Gabriel Valley Area 1 (El Monte) Superfund Site in Zone 5. However, a groundwater plume has not been delineated yet for the San Gabriel Valley Area 3 (Alhambra) Superfund Site in Zone 4. Because there is the potential of encountering the contaminated groundwater during the tunneling phase (if any of these zones is the preferred alternative), these NPL sites are considered to have a potential to impact the project. A brief summary of Superfund sites is provided below:

Contamination in Zone 1 – Located in the northwestern end of Zone 1 within the Pollock region of the groundwater basin. USEPA implemented a containment system several years ago and began treatment in 1998.

Contamination in Zone 4 – The contaminated site is located approximately at the southwest end of Zone 4. USEPA is currently evaluating the extent of the contamination and will subsequently complete a Record of Decision (ROD). Following completion of the ROD, the containment system and remedial design will be developed.

Contamination in Zone 5 – The contaminated area is located at the midpoint of Zone 5 and extends in an easterly direction. USEPA is currently designing a containment system to control the movement of contaminants and anticipates construction in the next few years.

If it is suspected that groundwater associated with these NPL sites will be encountered, it is recommended that coordination with the primary federal, state, and local stakeholders occur prior to tunnel advancement. Any drill cuttings, excavated soils, and/or water generated during drilling activities should be sampled, profiled, and disposed in accordance with the relevant regulatory requirements.

In addition to the above NPL sites, there are localized groundwater contamination sites within Zones 1, 2, 3, 4, and 5 (Figure 6-1) that have the potential to impact the project during the tunneling phase depending upon the final tunnel alignment. If groundwater with suspected contamination is encountered, it is recommended that drill cuttings, excavated soils, and/or water generated during drilling activities should be sampled, profiled, and disposed in accordance with the relevant regulatory requirements.

Finally, there are sites with localized soil contamination issues within Zones 1, 2, 3, 4, and 5 that have the potential to impact the project during the tunneling phase depending upon the final tunnel alignment. Generally, the soil contamination at these sites is shallow and is comprised of metals, total petroleum hydrocarbons (TPHs), or VOCs. If the tunnel alignment encounters contaminated soil at these localized sites, it is recommended that drill cuttings or excavated soils generated during drilling activities should be sampled, profiled, and disposed in accordance with the relevant regulatory requirements.

Figure 6-1 Hazardous Materials Location Map

SR-710 Tunnel Technical Study
Los Angeles County, California

SECTION 7

Site Conditions for Zone 1

7.1 General

Zone 1 is located entirely within the City of Los Angeles. As depicted in Plates 1 and 5, Zone 1 is generally located west to northwest of the northern terminus of SR-710, southeast of the SR-2/I-5 intersection, and south of Mount Washington; it includes Elysian Valley and the northern portion of Elysian Park. Zone 1 terminates at SR-2 and measures approximately 5.0 to 5.5 miles long by 1.5 miles wide at its western limit. The delineation of Zone 1 anticipates a connection between the northern terminus of SR-710 and SR-2 or I-5 to the northwest. The general location of Zone 1 relative to the other study zones is shown in Figure 7-1.

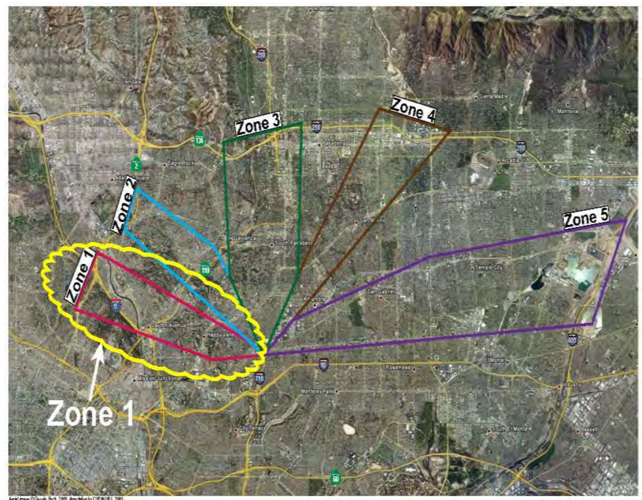

Figure 7-1. Zone 1 Location Map.

7.2 Existing Developments

Most of the Zone 1 area is densely populated and is occupied predominantly by residential and commercial/industrial developments. Two major southern California freeways cross the western half of Zone 1. I-5 runs in a northwest-southeast direction along the northeastern foothills of the Elysian Park Hills, and SR-110 crosses perpendicularly the central portion of the zone. Other important surface roads include, from east to west, Alhambra Avenue, Eastern Avenue, Huntington Drive, Pasadena Avenue, Figueroa Street, San Fernando Road and Riverside Drive. Railroad tracks cross the eastern portion of the zone between Alhambra Avenue and Valley Boulevard.

The former Taylor railroad yard, a relatively large rail yard, was located within the western portion of Zone 1, along the northern flood plain of the Los Angeles River and immediately south of San Fernando Road. The majority of the former rail yard has been redeveloped and now consists of open space, an industrial park, and a state park. The remaining part is a switching yard and maintenance facility for the Metro light rail system.

The Upper Reach of the NEIS line tunnel extends northwesterly from just south of the intersection of the Los Angeles River and SR-110 to the intersection of San Fernando Road and Division Street (immediately to the east of the former Taylor rail yard). The Upper Reach of the NEIS sewer line consists of a concrete-lined tunnel that is approximately 12 feet in diameter and 2 miles long and is located along the Los Angeles River floodplain, below the San Fernando Road centerline. At Division Street, the Upper Reach of the NEIS sewer line is at an approximate elevation of 230 feet above mean sea level (msl), or roughly 150 feet bgs. In the vicinity of the southern limit of Zone 1, the sewer line is located at an approximate elevation of 220 feet msl, or a depth of roughly 125 feet bgs. In the vicinity of SR-110, the invert of the Upper Reach of the NEIS sewer line is located approximately 150 feet bgs.

An abandoned water supply tunnel, known as the "Narrows Gallery," intersected the NEIS sewer tunnel alignment approximately 400 feet north of its Humboldt Shaft. This location is approximately 1,500 feet to the south of the southern limit of Zone 1 near the corner of San Fernando Road and Humboldt Street. This abandoned water supply tunnel was constructed in 1904 and later abandoned in the 1950s due to reported high levels of contamination. The tunnel is reported to be elliptical in shape and is approximately 5.2 feet high by 4.9 feet wide. The orientation, length, and depth of the tunnel are unknown.

7.3 Zone Geology

7.3.1 Physiography

From west to east, Zone 1 includes the Elysian Hills, Los Angeles River flood plain, Arroyo Seco and several associated local low-lying areas, and the Repetto Hills (Plate 1). Mount Washington, the highest point within the Repetto Hills, with an approximate peak elevation of 850 feet msl, is north of the confluence of the Los Angeles River and Arroyo Seco. The Elysian Hills west of the river rise to a peak elevation of approximately 740 feet msl. The lowest point within Zone 1 is in the vicinity of the confluence of the Los Angeles River and Arroyo Seco, at an approximate elevation of 320 feet msl.

Both the Elysian Hills and the Repetto Hills comprise gently to steeply sloping hills. The southeasterly draining Los Angeles River has eroded a wide floodplain between the Elysian Hills to the west and the Repetto Hills to the east. The southwesterly draining Arroyo Seco has formed a major southwesterly draining valley between the northwestern (Mount Washington area) and southeastern (Montecito Heights) portions of the Repetto Hills. The Arroyo Seco joins the Los Angeles River in the vicinity of the Elysian Hills. Four other smaller intermittent drainages, that flow south to southwesterly with narrow gently sloping floodplains, dissect the Repetto Hills in the eastern half of Zone 1.

7.3.2 Stratigraphy

The geologic formations comprising Zone 1 consist predominantly of Puente Formation and Quaternary Alluvium (Plates 1 and 5). The majority of the tunnel is expected to be within the Puente Formation. Alluvium is expected to be encountered only at the northwestern and southeastern portions of the zone and along the Los Angeles River. The general characteristics of the alluvium and rock units are described in Section 4.1.2.

The shear wave velocities obtained as part of the surface wave survey at different points through Zone 1 allowed for the interpretation of the thickness of the alluvial materials and its contact with the underlying bedrock. This information was used to complement our knowledge of the subsurface conditions along the Los Angeles River, Arroyo Seco, and other smaller drainages, at points where no borings were advanced and/or where no such data existed. In addition, when surface wave survey points were located at the end of the seismic refraction lines, the same parameters were interpreted since the seismic reflection array used could not allow for a good resolution at shallow depths.

Alluvial materials within Zone 1 also occur along the Arroyo Seco and all other secondary drainages that dissect Zone 1. The alluvial materials are approximately 75 feet thick at the confluence of the Los Angeles River and Arroyo Seco, whereas thicknesses in excess of 200 feet are reported near the northwesternmost corner of Zone 1 (Yerkes et al., 1977). The thickness of the alluvial materials along the Arroyo Seco decrease upgradient to approximately 25 feet at the northern limit of Zone 1. The alluvial materials in all other smaller drainages located in the eastern half of Zone 1 range in thickness between 40 to 70 feet. The water-bearing Young Alluvium commonly is considered to be susceptible to liquefaction. However, based on the anticipated tunnel depths, these conditions should not impact the tunnel itself.

The Puente Formation is expected at the tunnel depth in Zone 1. Except for the easternmost 2,000 linear feet that are anticipated to be excavated into rocks of the siltstone member (Tpsl) of the Puente Formation, a typical tunnel would be constructed in the sandstone member (Tpss). The sandstone member contains approximately 20 to 30 percent fine-grained interbeds (siltstone). In addition to these two units, the shale member (Tpsh) crops out in portions of Zone 1 and could occur mostly at shallow depths above a typical tunnel.

7.3.3 Structural Geology

Zone 1 generally parallels the trend of the major geologic structural features of the Elysian Hills and Repetto Hills. The representative geologic profile for Zone 1 (Plate 5) shows the typical structural conditions anticipated throughout this zone. Faulting along the Elysian Park Blind Thrust Belt deep below Zone 1 has folded rocks within the northwest-trending and southeast-plunging Elysian Park Anticline (Oskin et al., 2000). Uplift of this anticline has produced the Elysian and Repetto Hills. Topographic relief throughout the region correlates well with the areal extent of the anticline and with the trends of secondary folds (Plate 1 and Plate 5). However, the anticline has been extensively incised by surficial erosion.

The axis of the Elysian Park Anticline trends approximately along the middle of Zone 1. As a result, bedding within the northern portion of Zone 1 generally dips toward the northeast at 40 to 55 degrees, whereas southwest-dipping beds predominate along the southern portion of the zone, dipping at 20 to 30 degrees. Local deviations from these orientations can occur anywhere within the region due to secondary folding and faulting. A review of the ATV logs (see Appendix C.1) for the boreholes excavated north and south of the anticline axis generally confirmed the northeast and south-southwest dipping beds as discussed above and as shown on the geologic base map (Plate 1). The ATV logs and field boring logs also show very slightly to slightly fractured bedrock. Numerous secondary folds and inactive faults associated with the folding of the Elysian Park Anticline have been mapped within Zone 1, particularly in the eastern portion. The majority of these secondary folds and the more continuous faults generally parallel the trend of the Elysian Park Anticline; however, several shorter faults have been mapped trending perpendicular and oblique to the Elysian Park Anticline.

The geologic structure and distribution of the geologic units to be encountered within a typical tunnel depth will be a function of which limb of the Elysian Park Anticline that the selected alignment will cut through.

7.4 Faulting

Zone 1 is not located within an APEFZ, and no active faults are mapped as crossing or projecting toward Zone 1 in available geologic literature. Therefore, the potential for ground-surface fault rupture and fault displacements inside this zone are considered low.

Several faults were mapped within the limits of Zone 1 by Lamar (1970). All of the mapped faults are considered inactive. The longest of these faults is the southeast-trending Elysian Park fault (not to be confused with the subsurface Elysian Park Fold and Thrust Belt). The steeply northward-dipping and Pliocene-age Elysian Park fault as mapped by Lamar (1970) exhibits approximately 2,100 feet of north-side down-vertical separation. The Elysian Park fault and all other, steeply dipping faults mapped in this area at the currently anticipated tunnel depth could juxtapose various units of the Puente Formation, but generally the rock types on both sides of a fault are expected to have similar geotechnical properties. No new fault displacements are anticipated to occur along these inactive faults.

An inclined continuous-core boring, with a total inclined depth of 326 feet bgs, was drilled to investigate the presence and characteristics of the Elysian Park fault at depth. R-09-Z1B2 was located a couple of hundred feet to the north of the trace of the fault mapped by Lamar (1970) where it crosses Stadium Way in the Elysian Hills. The boring was drilled at an angle of 60 degrees (from horizontal) in an attempt to intersect the fault. No indications of faulting, such as clay gouge or change in rock type, were encountered in R-09-Z1B2. In addition, continuous seismic reflectors dipping to the southwest can be observed in the seismic-reflection profile of Line Z1-G3 located directly across the fault. Furthermore, Dibblee's (1989b) geologic map for the Los Angeles quadrangle does not show the Elysian Park fault. This suggests that the Elysian Park fault might not exist or is a minor feature at the location mapped by Lamar (1970).

7.5 Groundwater and Surface Water Conditions

The depth to groundwater along the portion of the Los Angeles River encompassed by Zone 1 decreases gradually from the southeast to the northwest, opposite to the river flow, and exists under unconfined conditions. In 2006, the shallowest groundwater conditions of 20 feet bgs were observed approximately 4,500 feet north of SR-110, whereas a groundwater depth of approximately 50 feet bgs is reported near the intersection of the Los Angeles River and SR-2. Drilling by others in the bottom of the river reveals water flowing within the sand and gravel below the concrete bottom. The deeper groundwater conditions and inverted groundwater flow are influenced by groundwater extraction at the LADWP Pollock Treatment Plant located northwest of the intersection of the Los Angeles River and SR-2.

These shallow groundwater conditions along the Los Angeles River were confirmed by the estimation of groundwater depths at 16 of the surface wave soundings. Groundwater was modeled in the 10- to 33-foot depth range at these locations. The other four soundings (Z1-S1, Z1-S3, Z1-S5, and Z1-S6) in Zone 1 were located at higher elevations and in bedrock materials and MASW arrays were not long enough to map the approximate groundwater depth at these locations. Seismic reflection shot records along seismic line Z1-G3 indicate that the groundwater level may be shallower along surface wave soundings Z1-S5 and Z1-S6. Groundwater depth varied from 22 to 40 feet bgs in the six piezometers installed as part of the current study in Zone 1.

Based on groundwater information collected for this exploration, the groundwater table within Arroyo Seco was not observed within the upper 35 feet. According to the CDMG (1998d), the historical highest groundwater level at the Los Angeles River is reported to have been approximately 20 feet bgs.

No historical highest groundwater information is provided by CDMG (1998d) for Arroyo Seco or other smaller drainages located in the eastern portion of Zone 1.

The rocks of the Puente Formation are generally considered non-water-bearing. Perched groundwater conditions might be locally present within faulted and/or fractured zones. The Los Angeles River and Arroyo Seco are surface water bodies located within Zone 1. The Los Angeles River flows through the western portion of Zone 1 and Arroyo Seco flows through the central portion of Zone 1. The Los Angeles River and Arroyo Seco are generally concrete and riprap-lined channels. No major springs are known to occur in the upland bedrock areas. Although there are no large surface water recharge areas within Zone 1, normal inflow of water from the ground surface will occur during periods of rainfall.

7.6 Hazardous Materials

The ISAs and ESA identified 10 open or active sites located within Zone 1. The locations of these sites are shown in Figure 6-1. The southern region of the San Fernando Valley (Area 4) Pollock Wellfield NPL Site is located in the western portion of Zone 1. A portion of this groundwater basin is currently contaminated with chlorinated VOCs (trichloroethylene [TCE] and tetrachloroethylene [PCE]), methyl tertiary butyl ether (MTBE), perchlorate, nitrate, chromium VI, manganese, and thallium. Concentrations of PCE and TCE within Zone 1 range from greater than detection limit to approximately 100 μg/L (CH2M HILL, 2007). The approximate plume boundaries for the San Fernando Valley (Area 4) Pollock Wellfield NPL Site above MCLs are shown in Figure 6-1.

An Interim Investigation was completed for the San Fernando Valley Pollock Wellfield NPL site in April 1994. In 1998, treatment of groundwater was reactivated by the Los Angeles Department of Water and Power. Investigations for this NPL site are ongoing to determine the full nature and extent of contamination at this area. A Cooperative Agreement between USEPA and the California RWQCB has been initiated to perform an investigation of potential sources of the contamination in the San Fernando Basin (USEPA, 2009a).

Ten sites (including the San Fernando Valley [Area 4] Pollock NPL Site) with localized groundwater or soil contamination are located within Zone 1. One of these sites, summarized below, is located in proximity (that is, less than 0.5 mile) to the western end of Zone 1:

- Hurst Chemicals, 2500 San Fernando Road, Los Angeles, California (Map ID 255/12), which is located within 0.5 mile of the western end for Zone 1. The site has contaminated the groundwater with TCE. Depending on the final tunnel alignment, this site could potentially impact the project because it is located within the western portal zone for Zone 1 and has impacted the groundwater.

The remaining eight sites (not including the NPL site) with localized soil or groundwater contamination were identified as being in the central portion of Zone 1 and are considered to have a low potential to impact the project because they are characterized with soil or groundwater contamination at a depth of less than 150 feet bgs. Additional details for each of these sites, including the corresponding soil and/or groundwater contaminants, corresponding concentrations, and depth of maximum concentration, are included in the Environmental Screening Evaluation in Appendix F.

7.7 Potential for Naturally Occurring Gas

The Puente Formation is one of the more prolific petroleum sources in the Los Angeles Basin. Although, no known oil or natural gas fields are located within Zone 1, naturally occurring tar and hydrocarbon odors were encountered within the Puente Formation during drilling of boring R-09-Z1B7. Three samples collected from this boring were tested for petroleum hydrocarbons (carbon chain speciation) utilizing USEPA Method 8015M. The analytical laboratory reported carbon chain C9 - C44 concentrations of 30,000, 18,000 and 22,000 milligrams/kilogram.

During the field investigation performed for the Upper Reach segment of the NEIS sewer line and during its construction, hydrogen sulfide (H_2S) gas was encountered. After careful examination, it was determined that the hydrogen sulfide gas was released into the atmosphere from groundwater flowing into the cutting chamber of the tunnel boring machine (TBM). In addition, methane gas, in excess of 20 percent of the lower explosive limit (LEL), was encountered during tunnel excavation.

Based on previous observations of naturally occurring gas in other tunneling projects, naturally occurring gas conditions can be expected within Zone 1. The levels of gassy conditions encountered to-date in the zone and elsewhere within the Los Angeles basin should be manageable, as long as appropriate considerations is given to this condition during construction.

7.8 Geotechnical Considerations for Tunnel Design and Construction

7.8.1 Key Ground Characteristics

Based on the results of this evaluation, the key geologic factors for this zone in terms of tunnel design and construction considerations (along the generalized geologic profile shown in Plate 5) are:

- Subsurface conditions are fairly uniform in most of this zone, consisting mainly of weak sedimentary rocks of the Puente Formation. Typically, the formation in this zone consists mostly of sandstone, siltstone, and shale. Locally, there is a potential for encountering alluvium (or soil) near the northwestern and southeastern portions of the zone and in shallow cover beneath the Los Angeles River.

- Rock mass is generally only slightly fractured. Although several inactive faults will likely be encountered, no active faults are mapped within this zone.
- Most of the rock is considered weak to moderately weak, although there is a potential for stronger cemented layers and concretions within the Puente Formation.
- The groundwater table within the alluvium is shallow (approximately 20 to 50 feet bgs) in parts of this zone. The rock mass is not expected to transmit large quantities of groundwater into the tunnel, except for possibly beneath the Los Angeles River. In this area recharge from the river could lead to higher sustained groundwater inflows. Potential for high groundwater inflows exists within fractured and poor-quality rocks. High groundwater inflows are also expected in the saturated alluvium at the northwestern and southeastern portions of the zone.
- The water-bearing alluvial materials along the Los Angeles River within the limits of Zone 1 are considered to be susceptible to liquefaction (CDMG, 1999d) in areas where groundwater is near the ground surface and loose, cohesionless soils are present.
- One Superfund site is located in the northwest portion of the zone, which could be a source of contaminated soil and groundwater in this area.
- There is a relatively high potential of encountering naturally occurring gas (methane and/or hydrogen sulfide) in this zone because the zone is underlain by Puente Formation.

7.8.2 Preliminary Assessment of Tunneling Considerations

Information presented above and in previous sections of this report was used to perform a preliminary assessment of tunnel design and construction requirements, as summarized below.

Tunnel excavation in this zone at the likely tunnel depth would be almost entirely in the Puente Formation sandstone (Tpss)—the exception being at the portal zones where the tunnel would likely encounter alluvium in the transition from the ground surface to the tunnel. The Puente Formation generally consists of weak sedimentary rocks that can be excavated by using current tunneling technologies, such as a TBM. Several tunnels have been successfully constructed through this same formation in the Los Angeles area. Due to the large tunnel size required for the SR-710 tunnel and the heavily developed nature of this urban area, it is possible that specialized tunneling machines, as discussed below, could be required to control loss of ground or potential settlement. Due to the relative uniformity of the geologic conditions in this zone, it is likely that only a single excavation method would be needed. The strength and uniformity of the ground conditions in this zone reduce the demand on the tunneling equipment and construction processes and allow for more efficient construction and higher production rates.

Some inherent variability exists in the Puente Formation, such as occasional strong to very strong cemented layers and concretions within the formation. These layers should be considered in the selection/design of tunnel excavation equipment. Although they would reduce tunnel excavation advance rates somewhat, the layers do not impact the feasibility of constructing a tunnel in this formation.

The tunnel profile will have to be low enough to avoid conflicting with the existing NEIS tunnel (Plate 5). Depending on the rock mass strength and character at this crossing, a clear distance of at least 15 to 25 feet is needed to avoid impacting the existing tunnel.

Water-saturated alluvium (or soil deposits) would likely be encountered in excavations for the portals and limited portions of shallow tunnels beyond the portal zones. The risks of open excavation and tunneling in saturated alluvium include high groundwater inflows, flowing ground conditions, loss of ground outside the excavation, and settlement of the ground surface. The amount of settlement would depend on a variety of factors including the tunnel excavation and support methods, ground characteristics, diameter of the tunnel, and cover above the tunnel (i.e., distance from the tunnel crown to the ground surface). Typically, a ground cover of at least two tunnel diameters is desirable for minimizing the risk of excessive settlement magnitudes. To control settlement, ground loss should be actively controlled at the tunnel face so that ground surface settlement is minimized.

Tunneling methods are available to handle saturated alluvium conditions. Control of unstable ground conditions and groundwater inflows can be provided by specialized tunneling machines with face control capabilities. These machines generally utilize either earth-pressure balance (EPB) or slurry methods. Such machines have been used successfully on previous tunneling projects in Los Angeles, and this technology could be applied to the SR-710 extension as well. It may also be advantageous to use a TBM that is convertible and can be operated in open mode in stable rock conditions or in closed mode (utilizing EPB or slurry methods) when unstable ground conditions (saturated alluvium or weak fractured/ sheared rock) are encountered in the tunnel. In some cases, it is possible to implement systematic ground improvement measures on a localized basis including a combination of dewatering, permeation grouting, or jet grouting to stabilize the deposits and reduce the loss of ground to tolerable limits.

Where groundwater is present in the alluvium, it will be necessary to have a watertight lining system to avoid groundwater inflows, which could impact groundwater levels adjacent to the tunnel and result in additional maintenance within the tunnel. This type of lining, while more expensive, has been used for most of the Los Angeles Metro tunnels. Watertight linings typically have gaskets along the circumferential and longitudinal joints to control groundwater inflows and to make the lining essentially watertight.

Below the Los Angeles River, even if the tunnel is located in the Puente Formation, there is a potential of encountering higher groundwater inflows and unstable ground conditions. Rock formations below river valleys are often more highly fractured and more deeply weathered leading to weaker, more pervious ground conditions. Greater bedrock cover may be required in this area to minimize instability and the potential for high groundwater inflows. The bedrock surface in this area could also be highly variable (or undulating) and additional cover may be desirable to avoid the risk of encountering saturated alluvium in the tunnel unexpectedly.

Although several steeply dipping faults are located in Zone 1, they are all considered inactive. Tunneling through these faults will require the excavation of fractured rock, control of groundwater, and may involve excavation of clay gouge formed by prior fault movements. Specialized TBMs should be able to complete this work without major difficulty, but with slower progress. Furthermore, fault zones have the potential to act as groundwater barriers; therefore, the groundwater conditions should be fully characterized prior to tunnel construction to determine what types, if any, of groundwater control measures are necessary.

The Puente Formation is expected to require immediate support in the large tunnel excavations proposed for this study. If the tunnel is excavated by a full-face TBM, a precast reinforced concrete segmental tunnel lining installed as the TBM advances is a likely method of ground support. This approach provides immediate and full perimeter ground support required for a tunnel in this formation. Timely installation of effective ground supports is also required to control loss of ground and ground surface settlement.

The Superfund site in the northwest portion of Zone 1 may impact tunnel construction and muck disposal operations. Depending on the extent of the contaminated soils and groundwater, a tunnel in this zone could encounter hazardous materials. This would affect the tunneling operations if the contaminant concentrations are high enough to significantly affect working conditions in the tunnel; it would also affect tunneling costs if concentrations require special disposal of the tunnel spoils. It would be undesirable if tunneling operations impacted a contaminated groundwater plume or caused it to migrate. However, the potential for migration along the tunnel alignment is very low. Normal backfill grouting operations associated with the installation of the tunnel lining will seal off water migration paths.

Another important tunnel construction consideration is the potential for naturally occurring gas in the Puente Formation. Based on the findings reported by Dubnewych et al. (2005) for the Upper Reach of the NEIS tunnel line, the presence of methane and/or hydrogen sulfide gas is expected in this zone and the tunnel will likely be classified as “Potentially Gassy” or “Gassy” by California Occupational Safety and Health Administration (Cal-OSHA). This is not unusual in the Los Angeles area and several tunnels (such as the NEIS and ECIS) have been safely excavated within areas of naturally occurring gas, with proper provisions. Contaminated muck may need to be disposed of at hazardous waste landfills if concentrations of the contaminants exceed certain limits.

Based on the information collected and reviewed in Zone 1, tunneling is considered to be feasible in this zone from a geotechnical standpoint. Subsurface conditions and appropriate design and construction provisions should be further evaluated in this zone during more detailed tunnel design studies.

SECTION 8

Site Conditions for Zone 2

8.1 General

Zone 2 is located entirely within the City of Los Angeles. As depicted in Plates 1 and 6, Zone 2 extends northwest from the northern terminus of SR-710 to the SR-2/Verdugo Road intersection within the City of Los Angeles. Zone 2 is approximately 5.0 to 5.5 miles long and approximately 1.0 mile wide at its northwestern terminus. The delineation of Zone 2 anticipates a connection between the northern terminus of SR-710 and SR-2. The general location of Zone 2 is shown in Figure 8-1.

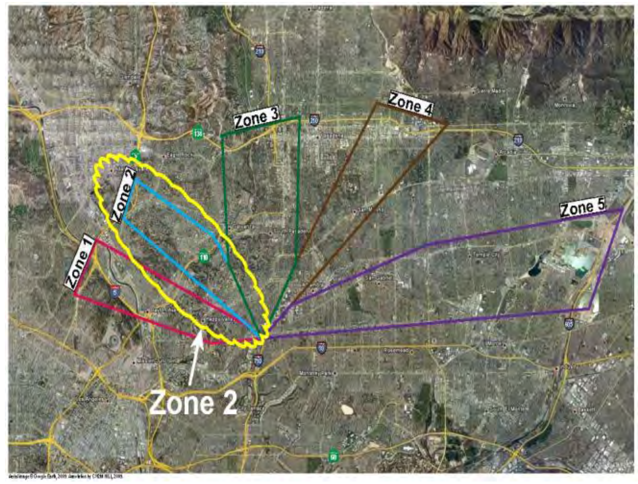

Figure 8-1. Zone 2 Location Map.

8.2 Existing Developments

Most of Zone 2 is densely populated and occupied predominantly by residential and small commercial developments. SR-110 crosses the central portion of the zone perpendicularly, following the configuration of Arroyo Seco. Other important surface roads from east to west that cross the zone include Alhambra Avenue, Huntington Drive, Monterey Road, Figueroa Street, Eagle Rock Road, and Verdugo Road. The Los Angeles–Pasadena Metro Line (Gold Line) runs from Union Station to Pasadena along Arroyo Seco, crossing Zone 2 through its middle portion. In addition, railroad tracks cross the eastern portion of the zone between Alhambra Avenue and Valley Boulevard.

The City of Los Angeles Avenue 45 sewer pipeline runs at an approximate depth of 10 to 50 feet bgs through the portions of Arroyo Seco located within Zone 2. In addition, several utility lines are located at shallow depths within the zone.

8.3 Zone Geology

8.3.1 Physiography

The regional physiographic conditions of the area surrounding Zone 2 are described in Section 4. Zone 2 is located in the Repetto Hills, a hilly region of topographically abrupt hills and narrow valleys within the City of Los Angeles. In general, the Repetto Hills consist of small rounded hills with gentle to very steep slopes. Mount Washington, with a maximum elevation of about 920 feet, is located in the west-central portion of the zone and represents the highest hill of the area. As a result, a portion of the western half of this zone is located on the northeast-facing slopes of Mount Washington, which, in turn, are surrounded by relatively broad valleys located along Arroyo Seco, York Boulevard, and Eagle Rock Boulevard.

The floors of Arroyo Seco and York Boulevard valleys are at an approximate elevation of 500 feet above msl, and the elevation of the north-trending valley of Eagle Rock Boulevard is at up to 420 feet above msl. Unnamed high peaks in the south-central portion, immediately to the southeast of Arroyo Seco, reaching a maximum elevation of approximately 880 feet msl. The southeastern portion of Zone 2 is at an approximate elevation of 450 feet, a relatively flat area with gentle southwesterly slopes.

Several southwest-trending drainages cut through the Repetto Hills. The southwesterly draining Arroyo Seco represents the widest and most important topographic break through Zone 2, essentially dividing the zone into two equal portions. Arroyo Seco is a broad, flat floored valley that drains southerly and westerly from the San Gabriel and Verdugo mountain ranges in the north, along the eastern edge of the San Rafael Hills to the Los Angeles River just west of the Elysian Hills. Runoff in the Arroyo Seco channel is within a concrete-lined open aqueduct. Other southwest-flowing intermittent drainages perpendicularly dissect the Repetto Hills. One of the drainages is located along Eagle Rock Boulevard at the northwesternmost portion of the zone, whereas two other drainages are located in the southeastern portion of the zone. These drainages consist of gently sloping floodplains/canyons. The topographic conditions for Zone 2 are shown in Plates 1 and 6.

8.3.2 Stratigraphy

There are four major geologic units present within Zone 2. These include the Topanga, Puente, and Fernando Formations, and Quaternary Alluvium (Plates 1 and 6). The general characteristics of these units are described in Section 4.1.2.

Quaternary alluvial materials occur within the dissecting drainages and topographically lower areas northwest of Arroyo Seco and in the northwestern and southeastern portions of Zone 2. The alluvium is approximately 25 to 35 feet thick along Arroyo Seco and 5 to 30 feet thick at the northwestern portion of the zone. However, immediately east of the intersection of Eagle Rock Boulevard and York Boulevard, alluvium thickness changes abruptly from south to north from approximately 75 feet to slightly over 275 feet in a very short distance. The water-bearing Young Alluvium is considered to be susceptible to liquefaction (CDMG, 1998d). Liquefaction may affect shallow structures but is not expected to affect a deep tunnel.

As mapped by Lamar (1970), the Fernando Formation within Zone 2 in the Highland Park area comprises a fault-bounded block consisting of conglomerate, conglomeratic sandstone (Tfcg), and interbedded sandstone (Ttss). These rocks contrast sharply with the fine-grained massive claystone and siltstone typical of the Fernando Formation in the easternmost portion of the zone. The coarse-grained member is anticipated to be encountered only if the tunnel crosses the northern portion of the zone, west of Arroyo Seco.

The sandstone (Tpss), shale (Tpsh), and siltstone (Tpsl) units of the Puente Formation are anticipated to be encountered along different sections of a typical tunnel through Zone 2. The sandstone unit (Tpss) is exposed north of the Highland Park fault and between the Highland Park fault and Mount Washington. The shale unit (Tpsh) occurs predominantly in the southern portion of the zone in the general vicinity of Arroyo Seco. Finally, the siltstone (Tpsl) unit crops out in the eastern portion of the zone.

The units of the Topanga Formation that have been identified within Zone 2 include siltstone (Ttsl), overlain by sandstone (Ttss). The sandstone unit (Ttss) crops out at the northwesternmost portion of Zone 2 in a fault block.

Boring R09-Z2B4 was excavated into the Puente Formation (Tpsl) and yielded rock core recovery between 105 and 140 percent between the depths of 135 and 245 feet and between 355 and 400 feet bgs. The core diameters varied locally from about 2 inches to 1.7 inches. However, the caliper log for this boring showed that the diameter of the borehole below a depth of 100 feet is roughly the same as the diameter of the drill bit used. Apparently the material was stretched during extraction of the core from the core barrel (necking). Expansion index testing performed on core material collected at this depth interval showed medium expansion potential.

A tunnel through the southern portion of Zone 2 should encounter the sandstone (Tpss), shale (Tpsh), and siltstone (Tpsl) units of the Puente Formation. A tunnel through the northern portion of Zone 2 would encounter the siltstone (Ttsl) and sandstone (Ttss) units of the Topanga Formation. However, within the northeastern portion of Zone 2, a tunnel would encounter the shale (Tpsh) and siltstone (Tpsl) units of the Puente Formation. A tunnel through the western half would encounter the siltstone (Ttsl) and sandstone (Tpss) units of the Topanga Formation, along with sandstones (Tfss) and conglomerates (Tfcg) of the Fernando Formation.

8.3.3 Structural Geology

Zone 2 generally parallels the northwest-southeast trend of the major geologic faults and folds of the Repetto Hills. Faulting along the Elysian Park Blind Thrust Belt has folded rocks, within the northwest-trending and southeast-plunging Elysian Park Anticline (Oskin et al., 2000). Uplift of this anticline has produced the Elysian and Repetto Hills. In addition, the highest topographic relief throughout Zone 2 corresponds approximately with the areal extent of the anticline and with the trends of secondary folds (Plates 1 and 6).

The northwest-trending and southeast-plunging axis of the Elysian Park Anticline runs approximately along the middle length of Zone 1. Consequently, Zone 2 (to the north of Zone 1) is within the northeastern limb of this major fold structure. Based on this structural location, bedding along this zone would be expected to dip predominantly toward the northeast. Such bedding orientations were confirmed with ATV logs for R-09-Z2B3 and R-09-Z2B4 where bedding dips in general to the north at approximately 10 and 70 degree angles, respectively. However, abrupt dip reversals from the expected and measured bedding orientations are common mainly due to fault-bounded blocks south of the Highland Park fault. Furthermore, due to tightly folded secondary folds associated with the Elysian Park Anticline, deviations from those expected bedding conditions, including overturned bedding, also occur in the area located south of the Highland Park fault and west of Arroyo Seco. Bedding in R-09-Z2B1 in the York Boulevard valley near the Raymond fault dips about 35 to 45 degrees in the upper 40 feet, similar to outcrops a short distance to the north and south, but the bedding abruptly became nearly vertical from 40 feet to the bottom of the boring. According to the ATV log for boring R-09-Z2B5 bedding under the alluvial cover at that boring location dips 15 to 30 degrees in an east-southeast direction. In summary, bedding orientations and inclinations are highly variable, and their dips can be expected to range from 25 degrees to vertical.

Based on the ATV logs for the borings advanced within Zone 2, fracturing appears to be randomly oriented. However, data collected from the ATV log for boring R-09-Z2B5 indicated that a fracture set may exist between roughly 150 and 240 feet bgs.

8.4 Faulting

The geologic structure of most of the area is not only complicated but difficult to decipher because of the dense cover of paved streets, residential structures, commercial buildings and vegetation. Fourteen inactive faults are mapped (Lamar, 1970) within the limits of Zone 2 forming a complicated mosaic of intersecting faults and fault-bounded blocks. The largest of these faults corresponds to the trace of the northwest-trending Highland Park fault and dissects the middle of the entire length of Zone 2 (Plates 1 and 6). The Highland Park fault appears to terminate against the western continuation of the Raymond fault located along York Boulevard. The Highland Park fault is not considered by the CGS (2002b) and CDMG (1977) as active.

Among the other 13 inactive faults of the complicated fault mosaic mapped by Lamar (1970), 9 faults have been mapped in rocks of the Puente Formation located southwest of the Highland Park fault. In addition, the remaining four faults are mapped northeast of the Highland Park fault in rocks of the Fernando, Puente, and Topanga Formations. All of these fault traces are shorter and more discontinuous than the Highland Park fault. The orientation of the faults located southwest of the Highland Park fault varies from parallel, oblique, to perpendicular. Northeast of the same fault, the orientation is predominantly perpendicular to the Highland Park fault. The Highland Park fault and all other steeply dipping faults within Zone 2 might juxtapose various units of the Fernando, Puente, and Topanga Formations at the anticipated tunnel depth.

The active Raymond fault projects westerly from Raymond Hill into the valley along York Boulevard. However, the fault is poorly expressed in the surface morphology west of Arroyo Seco so the location is poorly known. Geophysical data collected during this investigation and previously by the USGS (USGS, 2009c) suggested faulting but was inconclusive. However, surface faulting was documented in fault trenches near Figueroa Avenue just west of Arroyo Seco. The aerial photograph lineament study revealed geomorphic features that suggest surface faulting along the edge of the hills north of York Boulevard.

The APEQFZ established by CDMG (1977) shows the Raymond fault extending westerly along the York Boulevard valley and terminating immediately before the northern limit of Zone 2. The presence of faulting is indicated by groundwater variations in wells at the Sparkletts plant near Lincoln Avenue and York Boulevard, where the thickness of alluvial materials varies abruptly by about 200 feet between two of the Sparkletts plant wells located within 40 feet of each other (approximately 120 feet south of Lincoln Avenue). Seismic-reflection line Z2-G1 (Appendix C.2) near the western end of Zone 2 indicates two faults, one north of York Boulevard and one to the south. All of these features provide compelling evidence of a zone of young active faulting within the York Boulevard valley extending as far west as about Eagle Rock Boulevard. At this time, it is uncertain whether these features represent branches of the Raymond fault or whether they represent separate faults. The zone of faulting is expected to cross the northwestern portion of Zone 2.

8.5 Groundwater and Surface Water Conditions

Based on the information collected during this investigation, groundwater is under unconfined conditions within the granular and unconsolidated alluvial materials at approximate depths of 10 feet to 25 feet bgs along Arroyo Seco.

According to CDMG (1998d), the historical highest groundwater level at the northwesternmost portion of Zone 2 along the Eagle Rock Boulevard valley was at an approximate depth of 20 feet bgs in the central part of the valley.

No historical highest groundwater information is available for Arroyo Seco or other smaller drainages in the eastern portion of Zone 2. However, construction excavations underway during this investigation encountered groundwater about 5 feet deep on the north side of York Boulevard. Similar abrupt variations in ground water are reported at the Sparkletts water plant on the south side of the valley. Some of these groundwater variations appear to be due to faults that form barriers to groundwater flow. Groundwater depth varied from 10 to 48 feet bgs in the four piezometers installed as part of the current study in Zone 2.

Groundwater depths at 11 of the 12 surface wave soundings (Z2-S1 to Z2-S4 and Z2-S6 to Z2-S12) were estimated using simple seismic refraction analysis of MASW shot records with groundwater modeled in the 7- to 30-foot depth range. The MASW array was not long enough at Z2-S5 to interpret the approximate depth to groundwater.

The rocks of the Fernando, Puente, and Topanga Formations are considered non-waterbearing. Packer tests performed on the bedrock within Zone 2 confirm the very low permeability of these materials (Table 4-5). However, localized fracture zones might have larger groundwater inflow potential than reported.

No major springs are known to occur in the upland bedrock areas within Zone 2. Although there are no large surface water recharge areas within the zone, normal inflow of water from the ground surface will occur during periods of rainfall.

8.6 Hazardous Materials

The ISAs and ESA identified eight open cases located within Zone 2. The locations of these sites are shown in Figure 6-1. No regional groundwater contamination sites (NPL site) were identified in Zone 2.

Eight sites with groundwater or soil contamination are located within Zone 2. Two of these sites, summarized below, are located in proximity (that is, less than 0.5 mile) to a portal zone for Zone 2:

- Chevron Station 9-0477, 4005 Eagle Rock Boulevard, Los Angeles, California (Map ID: 135/6). This site is located within 0.5 mile of the northwestern portal zone for Zone 2. The site has groundwater impacted with MTBE. This site is considered to have a potential to impact the project because it is located within the western portal zone for Zone 2 and has impacted the groundwater.

- ARCO - Serrato, Rudy C., 5555 E Alhambra Avenue, Los Angeles, California (Map ID: 558/22). This site is located within 0.5 mile of the southeastern portal zone for Zone 2. The site has soil impacted with gasoline. This site is considered to have a potential to impact the project because it is located within the southeastern portal zone for Zone 2 and has impacted the soil.

The remaining six sites with localized soil or groundwater contamination were identified as being in the central portion of Zone 2 and are considered to have low potential impact to the project because they are located greater than 0.5 mile from a portal zone and are characterized with soil or groundwater contamination at a depth of less than 150 feet bgs. Additional detail for each of these sites, including the corresponding soil and/or groundwater contaminants, their corresponding concentrations, and depth of maximum concentration is included in the Environmental Screening Evaluation in Appendix F.

8.7 Potential for Naturally Occurring Gas

The Puente Formation is one of the more prolific petroleum sources in the Los Angeles Basin. However, no known oil and/or natural gas fields are located within Zone 2.

The Upper Reach of the NEIS tunnel excavated within the Puente Formation in Zone 1 experienced hydrogen sulfide and methane. Although the NEIS tunnel is located under the Los Angeles River in Zone 1, the similarity of geologic conditions suggests that gassy conditions could be encountered in Zone 2.

8.8 Geotechnical Considerations for Tunnel Design and Construction

8.8.1 Key Ground Characteristics

Based on the results of this evaluation, the key geologic factors for this zone in terms of tunnel design and construction considerations (along the generalized geologic profile shown in Plate 6) are:

- Subsurface conditions are fairly uniform in this zone, consisting mainly of weak sedimentary rocks of the Puente and Topanga Formations. The Puente Formation includes sandstone, siltstone, and shale and is found in the southern portion of the zone; siltstone and sandstone of the Topanga Formation is expected in the northern portion (Plate 6). In addition, depending on the location of the tunnel, sandstones and conglomerates of the Fernando Formation may also be encountered. Locally, alluvium (or soil) is expected near the portal zones.

- The rock mass is generally slightly to moderately fractured. Several inactive faults will be encountered in this zone (Plate 1). The active Raymond fault crosses the northwest portion of the zone and could be encountered within the tunnel portal zone.
  The Raymond fault is capable of generating earthquakes in the range of M_W 6 to 6.7, producing estimated displacements at the tunnel level of approximately 0.8 to 3.4 feet.

- Most of the rock is considered very weak to weak, although there is a potential for stronger cemented layers and/or concretions in the Puente and Topanga Formations.
- Groundwater is shallow in alluvial valleys (approximately 20 feet bgs) but it is believed to be perched on top of bedrock. The rock mass generally has low permeability and, therefore, is not expected to transmit large quantities of groundwater into the tunnel except where saturated alluvium is encountered at the ends of the tunnel. Potential for high groundwater inflows exists within fractured, poor-quality rock and within the fault zone.
- Some minor soil and groundwater contamination, associated with two gas stations, could result in hazardous materials being encountered in the portal zones (northeast end of Zone 2).
- CDMG (1999d) identifies the alluvium within the drainages that cross Zone 2 as potentially susceptible to liquefaction in areas where the groundwater levels saturate loose, cohesionless soils.
- There is a relatively high potential of encountering naturally occurring gas (methane and/or hydrogen sulfide) in this zone because a significant portion of the zone is underlain by Puente Formation.

8.8.2 Preliminary Assessment of Tunneling Considerations

Information presented above and in previous sections of this report was used to perform a preliminary assessment of tunnel design and construction requirements, as summarized below.

A typical tunnel through the southern portion of Zone 2 would be excavated almost exclusively in sandstone (Tpss), shale (Tpsh) and siltstone (Tpsl) units of the Puente Formation. Except for the westernmost 6,000 feet where the tunnel will be in rocks of the siltstone (Ttsl) and sandstone (Ttss) members of the Topanga Formation. However, the eastern half (approximately) of a typical tunnel along the northern portion of Zone 2 is anticipated to be in the shale (Tpsh) and siltstone (Tpsl) units of the Puente Formation, whereas the western half would be in the siltstone (Ttsl) and in sandstone (Tpsl) units of the Topanga Formation and sandstones (Tfss) and conglomerates (Tfcg) of the Fernando Formation (Plate 6).

These formations have been encountered in previous tunnels completed in the Los Angeles area and can be readily excavated using current tunneling technologies, similar to Zone 1. The finer-grained portions of the Fernando, Topanga and Puente Formations are generally similar in terms of tunnel excavation and support requirements.

Similar to Zone 1, the uniformity of these formations (i.e., they are all weak sedimentary rock) will simplify construction activities and reduce the need for multiple excavation methods. As discussed for Zone 1, groundwater control methods will be required for the saturated alluvium present in the vicinity of the portal zones. In Zone 2, there appears to be less alluvium than in Zone 1; however, this may depend on the actual tunnel alignment, portal location, and tunnel depth. The need for special ground improvement measures or specialized tunneling machines for tunneling through saturated alluvium is the same as discussed above for Zone 1. The support requirements and lining necessary for the formations in Zone 2 will be similar as those discussed for Zone 1 in Section 7.8.2.

Several steeply dipping inactive faults are located in Zone 2. Tunneling through these faults will require the excavation of fractured, poor-quality rock; control of groundwater; and may involve excavation of clay gouge formed by prior fault movements. Control of ground movements during tunnel construction will be necessary to avoid loss of ground, settlement, and tunneling delays. A trace of the active Raymond fault is present at the northwestern end of the zone. Appropriate measures should be taken during design to account for the crossing of a fault. As discussed previously for Zone 1, these faults could affect groundwater levels and inflow magnitudes into the tunnel. Additional characterization of these faults, groundwater conditions, and ground conditions will be needed to develop groundwater control strategies.

Naturally occurring gas could be encountered in this zone. Tunneling experience in the Puente Formation suggests that gas will likely be encountered in this formation. Safety precautions and equipment similar to those in Zone 1 would apply to this zone for tunnel construction because of the potential for gases or soil and/or groundwater contamination.

Based on the information collected and reviewed in Zone 2, tunneling is considered to be feasible in this zone from a geotechnical standpoint. Subsurface conditions and appropriate design and construction provisions should be further evaluated in this zone during more detailed tunnel design studies.

SECTION 9

Site Conditions for Zone 3

9.1 General

As depicted in Plates 1 and 7, Zone 3 extends north-south from the northern terminus of SR-710 through the cities of Los Angeles, Alhambra, South Pasadena, and Pasadena approximately to the intersection of I-210/ SR-134. Zone 3 is approximately 4.5 to 5.0 miles long and 2.4 miles wide at its northern limit (Plate 1). The delineation of Zone 3 anticipates a connection between the northern terminus of SR-710 and SR-134, I-210, or SR-710 to the north. The general location of Zone 3 is shown in Figure 9-1.

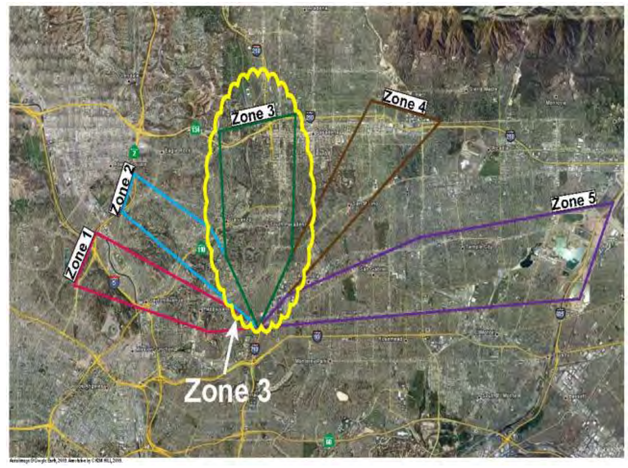

Figure 9-1. Zone 3 Location Map.

9.2 Existing Developments

Existing developments within Zone 3 consist primarily of single-family residential structures with some apartment and condominium buildings and local businesses along some of the major arterial streets. The northern part of the zone in the Pasadena area has a much greater number of commercial enterprises than the southern two-thirds, which is largely residential. The Huntington Hospital is in the northern part of the zone. Few of the buildings are multistory buildings over three or four stories high.

SR-110 (the Pasadena Freeway) passes through the northern part of the zone, entering from the west along the Pasadena/South Pasadena city boundary and extending northerly around Raymond Hill where shortly thereafter it changes into Arroyo Parkway, which continues northerly to downtown Pasadena. The Metro light rail (Gold Line) track crosses the northern part of the zone diagonally, somewhat parallel to SR-110 and then north into Pasadena just west of Arroyo Parkway.

Other important surface roads that cross Zone 3 in a general east-west direction include, from south to north, Valley Boulevard, Main Street, Huntington Drive, California Boulevard, and Colorado Boulevard. Fair Oaks Avenue and Orange Grove Boulevard run in a north-south direction in the northern portion of the zone. In addition, railroad tracks cross the southwestern part of the zone between Mission Road and Valley Boulevard.

Based on the densely urbanized nature of the area, it is anticipated that a large network of very shallow underground utilities are present directly underneath the surface streets.

However, during our investigation we did not become aware of any major underground utility or other infrastructure that could potentially impact the excavation of a tunnel at an anticipated depth of 200 feet.

9.3 Zone Geology

9.3.1 Physiography

The regional physiography of the area surrounding Zone 3 is described in Section 4.1 (Regional Geology). About half of Zone 3 is within the western part of the San Gabriel Valley, and half consists of the San Rafael Hills and the Repetto Hills (Figure 4-1).

The Repetto Hills and San Rafael Hills in the western part of the zone are characterized by small- and medium-sized rounded hills and intervening valleys. The maximum relief in the Repetto Hills of Zone 3 is generally in the 200- to 300-foot range. Although not of great relief, many of these hills have steep slopes.

A major geomorphic feature in Zone 3 is Arroyo Seco, which extends through Pasadena down the west-central part of Zone 3 and veers southwesterly near the Pasadena/South Pasadena city boundary. The arroyo continues southwesterly and exits Zone 3 to the west near the central part of the zone. Arroyo Seco is a steep-walled, flat-floored ravine about 500 to 1,000 feet wide and 50 feet deep. The arroyo widens into a relatively flat plain in South Pasadena. This change in relief is related to the Raymond fault scarp, which crosses through the central part of Zone 3. This scarp is a result of vertical fault displacement on the Raymond fault. Relief across the scarp is about 40 or 50 feet but has been highly modified by urban development.

The San Gabriel Valley, which encompasses the eastern part of Zone 3, is essentially a flat, gently south-sloping surface consisting of ancient (Pleistocene age) alluvial fans, flood plain, and basin fill alluvium. Elevations in the northern part of the Valley are in the 800- to 900-foot range, whereas in the south, elevations are in the 400- to 500-foot range. The flatness of the San Gabriel Valley surface is interrupted by several small hills and knolls, which are outliers of the Repetto Hills and San Rafael Hills. The largest of these hills is Raymond Hill, which is about 90 feet high. A smaller knoll just northwest of Raymond Hill is called Grace Hill. The other knolls are not named and are relatively subtle features that go largely unnoticed by the general public. Although subtle, these small knolls are important for understanding the geology of the region because they are bedrock exposures that reveal information regarding the surrounding subsurface geology.

9.3.2 Stratigraphy

The majority of Zone 3 rocks consist of Tertiary age (2 to 16 million years old) marine sedimentary rocks (Table 4-1). From oldest to youngest, these rocks are included in the Topanga, Puente, and Fernando Formations. Plate 1 shows the distribution of these units throughout Zone 3. Plate 7 illustrates the subsurface relationships of these various rock types along a north-south transect in the central part of Zone 3. However, it is important to recognize that the geologic profile is idealized and simplified to represent the entire zone. Zone 3 has the most diverse geology of all the five zones, illustrating the structure and stratigraphy of Zone 3 in a single geologic profile is complicated by the fact that the geological character changes considerably from the west to the east side of Zone 3. The west side consists primarily of rock formations, whereas the east side has thick alluvial deposits over the rock formations at depth.

Quaternary-age alluvium occurs as narrow valley fill in the valleys of the Repetto Hills and over the entire San Gabriel Valley. Alluvium is present at the northern portion of the zone, where it is approximately 500 to 600 feet thick, and at the southern portion of the zone where it is much thinner and on the order of 0 to 50 feet. Alluvium at the north portion of the zone is expected to consist of clay, silt, and sand with a major component of gravels and cobbles and some boulders, all composed of igneous and metamorphic rocks. The alluvium in the small valleys of the Repetto Hills is more silty and clayey with a smaller proportion of sand and gravel.

The principal formation in the southernmost portion of Zone 3 is the Fernando Formation which consists of soft and weak, massive claystone and siltstone. The Fernando Formation overlies the Puente Formation in the southern part of Zone 3. The contact is sharp and possibly unconformable (Dibblee, 1992).

The central part of Zone 3 is composed of the Puente and Topanga Formations separated by a fault on the north flank of the South Pasadena Anticline. The Puente Formation ranges from soft to moderately hard, well-bedded, siltstone, mudstone and sandstone, minor local zones of carbonate-cemented beds form hard rock. Such hard cemented beds comprise no more than about 5 to 10 percent of the formation. The Puente Formation in the southern portion of Zone 3, includes white to very pale-brown, soft, siliceous shale and thin-bedded mudstone. These rocks have a high percentage (sometimes nearly 100 percent) of diatoms or volcanic ash particles. The Topanga Formation occurs in the northern half of Zone 3. The Topanga Formation includes a wide variety of rock types ranging from coarse-grained rocks such as breccia, conglomerate, and sandstone to fine-grained sandstone and siltstone with minor claystone (mudstone). The part of the Topanga Formation south of the Raymond fault is predominantly thin- to thick-bedded siltstone with thin interbeds of sandstone and shale. These rocks are commonly very similar to those of the Puente Formation and various authors have in fact mapped them as Puente Formation. The Topanga Formation north of the Raymond fault is predominantly sandstone, conglomerate, and breccia. The Topanga Formation also has intrusive volcanic rocks. For example, a 10-foot-thick zone of hard volcanic rock was encountered in the 2006 Metro assessment within boring EMI-2, immediately south of the Raymond fault (Plate 7).

The northern part of Zone 3, north of the San Rafael fault, consists of the Cretaceous age (approximately 120 to 160 million years ago) basement complex that is generally mapped in exposures of the San Rafael Hills as Wilson Diorite or Quartz Diorite (Dibblee, 1989c; Lamar, 1970).

The geologic conditions discussed in the 2006 Metro assessment for the three (then-proposed) tunnel alignments in this zone (PBI, 2006) are similar to those determined in this study. The Metro assessment indicated that the tunnel would be excavated through geologic terrain typified by folded and faulted bedrock composed of a variety of Tertiary-age sedimentary rocks and Mesozoic-age crystalline igneous and metamorphic rocks (basement complex rocks), both overlain locally by unconsolidated Quaternary-age alluvium.

9.3.3 Structural Geology

As shown in Plate 7, the geologic strata are deformed into a series of folds and faults. Most of the folds and faults are continuations of geologic structures in the Santa Monica Mountains and the Elysian Hills to the west. These structures trend southeasterly through the Repetto Hills and continue below the flat-lying Quaternary alluvium of the San Gabriel Valley. The major folds are the Elysian Park Anticline and the South Pasadena Anticline.

The folding shown in Plate 7 is generalized and simplified. In reality, there are numerous small-scale folds within the larger fold trends. Frequent changes in bedding orientation due both to folding and faulting should be expected at tunnel depths. Such changes in bedding orientation are portrayed in the stereonets derived from the ATV logs obtained at 10 of the borings drilled in this zone.

Many of the faults are intraformational features, meaning that the faults offset rocks of the same type. However, some of the faults could comprise highly fractured or clayey gouge zones.

9.4 Faulting

The faults of most interest to the proposed tunneling are the active faults that might result in ground rupture and displacement during an earthquake, and faults that might generate strong shaking of tunnel facilities. The faults of most interest for Zone 3 are the Raymond fault, the San Rafael fault, and the Eagle Rock fault. As described in Section 4.2, the Eagle Rock fault and San Rafael fault are considered in this study to be separate and discrete features following the mapping of Lamar (1970). Depending upon final route selection, the Eagle Rock fault might not be crossed within Zone 3, but the Raymond and San Rafael faults will be intersected by tunnel alignments within this zone.

The Raymond fault is capable of generating earthquakes in the magnitude range of 6 to 6.7. Fault rupture displacement at the tunnel level can be expected to be in the 2- to 4-foot range. This displacement should be in a left-lateral oblique sense with the ground on the north side of the fault shifting to the left and upward relative to the south side. The Raymond fault in Zone 3 appears to be much narrower than to the east in Zone 4. In Zone 3, the fault may be a few tens of feet to a few hundred feet wide. However, the Raymond fault might be associated with another fault or several faults (the unnamed fault zone) to the south near Monterey Road (Plate 7), the existence of these unnamed faults is uncertain. If these southern faults exist at tunnel depth, the tunnel could go through a zone of faulting about 2,000 to 3,000 feet wide.

The San Rafael fault occurs on the north side of Raymond Hill and separates basement complex rock from the Topanga Formation (Plates 1 and 7). Published geologic maps (Lamar, 1970) show two surface traces. The aerial photograph lineament analysis and drilling performed for this study suggest that the more likely fault location is the northern branch. Recent trenches excavated across this branch did not reveal any active faulting. Borehole R-09-Z3B3 encountered a light-gray clay fault gouge about 85 feet thick. This material is primarily sheared and pulverized basement diorite rock. The large thickness of the gouge encountered in the boring is believed to represent the down-dip thickness (that is, the boring was drilled down a steeply dipping fault zone). If so, the width of the fault zone during tunneling would be expected to be approximately 20 to 40 feet wide.

The Eagle Rock fault is about 2,000 feet south of the San Rafael fault (Plates 1 and 7). The fault extends southeasterly into the Topanga Formation rocks in the knolls west and south of Raymond fault. Seismic-reflection line Z3-G2 (Appendix C.2) extends across this trace and indicates folding and faulting. Although the relationships are not clear, the seismic-reflection data are compatible with a steeply north-dipping fault. In addition, surface wave soundings Z3-S6 and Z3-S7 were conducted at the northern and southern ends of seismic line Z3-G2, respectively. S-wave velocity models for these soundings indicate that there is significant lateral velocity variation along the seismic line, possibly resulting from a fault bisecting seismic line Z3-G2. The Eagle Rock fault is considered potentially active. According to the Caltrans Seismic Design Criteria (2009) fault database, the Eagle Rock fault could produce an earthquake with a maximum magnitude of about 6.8.

9.5 Groundwater and Surface Water Conditions

The rocks in the Repetto Hills within Zone 3 are generally considered to contain little groundwater (Eckis, 1934) and this has been verified by permeability testing as part of this study. However, important groundwater aquifers do occur in the sand and gravel deposits of the San Gabriel and Raymond Basins, where they are the principal sources of water. The deep aquifers are overlain by perched groundwater bodies.

The historically highest groundwater in the sand and gravel deposits is shallowest on the north side of the Raymond fault where historically it has seeped or risen to the ground surface and formed small ponds and springs. According to (CDMG, 1998d) the water level has been as shallow as 10 feet. The depth to water gradually increases both northerly and southerly to about 200 feet in the south part of Zone 3 and to about 100 feet below the ground surface in the northern part.

Plate 7 illustrates the variation of the groundwater conditions along Zone 3. Plate 7 also shows the groundwater contours in Zone 3. Groundwater depth varied from 13 to 158 feet bgs in the 11 piezometers installed as part of the current study in Zone 3.

Groundwater depths for 16 of the 24 surface wave soundings (Z3-S1, Z3-S6, Z3-S7, Z3-S9 to Z3-S11, Z3-S13, Z3-S14, Z3-S16 to Z3-S18 and Z3-S20 to Z3-S24) were estimated from simple seismic refraction analysis of MASW or seismic reflection shot records with groundwater modeled in the 10- to 56-foot depth range. Groundwater depths for four soundings (Z3-S2 to Z3-S5) were interpreted from nearby borehole velocity logs and interpolated as necessary. Groundwater in the vicinity of these surface wave soundings was estimated to occur in the 98- to 148-foot depth range. The MASW profiles were not long enough to image depth to groundwater at four of the sounding locations (Z3-S8, Z3-S12, Z3-S15, and Z3-S19).

No major springs are known to occur in the upland bedrock areas within Zone 3. Although there are no large surface water recharge areas within the zone, normal inflow of water from the ground surface will occur during periods of rainfall.

9.6 Hazardous Materials

The ISAs and the limited ESA identified 11 open cases located within Zone 3. The locations of these sites are shown in Figure 6-1. No regional groundwater contamination sites (NPL site) were identified in Zone 3.

Twelve sites with localized groundwater or soil contamination are located within Zone 3. Two of these sites, summarized below, are located in proximity (that is, less than 0.5 mile) to a portal zone for Zone 3:

- Kaiser Permanente, 393 Walnut Street, Pasadena, California (Map ID: 393 Walnut). This site is located within 0.5 mile of the northern portal zone for Zone 3. The site has soil impacted with gasoline. This site is considered to have a potential to impact the project because it is located within the northern portal zone for Zone 3.
- Demolition Contractors, 5600 Alhambra, Avenue, Los Angeles, California (Map ID: 556/22). This site is located within 0.5 mile of the south portal zone for Zone 3. The site is suspected of having soil contamination. This site is considered to have a potential to impact the project because it is located within the southern portal zone for Zone 3.

Ten other sites with localized soil or groundwater contamination were identified in the central portion of Zone 3. They are considered to have a low potential impact to the project because they are greater than 0.5 mile from a portal zone and are at a depth of less than 150 feet bgs. Additional details for each of these sites, including the corresponding soil and/or groundwater contaminants, their corresponding concentrations, and depth of maximum concentration is included in the ESA in Appendix F.

9.7 Potential for Naturally Occurring Gas

During drilling of boring R-09-Z3B11, gassy odors were noted. Headspace measurements conducted in the field indicated mostly low VOC readings in the range of 5.0 to 20.0 ppm. Because the Puente Formation is a major petroleum-bearing unit in the Los Angeles region, there is potential for encountering gassy conditions within this formation. The potential is considered lower than in Zones 1 and 2 since the reach of the Puente Formation is shorter in Zone 3.

9.8 Geotechnical Considerations for Tunnel Design and Construction

9.8.1 Key Ground Characteristics

Based on the results of this evaluation, the key geologic factors for this zone in terms of tunnel design and construction considerations (along the generalized geologic profile shown in Plate 7) are:

- Subsurface conditions vary in this zone at tunnel depth including unconsolidated soil deposits (alluvium), weak sedimentary rocks (Fernando, Puente and Topanga Formations), and strong granitic-type basement rocks (diorite or quartz diorite).

- Rock strength varies widely in this zone from the sedimentary rocks (which are very weak to weak) to the higher strength granitic-type rocks. There is a potential for strong cemented layers and/or concretions in the Puente and Topanga Formations. Strong volcanic flows, dikes, or sills are also present in the unnamed fault zone south of the Raymond fault. Additionally, cobbles and boulders can be expected in the northern portion of this zone, within the Topanga Formation conglomerate and the alluvium.
- The Raymond fault and San Rafael fault act as groundwater barriers. Depth to groundwater varies from as shallow as 50 feet bgs near the Raymond fault to more than 100 feet in both the northern and the southern parts of the zone. Groundwater elevations may vary by more than 100 feet on opposite sides of the San Rafael fault. Rock formations are not expected to transmit large quantities of groundwater into the tunnel. Potential for high groundwater inflows exists within fractured, poor-quality rock, as well as within the fault zone. However, groundwater inflows are expected when tunneling in the saturated alluvium.
- There is one active, two potentially active, and several inactive faults in this zone. The Raymond fault is active; it is capable of generating earthquakes in the range of M_W 6 to 6.7, and producing displacement at the tunnel level in the 2 to 4 foot range. The activity of the San Rafael and Eagle Rock faults is unknown; potentially active and inactive faults may act as groundwater barriers.
- CDMG (1999d and 1999f) identifies the alluvial materials within the drainages that dissect Zone 3 as potentially susceptible to liquefaction in areas where the groundwater location is in loose, cohesionless soils.
- Two sites with minor soil contamination are located at the northern limits of this zone and could impact the project depending on the actual portal location.
- There is a moderate potential of encountering naturally occurring gas (methane and/or hydrogen sulfide) in this zone, as the southern portion of the zone is underlain by the Puente Formation (Plate 7).

9.8.2 Preliminary Assessment of Tunneling Considerations

Information presented above and in previous sections of this report was used to perform a preliminary assessment of tunnel design and construction requirements, as summarized below.

Tunnel excavation in this zone would be through several different rock types. As discussed above, the tunnel excavation methods would need to address a range of conditions including alluvium (soil), weak sedimentary rocks, and stronger granitic-type rocks. This would require the use of tunneling equipment adaptable to this range of conditions or a flexible approach that allowed methods to be changed to suit the geology.

Tunneling machines are available for this wide range of ground conditions, including convertible TBMs that can be operated in open mode (for rock) or in closed mode (for soil or other unstable ground conditions) as discussed for Zone 1. This type of flexibility will be important in the selection of tunneling equipment for this zone.

Regardless of the excavation methods, special provisions will be necessary to address the inherent variability of the Puente and Topanga Formations, such as the cemented layers and concretions and variability between sandstone, siltstone, claystone, mudstone, and shale. These layers should be considered in the design of tunnel excavation equipment. Additionally, the design of the tunneling equipment should consider the size and strength/hardness of the cobbles and boulders.

As discussed above for Zone 1, in the alluvium (or soil) that will be encountered in the northern portion of Zone 3, loss of ground and surface settlement will be an important factor in the selection of tunneling methods and equipment. In addition, appropriate groundwater control measures will be required to control potentially unstable saturated alluvium. The need for special ground improvement measures or specialized tunneling machines for tunneling though saturated alluvium is the same as discussed for Zone 1. Tunnel support requirements and lining provisions for Zone 3 will be similar to those for Zone 1.

This zone has active and inactive steeply dipping faults. As indicated on the geologic cross section (Plate 7), these faults contribute to the variability of geologic conditions. Tunneling through these faults will require groundwater control measures; excavation of fractured, poor-quality rock; and potential clayey fault gouge. It is known that the Raymond fault is a groundwater barrier. Other fault zones also have the potential to act either as groundwater barriers or as conduits.

In addition, ground displacements may be generated by active faults that cross the tunnel. This will require special design features to allow the tunnel to accommodate the ground displacement without rupturing. Typically, this is accomplished by overexcavating a vault in the portion of the tunnel crossing the fault zone that is large enough to accommodate the fault displacements without impacting the inner tunnel lining, and the tunnel is constructed within the vault. This approach was used to construct the Metro Red Line tunnel crossing of the Hollywood fault (see Section 12.1.3).

Ground support, to control ground loss, and in turn surface settlement, similar to those discussed for the other zones would be needed for the tunnel through rock. In the saturated alluvium, a watertight initial support system as well as final lining would be required such as a bolted and gasketed precast concrete segmental lining system. At the fault crossings, where clay gouge may be present, squeezing ground may lead to much higher ground loads than in other portions of the tunnel. Squeezing ground refers to the time-dependent convergence that occurs around a tunnel excavation when the ground is overstressed. In addition, naturally occurring gas may be present in the southern portion of the zone and safety precautions similar to those mentioned for Zones 1 and 2 will be required.

Based on the information collected and reviewed in Zone 3, tunneling is considered to be feasible in this zone from a geotechnical standpoint. Subsurface conditions and appropriate tunnel design construction provisions should be further evaluated for this zone in more detailed tunnel design studies.

SECTION 10

Site Conditions for Zone 4

10.1 General

As depicted in Plates 2 and 8, Zone 4 extends northeasterly from the northern terminus of SR-710 through the cities of Alhambra, San Gabriel, San Marino, Pasadena, and Arcadia to I-210. Zone 4 is approximately 6 to 7.5 miles long and 2 miles wide at its northeastern limit. The delineation of Zone 4 anticipates a connection between the northern terminus of SR-710 and I-210 to the northeast. The general location of Zone 4 is shown in Figure 10-1.

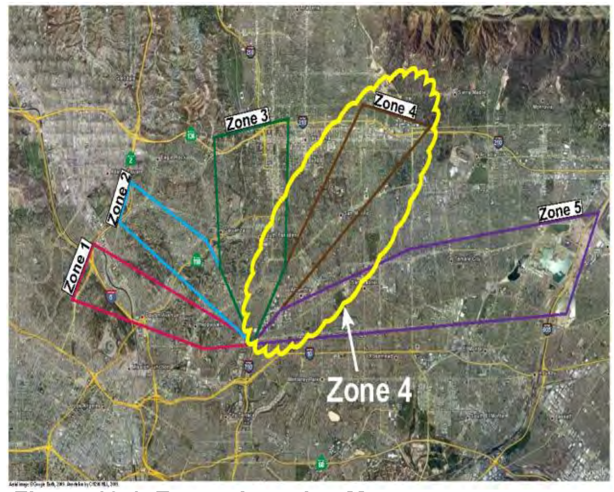

Figure 10-1. Zone 4 Location Map.

10.2 Existing Developments

Surface developments within the zone consist primarily of single-family residential structures with some apartment and condominium buildings and local businesses along some of the major arterial streets. Few multistory buildings are over 3 or 4 stories high. The tallest building accommodates the LACDPW offices in the Titemanson Building along Fremont Avenue.

Interstate 210, a major southern California freeway, extends in an east-west direction and forms the northern terminus of the zone. Other important surface roads that cross through Zone 4 in a general east-west direction include, from south to north, Valley Boulevard, West Mission Road, Main Street, Huntington Drive, California Boulevard and Colorado Boulevard. Fremont Avenue, Sierra Madre Boulevard and San Gabriel Boulevard run in a north-south direction in the southern and northern portions of the zone. In addition, railroad tracks cross the southwestern part of the zone between Mission Road and Valley Boulevard.

Based on the densely urbanized nature of the San Gabriel Valley, it is anticipated that a large network of very shallow underground utilities is present underneath the surface streets. However, during our investigation we did not become aware of any major underground utility or other infrastructure that could potentially impact the excavation of a tunnel at an anticipated depth of 200 feet.

10.3 Zone Geology

10.3.1 Physiography

Zone 4 is located entirely within the San Gabriel Valley. The San Gabriel Valley is essentially a flat, gently south-sloping surface consisting of ancient (Pleistocene-age) alluvial fan, stream, and basin fill deposits. Elevations in the northern part of the San Gabriel Valley are in the 800- to 900-foot range; whereas in the south, elevations are in the 400- to 500-foot range. The gentle southward slope of the San Gabriel Valley is interrupted about halfway by the Raymond fault scarp, which crosses diagonally through the central part of Zone 4 (Plate 8). This scarp is a result of vertical fault displacement on the Raymond fault. Maximum relief across the scarp in Zone 4 is about 100 to 150 feet. In addition, a small knoll, representing an outlier of the Repetto Hills, occurs in the southwest part of the zone (Plate 2).

The intermittent Alhambra, San Pascual, Rubio, and Eaton Washes drain the zone in a southeasterly direction and flow into Rio Hondo south of Zone 5.

10.3.2 Stratigraphy

Geologic formations within Zone 4 consist of Tertiary-age marine sedimentary rocks, and Quaternary-age nonmarine alluvial sediments (Table 4-1). From oldest to youngest, these rock formations are Topanga Formation, Puente Formation, and Fernando Formation. Plate 2 shows the surface distribution of geologic units and Plate 8 illustrates the subsurface relationships of these various rock types along a northeast-southwest transect in the central part of Zone 4. However, it is important to realize that the geologic profile is idealized and simplified to represent the entire zone.

The tunnel is expected to be primarily within the alluvium as shown in Plates 2 and 8. The alluvial thickness ranges from about 0 to 50 feet at the southern end to over 600 feet at the northern end. A small portion of the tunnel will be in bedrock at the southern end. The alluvium is generally Old Alluvium (Pleistocene age), but local thin deposits of Young Alluvium (Holocene age) exist in the uppermost levels of some intermittent gullies and washes. The alluvium in Zone 4 consists of clays, silts, sands, gravels, and cobbles. The sands and gravels are generally water-bearing and form the major aquifers of the basin. The finer-grained materials (clays and silts) are less permeable than the sands and gravels and thus form aquitards that impact the flow and distribution of subsurface water bodies.

Bedrock of the Fernando and Puente Formations underlies the alluvium in the southwestern portion of Zone 4 (Plate 8). The Fernando Formation consists of massive (unbedded) soft, dark gray to black, marine claystone and siltstone.

Siltstone of the Puente Formation ranges from soft to moderately hard and is well bedded with abundant partings along bedding planes. Although carbonate is common in the formation, only local zones are cemented into hard rocks. Such hard-cemented beds comprise no more than about 5 to 10 percent of the formation. Near the southwesternmost end of Zone 4, the Puente Formation might also include some white, soft, siliceous shale and thin-bedded mudstone.

Within the central and northeastern portions of Zone 4, Topanga Formation and basement complex rocks are present at a depth well below a typical tunnel elevation and, as such, are not expected within the tunnel (Plate 8).

10.3.3 Structural Geology

As shown in Plate 8, the geologic strata are deformed into a series of folds and faults. Most of the folds and faults are continuations of geologic structures in the Repetto Hills to the west. These structures trend southeasterly and continue below the flat-lying Quaternary alluvium of the San Gabriel Valley. The major folds in this area are the Elysian Park Anticline and the South Pasadena Anticline.

The folds are offset by many faults, most of which are ancient features that are no longer active. The folding shown in Plate 8 is generalized and simplified. In reality, there are numerous small-scale folds within the larger fold trends. Frequent changes in bedding orientation should be expected during tunneling, due both to folding and faulting. Many of the faults are intraformational features, meaning that they offset rocks of the same type. If these faults are minor breaks, they may not significantly affect a TBM.

10.4 Faulting

The faults of most interest to proposed tunneling are the active faults that might result in displacement during an earthquake, and faults that might generate strong shaking of project facilities. For Zone 4, these are the Raymond fault and the Alhambra Wash fault. The surface scarp of the Alhambra Wash fault is short and does not extend into Zone 4 (Plate 2). However, seismic-reflection lines Z4-G2 and Z5-G2 (Appendix C.2) indicate deformation of Quaternary sediments along projections of the fault suggesting that it may continue through the zone in the subsurface.

Seismic-reflection data of line Z4-G1 indicate that the main branch of the Raymond fault is approximately several hundred feet wide. In addition, there appear to be several subparallel branches so the zone of faulting could be as wide as about 3,000 feet locally (Plate 8). This condition is confirmed by the S-wave velocity models obtained for surface wave soundings Z4-S2 through Z4-S4. These soundings were located in the northern, central and southern portions of seismic line Z4-G1, respectively. The S-wave velocity models for these soundings are quite variable, as may be expected because the Raymond fault bisects the seismic line.

As discussed in Section 4.2, the Raymond fault is capable of generating earthquakes in the 6 to 6.7 range. Fault rupture at the tunnel level can be expected to shift the ground in the 2- to 4-foot range. This displacement should be in a left-lateral oblique sense with the ground on the north side of the fault moving to the left and upward relative to the south side. The approximate magnitude of the maximum earthquake on the Alhambra Wash fault could be about 6.25 (see Section 4.2). Based on this, potential surface rupture displacement along the Alhambra Wash fault would be expected to be much less than those that would be expected along the Raymond fault.

Based on hydrostratigraphic evaluation of the San Gabriel Valley Area 3 Superfund Site Remedial Investigation, the potential presence of a northwest-trending structural bedrock discontinuity is inferred in the Alhambra and South Pasadena areas of the San Gabriel Basin

(CH2M HILL, 2009c). The inferred bedrock discontinuity is shown from approximately the intersection of I-10 and Garfield Avenue in Alhambra on the south toward Raymond Hill and SR-110 in South Pasadena to the north. The existence of this structural bedrock discontinuity might explain a significant disparity in groundwater levels between the western and eastern portions (CH2M HILL, 2009c), and might correspond to an unnamed fault zone that extends across this area to the Raymond fault. On the other hand, the data that led to interpretation of the feature were not of high resolution and, thus, the feature may represent either the East Montebello fault or the Alhambra Wash fault (or both).

10.5 Groundwater and Surface Water Conditions

Groundwater occurs in the sand and gravel alluvial deposits of the San Gabriel Valley. The historically highest groundwater in the sand and gravel was shallowest on the north side of the Raymond fault where it was at the surface and formed small ponds and seeps. South of the Raymond fault, the historical high was at depth of about 100 feet, and it gradually deepens to about 200 feet bgs near the southwest end. The high groundwater level north of the Raymond fault gradually deepened to about 100 feet at the northeast end of Zone 4.

Significant amounts of groundwater inflows are expected only in alluvial deposits. The Tertiary sedimentary rocks are non-water-bearing and do not yield significant groundwater volumes.

Although there are no large surface water recharge areas within the zone, normal inflow of water from the ground surface will occur during periods of rainfall.

10.6 Hazardous Materials

The ISAs and ESA identified 14 open cases within Zone 4. The locations of these sites are shown in Figure 6-1.

The San Gabriel Valley NPL Site consists of four Operable Units (OUs) (Areas 1 through 4); however, only OU Area 3 (Alhambra) is located within the central and southern portions of Zone 4. Portions of the OU Area 3 (Alhambra) within Zone 4 are known to be contaminated with chlorinated VOCs including the following: PCE, and TCE, cis-1,2-dichloroethene (cis-1,2-DCE), 1,2,3-trichloropropane (1,2,3-TCP), carbon tetrachloride (CCl_4), perchlorate, and nitrate as NO_3 (CH2M HILL, 2009d). Well locations within OU Area 3 (Alhambra) that have detections of these contaminants above the maximum contaminant levels (MCLs) are shown in Figure 6-1.

In 1984, a study of the San Gabriel Valley groundwater was initiated by USEPA to determine the nature and extent of contamination. In 1999, a Remedial Investigation (RI) for Area 3 was initiated and later completed in June of 2009 (CH2M HILL, 2009c). The RI report assessed the nature and extent of groundwater contamination in Area 3 and the potential for harm to public health or the environment caused by the contamination. USEPA has not defined the lateral extent of contamination at this time. A Feasibility Study (FS) will be performed using the conclusions from the RI to identify and evaluate cleanup alternatives that will prevent and eliminate the release or the threat of release of contaminants in groundwater at the site (USEPA, 2009b). A ROD, will be completed after USEPA evaluates the extent of contamination. After completion of the ROD, a containment system and remedial design will be developed.

Fourteen sites (including the San Gabriel Valley Area 3 [Alhambra] NPL Site) with localized groundwater or soil contamination are located within Zone 4. Six of these sites, summarized below, are located near (that is, less than 0.5 mile) to a portal zone for Zone 4:

- Chevron #9-7762, 233 Altadena Drive N., Pasadena, California (Map ID: 4/2). This site is located within 0.5 mile of the northern portal zone for Zone 4. The site has soil impacted with hydrocarbons. This site is considered to have a potential to impact the project because it is located within the northern portal zone for Zone 4 and has impacted the soil.

- 76 Products Station. #5917, 3678 Foothill Boulevard E., Pasadena, California (Map ID: 8/3). This site is located within 0.5 mile of the northern portal zone for Zone 4. The site has soil impacted with solvents and/or nonpetroleum hydrocarbons. This site is considered to have a potential to impact the project because it is located within the northern portal zone for Zone 4 and has impacted the soil.

- Naval Information Research Foundation, 3202 E. Foothill Boulevard Pasadena, California (Map ID: 13/2). This site is located within 0.5 mile of the northern portal zone for Zone 4. The site has soil impacted with arsenic, dioxins, petroleum, polychlorinated biphenyl (PCBs), polycyclic aromatic hydrocarbons (PAHs), and VOCS. This site is considered to have a potential to impact the project because it is located within the northern portal zone for Zone 4 and has impacted the soil.

- Abandoned Property, 2159 Foothill Boulevard E., Pasadena, California (Map ID: 24/1). This site is located within 0.5 mile of the northern portal zone for Zone 4. The site is suspected to have soil contamination. This site is considered to have a potential to impact the project because it is located within the northern portal zone for Zone 4 and has impacted the soil.

- Kinneloa Avenue Property, 175 S Kinneloa Avenue, Pasadena, California (Map ID: 101/6). This site is located within 0.5 mile of the northern portal zone for Zone 4. The site has soil impacted with asbestos, halogenated organic compounds, metals, and other inorganics. This site is considered to have a potential to impact the project because it is located within the northern portal zone for Zone 4 and has impacted the soil.

- ARCO Station No. 6109, 3201 West Valley Boulevard, Alhambra, California (Map ID: 254/14). This site is located within 0.5 mile of the southern portal zone for Zone 4. The site has soil impacted with gasoline-range organics (GRO), MTBE, and tertiary butyl alcohol (TBA). This site is considered to have a potential to impact the project because it is located within the southern portal zone for Zone 4 and has impacted the soil.

The remaining six sites (not including the NPL site) with localized soil or groundwater contamination are in the central portion of Zone 4 and are considered to have a low potential impact to the project because they are located greater than 0.5 mile from a portal zone, or are characterized with soil or groundwater contamination at a depth of less than 150 feet bgs. Additional details for each of these sites, including the corresponding soil and/or groundwater contaminants, their corresponding concentrations, and depths of maximum concentration are included in the ESA in Appendix F.

10.7 Potential for Naturally Occurring Gas

The alluvium in the San Gabriel Basin is not a producer of hydrocarbons. However, there are rocks that serve as the source for hydrocarbons at the southern and western margin of the basin, and small oil fields are located around the southern margin. The basin represents an important groundwater aquifer and no incidents of naturally occurring hydrocarbons have been reported. Therefore, the potential for naturally occurring gas to be encountered within Zone 4 is considered low.

10.8 Geotechnical Considerations for Tunnel Design and Construction

10.8.1 Key Ground Characteristics

Based on the results of this evaluation, the key geologic factors for this zone in terms of tunnel design and construction considerations (along the generalized geologic profile shown in Plate 8) are:

- Subsurface conditions are fairly uniform in this zone at tunnel depth and consist mainly of Old Alluvium and sedimentary rocks (Fernando and Puente Formations) near the southern end of the zone. The majority of the tunnel is expected to be in the Old Alluvium. The Old Alluvium is generally expected to be uncemented coarse sand and gravel, interbedded with sand, silt, and clay. The Fernando Formation is expected to consist of siltstone and claystone. The Puente Formation is expected to be composed of clayey siltstone and silty claystone (commonly called mudstone), as well as some sandstone.
- The Old Alluvium exhibits the strength characteristics of a soil with low cohesion (i.e., low undrained shear strength). The Fernando and Puente Formations are expected to be moderately weak to weak rock. Cobbles and boulders can be expected in the Old Alluvium. Strong cemented layers and concretions may be encountered in the Puente Formation.
- The active Raymond fault and Alhambra Wash fault cross this zone, and could cause ground rupture during a large earthquake. Several inactive faults within the Tertiary-age rocks cross the southwestern portion of this zone.
- Most of the tunnel in this zone would be at or below the historically highest groundwater table. Current depth to groundwater varies; however, it could be as shallow as 100 feet bgs immediately north of the Raymond fault. The Raymond fault is a groundwater barrier; historically, groundwater is shallowest on the north side of this fault. Groundwater inflows could occur while tunneling below the groundwater table in the saturated alluvium.

- CDMG (1999b, 1999d, and 1999e) identifies the alluvial materials within the northeastern most portion of Zone 4 as potentially susceptible to liquefaction in areas where the groundwater levels saturate loose, cohesionless soils such as in shallow excavations in the portal zones.
- One Superfund site is located approximately at the southwest end of this zone. USEPA is currently evaluating the extent of the contamination and will subsequently complete a ROD. Six other sites with various levels of soil contamination are also present in this zone and are close enough to impact the tunnel. Most of these sites are located in the northern portion of the zone.
- There is a low potential for encountering naturally occurring gas in this zone due to the limited portion of the tunnel in the Puente Formation.

10.8.2 Preliminary Assessment of Tunneling Considerations

Information presented above and in previous sections of this report was used to perform a preliminary assessment of tunnel design and construction requirements, as summarized below.

Tunnel excavation in this zone would be mostly through alluvial materials consisting of silt, clay, sand and gravel. Cobbles and boulders are also expected throughout the alluvium. The remaining portion of the excavation will be through the Fernando and Puente Formations.

The uncemented alluvial sands would likely have the tendency to run or flow (depending on groundwater conditions) during excavation, requiring specific tunneling methods and equipment to prevent this type of instability. Tunneling characteristics of the Puente and Fernando Formations will be similar to those explained for Zones 2 and 3. Depending on the slope of the geologic contact between the alluvium and the Fernando Formation, there might be some length of tunnel excavated in mixed-face conditions, consisting of weak rock and alluvium. An excavation method capable of tunneling through both weak rock and alluvium under the groundwater table would be required to deal with these conditions.

The potentially running or flowing conditions in the alluvium could result in loss of ground and the potential for surface settlement. The amount of settlement would depend on a variety of factors including the tunnel excavation and support methods, ground characteristics, diameter of the tunnel, and cover above the tunnel (i.e., distance from the tunnel crown to the ground surface). Typically, a ground cover of at least two tunnel diameters is desirable for minimizing settlement magnitudes. The impacts can be mitigated as described previously (Section 7.8.2) in the discussion on Zone 1.

Considering the significant length of saturated alluvium in this zone, use of a pressurized face TBM (i.e., either an EPB or a slurry machine), as discussed for Zone 1, would be required to avoid unstable ground conditions, loss of ground, and surface settlement. This type of machine is critical for minimizing settlement associated with tunneling in developed urban areas.

In the saturated alluvium, a watertight initial support system, as well as a final lining, would be required—such as a bolted and gasketed, precast concrete, segmental lining system. Support in the sedimentary rocks would be similar to those described for Zone 1.

This zone includes several steeply dipping, active and inactive faults. Tunneling through these faults will be similar to that described in Zone 3. The active Raymond fault is a known groundwater barrier; however, the inactive fault zones have the potential to act as groundwater barriers or conduits as well. Because the groundwater levels vary greatly over this zone, tunnel excavation methods would have to accommodate a wide range in hydrostatic pressures. Special provisions will be necessary for lining construction across an active fault zone as discussed in Zone 3. Additionally, because there is a potential for tunneling through contaminated soil and groundwater, special precautions, such as those described for Zone 1, will be important with regard to the excavation and the disposal of contaminated muck. Considerations similar to those outlined in Section 7.8 will be necessary in the Puente Formation where naturally occurring gas may be encountered.

Based on the information collected and reviewed in Zone 4, tunneling is considered to be feasible in this zone from the geotechnical standpoint. Subsurface conditions and appropriate tunnel design and construction provisions should be further evaluated for this zone in more detailed tunnel design studies.

SECTION 11

Site Conditions for Zone 5

11.1 General

As depicted in Plates 2 and 9, Zone 5 extends to the east from the northern terminus of SR-710 through the cities of Alhambra, San Gabriel, Temple City, El Monte, and Arcadia to I-605. Zone 5 generally extends parallel to Valley Boulevard, north of I-10, and terminates at I-605 in the east. The northern limit roughly coincides with Las Tunas Drive/Live Oak Avenue/Arrow Highway. Zone 5 is approximately 9.5 to 11.0 miles long and as wide as 2.3 miles at its eastern end. The delineation of Zone 5 anticipates a connection between the northern terminus of SR-710 and I-605. The general location of Zone 5 is shown in Figure 11-1.

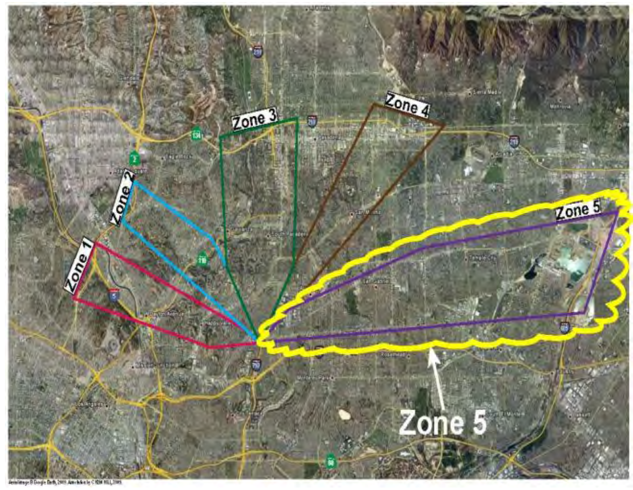

Figure 11-1. Zone 5 Location Map.

11.2 Existing Developments

The Zone 5 area is densely populated and urbanized with predominantly residential, commercial, and industrial developments. I-605, a major Southern California freeway, runs in a north-south direction and forms the easternmost terminus of the zone. The zone is roughly parallel to the east-west trend of I-10 that is located to the south. Other important surface roads that cross through Zone 5 in a north-south direction include (from west to east) Fremont Avenue, Atlantic Boulevard, Garfield Avenue, San Gabriel Boulevard, Rosemead Boulevard, Santa Anita Avenue, and Peck Road. Mission Road runs northeast-southwest in the western portion of the zone; whereas, Valley Boulevard and Las Tunas Drive run parallel to the zone in its southern and northern limits, respectively. In addition, railroad tracks cross the western portion of the zone between Mission Road and Valley Boulevard.

The intermittent Alhambra, Rubio, and Eaton washes cross the western portion of the zone in a southeasterly direction, whereas the intermittent Arcadia and Santa Anita washes drain the central portion in a southerly direction. The perennial Rio Hondo and San Gabriel River run parallel and drain in a southwesterly direction the eastern portion of Zone 5. The Alhambra, Rubio, and Eaton washes drain into Rio Hondo outside the southern limit of the zone. The Arcadia and Santa Anita washes also drain into Rio Hondo within Zone 5 limits.

Based on the densely urbanized nature of the San Gabriel Valley where Zone 5 is located, it is anticipated that a large network of shallow underground utilities are present directly underneath the surface streets. However, during this investigation, no major underground utility or other infrastructure was apparent that could potentially impact the excavation of a tunnel at an anticipated depth of 200 feet.

11.3 Zone Geology

11.3.1 Physiography

Zone 5 is mostly within the relatively flat San Gabriel Valley at an average topographic elevation of approximately 400 feet above msl. Rio Hondo, the San Gabriel River, and their tributaries, form the major stream system that drains the San Gabriel Valley. Both streams have headwaters in the San Gabriel Mountains to the north, where most of the runoff is derived. Both rivers have a common exit from the basin through Whittier Narrows from where they continue to the sea through the Los Angeles coastal plain. Rio Hondo drains the northwestern portion of the San Gabriel Basin, and its tributaries (Alhambra, Rubio, Eaton, Arcadia, and Santa Anita washes) enter the valley from the Raymond Basin located in the Pasadena area. All of the drainages are presently confined within riprap- or concrete-lined aqueducts except for spreading basins and quarries in the eastern portion of the zone.

11.3.2 Stratigraphy

Three major geologic units occur within Zone 5, including the Puente and Fernando Formations, and Quaternary alluvium. The approximate configuration of the interface between the underlying sedimentary bedrock and the overlying water-bearing Old Alluvium is generalized in Plates 2 and 9. However, it is important to realize that the geologic profile is idealized and simplified to represent the entire zone.

The majority of the tunnel in Zone 5 is expected to be within Old Alluvium. The eastern and west-central portions of the zone could be located within the Young Alluvium. In the western portion of Zone 5, the thickness of the alluvium ranges from 0 to 250 feet; at the south-central portion of the zone, the thickness can be over 1,900 feet.

Old Alluvial materials are reported to consist of unsorted deposits of boulders, gravel, sand, silt, and clay. These deposits are generally coarser grained closer to the San Gabriel Mountains and become finer grained farther toward the south, such as near Whittier Narrows. The sediments underlying the Rio Hondo and San Gabriel River drainage system and the alluvial fan built up by this system in the eastern portion of Zone 5 contain in general less finer-grained materials than the Old Alluvium present in other parts of the basin. The presence of interbedded aquitards is well documented within the Old Alluvium in the entire San Gabriel Basin (CDWR, 1966; CDM, 1998, 2006, 2008a, and 2008b; GeoSyntec, 2006a and 2006b; CH2M HILL, 2003, 2006, and 2009c).

Pliocene sedimentary rocks were encountered underlying Old Alluvium at a depth of approximately 4,100 feet just north of the Whittier Narrows Flood Control Basin, which probably represent the maximum thickness of Old Alluvium in the basin. The thickest alluvium fill along Zone 5 appears to be in the vicinity of Rio Hondo, San Gabriel River, and their floodplains (CDWR, 1966).

Very limited outcrops of the Fernando and Puente Formations occur at the westernmost portion of Zone 5 (CDWR, 1966; Dibblee, 1989b and 1999; Tan, 2000b). In the subsurface, the Fernando Formation is interpreted to underlie Zone 5 east of the Highland Park fault; whereas, the Puente Formation is interpreted to occur to the west of the same fault at a very shallow depth (Yeats, 2004). The Fernando Formation is reported to be composed predominantly of weakly cemented sandy siltstones and mudstones. Very few randomly oriented bedding attitudes were recorded at the same location. Bedding dip inclinations range from approximately 60 to 25 degrees within the massive claystone and are essentially flat within the massive siltstone. The few bedding attitudes and their random orientation might be an expression of the massive nature and the poorly developed bedding of the claystone and siltstone rocks of the Fernando Formation in the western portion of Zone 5.

The underlying Puente Formation is reported to consist of siltstones, shales, and conglomerates, with interbedded sandstone and mudstone.

11.3.3 Structural Geology

Zone 5 is in the western portion of the topographically flat alluvial San Gabriel Basin. The alluvial deposits in this basin are nearly horizontal or have a gentle inclination to the south, similar to the slope of the existing surface topography. A few north-northwest trending faults are reported to transect the westernmost portion of the San Gabriel Basin. The most notable of which are the Alhambra Wash, Workman Hill, and Highland Park faults (CDWR, 1966; Lamar, 1970; Dibblee, 1989b and 1999; Treiman, 1991b; Tan 2000b; Yeats, 2004). The specific faulting considerations associated with Zone 5 are discussed below. A detailed description of faulting is presented in Section 4.

11.4 Faulting

The Alhambra Wash fault is currently zoned as an APEFZ for a short distance of approximately 2 miles (CDMG, 1991). The northernmost limit of the designated APEFZ is located approximately 1.2 miles south of Zone 5. However, the geomorphic evidence in the form of weakly developed elevation changes suggests that the Alhambra Wash fault may continue well beyond the designated APEFZ limits and that it might represent a longer fault (Tan, 2000b; Bullard and Lettis, 1993; Treiman, 1991b). Surface wave modeling for soundings Z5-S8 and Z5-S9 located at the eastern and western portions of seismic line Z5-G2, indicate that there is not significant lateral velocity variation in the immediate vicinity of the seismic line within the upper 200 feet. However, seismic-reflection data (line Z5-G2, Appendix C.2) with a much deeper zone of investigation revealed deformed Quaternary sediments along the projection of this fault. Therefore, it is assumed that the Alhambra Wash fault is projected to intersect Zone 5 and is considered to be active fault. As discussed in Section 4.2, the approximate magnitude of the maximum earthquake on the Alhambra Wash fault could be about 6.25. Based on this, potential surface rupture displacement along the Alhambra Wash fault would be expected to be much less than those that would be expected along the Raymond fault (less than 2 to 4 feet, see Section 4.2).

In addition to the active Alhambra Wash fault, three inactive faults cross Zone 5. The Workman Hill fault, Highland Park fault, and Montebello fault are interpreted to cross Zone 5 in the western portion of the zone. None of these faults are well known; they are interpreted from sparse subsurface data such as groundwater and oil-well data and are not exposed at the surface.

Based on hydrostratigraphic evaluation of the San Gabriel Valley Area 3 Superfund Site Remedial Investigation, the potential presence of a northwest-trending structural bedrock discontinuity is inferred in the Alhambra and South Pasadena areas of the San Gabriel Basin (CH2M HILL, 2009c). The inferred bedrock discontinuity is shown from approximately the intersection of I-10 and Garfield Avenue in Alhambra on the south toward Raymond Hill and SR-110 in South Pasadena to the north. According to CH2M HILL, the existence of this structural bedrock discontinuity might explain a significant disparity in groundwater levels between the western and eastern portions and might correspond to an unnamed fault zone that extends across this area to the Raymond fault. On the other hand, the data that led to interpretation of the feature were not of high resolution and, thus, the feature may represent either the East Montebello fault or the Alhambra Wash fault (or both).

11.5 Groundwater and Surface Water Conditions

According to the MSGW (2006) groundwater-contour map for the entire basin, the groundwater levels in 2006 occurred at a depth of approximately 300 feet and at 0 to 100 feet in the western and eastern portions, respectively. CDMG (1998a, 1998b, 1998d) identifies historical highest groundwater levels at 100 to 150 feet and 10 to 50 feet in the western and eastern portions, respectively, of Zone 5.

Groundwater flows to the east from the westernmost limit of Zone 5 to the vicinity of Alhambra Wash. The groundwater flow reverses to a westerly direction from the easternmost portion of the zone to the same general area of the Alhambra Wash (Plates 2 and 9). Recharge basins that can seasonally become lakes are present in the eastern portion of Zone 5 between the Rio Hondo and San Gabriel River (Dibblee, 1999). Numerous gravel pits are also present within this area.

From west to east, surface water features located within Zone 5 include Alhambra Wash, Easton Wash, Arcadia Wash, and Rio Hondo. The San Gabriel River and Santa Fe Flood Control Basin are located in the eastern portion of Zone 5.

11.6 Hazardous Materials

The ISAs and ESA identified the numerous open cases located within Zone 5. The locations of these sites are shown in Figure 6-1.

Portions of the San Gabriel Valley OU Area 1 (El Monte) and OU Area 3 (Alhambra) NPL Sites are located in Zone 5. The approximate plume boundaries for San Gabriel Valley OU Area 1 (El Monte) and the well locations associated with Alhambra OU Area 3 that have detections above MCLs are shown in Figure 6-1.

Portions of the OU Area 1 (El Monte) within Zone 5 are known to be contaminated with chlorinated VOCs including the following: 1,4-dioxane, 1,1-dichloroethene (1,1-DCE), 1,2-dichloroethane (1,2-DCA), 1,2-dichloroethene (1,2-DCE), benzene, hexachrome (Cr^{6+}), perchlorate (ClO_4), n-nitrosodimethylamine (NDMA), nitrate (NO_3), TCE, and PCE (CDM, 2008a, 2008b). In 1984, a study of the San Gabriel Valley groundwater was initiated by USEPA to determine the nature and extent of contamination. In March 1995, an agreement was reached between USEPA and 15 potentially responsible parties (PRPs) to complete a regional investigation of the area, which was completed in 1998. An Interim ROD was signed in June 1999 (USEPA, 2009b). Compliance Monitoring Plans for the Gabriel Valley OU Area 1 (El Monte) were completed in October 2006 and January 2008. USEPA is currently designing the containment system to control the movement of the contaminants and anticipates construction in the next few years.

Portions of the OU Area 3 (Alhambra) within Zone 5 are known to be contaminated with chlorinated VOCs including the following: PCE, TCE, cis-1,2-DCE, 1,2,3-TCP, CCl_4, perchlorate, and nitrate as NO_3 (CH2M HILL, 2009d). A summary description of the activities and investigations that have been performed at the San Gabriel Valley OU Area 3 (Alhambra) is provided in Section 10.6.

Thirty-nine localized groundwater or soil contamination sites (including the San Gabriel Valley Area 3 [Alhambra] NPL Site and San Gabriel Valley OU Area 1 [El Monte] NPL Site) are located within Zone 5. Four of these sites are located in proximity (that is, less than 0.5 mile) to a portal zone for Zone 5, and one site with localized groundwater contamination is located in the central portion of Zone 5. The five sites are summarized below:

- United Rock Products, 1245 Arrow Highway E., Irwindale, California (Map ID: 7/4-5). This site is located within 0.5 mile of the eastern portal zone for Zone 5. The site has soil impacted with diesel, waste oil, motor oil, hydraulic oil, and lubricating oil. This site is considered to have a potential to impact the project because it is located within the eastern portal zone for Zone 5 and has impacted the soil.

- NU-WAY Industries, 400 Live Oak Avenue E., Irwindale, California (Map ID: 28/4). This site is located within 0.5 mile of the eastern portal zone for Zone 5. The site has soil impacted with gasoline. This site is considered to have a potential to impact the project because it is located within the eastern portal zone for Zone 5 and has impacted the soil.

- Agere Systems, 4920 N. Rivergrade Road, Irwindale, California (Map ID: 4920 N. Rivergrade Road). This site is located within 0.5 mile of the eastern portal zone for Zone 5. The site has soil impacted with diesel. This site is considered to have a potential to impact the project because it is located within the eastern portal zone for Zone 5 and has impacted the soil.

- ARCO Station No. 6109, 3201 West Valley Boulevard, Alhambra, California (Map ID: 590/14). This site is located within 0.5 mile of the southern portal zone for Zone 5. The site has groundwater impacted with GRO, MTBE, and tertiary butyl alcohol (TBA). This site is considered to have a potential to impact the project because it is located within the western portal zone for Zone 5 and has impacted the groundwater.

- Al Sal Oil Company, 911 S. San Gabriel Boulevard, San Gabriel, California (Map ID: 261/8). This site is located in the central portion of Zone 5. The site has impacted the groundwater with TPH- gasoline and MTBE at depths exceeding approximately 204 feet bgs. This site is considered to have a potential to impact the project because it has impacted the groundwater at a depth of greater than 200 feet (near the tunnel crown) near the center of Zone 5.

The remaining 32 sites (not including the NPL sites) with localized soil or groundwater contamination were identified as being in the central portion of Zone 5 and are considered to have a low potential impact to the project because they are located greater than 0.5 mile from a portal zone or are characterized with soil or groundwater contamination at a depth of less than 150 feet bgs. Additional details for each of these sites, including the corresponding soil and/or groundwater contaminants, their corresponding concentrations, and depths of maximum concentration are included in the ESA in Appendix F.

11.7 Potential for Naturally Occurring Gas

The alluvium making up the San Gabriel Basin is not a producer of hydrocarbons. However, there are rocks that serve as the source for hydrocarbons at the southern and western margins of the basin, and small oil fields are located around the southern margin. The basin represents an important groundwater aquifer and no incidents of naturally occurring hydrocarbons have been reported. Therefore, the potential for naturally occurring gas to be encountered within Zone 5 is considered low.

11.8 Geotechnical Considerations for Tunnel Design and Construction

11.8.1 Key Ground Characteristics

Based on the results of this evaluation, the key geologic factors for this zone in terms of tunnel design and construction considerations (along the generalized geologic profile shown in Plate 9) are:

- Subsurface conditions are fairly uniform in this zone at tunnel depth and consist mainly of Old Alluvium and sedimentary rocks (Fernando and Puente Formations) near the southern end of the zone. The majority of the tunnel is expected to be in the Old Alluvium. The Old Alluvium is generally expected to be uncemented coarse sand and gravel interbedded with sand, silt, and clay. The Fernando Formation is expected to consist of siltstone and claystone. The Puente Formation is expected to be composed of clayey siltstone and silty claystone (commonly called mudstone), as well as some sandstone.
- The Old Alluvium exhibits the strength characteristics of a soil with low cohesion (i.e., low, undrained, shear strength). The Fernando and Puente Formations are expected to be moderately weak to weak rock. Cobbles and boulders can be expected in the Old Alluvium. Strong cemented layers and concretions may be encountered in the Puente Formation.
- Alhambra Wash fault is considered active and projects into this zone. The inactive Workman Hill fault projects toward the western portion of the zone.
- Most of the tunnel in this zone would be at or below the current and historically highest groundwater table. Current depth to groundwater varies; however, the depth could be as shallow as 0 feet below grade at some locations. Groundwater inflows could occur when tunneling below the groundwater table in alluvium. Additionally, many aquitards exist throughout this zone.
- The perennial Rio Hondo and San Gabriel River, as well as recharge lakes, are located in the eastern portion of this zone.

- As a result of the shallow historical highest groundwater level, and based on the composition of the shallow alluvial materials that occur along the eastern portion of Zone 5, potentially liquefiable conditions have been identified for the eastern half of this zone (CDMG, 1998a, 1998b, 1998d, 1999a, 1999b, and 1999d). In addition, based on the potential presence of lakes at the easternmost portion of the zone and the perennial character of the Rio Hondo and San Gabriel River (Dibblee, 1999), potentially liquefiable conditions are anticipated within the eastern portion of the zone where the groundwater levels saturate loose, cohesionless soils.
- One Superfund site is located in the south-central portion of the zone, which could be a source of soil and groundwater contamination in this zone. Seven other sites with various levels of soil and groundwater contamination are also present in this zone close enough to potentially impact the tunnel. Most of these sites are located near the eastern or central portion of the zone.
- There is a low potential for encountering naturally occurring gas in this zone due to the limited length of the tunnel in the Puente Formation.

11.8.2 Preliminary Assessment of Tunneling Considerations

Information presented above and in previous sections of this report was used to perform a preliminary assessment of tunnel design and construction requirements, as summarized below.

Tunnel excavation in this zone would be mostly through uncemented, very dense, alluvial silt, sand and gravel. Cobbles and boulders are also expected throughout the alluvium. The remaining portion of the excavation will be through the Fernando and Puente Formations. Considerations for tunneling in these geologic and groundwater conditions are similar to those of Zone 4 because geologic conditions are very similar. Tunnel excavation methods, support requirements, and settlement control measures will be similar to those discussed for Zone 4.

Zone 5 has active and inactive steeply dipping faults that have the potential to act as groundwater barriers. Because the groundwater levels vary greatly over this zone, tunnel excavation methods will have to be able to accommodate the wide range in hydrostatic pressures, as in Zone 4.

Special considerations will need to be made for excavating through and lining the tunnel in an active fault zone as discussed in Zones 3 and 4. Additionally, because there is a potential for tunneling beneath two Superfund sites with VOC-contaminated soil and groundwater, special precautions, such as those described previously, will be necessary to safely excavate and dispose of the contaminated soil and groundwater.

Based on the information collected and reviewed in Zone 5, tunneling is considered to be feasible in this zone from a geotechnical standpoint. Subsurface conditions and appropriate tunnel design and construction provisions should be further evaluated for this zone in more detailed tunnel design studies.

SECTION 12

Previous Tunneling Experience

12.1 Local Tunneling Experience

This section summarizes some local tunneling projects constructed in geologic conditions similar to the various zones being considered for the SR-710 tunnel. These local projects include the NEIS, the ECIS, and the Metro Red Line and Gold Line Eastside Extension. The NEIS tunnel is located in and south of Zone 1, and other tunnels are located south of Zone 1. Histories from these tunnels provide information about tunneling in similar geology, as well as lessons learned from challenges encountered and overcome in the previous projects. Figure 12-1 shows these local projects in relation to the SR-710 study area.

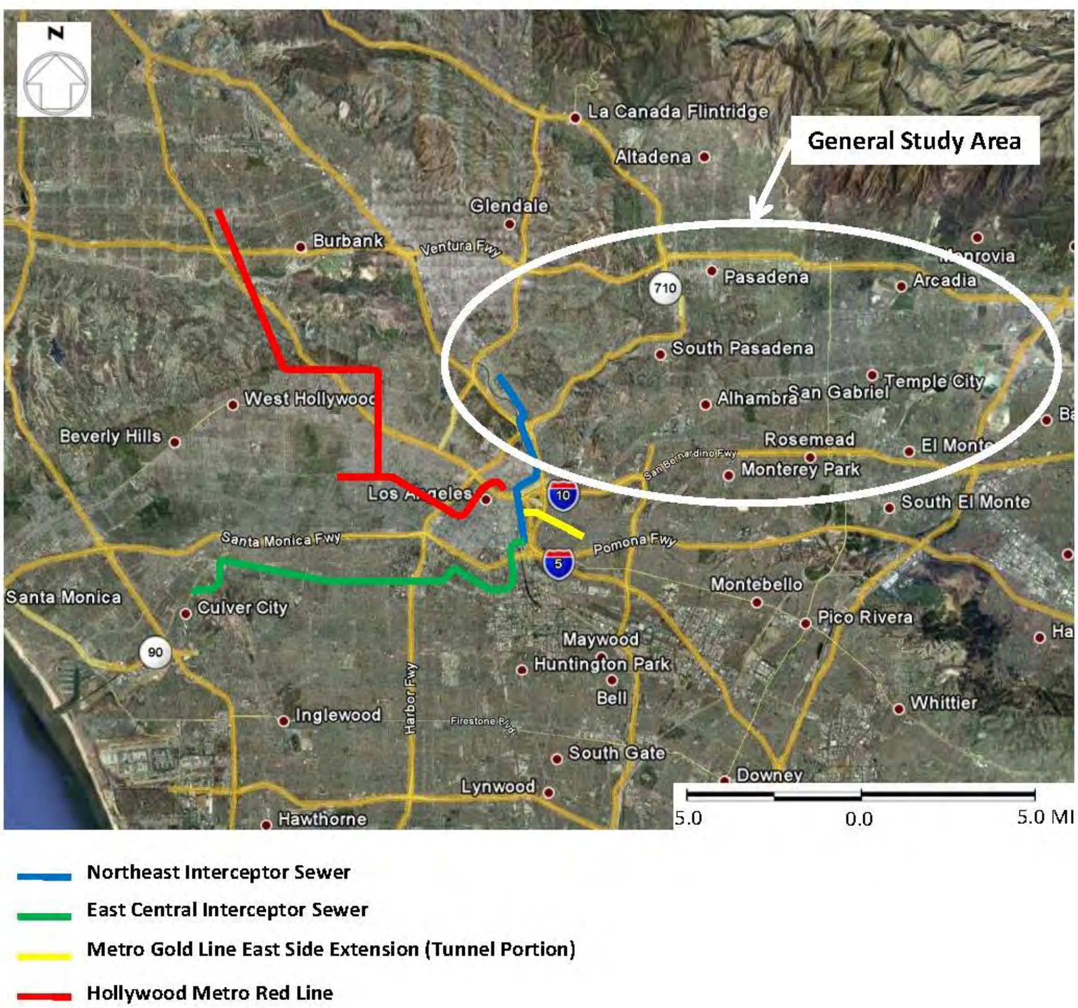

Figure 12-1. Approximate Location of Local Tunnels in Relation to SR-710 Study Area
Background image source: GoogleEarth.

12.1.1 Northeast Interceptor Sewer

Project Description. The NEIS is part of a sewer system that provides hydraulic relief for the existing North Outfall Sewer (NOS), located in the northeast communities of Los Angeles. The tunnel has an excavated diameter of 13 feet and is 5.3 miles in length. The finished diameter of the tunnel is just under 8 feet. Construction was completed in 2005, and the tunnel is currently in operation (Zernich et al., 2005).

Geologic Conditions. The NEIS tunnel was excavated through alluvial soils and weak sedimentary rock with up to 3 bars of groundwater pressure. The weak sedimentary rock encountered in the NEIS tunnel was predominantly Puente Formation with shorter reaches of Fernando Formation and Old Alluvium. The Puente Formation consisted of claystone, weak sandstone, and strongly cemented sandstone. Photographs of the Puente Formation are shown in Figure 12-2. The Old Alluvium consisted mostly of very dense sands with silt and clay with occasional boulders and cobbles. The ground cover above the tunnel ranged from approximately 70 to 140 feet along the alignment.

Tunneling Methods and Construction Observations. Due to the weak rock, saturated soil deposits, and high groundwater pressures, the NEIS contract required the use of three TBMs—two EPB TBMs and one hard rock TBM. The EPB TBMs were specified for the soft ground reaches to maintain excavation stability, control loss of ground, and avoid surface settlement. Because the tunnels were constructed underneath the groundwater table, watertight ground support, consisting of gasketed precast concrete segments, was installed as the initial support. Watertight construction methods were also used to excavate the shafts. Four large work shafts used for TBM launch and retrieval were constructed using slurry walls.

The NEIS alignment traverses a region well known for naturally occurring petroleum hydrocarbons, and it was expected that high concentrations of methane and hydrogen sulfide were to be encountered along the entire tunnel drive. The tunnels were all classified by Cal-OSHA Division of Mines and Tunnels as "gassy" due to the presence of methane and hydrogen sulfide concentrations. During tunneling procedures, operations were stopped when gas concentrations exceeded the allowable threshold. The problems were mitigated by installing fans in strategic locations to ensure that there were no areas of stagnant air. This allowed adequate quantities of fresh air to be introduced near the heading so that the dilution of the toxic and combustible gases occurred. Additionally, sodium percarbonate was added to a sump area to help with degradation of hydrogen sulfide (Dubnewych et al., 2005).

Relevance to SR-710 Study: Tunneling conditions in some of the zones of the SR-710 tunnel are expected to be in similar geology as the NEIS tunnel (that is, the Puente Formation in Zones 1 through 5 and Fernando Formation in Zones 3 and 4). The Upper Reach of the NEIS alignment crosses the western portion of Zone 1, and the Puente Formation is the same formation that is expected in many of the zones for the SR-710 tunnel. A watertight lining similar to the one used in the NEIS tunnel will likely be needed for the SR-710 tunnel. Additionally, the naturally occurring gas that was encountered in the NEIS project could possibly be expected in Zones 1 through 5 of the SR-710 Tunnel Technical Study.

Figure 12-2. Exposed Face of Puente Formation encountered--when excavating a connector tunnel for a future sewer tie-in on the NEIS project (top). Shaft excavation in the Puente Formation--on the NEIS project (bottom).

12.1.2 East Central Interceptor Sewer

Project Description: The East Central Interceptor Sewer (ECIS) is an approximately 11.4-mile-long sewer tunnel that runs from Culver City to East Los Angeles. This tunnel is part of the same sewer system as the aforementioned NEIS tunnel. The excavated diameter of the tunnel was approximately 15.4 feet. The finished diameter of the tunnel is approximately 11 feet. Construction was completed in 2004, and the tunnel is currently in operation.

Geologic Conditions: This tunnel was excavated entirely in alluvium and marine sediments. Approximately 80 percent of the tunnel was excavated in the Lakewood Formation (Old Alluvium), which typically consists of dense silty sands and sandy silts with occasional gravel, cobbles, and boulders (Critchfield and Miya, 2004). A photograph of the muck generated while tunneling through the Lakewood Formation is shown in Figure 12-3. Approximately 10 to 15 percent of the tunnel was excavated in the hard silts and clays of the San Pedro Formation, and the remaining 5 to 10 percent of the excavation was through recent (Young) alluvium, consisting of loose to dense, silty, and sandy soils with gravel, cobbles, and boulders. The depth-to-tunnel invert generally ranges from 30 to 100 feet; however, it is as much as 360 feet in the area where the alignment goes under the Blair Hills.

Tunneling Methods and Construction Observations: ECIS was driven in five separate tunnel drives by four EPB TBMs. Each of these TBMs was identical – four were used simultaneously to meet schedule concerns. Tunneling in this urban environment requires a higher degree of ground loss control than other areas. EPB machines were specified for use on the ECIS to mitigate ground loss, surface settlement, and damage to existing structures. Additionally, construction monitoring—consisting of surface surveys, muck volume monitoring, and muck testing—occurred continuously during mining (Seeley, 2004). Ground treatment after tunneling was performed if needed based on the analysis.

While these machines and techniques generally achieved the goal of no surface disruption, there were instances of overexcavation. Unintended ground loss occurred during machine stoppages for cutterhead maintenance, especially in uncemented sands. This challenge can be overcome by a machine design which allows human entry to the cutterhead while maintaining control of the tunnel face. The initial lining of the tunnel was a precast concrete segmental liner. As in the NEIS tunnel, hydrogen sulfide and methane gases were encountered during the excavation. Additionally, contaminated soils were encountered at some locations along the alignment (Critchfield and Miya, 2004).

Relevance to SR-710 Study: Tunneling through the Young Alluvium and the Old Alluvium (Lakewood Formation) will likely be similar to some to the tunneling conditions in the alluvial soils expected in Zones 4 and 5 of the SR-710 tunnel. Ground loss and surface settlement can be mitigated not only with strict specifications and construction monitoring but also because there have been machine improvements since ECIS. A watertight lining similar to the one used in the NEIS tunnel will likely be needed for the SR-710 tunnel if constructed in these zones. Additionally, naturally occurring gas and contaminated soils were encountered in ECIS, and the same is expected in Zones 1 through 5 for the SR-710 tunnel.

Figure 12-3. Alluvium of the Lakewood Formation, with cobbles, falling off a conveyor during excavation of the ECIS Tunnel.

12.1.3 Los Angeles Metro Red Line Project

Project Description: The Metro Red Line extends from Downtown Los Angeles (Union Station) to the community of North Hollywood in the San Fernando Valley. This twin-bore tunnel system was built in three different segments at different times. Segment 1 was completed in two phases and extends from Union Station to Alvarado Street (Phase 1) and from Alvarado Street to Western Avenue (Phase 2). The middle segment – known as Segment 2 – extends from the Wilshire/Vermont Station to the Hollywood/ Highland Station. Segment 2 runs north-south along Vermont Avenue and east-west along Hollywood Boulevard. The third Segment runs from the Hollywood/Highland Station north through the Hollywood Hills to the San Fernando Valley and is called Segment 3. The two bores are connected with cross passages and have excavated and finished diameters of approximately 22 feet and 18 feet, respectively.

Geologic Conditions: Segment 1 was excavated through both the Fernando Formation and Los Angeles River alluvial deposits. The Fernando Formation consisted of well-stratified claystone and siltstone with significant cohesive strength (Robinson et al., 1989). The alluvium consisted of firm to very stiff silts and clays, and medium-dense to very dense sands (Robinson and Wardwell, 1991).

The section of tunnel underneath Vermont Avenue (Segment 2) was excavated almost entirely in the Puente Formation. The lithology of the Puente Formation encountered was predominantly stratified and interbedded claystone and siltstone with harder sandstone beds. The Hollywood Boulevard tunnel section of Segment 2 was excavated predominantly in alluvium (Gordon et al., 1995). The depth of ground cover over the tunnels ranged from 20 to 161 feet in this section of the excavation.

Segment 3 was excavated through shale and sandstone of the Topanga Formation, the Simi Conglomerate, as well as intact to fractured granodiorite with fault gouge in the Santa Monica Mountains (Kramer et al., 1998). In the San Fernando Valley, the tunnel was excavated through young and Old Alluvium and the Topanga Formation. The young and Old Alluvium consisted of dense and stiff sands and clays, and the Topanga Formation was generally well-cemented siltstone, sandstone, and claystone.

Tunneling Methods and Construction Observations: The headings for Segment 1 were mined with digger shields. Settlement was something that was monitored very closely in this segment because the tunnels were underneath many tall buildings in downtown Los Angeles. In the cohesionless alluvial soils, chemical grouting was used to ensure face control. This chemical grouting was performed after it was realized that compaction grouting under the buildings might not be sufficient to limit settlement, especially in the cohesionless soils (Robinson and Wardwell, 1991). The excavation characteristics of the Fernando Formation were considered firm, with little to no raveling occurring; however slow raveling occurred in the alluvium (Escandon et al., 1989). Additionally, due to the presence of naturally occurring gas, a liner of high-density polyethylene (HDPE) was installed between the initial and final lining to restrict the flow of gases into the tunnel during operation of the subway (Navin, 1991).

All headings for Segment 2 were excavated using digger shields (Gordon et al., 1995). A photograph of a digger shield used for the Red Line is shown in Figure 12-4. During the excavation, both of the sections of tunnels were considered “gassy.” Additionally, both contaminated soil and groundwater were anticipated and encountered during the excavation of the tunnels in Segment 2. The Hollywood Boulevard tunnels encountered high groundwater inflows not long after the mining commenced and was subsequently shut down for dewatering, which lasted for many months. Even after dewatering, this section was plagued with groundwater inflow problems, as well as cobbles and boulders that were unforeseen in the alluvium. These groundwater inflows could have been prevented if the tunnels were excavated using a machine with pressurized-face technology.

The section of Segment 3 through the hard rock of the Santa Monica Mountains was excavated using two rock main-beam TBMs. The crossing of the Hollywood fault is a noteworthy aspect of Segment 3. This is an active thrust fault and the largest active fault that the entire Red Line will cross. A special seismic section was developed consisting of an oversized sacrificial vault section with a special lining. The lining for this section consisted of steel-fiber reinforced shotcrete and lattice girders, and it was mined using the New Austrian Tunneling Method (NATM) techniques (Albino et al., 1999). After completing the vault, the concrete segmental lining was erected in the tunnel and the annular space between the vault and the segmental lining backfilled with a compressible material. If there is offset in this fault trace, the vault section will be displaced and the movement dissipated within the compressible material, keeping the segmental lining and the tunnel intact and serviceable although the tracks may need to be realigned.

Relevance to SR-710 Study: Many aspects of the Los Angeles Metro Red Line will be similar to those of the proposed SR-710 tunnel, depending on the alignment chosen. Both tunnels are twin-bore transit tunnels with cross passages and excavation in a very urban environment. The SR-710 tunnel will likely go under occupied buildings for which settlement and ground loss would need to be designed. Also, the SR-710 tunnel passes through active faults in Zones 3 through 5 and would need a special seismic design for the lining through those fault zones, such as the oversized excavation used in the Metro Red Line fault crossing or other methods. The geology has the potential to be quite varied (hard and soft rock, and alluvium) in Zone 3 of the SR-710 as it was along the many segments of the Metro Red Line. And, as mentioned for many of the projects in the Los Angeles area, the potential for naturally occurring gas (in Zones 1 through 5) or other contaminants (in Zones 1, 4, and 5) is expected in the SR-710 tunnel as it was encountered for the Metro Red Line tunnels.

Figure 12-4. Digger Shield used in Los Angeles Metro Red Line Tunnel.

12.1.4 Los Angeles Metro Gold Line Eastside Extension Project

Project Description: The Metro Gold Line East Side Extension Project consists of 6 miles of new light rail and eight new metro stations. Approximately 1.7 miles of this alignment include a twin bore of 21.5-foot (excavated diameter) tunnels (Robinson and Bragard, 2007). There are six cross passages that connect the two bores. This extension project originates in downtown Los Angeles at Union Station and continues to serve areas east of downtown, crossing underneath several existing structures in this urban environment. The tunnel excavation began in 2005 and is now complete.

Geologic Conditions: The soils encountered in this project were Old and Young Alluvium—the majority of the excavation in Old Alluvium. The Old Alluvium is composed of loose to very dense sand and gravel with varying amounts of stiff clay and silt, as well as cobbles and occasional boulders. Generally, the Old Alluvium was denser than the Young Alluvium (Choueiry et al., 2007). The majority of the tunnel was excavated under the groundwater level, which reached a high of about 13 feet above the invert in the middle of the tunnel alignment. The ground cover was as shallow as 35 feet in some areas along the alignment.

Tunneling Methods and Construction Observations: The tunnels were excavated using two EPB TBMs, and the two tunnels were mined approximately 40 feet apart, from center to center. Figure 12-5 is a photograph of one of the TBMs being launched. At certain locations along the alignment, the cover was as little as 35 feet. The six cross passages were mined using sequential excavation methods, consisting of a top heading and bench. According to Robinson and Bragard (2007), the mix of clay and sand was quite good for tunneling—noting that the clayey ground had sufficient sand in it so the muck did not get too sticky, and the sandy ground had the amount of clay needed to give the muck some "body."

Approximately 220 structures were identified as being within the zone of influence of tunneling. To avoid settlement or differential settlement of any of the buildings, compensation grouting was selected as a "real-time" control over the potential settlement. Grout pipes were directionally drilled beneath the structures of interest, in advance of the tunnel heading. Grouting crews were on standby when a TBM was within 100 feet of a structure to be ready to perform compensation grouting if settlement reached the action levels specified. The settlement was monitored by using small reflectors stationed on the roof corners of targeted buildings. A total station instrument measured the monitors constantly and reported back to engineers who were analyzing the data. Ultimately, no surface settlement reached the action level set forth in the specifications to warrant grouting (Choueiry et al., 2007).

The alignment passed through zones of contaminated soils, and the muck generated from those areas was segregated and transported to an appropriate disposal site. Similar to the NEIS project, this tunnel was considered "gassy" by Cal-OSHA regulations; ventilation was a serious concern due to high levels of methane gas. The maximum advance rate (best day) was 91 feet per day and 95 feet per day for the eastbound and westbound tunnels, respectively.

Relevance to SR-710 Study: Similar geologic conditions (saturated alluvium) that were encountered in the Metro Gold Line East Side Extension Project will likely be encountered in Zones 3 through 5 of the SR-170 tunnel. Also, the presence of contamination (expected in Zones 1, 4, and 5) and naturally occurring gas (expected in Zones 1 through 5) were aspects of the Metro's project that will be encountered in the SR-710 study. Additionally, the Gold Line project was constructed under many occupied buildings, and virtually no surface settlement was allowed. Depending on the zone and alignment chosen for the SR-710 tunnel, it could be constructed similarly under occupied buildings or structures that would not be able to tolerate settlement or angular distortion.

Figure 12-5. TBM Being Launched for the Metro Gold Line Eastside Extension in Los Angeles.

12.2 Recent Large-Diameter Highway Tunnels

In addition to local tunneling projects, information about some large-diameter highway tunnels that have been recently designed and constructed in California and around the world was collected and reviewed. These projects are considered to be relevant to the SR-710 tunnel for the reasons discussed below. Included in the following sections are summaries of the Caldecott Fourth Bore (California, USA), Devil's Slide Tunnels (California, USA), Calle 30 Tunnel (Madrid, Spain), Shanghai Yangtze River Tunnel (Shanghai, China), and SOCATOP A86 Tunnel (Paris, France). This information is not intended to be comprehensive, but the discussion provides some background information relative to large-diameter highway tunnels similar to the SR-710 tunnel.

12.2.1 California

12.2.1.1 Caldecott Fourth Bore Tunnel

Project Description: The Caldecott Fourth Bore Tunnel is a vehicular tunnel along SR-24 that has been designed, with construction expected to begin in late 2009 or early 2010. This tunnel is located in Alameda and Contra Costa counties in Northern California. The owner of the project is Caltrans. This project will increase the number of vehicular lanes in the Caldecott tunnels, which currently consist of three bores. The project will add a 3,400-foot horseshoe-shaped tunnel that is 50 feet wide and 32 feet high with two traffic lanes. Additionally, seven cross passage tunnels between the planned fourth bore and existing third bore will be constructed (Thapa et al., 2007). A rendering of the portal zone for the new tunnel can be seen in Figure 12-6.

Geologic Conditions: The tunnel is expected to pass through shale, chert, sandstone, siltstone, claystone, and conglomerate and to cross four major inactive faults. These faults occur at contacts between geologic units. The rock was broken into four ground classes, based on mechanical characteristics and on anticipated ground behavior in response to excavation.

Tunneling Methods and Construction Observations: The tunnel excavation design is based on the sequential excavation method (SEM) consisting of a top heading and bench. Some initial support elements include plain and fiber-reinforced shotcrete, lattice girders, fast-setting cement-grouted rock dowels, fiberglass rock dowels, self-drilling and grouted spiles, injection spiles, and self-drilling grouted pipe spiles. The final lining of the tunnel will be a cast-in-place (CIP), reinforced-concrete lining. A waterproofing membrane with a geotextile backing layer for drainage will be installed between the initial support and the final lining.

Relevance to SR-710 Study: This large-diameter highway tunnel is planned to be excavated in the future in Northern California. Similar to the SR-710 study, Caltrans will be the owner; therefore, many of the design elements will be similar. Additionally, the variable geology is similar to that of Zone 3 of the SR-710 tunnel, and the potential for encountering inactive faults is similar to all zones of the SR-710 tunnel.

Figure 12-6. The Caldecott Fourth Bore Tunnel portal showing the existing tunnels and simulation of the proposed tunnel (highlighted with yellow circle).

12.2.1.2 Devil's Slide Tunnel

Project Description: The Devil's Slide Tunnel is a vehicular tunnel currently under construction. It is located along SR-1 in San Mateo County in Northern California. The owner of the project is Caltrans. The road alignment passes through a pair of approximately 3,950-foot-long tunnels that will run 650 feet beneath San Pedro Mountain. The width and height of the horseshoe-shaped excavation is approximately 36 feet and 27 feet, respectively. The horseshoe shape of the tunnels provides for one lane with a wide emergency shoulder. Ten emergency cross passages will connect the two bores, spaced approximately 400 feet apart. A central cross passageway also provides access for emergency vehicles. At the two portal exits, the tunnels will be enlarged by 8 feet each to provide a turnout lane with extra visibility for maintenance vehicles.

Geologic Conditions: The tunnel will be excavated through granitic-type rock in the South Reach, sandstone in the Central Reach, and claystone-siltstone, sandy conglomerate including, fine-grained sandstone intervals crushed and sheared to gouge in the North Reach. Three inactive faults divided the mountain geologically. Except for the portal areas, the groundwater table is above the tunnel. Major groundwater migration pathways are fractured fault zones, contact surfaces between different formations, and different materials within the formations.

Tunneling Methods and Construction Observations: Based on the varying and challenging geologic conditions, the NATM technique was selected as the most suitable approach for construction. The advance lengths vary between 3 feet and 7 feet, depending on the geologic conditions. The initial support varied depending on the anticipated geologic conditions. A steel fiber reinforced shotcrete lining in combination with rock dowels provides initial support for the best conditions. A photograph of the shotcreting operation is shown in Figure 12-7. As rock quality degrades, the addition of steel lattice girders and spiles provides improved support. For worse conditions, additional face support measures (long face dowels, core, shotcrete face sealing) and a reinforced shotcrete invert arch are required. The ground conditions for excavation are classified as potentially gassy conditions.

Relevance to SR-710 Study: This highway tunnel is currently being excavated in northern California for Caltrans. Additionally, the varied geologic conditions and faulting along its alignment are similar to the mixed conditions in Zone 3 of the SR-710 tunnel. Additionally, the crossing of inactive faults and the potential for naturally occurring gas are similar between the tunnels.

Figure 12-7. Shotcreting in the Devil's Slide Tunnel.

12.2.2 Worldwide Experience

12.2.2.1 Calle 30 Tunnel, Madrid

Project Description: The south bypass M-30 twin-tube tunnels in Madrid, Spain, are vehicular tunnels that have an approximate excavated diameter of 49 feet. The tunnels will accommodate cars and heavy trucks and was the only solution for relieving traffic in this heavily congested area. Each bore allows three lanes of vehicular traffic. In addition to the three traffic lanes, each tunnel houses two emergency lanes located beneath the concrete road slab, along with ventilation conduits and other essential facilities. Figure 12-8 shows a schematic of this cross section and the installation of the road deck slab separating the traffic lanes from the emergency access below. The two bores are each approximately 2.2 miles long and are connected with eight cross passages—five passages for emergency pedestrian access and three for emergency vehicular access. A ventilation shaft is also needed for each tube (Fernandez, 2007).

Geologic Conditions: The subsurface conditions consisted of sandy clay and hard clay with gypsum. The maximum hydrostatic pressure that was expected was 6 bar; on average, the maximum overburden ranged from 100 feet to 215 feet. However, at the portals, there was as little as one tunnel diameter of overburden to reduce the depth of the rectangular shafts used to launch the machines.

Tunneling Methods and Construction Observations: The tunnels were excavated using two EPB TBMs, each supplied by a different manufacturer. Some specifications for the TBMs included the ability to work in as high as 6 bars of pressure and avoid horizontal ground loss at the face of the excavation. Additionally, the design specified that boulders up to a size of 28 x 12 x 12 inches needed to be able to fit through the screw conveyor of the EPB machine. To achieve a relatively fast excavation rate and to comply with all of the other specifications of the contract, innovative designs by the TBM manufacturers were submitted.

The lining of this tunnel used 2-foot-thick precast bolted segments in a nine-segment plus key configuration. The average daily advance rate for this tunnel was 60 feet per day, and the maximum advance rate was 151 feet per day (best day of production).

Relevance to SR-710 Study: The TBMs used for this job are some of the largest TBMs ever manufactured. A TBM of this size or a similar size could possibly be necessary to excavate the SR-710 study, depending on the traffic requirements and design of the tunnel cross section. The main similarity between this tunnel and the SR-710 tunnel is the size of the excavation and final use of the tunnel; however, similar geology (soft ground) and groundwater conditions are expected in the SR-710 tunnel as well.

12.2.2.2 Shanghai Yangtze River Tunnel

Project Description: The Shanghai Yangtze River Tunnels are part of a major transportation infrastructure project located at the mouth of the Yangtze River in China. The entire project includes a tunnel, a cable-stayed bridge, and a series of approach roads that total just under 16 miles. The tunnel portion of the project is approximately 4.5 miles. Three lanes of vehicular traffic and one rail line will be provided in each bore of this twin-bore tunnel. Each bore has an excavated diameter of approximately 50.5 feet, and they are spaced approximately 100 feet apart.

Figure 12-8. Roadway slab construction for the Calle 30 tunnel in Madrid (top) Schematic showing the final use of the tunnel (bottom).

Geologic Conditions: The geology along the tunnel excavation is predominantly silty clay with occasional sand and sandy silt layers. The overburden ranges from approximately 20 feet at the TBM launch area to 60 feet, and the majority of the tunnel is excavated underneath the groundwater table (Ferguson et al., 2008).

Tunneling Methods and Construction Observations: Due to the high water pressures, ground conditions, and shallow cover, two slurry TBMs were selected to excavate the tunnels; one is shown in Figure 12-9. To deal with the anticipated 6-bar hydrostatic pressure, the cutterhead arms were outfitted with special facilities to allow changing the cutter tools without entering the pressurized excavation chamber. If the workers had to enter the chamber under 6-bar hydrostatic pressure, mixed gases would have to be used, extending the time needed for tool changes.

Bolted and gasketed precast concrete segments were used as the initial lining of the tunnel. The segments used are approximately 2.1 feet thick and are installed in a nine-segment plus key configuration. The average advance rate for these tunnels was approximately 39 feet per day with the maximum advance rate (best day) of 85 feet per day (*Tunnelbuilder*, 2008).

Relevance to SR-710 Study: Similar to the M-30 tunnel in Madrid, the TBMs used for this project are two of the largest TBMs ever manufactured. The Shanghai Yangtze River Tunnel will have a similar number of traffic lanes as required for the SR-710 tunnel, and the geology and groundwater conditions are similar to the alluvial soils expected in some parts of Zones 3 through 5 of the SR-710 tunnel. The case history of this project can be used to help with planning of the SR-710 study, another large-scale highway tunnel.

Figure 12-9. Largest TBM in the world to date, for the Shanghai Yangtze River Tunnel Project (Herrenknecht, 2009).

12.2.2.3 SOCATOP A-86 Highway Tunnels, Paris

Project Description: The SOCATOP A-86 tunnel is a vehicle tunnel located in the suburbs of Paris, France. The twin-level tunnel is approximately 38 feet in excavated diameter and allows for three lanes of vehicular traffic in each direction. The tunnel is approximately 6.2 miles long with emergency exit shafts every 3,280 feet. Figure 12-10 shows a cross section of the tunnel at a location with an emergency alcove and pressurized shelter.

Geologic Conditions: The tunnel excavation was through extremely variable geological conditions including rock (limestone and chalk) and soils (sands, silts, and clays).

Tunneling Methods and Construction Observations: Due to the mixed conditions along the length of the alignment, a mixed-mode TBM was developed to be able to mine the range of anticipated geological conditions. This machine is capable of operating in EPB or Slurry mode (Fulcher et al. 2006). The machine's configuration can be changed for different types of geology in about 24 hours. Precast concrete segments in a seven-segment plus key arrangement were used to line the tunnel. The average advance rate on this job ranged from about 40 to 46 feet per day.

Relevance to SR-710 Study: The TBM used in this highway tunnel project has been designed to mine through many different types of materials and has a relatively large diameter. Technology such as this could be very useful in mining Zone 3 of the SR-710 tunnel with similarly varied geologic conditions.

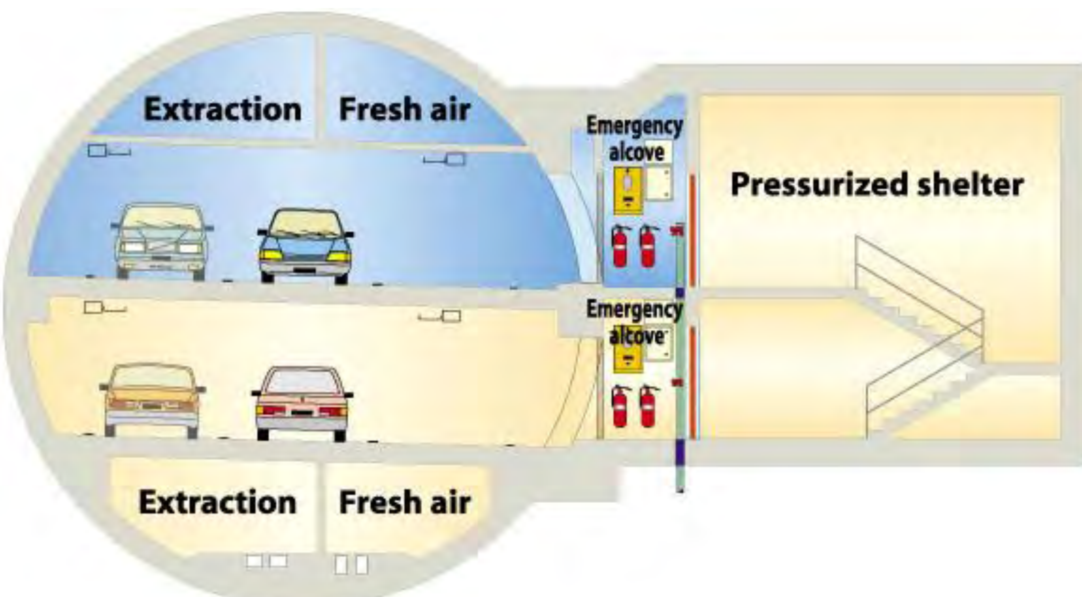

Figure 12-10. Cross Section of SOCATOP A86 Tunnel at Location of Pressurized Refuge Chamber (Cofirouteusa, 2009).

12.3 Summary of Relevance to SR-710 Study

In the previous sections, case histories of other tunnel projects were discussed. Each of these projects has relevance to the SR-710 study due to similar geologic conditions, construction methods, or both. Table 12-1 summarizes which aspects the SR-710 tunnel would be similar to the aforementioned tunnel projects. Worldwide tunnel projects like the Madrid Calle 30 Tunnel, Shanghai Yangtze River Tunnel, and Paris A-86 Highway Tunnel demonstrate that the technical capability exists for constructing large-diameter highway tunnels (35 to 50 feet) with lengths up to 6 miles. Available technology does not limit the tunnel length that can be constructed as similar tunnels up to 10 miles in length are in the planning stages.

TABLE 12-1
Summary of Case History's Relevance to SR-710 Tunnel

Tunnel Name	Geology	Fault Crossings	Naturally Occurring Gas	Contaminate Soils	Tunnel Size (>35 feet)	Highway Tunnel	Urban Setting	Tunnel Length (>4 miles)
NEIS	■		■				■	■
ECIS	■		■	■			■	■
Metro Red Line	■	■	■	■			■	
Metro Gold Line	■		■	■			■	
Caldecott Fourth Bore		■			■	■		
Devil's Slide		■	■		■	■		
Madrid Calle 30					■	■	■	
Shanghai Yangtze River					■	■		■
Paris A-86 SOCATOP	■				■	■		■

12.4 Comparison of Sewer, Water, and Highway Tunnels

The previous sections detail design and construction aspects of selected tunnels; however, not all of the case histories selected are for highway tunnels such as the SR-710 tunnel. While some permanent features of a tunnel are dependent on its final use, the majority of the aspects of tunnel construction are independent of its final use, making many aspects of these types of tunnels similar. Some of the main characteristics of these types of tunnels are explained herein.

12.4.1 Shape

Most water and wastewater tunnels are circular, which is the preferred shape for hydraulic reasons. Highway tunnels can be either circular or horseshoe shaped. A horseshoe shape is usually more efficient for highway tunnels in rock; however, if a TBM is used to excavate the tunnel, it will be circular. The excavation methods for the tunnel may differ depending on the final shape of the tunnel, but not based on its final use (i.e., sewer, water, or highway).

12.4.2 Final Lining

In a water or wastewater tunnel, the final lining must provide a durable and smooth interior surface that minimizes hydraulic head losses and controls leakage (exfiltration) from the tunnel. If a water tunnel is pressurized, the final lining must be able to withstand internal water pressures. Additionally, the final lining of a wastewater tunnel must be corrosion protected from the hydrogen sulfide gases that effluent produces. Similarly for a highway tunnel, a waterproof membrane or gasketed segments typically would be used when the tunnel is constructed underneath the water table to control water inflows. Often, the final lining of a highway tunnel is not seen due to permanent finishes or the road or roof deck that cover the lining.

12.4.3 Fire-Life-Safety

Highway tunnels are occupied facilities with the public traveling through the tunnel. This makes public safety a key issue; thus, the design of appropriate fire-life-safety provisions is a requirement of the project. Water and wastewater tunnels have personnel entering the tunnel only when the tunnels are inspected, typically at 5-year intervals.

All tunnels must adhere to fire-life-safety standards for the workers of the tunnel during construction; however, a highway tunnel must have a permanent fire-life-safety system in place. Some of the safety systems include proper emergency ventilation, fire suppression, communications, refuge areas, emergency exits (to the surface or a cross passage to an adjacent tunnel), and alarms. In addition to the ventilation needed for a fire to clear out harmful chemicals, a highway tunnel needs ventilation under normal operations to eliminate the products of combustion in vehicles traveling though the tunnels. In addition to ventilation, other permanent finishes such as the road deck, lighting, and signage are needed for a highway tunnel that would not be needed in a wastewater or water tunnel.

12.4.4 Diameter

The diameter of highway tunnels is typically much larger than water or wastewater tunnels due to the clearance envelope needed for a lane or multiple lanes of cars and trucks. Highway tunnels are typically about 35 to 50 feet in diameter, whereas most water and wastewater tunnels are 20 feet in diameter or less.

12.4.5 Summary

The general excavation and support methods of the tunnels would not vary greatly based on the final use of the tunnel. Additionally, construction methods would be similar between the types of tunnels. Therefore, although the examples presented in Sections 12.1 and 12.2 are not exclusively highway tunnels, the case histories are valid to use as a reference for the feasibility of the SR-710 tunnel.

SECTION 13

Comparison of Zones

13.1 Geologic Conditions

This section compares key ground characteristics for tunneling, such as subsurface conditions, groundwater, faulting and seismicity, hazardous materials, and potential for gassy conditions, for each zone. These characteristics are also summarized in Table 13-1. Representative geologic profiles of the five zones are presented in Plate 10. This comparison of geologic conditions is used in later discussions as a basis for summarizing a number of tunnel design and construction issues, including tunnel excavation methods, seismic response, groundwater control, tunnel support and lining, settlement potential, and special hazardous materials considerations.

13.1.1 Stratigraphy

Tunnel excavations in Zones 1 and 2 will likely be in the Fernando, Puente, and Topanga Formations depending on the location of the tunnel through the study zones. These formations consist of sedimentary rocks that have similar characteristics. There is some inherent variability within these formations, such as scattered cemented layers and concretions within sandstone layers; however, these formations tend to be fairly consistent and predictable.

Variable geologic conditions are anticipated within Zone 3. Alluvium (soil), low-strength rock, and high-strength rock are all expected to be encountered in this zone. The bedrock material is expected to consist of the weak rocks of the Fernando, Puente, and Topanga Formations, as well as strong to very strong basement complex rocks (Wilson Quartz Diorite) and limited amounts of volcanic rocks. Strong cemented layers or concretions may be present in the sedimentary rock formations, and cobbles and boulders may be encountered in the alluvium and conglomerate of the Topanga Formation at the northern portion of the zone.

Zones 4 and 5 both consist mainly of Old Alluvium with some weak sedimentary rocks of the Fernando and Puente Formations near the western portion of these zones. The majority of the tunnel in these two zones will be excavated through unconsolidated Old Alluvium. The alluvium is generally expected to be uncemented, coarse sand and gravel interbedded with sand, silt, and clay with potential for cobbles and boulders.

The differences in stratigraphy for the various zones will be an important factor in the selection of tunnel excavation methods; however, as discussed later in this section, the stratigraphy does not preclude successful tunnel construction in any of the zones

13.1.2 Groundwater

Groundwater is approximately 20 to 50 feet bgs within the alluvium in Zones 1 and 2. Shallow groundwater depth could affect portal construction on the western ends of both zones. The potential for water inflows within the bedrock formations is expected to be low, except where the tunnel encounters porous strata, fractured or faulted rock. The potential for water inflow could be moderate to high at fault crossings due to the presence of fractured zones.

Variable groundwater depths should be anticipated in Zones 3 and 4 because of the presence of the Raymond fault in these zones. The Raymond fault acts as a groundwater barrier in both zones. A bedrock discontinuity was identified in Zones 4 and 5; this feature acts as a potential groundwater barrier, resulting in variable groundwater depths. The depth to groundwater varies in the alluvium of Zones 4 and 5; however, it is anticipated that the majority of the tunnel excavation would be in saturated ground.

Based on these observations, groundwater conditions will be an important consideration for the design, construction, and operation of the tunnel in each zone. Groundwater is encountered during most tunnel projects and, therefore, is not considered a unique issue. Alternatives for groundwater control are discussed later in this section.

13.1.3 Faulting and Seismicity

There are steeply dipping, inactive faults in all five zones. The active Raymond fault crosses near the northwest end of Zone 2 and the central portion of Zones 3 and 4. A potential fault displacement in the 2- to 4-foot range is estimated during a major seismic event on the Raymond fault.

The potentially active San Rafael and Eagle Rock faults are also mapped across Zone 3, as are several inactive faults. The Alhambra Wash fault is considered active and was previously mapped south of Zone 5; however, based on this study, the Alhambra Wash fault has been projected north into Zones 5 and 4.

Active and inactive faults represent important design and construction considerations for tunneling. Alignments crossing active faults with the potential of several feet of seismic-related fault displacement will require special design approaches to accommodate the movement without impacting tunnel operations. As discussed previously in this report, these design and construction methods have been used elsewhere in the Los Angeles area.

13.1.4 Hazardous Materials

The major contamination issues are the existence of the two NPL sites within Zones 1, 4, and 5. These two NPL sites (also known as Superfund sites) are the San Fernando Valley Superfund Site (Zone 1) and the San Gabriel Valley Superfund Site (Zones 4 and 5). In addition to the NPL sites, there are several localized soil and groundwater contamination sites within all of the zones (shown in Figure 6-1) that have the potential to impact the project, depending on the final tunnel alignment.

Tunnels located below NPL sites will pose a potentially difficult situation in terms of being able to demonstrate that contaminated soil and groundwater will not pose a risk during construction and operations. While it may be technically possible to construct tunnels within this area, the risks could impact the normal progress of the project.

13.1.5 Naturally Occurring Gas

Based on conditions encountered in other tunnel projects in the area, it appears that there is a high potential for encountering naturally occurring gas in the Puente Formation. Gas could also be encountered in other formations; however, the potential appears to be considerably lower. Because the Puente Formation extends for significant distances in Zones 1 and 2, the potential for encountering gas in these two zones is higher than the other zones. There is a moderate potential for naturally occurring gas in Zone 3 due to the extent of the Puente Formation. Likewise, there is a lower potential for naturally occurring gas in Zones 4 and 5.

The gassy conditions encountered during the sewer and subway tunnel construction in the Los Angeles area are described in Section 12.0 of this report. Such conditions are not unusual, especially in Los Angeles, and special tunneling equipment, air monitoring, ventilation methods, and safety procedures have been developed to allow tunnel construction in a safe manner.

13.2 Tunnel Excavation Methods

In view of the stratigraphy and groundwater conditions noted above, tunneling methods will likely vary from zone to zone, and could vary within a zone. Factors that will affect the selection of the tunneling method are identified below:

Tunnel excavations in the Fernando, Puente, and Topanga Formations that are anticipated in Zones 1 and 2 are considered to be routine with current tunneling technologies, such as the TBMs used for the NEIS project. Several tunnels have been successfully constructed through these or similar formations in the Los Angeles area. The uniformity of geological conditions in Zones 1 and 2 will simplify construction planning. The impact of the cemented layers and concretions would have to be addressed in the selection/design of tunnel excavation equipment, which might reduce tunnel advance rates; however, construction of tunnels in these formations has been completed successfully. Depending on the tunnel alignment in these zones, a specialized TBM that can provide positive face control may be needed to control unstable ground conditions and reduce the potential for surface settlement.

An excavation through Zone 3 will encounter varied geologic conditions. Zone 3 includes soil, and low-and high-strength rock. The low-strength Puente and Topanga Formations are similar to those described above for Zones 1 and 2. Cobbles and boulders present in the alluvium and Topanga Formation conglomerate may reduce the excavation rate. The diorite and potential volcanic rocks in the northern part of the alignment is a harder rock that would excavate differently than the sedimentary rocks previously discussed. Although Zone 3 presents the most varied lithology of all the zones, excavation of a tunnel in this zone could be done with a specialized TBM suited for different types of lithology or a combination of excavation methods. One approach would be to use a TBM that is convertible to operate in open mode (for rock or stable ground conditions) or in closed mode utilizing EPB or slurry methods (for the alluvium and other unstable ground conditions). This type of TBM is adaptable to a wide range of ground conditions and should be compatible with the conditions expected in Zone 3.

Tunneling through alluvium involves a greater potential for surface settlement than tunneling through rock. Alluvium is the main material in Zones 4 and 5, and it may be present in short reaches near portal zones in Zones 1, 2, and 3. It is expected that the majority of the soil at tunnel depth will be saturated, which increases the potential for instability and surface settlement.

Specialized TBMs with face control capabilities using earth-pressure balance or the slurry methods can minimize ground loss and control surface settlement. The design of specialized TBMs and tunnel operations become more complex as the groundwater head increases. A tunnel excavation method for Zones 4 and 5 would have to be designed for the saturated alluvium, which contains cobbles and boulders, as well as the sedimentary rock at the southern and western ends of Zones 4 and 5, respectively.

Open cut excavations in alluvial soils will likely be necessary in the tunnel portals in all of the zones. This construction will require groundwater and ground control by dewatering, permeation grouting, jet grouting, and/or installation of ground supports. Without these controls, there is the potential of high groundwater inflows, loss of ground, and surface settlement.

There are steeply dipping, inactive faults in all five zones. Tunneling through these faults is expected to include fractured rock, clay gouge, and varied groundwater conditions. The groundwater head and the potential for groundwater inflow commonly change during a fault zone crossing. A TBM can normally excavate these fault crossings without major difficulty, although the rate of excavation is normally less than the rate in unfaulted rock. A precast concrete segmental initial (outside) tunnel lining (installed as a TBM advances) is expected to provide the ground support in the alluvium, Fernando, Puente, and Topanga Formations, granitic-type rock, and the inactive fault zones. Ground support in the crossing of active faults may require a special lining similar to the Metro Red Line Project crossing of the Hollywood fault described in Section 12.1.3. Ground support in the open excavations may be provided by cast-in-place concrete box structures.

As discussed previously in this report, numerous faults transect the study area. When mining the tunnel, there is a possibility of squeezing conditions in clayey fault gouge. Special procedures might be required to advance the TBM shield through clayey gouge zones and provide permanent ground support.

13.3 Seismic Considerations

Special considerations will be required for excavating through a fault and lining the tunnel in an active fault zone. For example, the Metro Red Line in Los Angeles was excavated through the Hollywood fault. An oversized vault was excavated in the fault zone to accommodate fault offset (see Section 12.1.3). This oversize excavation is something that is typically used in an excavation through a fault zone to accommodate a certain amount of displacement due to fault rupture.

13.4 Groundwater Control

Groundwater control measures will be important in saturated alluvium where moderate to heavy inflows could be expected. The potential for high groundwater inflows is expected for tunneling within saturated alluvium; such conditions are expected in all zones. However, saturated alluvium is the predominant material at tunnel depth in Zones 4 and 5. Additional heavy to moderate inflows could be expected in the fault zones (active and inactive), which could provide conduits for groundwater. In addition to the alluvium, there could be localized groundwater inflows when excavating in the other formations, which do not constitute aquifers. Porous strata, fracture zones or fault zones may locally yield small to large inflows.

Specialized techniques would need to be implemented locally in Zones 1 through 3 where saturated alluvium or fault zones are expected, and over the majority of Zones 4 and 5 to mitigate unwanted groundwater inflows. These methods are expected to include use of pressurized-face tunneling machines utilizing earth-pressure balance or slurry systems to resist the water pressure and preclude groundwater inflows into the tunnel. In addition to these specialized machines, a watertight lining for the tunnel would be required to control groundwater behind the machines.

Groundwater inflow will be an important consideration for most potential portal locations. Groundwater pumping systems; ground improvement by dewatering, permeation grouting, or jet grouting; or combinations of these can be used to control water.

In addition to consequences inside the tunnel, groundwater inflows could impact the groundwater regime of the study area if inflows are not properly controlled. Controlling such inflows will avoid lowering of groundwater in the areas adjacent to the tunnel, and avoid impacts to contaminated groundwater plumes.

13.5 Tunnel Support and Lining

The stability of the sedimentary rock formations and hard rock units generally results in the need for full-perimeter ground support requirements in most areas; however, additional requirements may be needed for some areas, as summarized below.

Especially in this urban area, a full perimeter support system should be provided to control any loss of ground. Examples include steel ribs with timber lagging or a precast concrete segmental lining. Locally, where there is fault gouge or indications of squeezing ground, the ground support may need to be more robust because of the higher ground loads that will build up on the tunnel supports over time.

In the saturated alluvium, which occurs mostly in Zones 4 and 5, a watertight initial support system as well as final lining would be required such as a bolted and gasketed precast concrete segmental lining system. Squeezing ground conditions may also be present within the alluvium and may require support systems similar to those discussed above.

13.6 Settlement Potential

Face instability during excavation could lead to a loss of ground and the potential for measurable surface settlement. Control of such conditions is possible by using systematic ground improvement in the portal zones by dewatering, permeation grouting, or jet grouting. In the tunnel, specialized tunneling machines (such as earth-pressure balance or slurry machines) could be used to control these conditions. The magnitude of surface settlement depends on the depth of the tunnel (relative to its diameter), as well as the physical characteristics of the ground and the amount of ground lost at the tunnel face. These concerns are limited to the portions of the tunnel in alluvium, because ground movements associated with tunnel construction in the bedrock can be controlled without the need for ground improvement measures. Zones 4 and 5 would be excavated primarily through saturated alluvium; therefore, tunnel construction in these zones has the greatest risk for surface settlement.

13.7 Special Hazardous Materials Considerations

The Superfund sites in Zones 1, 4, and 5 have the potential to impact the tunnel excavation and muck disposal operations. Although these sites are located well above the tunnel, plumes of contaminated groundwater and soil contaminated by the groundwater might be encountered in the tunnel excavation. The severity of the contamination might be less at tunnel depth than at the ground surface; however, depending on chemical concentrations, handling hazardous materials in the tunnel could be challenging. The contaminated soil, water, and vapors must be controlled to protect the workers and avoid contaminating adjacent areas. The contaminated soil and water must be conveyed to treatment facilities and transported to final disposal sites. This would likely reduce the advance rate of the excavation in the contaminated areas, as well as increase the cost for disposal of the contaminated muck.

If hazardous materials or gases are expected, continuous air monitoring would be necessary in the working area of the tunnel. In addition, workers could be required to wear respirators and other personal protective equipment (PPE) to safeguard against exposure to these contaminants depending on the level of exposure. To control against contaminated conditions, a specialized tunneling method such as a slurry TBM might be used. Slurry TBMs use closed pipes. The contaminated material would be transported to the portal within the slurry pipes. The workers would not be exposed to VOC-contaminated muck because the excavated material would be contained inside pipes.

The VOC-impacted muck would need to be stockpiled separately from the "clean" muck, tested, and disposed of at a landfill designated to receive hazardous wastes. In addition, the presence of contaminated groundwater minimizes the ability to dewater at the portals. Ground improvement such as jet grouting and/or ground freezing may be necessary to control and prevent the movement of contaminated groundwater in the portal zone.

TABLE 13-1
Comparison of Zones

Zone	Approximate Length of Zone (miles)	Number of Geologic Formations	Predominant Geologic Formation(s)	Percentage of Zone in each Formation	Number of Reported/ Mapped Faults	Number of Active Faults	Potential for Gassy Condition [a]	Percent of Zone under Superfund Sites
1	5.0 to 5.5	2	Puente	80 to 90	5	0	H	5 to 10
			Alluvium	10 to 20				
2	5.0 to 5.5	4	Puente	70 to 80	7	1	H	0
			Topanga	10 to 15		(NW end)		
			Fernando	5 to 10				
			Alluvium	5 to 10				
3	4.5 to 5.0	5	Topanga	30 to 40	7	1[b]	M	0
			Alluvium	10 to 20				
			Puente	20 to 30				
			Fernando	5 to 10				
			Diorite	10 to 20				
4	6.0 to 7.5	3	Alluvium	70 to 80	5	2	L	5 to 15
			Fernando	10 to 15				
			Puente	10 to 15				
5	9.5 to 11.0	3	Alluvium	75 to 85	3	1	L	5 to 30
			Fernando	10 to 15				
			Puente	5 to 10				

Notes:
[a] H-High, M-Moderate, L-Low
[b] Two potentially active faults cross Zone 3

13.8 Geotechnical Conditions

An approach has been developed for comparing the significance of the geotechnical conditions discussed in Sections 7 through 11. The proposed approach for comparing the geotechnical conditions was developed based on the procedures described in the Caltrans Project Risk Management Handbook (2007b) and a similar approach developed for evaluating the risks involved with tunneling by British Tunneling Society (BTS, 2003).

The significance of the geotechnical conditions was determined by evaluating two factors. The first factor considers the likelihood of a certain issue or condition being encountered, and the second considers the impact or consequence of the issue or condition if it is encountered. These two factors were used to assess the significance of the geotechnical conditions in Table 13-2. Additionally, each geotechnical condition has been categorized as design-, construction-, or operation-related. This classification is independent of how significant the issue is; however, it assists in identifying the phase or phases of the project that each condition pertains to most.

The results of the evaluation summarizing the comparative analyses are presented in Table 13-2. The detailed methodology used for the development of the comparison of geotechnical conditions are presented in the memorandum included in Attachment 1. Although Table 13-2 shows moderate and high significance for some of the geotechnical conditions, it should be recognized that these conditions can be successfully mitigated.

TABLE 13-2
Summary of Significance of Geotechnical Conditions by Zone

Zone	Variable Ground Conditions	Unstable Soils	Active/ Potentially Active Fault Crossings	Groundwater Conditions	Gassy Conditions	Contaminated Soil and/or Groundwater
1	Low	Moderate	Low	Low	High	Low
2	Low	Low	Low	Low	High	Low
3	Moderate	Moderate	Low	Low	Moderate	Low
4	Moderate	High	Low	Moderate	Low	Moderate
5	Moderate	High	Low	High	Low	Moderate
Type*	D, C	D, C	D, C, O	C, O	C, O	D, C

*Type of Geotechnical Condition: Design (D), Construction (C), Operational (O).

It should be recognized that these geotechnical conditions are routinely encountered in tunnel design, construction, and operation and can be successfully addressed, as discussed in Section 12 of this report. Preliminary concepts to mitigate these geotechnical conditions are described in Sections 7 through 11 of this report. A memorandum regarding detailed descriptions of the mitigation concepts is presented in Attachment 2.

SECTION 14

Summary and Conclusions

Information in this report provides a preliminary summary of geotechnical conditions within the five zones being considered for the SR-710 tunnel. This section briefly summarizes some of the key tunneling considerations for each zone. Refer to Section 13 for additional details and Sections 7 through 11 for the individual zone descriptions.

Zone 1

A tunnel in Zone 1 will be mostly in the Puente Formation, a weak to moderately strong formation composed mainly of sandstone and siltstone. The low strength and uniform nature of this formation are favorable for TBM construction. Higher progress rates are expected in this zone, as compared to the other zones (except Zone 2). Alluvium may be encountered in the portal zones requiring localized ground improvement or groundwater control measures to avoid ground movements that could damage surface facilities. Although, the Puente Formation is not expected to produce significant groundwater inflows into the tunnel, higher inflows could be encountered in the lower cover beneath the Los Angeles River, depending on the amount of rock cover and rock quality beneath the river. These inflows can be controlled by grouting ahead of the tunnel excavation; however, there are still higher tunneling risks associated with the portion of the tunnel beneath the river. In this area, the groundwater may be contaminated due to the Superfund site in this zone. Methane gas also has been encountered in the Puente Formation at other tunneling projects in Los Angeles. Both of these issues will require special safety precautions and will be a factor in the selection of tunneling equipment and procedures. However, methods have been developed to allow safe tunnel construction where these conditions are present.

Zone 2

A tunnel in Zone 2 will encounter mainly the similarly weak Fernando, Puente, and Topanga Formations. Less alluvium is expected in the portal zones due to the topography, which is steeper and more hilly. Similar to Zone 1, weak sedimentary formations are expected to be favorable for efficient tunnel construction. Comparison of Zones 1 and 2 also shows that:

- There is no Los Angeles River crossing or Superfund site in Zone 2.
- There is similar potential for encountering methane gas in both Zones 1 and 2.
- A tunnel in Zone 2 may cross the active Raymond fault at the northwest corner of this zone; whereas, this fault is not present in Zone 1.

A special tunnel design will be required for the fault crossing to avoid rupture of the tunnel and possible collapse due to an earthquake on this fault. Similar fault crossings have been designed for the Los Angeles Metro's Hollywood Hills tunnel, which crosses the Hollywood fault.

Zone 3

A tunnel in Zone 3 will encounter the greatest range of geologic conditions compared to the other zones. These conditions include weak sedimentary rocks, strong basement complex rocks, and alluvium. Such a range of conditions is likely to result in less-efficient tunneling operations and lower overall progress rates. Mixed face transitions from one geologic formation to the next will also likely result in more difficult and complex tunneling operations and reduced progress rates. Tunneling through the alluvium will require specialized tunnel equipment to avoid surface settlement and damage to surface facilities. The active Raymond fault is also present in Zone 3. The crossing of the Raymond fault in Zone 3 is likely to be in a deep reach of the tunnel distant from the portal zone. This crossing is likely to require a special lining like the Metro Red Line crossing of the Hollywood fault. This fault may be acting as a groundwater barrier where it crosses the tunnel, which may require some additional grouting to maintain tunnel stability. The potential for methane gas appears to be lower in this zone than in Zones 1 and 2 because less of the tunnel is in the Puente Formation and no Superfund sites are present, thereby reducing the potential for encountering contaminated groundwater.

Zone 4

A tunnel in Zone 4 will encounter mainly alluvium or unconsolidated soil deposits. Most of the tunnel will be in cohesionless soil deposits below the groundwater table, requiring positive groundwater control to avoid loss of ground and surface settlement. Specialized tunnel machines (i.e., earth pressure balance or slurry machines) that are sealed to preclude groundwater inflows can be used; however, tunnel progress rates will be lower than in Zones 1 and 2 where the tunnel is in rock formations, and probably will be less than in Zone 3, too. In addition, constructing tunnels in alluvium involves some inherent risks because any loss of ground or overexcavation in the tunnel can lead to ground movements, surface settlement, and possible damage to surface facilities. This type of risk is limited in Zones 1, 2, and 3. A Superfund site is located at the southwest end of this zone. This can be handled as discussed above for Zone 1; however, the performance of the tunnel lining in this chemical environment (type and concentration of the contaminants) must be evaluated to determine if measures are required to protect the structural integrity of the tunnel.

A tunnel in this zone will cross two active faults, the Raymond fault and Alhambra Wash fault. These two locations will likely require special fault-crossing designs, as discussed above for Zone 2. Due to portions of the tunnel being in the Puente Formation, there is some potential for gas to be encountered in this zone, but the risk is much lower than in Zones 1 and 2 and probably lower than Zone 3.

Zone 5

A tunnel in Zone 5 will encounter mainly alluvium or unconsolidated soil deposits, similar to Zone 4. Tunneling concerns and risks are the same as discussed above for Zone 4. Groundwater control and potential ground movements will need to be controlled, similar to Zone 4, to avoid damage to surface facilities. Tunnel progress rates will not be as high as in Zones 1 and 2, and probably will be less than in Zone 3. Differences between Zone 4 and Zone 5 include: (1) in Zone 5, there is no crossing of the Raymond fault zone, and (2) the extent of the Superfund sites (or potential groundwater contamination) appears to be more extensive. Therefore, only one active fault (Alhambra Wash fault) crossing will need to be evaluated, and a greater length of tunnel could be exposed to chemical attack if the contaminants present at the Superfund sites are aggressive to concrete. The potential for encountering methane gas in this zone is approximately the same as in Zone 4.

Conclusion

Sections in this report contain detailed information about the geology, faults, seismicity, groundwater, contaminated materials, and potential for gassy conditions within each zone. This information provides a basis for evaluating the geotechnical feasibility of tunneling within each of the zones. Based on the information collected and reviewed as part of the current geotechnical study, tunneling is geotechnically feasible in all five zones. Geotechnical feasibility implies that it is feasible to construct a tunnel in the geologic formations expected, including the geotechnical conditions associated with these formations using currently available tunneling technologies. Section 12 discusses several tunnel projects and the construction technologies available for conditions similar to those present within the zones under consideration for this study.

SECTION 15
Limitations

This Geotechnical Summary Report has been prepared for the exclusive use of Caltrans and Metro for specific application to the study of the SR-710 extension, Los Angeles County, California. The report has been prepared in accordance with generally accepted engineering practices. No other warranty, express or implied, is made.

The geotechnical and geological information contained in this report is based on the data obtained from the review of available sources of information, such as geological maps and documents, the as-built plans, and our field investigation within the study area. The logs of soil and rock borings from the available information indicate subsurface conditions only at specific locations and times, and only to the depths penetrated. The borings do not necessarily reflect variations that could exist between locations or possible changes that might take place with time and depth. If variations in subsurface conditions from those described in this report are noted during further detailed study, the geotechnical information presented in this report should be reevaluated.

In the event that any change in the nature, design, or location of the proposed improvements occurs, the conclusions and recommendations of this report should not be considered valid unless such changes are reviewed, and conclusions of this report are modified or verified in writing by CH2M HILL. CH2M HILL is not responsible for any claims, damages, or liability associated with the reinterpretation or reuse of the subsurface data in this report by others.

SECTION 16

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TABLE 16-1
Summary of Reviewed References

Number	Reference	Applicability to Zones					Tunnel
		1	2	3	4	5	
1	Albee and Smith (1966)	X	X	X	X	X	
2	Albino et al. (1999)					X	
3	ASTM (2008)	X	X	X	X	X	
4	Argus et al. (1999)	X	X	X	X	X	
5	Benioff (1938)	X	X	X	X	X	
6	Bilodeau et al. (2007)	X	X	X			
7	Blake (2000)	X	X	X	X	X	
8	Borchardt and Hill (1979)			X	X		
9	Bryant (1978)		X	X	X		
10	BTS (2003)						X
11	Bullard and Lettis (1993)	X	X	X	X	X	
12	Buwalda (1940)		X	X	X		
13	Byer (1975)		X	X	X		
14	Cadiz et al. (1998)						X
15	CBGG (1998)	X	X	X	X	X	
16	Caltrans (1971)					X	
17	Caltrans (1974a)			X			
18	Caltrans (1974b)			X			
19	Caltrans (1991)	X					
20	Caltrans (1996a)	X	X	X	X	X	
21	Caltrans (1996b)	X	X	X	X	X	
22	Caltrans (2007a)	X	X	X	X		
23	Caltrans (2007b)	X	X	X	X	X	
24	Caltrans (2009)	X	X	X	X	X	
25	CDWR (1961)	X				X	
26	CDWR (1966)			X	X	X	
27	CDWR (2003)			X	X	X	
28	CDWR (2004a)			X	X	X	
29	CDWR (2004b)			X	X	X	
30	CDWR (2004c)			X	X		
31	CDWR (2004d)			X	X	X	
32	CDWR (2009)	X	X	X	X	X	
33	CDMG (1975)		X	X			
34	CDMG (1977)		X	X			
35	CDMG (1989)	X	X	X			
36	CDMG (1991)				X	X	
37	CDMG (1997)	X	X	X	X	X	
38	CDMG (1998a)					X	
39	CDMG (1998b)				X	X	

TABLE 16-1
Summary of Reviewed References

Number	Reference	Applicability to Zones 1	2	3	4	5	Tunnel
40	CDMG (1998c)	X					
41	CDMG (1998d)	X	X	X	X	X	
42	CDMG (1998e)				X		
43	CDMG (1998f)		X	X			
44	CDMG (1999a)					X	
45	CDMG (1999b)				X	X	
46	CDMG (1999c)	X					
47	CDMG (1999d)	X	X	X	X	X	
48	CDMG (1999e)				X		
49	CDMG (1999f)			X			
50	CDMG (2001)	X	X	X	X	X	
51	CDOGR (2001)	X	X	X	X	X	
52	CDWR (1934)			X	X		
53	CGS (2002a)	X	X	X	X	X	
54	CGS (2002b)	X	X	X	X	X	
55	CGS (2002c)	X	X	X	X	X	
56	CGS (2005)	X	X	X	X	X	
57	CGS (2009)	X	X	X	X	X	
58	CGMB (1996)	X	X	X	X	X	
59	CDM (1998)					X	
60	CDM (2006)					X	
61	CDM (2008a)					X	
62	CDM (2008b)					X	
63	Cao et al (2003)	X	X	X	X	X	
64	Chapman and Chase (1979)	X					
65	Chapman and Chase (1980)			X			
66	CH2M HILL (1992)			X	X		
67	CH2M HILL (2003)				X	X	
68	CH2M HILL (2006)				X	X	
69	CH2M HILL (2007)	X					
70	CH2M HILL (2008)	X	X	X			
71	CH2M HILL (2009a)	X	X	X			
72	CH2M HILL (2009b)	X	X	X			
73	CH2M HILL (2009c)				X	X	
74	CH2M HILL (2009d)	X	X	X	X	X	
75	Chapman and Chase (1979)	X					
76	Chapman and Chase (1980)			X			
77	Choueiry et al. (2007)						X
78	City of Alhambra (2005)			X	X	X	
79	City of Arcadia (2004)					X	

TABLE 16-1
Summary of Reviewed References

Number	Reference	Applicability to Zones 1	2	3	4	5	Tunnel
80	City of Los Angeles (1996)	X	X	X			
81	City of Los Angeles (2000)		X				
82	City of Los Angeles (2001)	X					
83	City of Los Angeles (2006a)		X				
84	City of Los Angeles (2006b)		X				
85	City of Pasadena (2002)			X			
86	Cofirouteusa (2009)						X
87	City of South Pasadena (2008)		X	X			
88	Critchfield and Miya (2004)						X
89	County of Los Angeles (2008)	X	X	X	X	X	
90	Crook et al. (1987)		X	X	X		
91	Crook (1988)				X	X	
92	Crook and Proctor et al. (1992)	X	X	X	X	X	
93	Davis and Namson (1998)	X	X	X	X	X	
94	Davis et al. (1989)	X	X	X	X	X	
95	Dibblee (1989a)	X				X	
96	Dibblee (1989b)	X	X	X	X	X	
97	Dibblee (1989c)		X	X			
98	Dibblee (1992)	X	X	X			
99	Dibblee (1998)				X		
100	Dibblee (1999)				X	X	
101	Dolan et al. (2003)	X	X	X	X	X	
102	Dolan et al. (2000a)		X	X	X		
103	Dolan et al. (1997)		X				
104	Dolan et al. (1995)		X	X	X		
105	Drumm (1992)	X	X	X	X	X	
106	Dubnewych et al. (2005)	X					
107	ECI (2005)				X		
108	EMI (2005)	X	X	X	X	X	
109	EMI (2006)	X	X	X	X	X	
110	Eastman (1987)				X		
111	Eastman (1993)				X		
112	Eastman (1997)				X		
113	Eckis (1934)		X	X			
114	Ehlig (1999)					X	
115	EGLI (2004a)				X		
116	Escandon et al. (1989)					X	
117	Ferguson et al. (2008)					X	
118	Fernandez (2007)					X	
119	Fuis et al. (2001)	X	X	X	X	X	

TABLE 16-1
Summary of Reviewed References

Number	Reference	Applicability to Zones 1	2	3	4	5	Tunnel
120	Fulcher et al. (2006)					X	
121	Fumal et al. (1993)	X	X	X	X	X	
122	Gallanes et al. (1996)						X
123	Gath et al. (1994)					X	
124	Geoscience (2004)				X		
125	GeoSyntec (2006a)					X	
126	GeoSyntec (2006b)					X	
127	GeoSystems (1982)				X		
128	GoogleEarth (2009)	X	X	X	X	X	
129	Gordon et al. (1995)						X
130	Hanks et al. (1999)	X					X
131	Harding and Tuminas (1988)	X					X
132	Hart and Bryant (2007)	X	X	X	X	X	
133	Hauksson (1994)	X	X	X	X	X	
134	Hauksson and Gross (1991)	X	X	X	X	X	
135	Hauksson et al. (1995)	X	X	X	X	X	
136	Hawkins (1985)				X		
137	Herrenknecht (2009)					X	X
138	ICBO (1988)	X	X	X	X	X	
139	ISRM (1985)	X	X	X	X		
140	JMMI (1992)	X					
141	Jennings (1994a)	X	X	X	X	X	
142	Jennings (1994b)	X	X	X	X	X	
143	Jones et al. (1990)		X	X	X		
144	Kleinfelder (2000)				X		
145	Kramer et al. (1998)					X	
146	Krulc et al. (2007)						X
147	Lamar (1970)	X	X	X	X	X	
148	Lamar (1975)	X	X				
149	Law/Crandall (1993)	X	X	X	X		
150	LAI (1977)				X		
151	LAI (1986)				X		
152	LAI (1990)	X	X	X	X	X	
153	LAI (2000)				X		
154	LACDPW (1996)	X	X	X	X	X	
155	LACDPW (2009)	X	X	X	X	X	
156	LACDRP (2009)	X	X	X	X	X	
157	Marin et al. (2000)		X	X	X		
158	MSGW (2006)				X	X	
159	McCalpin (2000)			X	X	X	

TABLE 16-1
Summary of Reviewed References

Number	Reference	Applicability to Zones 1	2	3	4	5	Tunnel
160	McCulloh et al. (2001)			X	X		
161	McCulloh et al. (2002)			X	X		
162	Meigs and Oskin (2002)	X	X	X	X	X	
163	Meigs et al. (2008)	X	X	X	X	X	
164	Merril (1975)		X				
165	Merriam and Shantz (2007)	X	X	X	X	X	
166	MTA (2005)			X			
167	Morton and Miller (2003)					X	
168	MCCI (1954)	X	X	X	X		
169	Myers et al. (2003)	X	X	X	X	X	
170	Navin (1991)						X
171	Nilsen et al. (2007)						X
172	Ninyo and Moore (1999)			X			
173	Ninyo and Moore (1999)			X			
174	Ninyo and Moore (2000a)			X			
175	Ninyo and Moore (2000b)			X			
176	Oakshotte (1958)	X	X	X	X	X	
177	Oskin et al. (2000)	X	X	X			
178	PBI (2006)			X			
179	Petersen et al. (1998)	X	X	X	X	X	
180	Petersen et al. (1996)	X	X	X	X	X	
181	Pratt et al. (2002)	X	X	X	X	X	
182	Proctor (1971)						X
183	Proctor (1975)		X	X	X		
184	RBMB (2006)			X	X		
185	RBMB (2007)			X	X		
186	Robinson and Bragard (2007)	X	X	X			X
187	Robinson and Wardell (1991)						X
188	Schell (1997)	X	X	X	X	X	
189	Schell and Hushmand (2002)				X	X	
190	Schell and Sexton (2009)	X	X	X	X	X	
191	Seely (2004)						X
192	Shamma et al. (2003)						X
193	Shaw and Shearer (1999)	X	X	X	X	X	
194	Shaw and Suppe (1996)	X	X	X	X	X	
195	Shaw et al. (2002)	X	X	X	X	X	
196	Sladden (2006)				X		
197	Smith (1978)			X			
198	SCEC (1995)	X	X	X	X	X	
199	SCEC (2001)	X	X	X	X	X	

TABLE 16-1
Summary of Reviewed References

Number	Reference	Applicability to Zones 1	2	3	4	5	Tunnel
200	SCEC (2009)	X	X	X	X	X	
201	Stein and Yeats (1989)	X	X	X	X	X	
202	Stetson (2005)			X	X	X	
203	Tan (2000a)					X	
204	Tan (2000b)				X	X	
205	TBM (2003)	X	X	X	X	X	
206	Thapa et al. (2007)						X
207	Thompson (1966)						X
208	Tinsley et al. (1985)	X	X	X	X	X	
209	Treiman (1991a)				X		
210	Treiman (1991b)					X	
211	Treiman (2000)		X	X	X		
212	Tunnelbuilder (2008)						X
213	USEPA (2003)					X	
214	USEPA (2006)	X					
215	USEPA (2009a)	X					
216	USEPA (2009b)				X	X	
217	USGS (1999)	X	X	X	X	X	
218	USGS (2001)	X	X	X	X	X	
219	USGS (2009a)	X	X	X	X	X	
220	USGS (2009b)	X	X	X	X	X	
221	USGS (2009c)		X	X	X		
222	URS (2006)		X				
223	Weaver and Dolan (1997)		X	X	X		
224	Weaver and Dolan (2000)		X	X	X		
225	Weber (1979)	X	X	X	X		
226	Weber (1980)	X	X	X			
227	Weldon et al. (2004)	X	X	X	X	X	
228	Wells and Coppersmith (1994)	X	X	X	X	X	
229	WGI (2004)			X			
230	Wright (1991)	X	X	X	X	X	
231	Yeats (2001)			X	X	X	
232	Yeats (2004)			X	X	X	
233	Yerkes (1997)	X					
234	Yerkes and Campbell (2005)	X	X	X	X	X	
235	Yerkes and Graham (1997a)	X					
236	Yerkes and Graham (1997b)	X	X	X			
237	Yerkes and Graham (1997c)	X	X	X			
238	Yerkes and Showalter (1990)	X	X	X			
239	Yerkes et al. (1965)	X	X	X	X	X	

TABLE 16-1
Summary of Reviewed References

Number	Reference	Applicability to Zones 1	2	3	4	5	Tunnel
240	Yerkes et al. (1977)	X	X	X			X
241	Zernich et al. (2005)						X
242	Ziony (1985)	X	X	X	X	X	
243	Ziony and Jones (1989)	X	X	X	X	X	

TABLE 16-2
Summary of Reviewed Aerial Photographs

Date Flown	Flight Number	Scale (Inch = Feet)	Photograph Frame Numbers
8/1927	C-113	1=1500	224-229, 260-265, 297-302, 353-355, 387-390, 435-428, 461-464, 495-496
6/21/28	C-238	1=1500	C:2-14, D:1-5
1928-1929	C-300	1=1500	K:138-143, 163, 181-187, 200-205, 227-233, 252, 256-258, 264-273, 292-298, 313-320, 336-341, 361-367
1/13/34	C-2878	1=1750	17-21, 38-48, 63-69, 81-85
3/10/38	C-5043	1=1500	4-15
1/1939	C5526A	1=1650	38-40
10/6/40	C-6630	1=2000	58-65, 95-101
1944-45	C-9220	1=600	8:95-99, 119-145, 9:56-57, 77-99, 160-161, 10:124-150, 16:14-38
2/27/46	C-10145	1=600	11-15
1947	C-1135	1=2000	B:1-8
6/1949	C-13775	1=2000	G:1-10, H:1-9
7/1949	C-13880	1=1500	1:58-64, 3-27-32, 89-95
6/1949	C-13990X	1=1500	1:163-172, 2:16-21,
2/1951	C-16123	1=5500	1:42-44
8/15/52	C-17876	1=2000	A:95-107, B:44-47, 18:72-88, 101-115
5/8/53	C-183215	1=2540	2:1-12
1953	C-19400	1=5250	B:17-20, 22, 48-49

TABLE 16-2
Summary of Reviewed Aerial Photographs

Date Flown	Flight Number	Scale (Inch = Feet)	Photograph Frame Numbers
7/12/54	C-20645	1=600	B:29-81, 64-61
10/1954	C-20941	1=2000	1:21-25
3/7/55	C-21784	1=1500	10-15
1/18/56	C-22325	1=1000	14-15
3/23/57	C-22067	1=3335	142-150, 273-277, 402-405

ATTACHMENT 1

Comparison of Geotechnical Conditions

PROJECT MEMORANDUM

To:	C. Yoga Chandran, GE (CH2M HILL)
From:	Steve Dubnewych, PE; Max John (ILF)
Reviewed By:	Steve Klein, GE
JA Job No.:	4150.0
Date:	April 1, 2010
Subject:	SR-710 Tunnel Technical Study: Comparison of Geotechnical Conditions

1 Methodology

As requested by the Steering Committee (SC) and the Technical Advisory Committee (TAC), this memorandum was developed to provide an approach for comparing the significance of the geotechnical conditions discussed in Sections 7 through 11 of the Geotechnical Summary Report for the State Route (SR) 710 Tunnel Technical Study (CH2M HILL, 2010). The proposed approach was developed based on the procedures described in the California Department of Transportation (Caltrans) *Project Risk Management Handbook* (2007). The British Tunneling Society (BTS) has developed a similar approach for evaluating the risks involved with tunneling (BTS, 2003). In the context discussed in this memorandum, the challenges associated with the geotechnical conditions are considered to be risks, and need to be addressed in an appropriate manner for the project to be successful.

In the approach outlined below, the significance of each condition is determined by evaluating two factors. The first factor considers the likelihood of a certain issue or condition being encountered, and the second factor considers the impact or consequence of that condition if it is encountered. The likelihood factor is scored by considering the probability of encountering a certain condition in each of the five zones identified in the Geotechnical Summary Report or by determining the percentage of the zone that may be affected by this condition. The second factor considers the potential impact or consequence in terms of the potential cost increase if the condition were to be encountered. Both factors – the likelihood and the potential impact – need to be considered to determine the significance of a particular issue or condition. For example, a condition with a high likelihood of being encountered but a low impact is not as significant as a condition with a high likelihood of being encountered and with a high impact.

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The impact factor considers the impact without mitigation efforts, which provides a sense of the significance of each condition without any artificial measures to control the impact. In this way, the factor better captures the significance of each individual challenge/issue. The impact factors are assigned based on our experience with similar conditions on similar projects. It should be recognized that all of the conditions discussed herein can be successfully mitigated using proven, available technologies as discussed in Section 12 of the Geotechnical Summary Report (CH2M HILL, 2010). Tables 1 and 2 provide the likelihood and potential impact factor scores, which were developed for this evaluation based on the Caltrans *Project Risk Management Handbook* (2007).

The product of the likelihood and the potential impact factors determines the total score, which is used to qualitatively assess the significance of a certain geotechnical condition. Table 3 shows whether the issue/condition has low, moderate, or high significance based on the value of the product relative to Caltrans (2007) criteria. It is important to understand that the likelihood of impact factors presented herein are for relative comparisons between zones and reflect the information available at the present time. Furthermore, these conditions have been evaluated independently of each other and independently of the length of each zone. In this way, the significance of each issue/condition by itself is established for each zone without consideration of whether a mitigation measure implemented to address one condition might reduce the severity of another condition.

Table 1: Likelihood Factor Scores*

Score	Probability or Percentage of Zone (%)	Qualitative Description	
		Probability	Percentage of Zone
1	0 – 9	Very Low	Localized
2	10 – 19	Low	Minor
3	20 – 39	Medium	Moderate
4	40 – 59	High	Moderately High
5	60 – 99	Very High	Major

* Based on Caltrans, 2007

Table 2: Potential Impact Factor Scores*

Score	Cost Increase Percentage	Qualitative Description
1	Insignificant	Very Low
2	< 5	Low
3	5 – 10	Moderate
4	10 – 20	High
5	> 20	Very High

* Based on Caltrans, 2007

Table 3: Significance Based on Likelihood and Potential Impact Scores*

Total Score	Significance
1 – 6	Low
7 – 14	Moderate
>14	High

* Based on Caltrans, 2007

In addition to identifying the significance of each condition using the aforementioned criteria, each condition has been categorized as pertaining to the design, construction, or operation phase of the project. This classification is not reflected in the scoring process; however, identifying the phase of the project that each condition pertains to most is helpful.

2 Significance of Geotechnical Conditions

Specific geotechnical conditions have been identified in Sections 7 through 11 of the Geotechnical Summary Report (CH2M HILL, 2010). These conditions are discussed below with a description of how the likelihood and potential impact factors have been determined for each zone. The significance of the issues is also indicated for each zone.

2.1 Variability of Ground Conditions

Variable ground conditions are more challenging for tunnel construction than uniform conditions because equipment and/or mining procedures may have to be changed frequently to adapt to the changes in ground conditions. Potential impacts include lower overall efficiency in the construction operations due to these changes, lower advance rates, and possibly the need for more expensive, specialized equipment.

Where mixed face conditions (soil and rock in the heading at the same time) are encountered, steering the tunnel boring machine (TBM) is more difficult, and there can be a tendency for loss of ground due to difficulties in maintaining proper face pressure with a TBM. In addition, if geologic conditions are highly variable, there is greater uncertainty (higher risk) and higher potential for unanticipated variations. This results in a higher potential for differing site condition claims, change orders, and construction delays.

In terms of variability, the greatest challenge is the length of tunnel where soft ground (or soil) conditions change from soil to rock and back again. The likelihood of the expected variable conditions was evaluated qualitatively per zone using Plate 10 from the Geotechnical Summary Report (CH2M HILL, 2010). For this evaluation, the number and frequency of changes between rock, weak rock, and alluvium is considered to define the risk of encountering variable conditions.

Geologic units such as the Puente and Topanga Formations are not expected to behave differently in terms of tunnel excavation.

The likelihood of experiencing variable ground conditions is summarized in Table 4 for each zone. For all of the zones, the impact score is a 3, corresponding to a cost increase of 5 to 10 percent. Ground variability is viewed to affect the design and construction phases of a project.

Table 4: Summary of Variable Ground Condition Scores by Zone

Zone	Ground Variability (Qualitative Description)	Likelihood Factor	Potential Impact Factor	Total Score	Significance
1	Minor	2	3	6	Low
2	Localized	1	3	3	Low
3	Moderately High	4	3	12	Moderate
4	Moderate	3	3	9	Moderate
5	Moderate	3	3	9	Moderate

2.2 Unstable Soils

The stability of soils at the face of an excavation is critical because unstable conditions can lead to loss of ground and surface settlement while tunneling. Settlement could damage surface facilities such as existing buildings, streets, utilities, and other improvements. Tunnels excavated in soft ground, such as cohesionless alluvium below the water table, are more susceptible to loss of ground that could result in surface settlement than rock or stiff, cohesive soil deposits.

In rock formations and stiff, cohesive soil deposits, face stability is generally good. These ground conditions are less prone to surface settlement because loss of ground that propagates to the ground surface is rare. In tunnels excavated through rock formations, arching develops above the tunnel, and ground movements do not propagate to the surface to cause settlement if there is sufficient cover above the tunnel. For the purposes of this evaluation, the percentage of tunnel in alluvium is considered to define the risk of encountering unstable soils.

The likelihood of experiencing unstable soil conditions is summarized in Table 5 for each zone. For all of the zones, the potential impact score is a 5, corresponding to a cost increase of greater than 20 percent. Unstable soils are viewed to affect the design and construction phases of a project.

Table 5: Summary of Unstable Soil Conditions Scores by Zone

Zone	Length of Unstable Conditions (% of Zone)	Likelihood Factor	Potential Impact Factor	Total Score	Significance
1	10 – 20	2	5	10	Moderate
2	5 – 10	1	5	5	Low
3	10 – 20	2	5	10	Moderate
4	70 – 80	5	5	25	High
5	75 – 85	5	5	25	High

2.3 Active and Potentially Active Fault Crossings

One important challenge/issue has to do with active and potentially active fault crossings. Tunnels, especially rock tunnels, generally perform well with respect to earthquake ground shaking. Where a fault capable of producing offset intersects a tunnel, fault displacements could shear the tunnel, which could lead to significant damage. Design of tunnels crossing an active or potentially active fault poses a design and operational challenge, since a special lining section would need to be developed to withstand fault offset or ground rupture.

Four active or potentially active faults were identified in this study, and their probable activity is summarized in Table 6. Preliminary estimates of the return periods are indicated for the maximum earthquake magnitude and the resulting fault displacement. These estimates are based on published values where specific investigations have been conducted (e.g., Weaver and Dolan, 2000, and Crook et al., 1987), and on comparison to similar faults using empirical relationships documented by Wells and Coppersmith (1994). The probability that each fault will experience such an event is based on the assumption of a design life of about 100 years and the fault-rupture return periods as presented in Table 6. These estimates are considered to be conservative, and the data should be used for comparison purposes only.

Table 6: Summary of Active/Potentially Active Faults and Fault Activity in the Project Area

Active/Potentially Active Fault	Maximum Earthquake Magnitude	Estimated Amount of Displacement (feet)*	Return Period (years)	Probability of Rupture During Design Life
Raymond	6.7	4	3,300	3%
Alhambra Wash	6.25	1.5	4,000	2.5%
San Rafael	6.0	<1	>5,000	2%
Eagle Rock	6.0	<1	>5,000	2%

* Return period (also known as recurrence interval) is a measure of the average interval of time between seismic events of a certain magnitude.

The likelihood of fault rupture during the design life of the tunnel, for each fault per zone, is summarized in Table 7. For each of the zones, the impact score depends on the number of active and potentially active fault crossings in each zone, assuming a 5 to 10 percent cost increase for each active fault and a cost increase of less than 5 percent for each potentially active fault. The issue of fault crossings is viewed to affect the design, construction, and operation phases of a project.

Table 7: Summary of Active/Potentially Active Fault Crossings Scores by Zone

Zone	Active/Potentially Active Faults	Probability of Rupture (%)	Likelihood Factor	Potential Impact Factor	Total Score	Significance
1	None	-	1	1	1	Low
2	Raymond	3	1	3	3	Low
3	Raymond San Rafael Eagle Rock	3 2 2	1	4	4	Low
4	Raymond Alhambra Wash	3 2.5	1	4	4	Low
5	Alhambra Wash	2.5	1	3	3	Low

2.4 Groundwater Conditions

Tunneling under high, external water pressure involves some significant risks. To prevent flooding of the tunnel, a pressurized-face, sealed TBM and a watertight, segmental lining system will be used. Problems with TBM seals or segmental lining gaskets may lead to significant water inflows into the tunnel. These inflows will potentially impact TBM mining operations and can lead to safety hazards in the tunnel. The higher the pressure, the greater the risk will be. If the excavation is below the groundwater table, the full pressure most likely will not be experienced in the excavation if the rock mass is tight (i.e., unfractured rock). In general the Puente Formation is a fine-grained unit with few joints. It is unlikely that high water pressure will be encountered in this weak rock below the observed groundwater table.

For the purposes of this evaluation, the length of tunnel anticipated to be below the historically highest groundwater conditions in the alluvium is considered to define the risk of encountering significant groundwater inflows. Published California Division of Mines and Geology (CDMG) seismic hazard evaluation reports for the Baldwin Park, El Monte, Hollywood, Los Angeles, Mount Wilson, and Pasadena quadrangles were used to establish conditions (CDMG, 1998a through 1998f). From previous excavation experiences, it is assumed that the weak rock formations (Puente, Topanga, and Fernando Formations) may transmit water if they are within one tunnel diameter of the alluvium.

The likelihood of groundwater inflows is summarized in Table 8 for each zone. For all of the zones, the impact score is a 3, corresponding to a 5 to 10 percent cost increase. The issue of groundwater is viewed to affect the construction and operation phases of a project.

Table 8: Summary of High Groundwater Inflow Scores by Zone

Zone	Tunnel Length Below Historically Highest Groundwater Condition (% of Zone)	Likelihood Factor	Potential Impact Factor	Total Score	Significance
1	15 – 20	2	3	6	Low
2	5 – 10	1	3	3	Low
3	15 – 20	2	3	6	Low
4	45 – 50	4	3	12	Moderate
5	95 – 100	5	3	15	High

2.5 Gas Potential

The presence of naturally occurring gas is not uncommon in the Los Angeles area. Naturally occurring methane and hydrogen sulfide gas has been encountered in other tunnels in Los Angeles, particularly in the Puente Formation, and has been dealt with successfully. The Puente Formation is generally recognized as one of the most prolific petroleum sources in the Los Angeles Basin. Although gas may be encountered in other formations, for the purposes of this evaluation, the percentage of tunnel in the Puente Formation is considered to define the risk of encountering gas. It should be noted that naturally occurring gas might not be present in every excavation in the Puente Formation.

The likelihood of encountering gassy conditions is summarized in Table 9 for each zone. For all of the zones, the impact score is a 3, corresponding to a 5 to 10 percent cost increase. Encountering naturally occurring gas is viewed to affect the construction and operation phases of a project.

Table 9: Summary of Naturally Occurring Gas Scores by Zone

Zone	Tunnel Length in Puente Formation (% of Zone)	Likelihood Factor	Potential Impact Factor	Total Score	Significance
1	80 – 90	5	3	15	High
2	70 – 80	5	3	15	High
3	20 – 30	3	3	9	Moderate
4	10 – 15	2	3	6	Low
5	5 – 10	1	3	3	Low

2.6 Contaminated Soil and/or Groundwater

Contaminated soil and/or groundwater will affect the tunneling operations in several ways. If the contaminant concentrations are high enough, special safety procedures and worker protective gear could be required. Contaminant concentrations could also impact the project if the concentrations encountered required disposal of tunnel spoils at a hazardous waste landfill. It would be undesirable if tunneling operations had an impact on a contaminated groundwater plume or caused the plume to migrate. Although localized contamination could occur outside Superfund sites, for the purposes of this evaluation, the length of tunnel in the Superfund sites is considered to define the risk of encountering contamination.

The likelihood of encountering contaminated soil and/or groundwater is summarized in Table 10 for each zone. For all of the zones, the impact score is a 4, corresponding to a 10 to 20 percent cost increase. Contaminated soil and/or groundwater are viewed to affect the design and construction phases of a project.

Table 10: Summary of Contaminated Soil and/or Groundwater Scores by Zone

Zone	Tunnel Length in Superfund Sites (% of Zone)	Likelihood Factor	Potential Impact Factor	Total Score	Significance
1	5 – 10	1	4	4	Low
2	0	1	4	4	Low
3	0	1	4	4	Low
4	5 – 15	2	4	8	Moderate
5	5 – 30	3	4	12	Moderate

3 Summary

The results of the likelihood/impact analyses are shown in Table 11 for each geotechnical condition identified. Additionally, each condition is classified as being a design, construction, and/or operational challenge. Although the table shows moderate and high significance for some of the conditions, it should be recognized that these conditions can be successfully mitigated. As discussed in the Geotechnical Summary Report, all of these conditions have been encountered and successfully addressed in previous tunnel projects (CH2M HILL, 2010).

Table 11: Summary of Significance of Each Geotechnical Condition by Zone

Zone	Variable Ground Conditions	Unstable Soils	Active/ Potentially Active Fault Crossings	Groundwater Conditions	Gas Potential	Contaminated Soil and/or Groundwater
1	Low	Moderate	Low	Low	High	Low
2	Low	Low	Low	Low	High	Low
3	Moderate	Moderate	Low	Low	Moderate	Low
4	Moderate	High	Low	Moderate	Low	Moderate
5	Moderate	High	Low	High	Low	Moderate
Phase*	D, C	D, C	D, C, O	C, O	C, O	D, C

* Phase: Design (D), Construction (C), Operational (O).

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ATTACHMENT 2

Concepts to Address Geotechnical Conditions

Tunneling Concepts to Address Geotechnical Conditions Encountered within the Study Area SR-710 Tunnel Technical Study

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DATE: April 1, 2010

Introduction

This technical memorandum presents a summary of preliminary concepts proposed to address geotechnical conditions described in the Geotechnical Summary Report for the SR-710 Tunnel Technical Study (CH2M HILL, 2010). These concepts are included as an attachment to the report, as requested during the Technical Advisory Committee and Steering Committee meetings. The findings of the geotechnical study indicate that each of the zones faces different geotechnical conditions that should be addressed during design, construction, and/or operation. The following sections describe preliminary concepts to address these conditions.

It should be noted that these conditions have been successfully addressed in other tunnels constructed in Los Angeles and around the world, as discussed in Section 12 of the Geotechnical Summary Report, and are considered to be relatively routine in present-day tunneling practice. However, these are important conditions that need to be carefully considered in the selection of tunneling methods and equipment. It should be recognized that some specialized tunneling methods may address more than one of the conditions. The following sections describe potential tunneling conditions and some of the concepts and approaches that have been developed to address these conditions at similar, successfully completed tunnel projects.

Variable Ground Conditions

Variable ground conditions create challenges for tunnel construction because mining procedures, and sometimes excavation equipment, have to be modified to adapt to the differences in ground conditions, which might involve significant variations in the strength and stability of the ground. Impacts include less-efficient construction operations, lower rates of tunnel advancement, or alternatively using specialized tunnel boring equipment. In the transition from soil deposits to rock, mixed face conditions will be encountered.

This condition can be difficult for tunnel construction because the best approach for excavating the soil deposits may not be feasible for excavating the rock. In this case, a compromise approach must be used, which may not be optimal for either soil or rock. All of these factors tend to increase construction costs. A thorough characterization of geologic conditions can minimize the potential for unexpected conditions to be encountered during construction. If geologic conditions are highly variable, there is greater uncertainty and a higher potential for variations between exploratory borings. This could also result in a higher potential for differing site condition claims, change orders, and construction delays.

One approach for mitigating the impact of variable ground conditions is to select a tunneling method that is adaptable to the range of ground conditions anticipated. For TBM methods, this may involve a machine designed to excavate all of the types of ground expected in the tunnel. For example, the cutterhead might have to be designed to handle both soft ground and hard rock, such as the cutterhead shown in Figure 1.

In mixed face conditions, the cutterhead is designed so that the excavation tools and opening configurations can be modified underground to adapt the machine to the ground conditions present in the tunnel. This is done by equipping the cutterhead with flexible rear-loading saddles or cutter boxes that permit the use of disc cutters for hard rock and ripper-style tools for soils. Additionally, replaceable scraper and bucket tools are configured in either case to gather the cuttings and direct them toward the openings. The tunnel boring machine (TBM) in Figure 1 was used to mine a portion of the Northeast Interceptor Sewer (NEIS) tunnel (located in Zone 1) through alluvium and weak sedimentary rock. It is equipped with a cutterhead that has rippers for soil and disc cutters for rock.

Controlling unstable ground at the soil/rock interface where these mixed face conditions are present is important to avoid surface settlement that could damage existing buildings, utilities, and streets. One common approach is to strengthen the soil deposits at the interface by grouting the ground prior to tunneling from the ground surface and through the cutterhead of the tunnel boring machine. A number of methods could be employed; however, usually, jet grouting or permeation grouting using cement or chemical grouts are the most effective methods for local ground treatment. After treating the soils at the interface, the stability of the soils is improved and the strength contrast with the rock is less, which reduces the impact of mixed face conditions.

Zone 3 exhibits the most variable ground conditions of the five zones, and Zones 1 and 2 are the least variable. Zones 4 and 5 exhibit moderately variable subsurface conditions.

Figure 1: Pressurized-Face TBM Equipped with Cutterhead for Rock and Soil

Unstable Soil Conditions

The stability of soils at the tunnel face is critical since unstable conditions can lead to loss of ground and surface settlement while the tunnel is being advanced, unless positive face support is provided. If unstable conditions are allowed to develop, settlement could damage surface facilities such as existing buildings, streets, utilities, and other improvements. The stability of the ground has a significant impact on the selection of tunneling methods and equipment, as well as on the type and quantity of ground support measures.

In general, there are two categories of tunnel face stability, defined as follows:

a) **Stable ground conditions**: No support of the tunnel face is required. This category encompasses good quality rock formations under dry conditions. These units will include intact diorite formation and much of the Puente, Topanga, and Fernando Formations.

b) **Unstable ground conditions**: Support of the tunnel face is required. This category covers all soil types such as the alluvium, as well as all fault zones and fractured or weak, weathered/altered rock. The instability is magnified when these units are present below groundwater table.

Face support may also be required locally in hard rock when adverse discontinuity orientation is encountered or highly fractured units are expected.

The Geotechnical Summary Report (CH2M HILL, 2010) describes the majority of the tunnel in Zones 4 (70 to 80 percent) and 5 (75 to 85 percent) to be in potentially unstable alluvium. Approximately 10 to 20 percent of the tunnel in Zones 1 and 3 and 5 to 10 percent of the tunnel in Zone 2 are also expected to be in alluvium.

The influence of unstable ground conditions can be mitigated by improving the ground to provide adequate strength to maintain stable conditions during tunneling operations or by selecting an excavation method that can control the ground and prevent instability from developing. Extensive ground improvement can be very expensive and disruptive to the public.

Within the past 10 to 15 years, sophisticated TBMs have been widely used to control adverse and unstable ground conditions. These machines utilize earth pressure balance (EPB) or slurry methods to apply a positive, controllable pressure at the tunnel face that can stabilize the ground at the face and withstand the hydrostatic and ground pressures. Most tunnels excavated today in unstable ground conditions utilize these types of TBMs to control the ground stability and enhance face stability to allow the tunnel to be advanced without loss of ground or surface settlement. An EPB TBM was used for the Los Angeles Metropolitan Transportation Authority (Metro) eastside extension tunnels on the Gold Line, which were successfully excavated in potentially unstable ground beneath several existing buildings without any surface settlement. Similar machines are available in the size required for highway tunnels, such as the 50-foot-diameter EPB TBM used for the Yanghtze River Tunnel crossing in Shanghai, shown in Figure 2.

Figure 2: TBM Used to Mine the Shanghai Yangtze River Tunnel
(Source: Herrenknecht, 2009)

Fault Crossings

All five tunnel zones cross active and/or inactive fault zones. During construction, difficult ground conditions typically associated with faults and fault zones may result in construction delays and other problems. After construction, the displacements associated with active and potentially active faults crossing the tunnel can disrupt operation of the tunnel and can lead to significant damage in the event of a seismic event on one of these faults. Therefore, faults present different challenges for the construction and operations phases of a project, as discussed below.

Construction Considerations: Excavating a tunnel through faults or fault zones impacts tunnel construction in several ways. Tunneling through faults might require the control of groundwater because faults can act as groundwater barriers, ponding water behind the fault, or as sources of significant inflows due to highly fractured rock conditions. Additionally, fractured rock, sheared rock, and clay gouge formed by previous fault movements might be encountered when tunneling through a fault zone. Weak rock conditions associated with faults can result in adverse conditions, such as unstable squeezing ground, flowing ground, or raveling ground.

The first step in mitigating the impacts of faults in tunnel construction is to fully understand the ground, groundwater, and seismic conditions. If large groundwater inflows are expected, pressurized-face technology can be utilized to provide the TBM with the ability to balance the water pressures and prevent inflows into the tunnel. Large inflows can also be controlled by a localized grouting program through the cutterhead to fill open rock fractures with grout, which reduces inflows to the tunnel. Groundwater inflows can be mitigated behind the TBM by installing a watertight, precast concrete, segmental lining that is designed to withstand the hydrostatic pressure acting on the tunnel. The potential ground instability at fault crossing can also be controlled by the use of a pressurized-face TBM.
A photo of a pressurized-face TBM is shown in Figure 2. This TBM is the largest TBM in the world to date; it was used to mine the Shanghai Yangtze River tunnel, which has an excavated diameter of approximately 50.5 feet.

Squeezing problems may occur in both cohesive soils and weak rock. Advancing a TBM through squeezing conditions requires methods that can overcome the ground pressure acting on the machine. The main area of concern is along the body of the TBM where high-friction forces caused by the convergence of the ground can result in trapping the TBM. To overcome these frictional forces, special provisions and tunneling procedures must be developed, such as:

- Adjustable gauge cutters (the cutters on the periphery of the cutterhead) to increase overcut to accommodate ground convergence
- Capability for injecting bentonite (under pressure) in the annulus along the shield
- Installation of strain gauges to continuously monitor pressure along the shield
- Use of a tapered shield, where the shield diameter reduces from the cutterhead to the end of the tail shield
- Continuous mining in areas identified as high risk for trapping the TBM

Operations Considerations: During the operational life of the tunnel, active and potentially active faults intersecting the tunnel could rupture, producing possible fault offset or displacement that could shear the tunnel. Fault displacements that shear the tunnel would disrupt safe operation of the tunnel and could make the tunnel impassable for vehicles. In addition, the tunnel structure could be severely damaged making it difficult to safely evacuate the public from the tunnel, depending on the magnitude of the displacements. For these reasons, it may be necessary to design the tunnel to accommodate potential fault displacements. These concerns apply mainly to Zones 2, 3, and 4 and possibly to Zone 5.

For small displacements, a flexible lining system could be designed for the fault zone. A special lining could consist of segments with shorter segmented lining elements that would better accommodate flexibility than standard segments. A representation of a tunnel with shorter elements through a fault zone is shown in Figure 3. An advantage of using a special lining in the fault zone is that the tunnel would not have to be modified to accommodate the fault displacements; however, this method is not practical for fault displacements in excess of about 6 to 12 inches depending on the fault geometry, tunnel size, and lining details.

For large fault displacements (greater than 6 to 12 inches), it is possible to construct an oversized tunnel, or vault, for the portion of the tunnel in the fault zone and for areas susceptible to ground rupture. This approach has been used successfully for several other tunnel projects. For this concept, the portion of the tunnel in the fault zone is enlarged to form a vault outside the design lines of the tunnel. This vault is large enough to accommodate the movement of the fault without disturbing the inner tunnel lining. A schematic section of the oversized tunnel concept is illustrated in Figure 4.

A number of tunnels have used the concept of enlarging the tunnel at a fault crossing. Examples include the Metro Red Line tunnel to North Hollywood, which crosses the Hollywood fault, and the East Bay Municipal Utility District Claremont Water Tunnel, which crosses the Hayward fault (Caulfield et al., 2005). Both of these tunnels were constructed with an oversized section to accommodate vertical and horizontal movements.

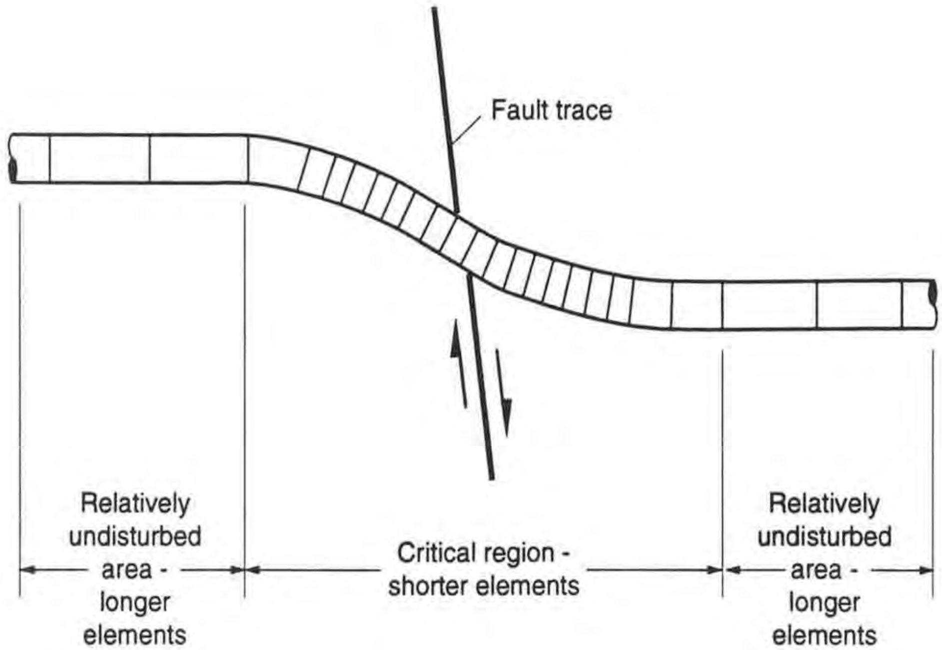

Figure 3: Diagram Showing Shorter Lining Elements in Fault Zone

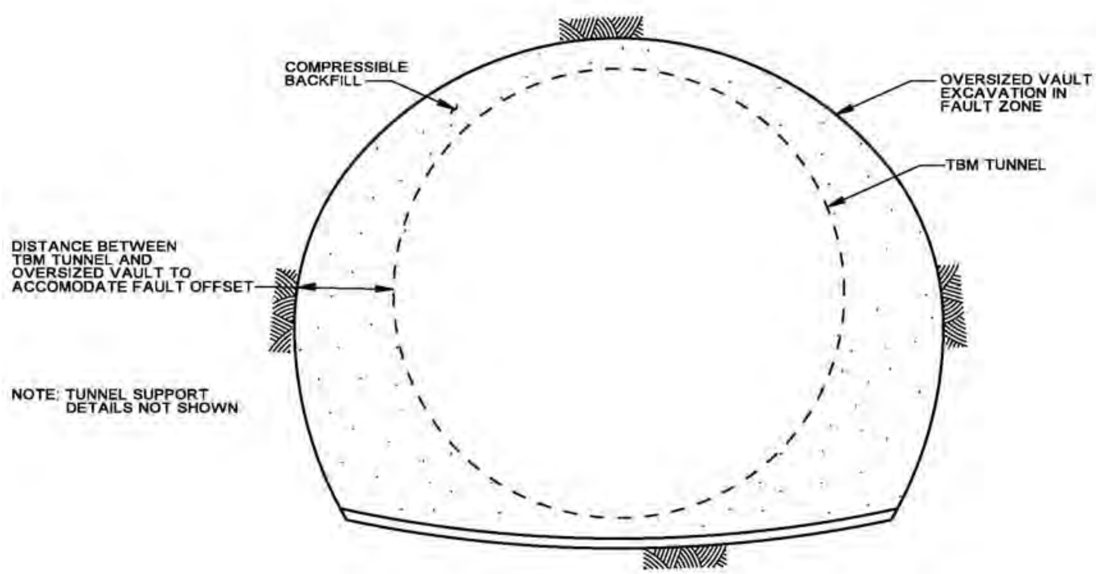

Figure 4: Schematic of an Oversized Tunnel to Accommodate Large Fault Displacements

Gas Potential

Gas has been encountered in several tunnels constructed in the Los Angeles area. Naturally occurring gas often has been observed in the Puente Formation, which is present in all five zones in various amounts, although gas could be encountered in other formations as well. Tunneling experience in the vicinity of Zone 2 in the Puente Formation encountered significant amounts of gas. The potential for encountering gassy conditions is considered to be high in Zones 1 and 2, medium in Zone 3, and low in Zones 4 and 5.

Encountering gas in a tunnel is mainly a safety issue during construction. In California the hazard is well recognized and the California Division of Occupational Safety and Healthy (Cal/OSHA) regulates tunnel construction to ensure that safe working conditions are maintained. Complying with current Cal/OSHA regulations addresses the majority of concerns regarding the hazards due to naturally occurring gas in tunnels. Cal/OSHA classifies tunnels based on the likelihood of encountering gas during as follows:

- **Nongassy**: There is little likelihood of encountering gas during excavation.
- **Potentially gassy**: There is a possibility that flammable gas or hydrocarbons will be encountered during excavation.
- **Gassy**: It is likely that gas will be encountered, and gas accumulations could be greater than 5 percent of the lower explosive limit (LEL) with normal ventilation
- **Extra hazardous**: There is a serious danger to the safety of the employees in the tunnel, and gas accumulations are greater than 20 percent of the LEL with normal ventilation.

The atmosphere in a tunnel excavation where gases are expected can be made safe by:

- Preventing hazardous concentrations of gas from accumulating
- Eliminating potential ignition sources in the presence of combustible gas
- Sounding an alarm to evacuate in the event that gas concentrations approach unacceptable levels

Atmosphere control measures include ventilation, gas monitoring, use of explosion-proof electrical equipment, and hazard awareness training for workers. Example ventilation concepts are shown in Figures 5a and 5b.

Cal/OSHA's Tunnel Safety Orders outline the regulations that the contractor must adhere to for the various tunnel classifications. Some examples of operational requirements for potentially gassy, gassy and extra hazardous classifications are summarized below. For complete details on the regulations, refer to California Code of Regulations (CCR) Title 8 (Cal/OSHA, 1996).

Potentially Gassy Tunnels

In potentially gassy tunnels, Cal/OSHA requires that the air in the tunnel and shaft be tested before employees are allowed to work. Normally, a manual flammable gas monitor is used as needed. The tunnel should be monitored at minimum at the beginning of each shift and at least every 4 hours thereafter to check that conditions have not changed.

Gassy and Extra Hazardous Tunnels

In any tunnel classified as gassy or extra hazardous, Cal/OSHA requires continuous testing for gas or vapors to ensure that the respective LELs are not exceeded. All electrical equipment used in these classifications must comply with Cal/OSHA Electrical Safety Orders, which require spark-free, sealed electrical components. Smoking is prohibited underground, and the contractor is responsible for collecting ignition sources, such as lighters, matches cameras, and radios. Gas monitors with sensors must be installed with visual and audible warnings and provide automatic shutdown of the electrical power except for ventilation and pumping equipment. Refuge chambers need to be maintained within 5,000 feet of the tunnel face. Workers need to be provided with emergency rescue equipment and be trained on how to use it.

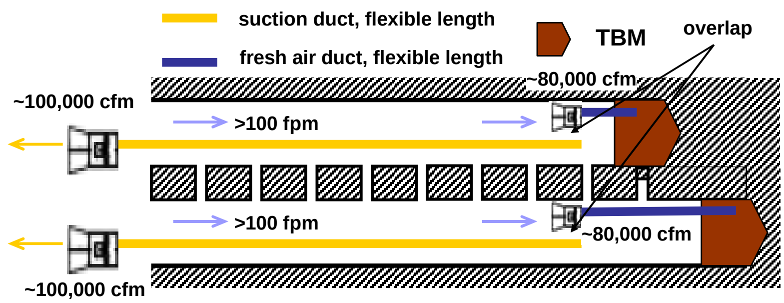

Figure 5a: Example Ventilation Concept for Short Tunnel

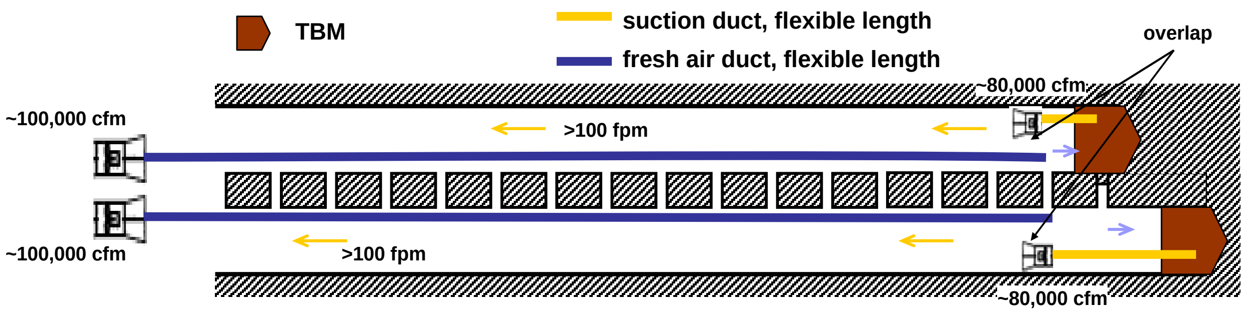

Figure 5b: Example Ventilation Concept for Long Tunnel

Soil and Groundwater Contamination

Although Superfund sites are not present in all five zones, localized soil and groundwater contamination is likely present within all five zones (CH2M HILL, 2010), which has the potential to impact the project during construction depending on the final tunnel alignment. Superfund sites are located in Zones 1, 4, and 5, and a tunnel in these zones probably has the greatest likelihood of encountering significant soil and groundwater contamination.

Tunnel excavation through contaminated soils and groundwater could pose challenges, depending on the type and concentration of the contaminant(s). The spoils generated from excavating through zones of contamination will likely require special handling and disposal. Additionally, the working environment in the tunnel could become unsafe if the contaminant were airborne in fine particles or were a gas that can be inhaled.

When excavating through contaminated materials, the contractor should have as much information as possible about the contamination in order to plan for the handling and disposal of the impacted spoils. A pressurized-face TBM, as shown in Figure 1, could be used to reduce the impact to contaminated groundwater plumes and minimize the amount of contaminated groundwater that will be handled in the tunnel.

An additional issue when excavating in and around contaminated groundwater plumes is that the construction activity could cause a plume to migrate. Excavations could disrupt a plume or cause pathways for contamination to migrate. Care must be taken during construction not to disturb the plumes when tunneling. Contact grouting the segmental concrete lining will reduce the risk of infiltration of polluted water. Monitoring the extent of the plumes, both during and following construction, is an important measure in ensuring that they do not migrate as a result of the excavation.

Groundwater Conditions

Groundwater is another significant factor in tunnel construction. The issues that need to be considered include the following:

- Impact of groundwater on face stability during excavation
- Design of the lining system
- Long- and short-term impacts of tunnel construction on the groundwater system

Uncontrolled and/or excessive groundwater inflow during tunnel construction could result in loss of ground, which could lead to surface settlements. Continued inflows during excavation and during operation of the tunnel could lead to localized groundwater drawdown. Additionally, these inflows could impact TBM mining operations and lead to safety hazards in the tunnel; therefore, inflows must be mitigated.

During the investigation, existing groundwater data were collected, including the historically highest groundwater level (CDMG, 1998a and 1998b) and the 2006 groundwater level (MSGW, 2006). The information is summarized in the Geotechnical Summary Report (CH2M HILL, 2010). Based on experience, it is known that the historically highest groundwater level is a realistic scenario. For the most part, the evaluation of the groundwater conditions was conducted based on the historically highest groundwater level. The majority of the tunnel in Zones 4 and 5 would be at or below the groundwater table. A portion of the tunnel in Zones 1 through 3 would be below groundwater table. The ground at tunnel level in Zones 4 and 5 is alluvial sand and gravel with layers of pervious ground and some impervious ground. There appears to be a large risk of large groundwater inflows in this ground. The ground at tunnel level in Zones 1, 2, and major part of Zone 3 is a fine grained, relatively unfractured Puente, Fernando, and Topanga Formations which are unlikely to convey large groundwater inflows to the tunnel.

Groundwater inflows could occur while tunneling below the groundwater table, especially in the saturated alluvium. Based on historical data, groundwater pressures could range from 0 to 6 bar. Excavation of the tunnel will require controlled-face, soft ground TBM methods, with rock excavation capabilities. A pressurized-face TBM is ideally suited due to the presence of high groundwater pressures combined with the varying permeability and strength of the soil units, including mixed face conditions (i.e., rock and soil in the excavation face) within the zones. The two most common types are slurry and EPB TBMs.

The choice between slurry TBM and EPB TBM excavation methods is influenced by several factors, including grain size distribution, strength, occurrence of boulders or obstructions, ground permeability, gas and contaminants, feasibility of soil separation and muck disposal, and settlement considerations. To ensure that water flows are controlled behind the TBM, a relatively watertight initial support system would be required, such as a bolted, gasketed, precast segmental reinforced concrete lining system when tunneling in saturated alluvium. To prevent or minimize water inflows into the tunnel, supplemental grouting operations would likely be used in conjunction with the bolted, gasketed, precast concrete lining system to satisfy the long-term operational requirements of the tunnel.

In portal areas where TBMs will not be used, other excavation techniques, such as cut-and-cover and sequential excavation methods (SEM), will need to be evaluated. These methods would most likely be used in conjunction with ground improvement. Ground improvement measures may include a combination of dewatering, permeation grouting, or jet grouting to stabilize the deposits below the groundwater levels. Because groundwater issues are expected in most of the zones, groundwater control measures need to be considered in the design.

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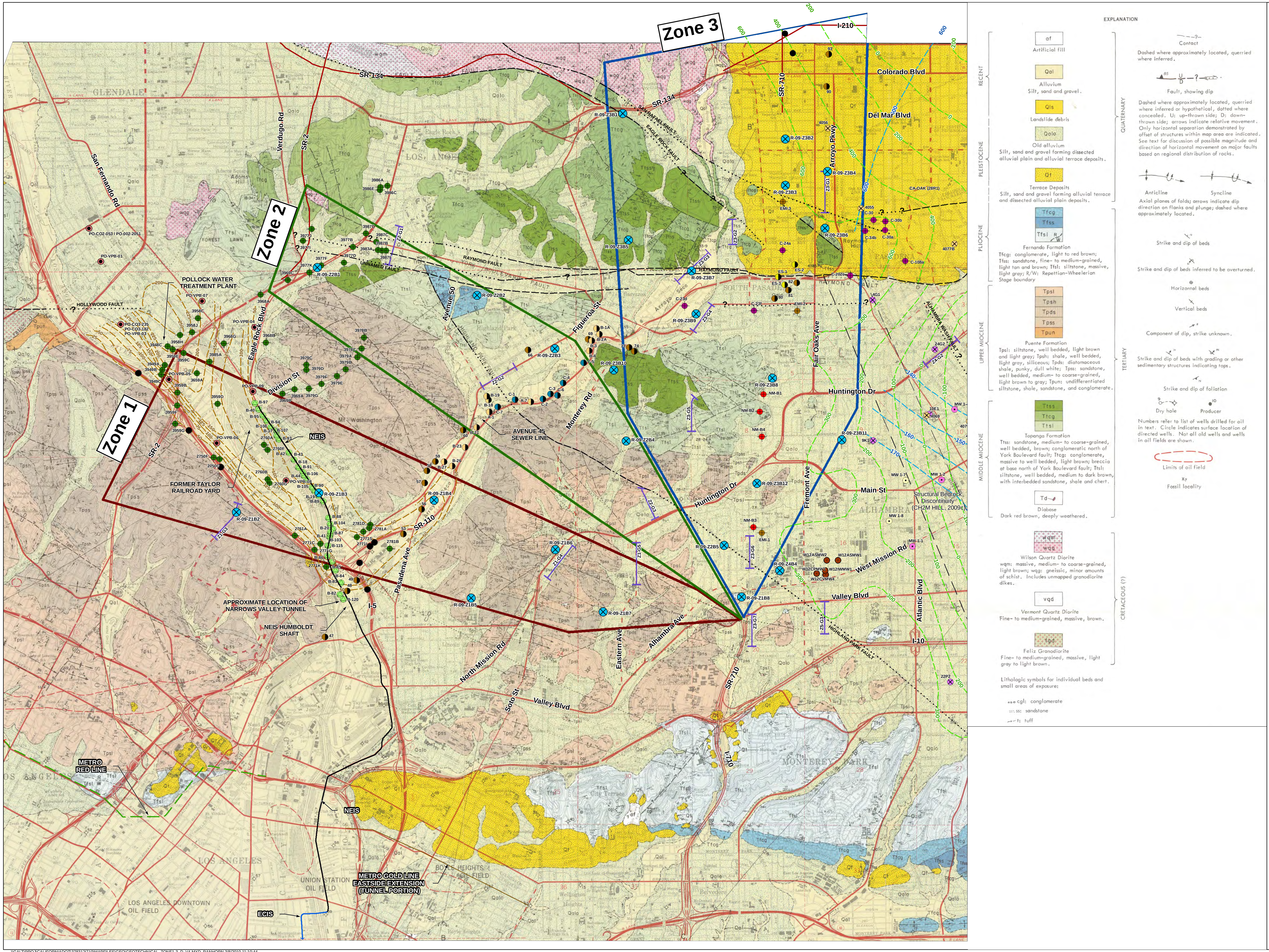
Plates 1 through 10



Legend
(All Locations are Approximate)

- Continuous Core Boring (CH2M HILL, this study)
- Facility Monitoring Well (CH2M HILL, 2009)
- Caltrans As-built LOTB's (Various Locations)
- Water Production Well; Location for which only Groundwater Data in Available (LACDPW, 2009)
- Continuous Core Boring (EMI, 2006)
- Geotechnical Boring (City of Los Angeles, 2000, 2006a, and 2006b)
- Geotechnical Boring (URS, 2006)
- Groundwater Monitoring Well (CH2M HILL, 2006)
- Groundwater Monitoring Well (CH2M HILL, 2003)
- Geotechnical Boring (City of Los Angeles, 2001)
- Boring (Ninyo and Moore, 1999)
- Geotechnical Boring (Law/Crandall, 1993)
- Monitoring Well, (JMMI, 1992 and CH2M HILL, 2007)
- Boring (Yerkes et al, 1977)
- Boring (Caltrans, 1974a)
- Geotechnical Boring (Caltrans, 1974b)
- Water Production Well (CDWR, 1966)
- Depth to Bedrock in Feet Below Existing Ground Surface (Yerkes et al, 1977)
- Structural Contour Line, Elevation at Top of Bedrock in Feet (MSL) (CDWR, 1966 and Geoscience, 2004)
- Groundwater Elevation in Feet (MSL) (San Gabriel Basin - MSGW, 2006 and Raymond Basin - RBMB, 2006 and 2007)
- Seismic Reflection Line (CH2M HILL, this study)
- Zone 1 Limits
- Zone 2 Limits
- Zone 3 Limits
- Northeast Interceptor Sewer (NEIS)
- East Central Interceptor Sewer (ECIS)
- Metro Red Line
- Metro Gold Line Eastside Extension (Tunnel Portion)
- Existing Street, Road, or Highway

Source of Base Map: Lamar, 1970

N

0 2,000 4,000 Feet

0 750 1,500 Meters

Plate 1
Geotechnical Map Zones 1, 2 and 3

SR-710 Tunnel Technical Study
Los Angeles County, California

CH2MHILL

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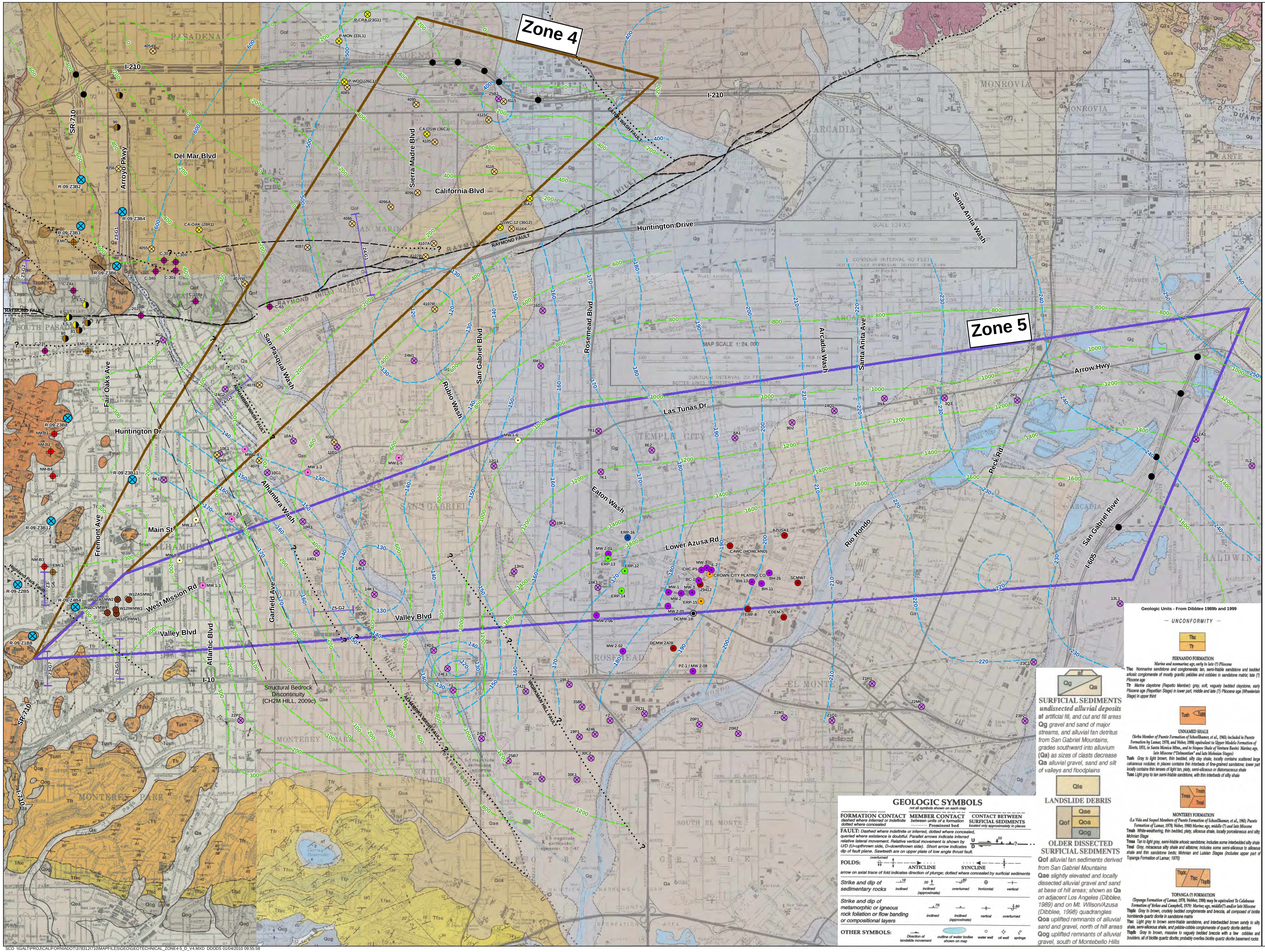


Legend

(All Locations are Approximate)

- R-09-Z1B8 — Continuous Core Boring (CH2M HILL, this study)
- W12ASMW2 — Facility Monitoring Well (CH2M HILL, 2009)
- 4077B — Water Production Well; Location for which only Groundwater Data is Available (LACDPW, 2009)
- Caltrans As-built LOTB's, (Various Locations)
- ERP-15 — Groundwater Monitoring Well (CDM, 2008a)
- ERP-16 — Groundwater Monitoring Well (CDM, 2008b)
- EMI-1 — Continuous Core Boring (EMI, 2006)
- ERP-14 — Groundwater Monitoring Well (CDM, 2006)
- MW-17 — Groundwater Monitoring Well (CH2M HILL, 2006)
- CDEM-5 — Groundwater Monitoring Well (Geosyntec, 2006b)
- DCMW-1 — Monitoring Well (Geosyntec, 2006a)
- CA-DSW — Water Production Well (Geoscience, 2004)
- MW 1-6 — Groundwater Monitoring Well (CH2M HILL, 2003)
- NM-B1 — Boring (Ninyo and Moore, 1999)
- MW2-02 — Groundwater Monitoring Well (CDM, 1998)
- 90 — Geotechnical Boring (Law/Crandall, 1993)
- C-65/C-23f — Boring (Caltrans, 1974a)
- ES-1 — Geotechnical Boring (Caltrans, 1974b
- 9D2 — Water Production Well (CDWR, 1966)
- 1400 — Structural Contour Line, Elevation at Top of Bedrock in Feet (MSL) (CDWR, 1966 and Geoscience, 2004)
- 220 — Groundwater Elevation in Feet (MSL) (San Gabriel Basin - MSGW, 2006 and Raymond Basin - RBMB, 2006 and 2007)
- Z2-G2 — Seismic Reflection Line (CH2M HILL, this study)
- Zone 4 Limits
- Zone 5 Limits

Source of Base Map: Dibblee, 1989b, 1989c, 1998, 1999

0 2,000 4,000 Feet

0 750 1,500 Meters

Plate 2
Geotechnical Map Zones 4 and 5

SR-710 Tunnel Technical Study
Los Angeles County, California

CH2MHILL

SCO \\GALT\PROJ\CALIFORNIADOT\378312\710\MAPFILES\GEO\GEOTECHNICAL_ZONE4-5_D_V4.MXD DDODS 01/04/2010 09:55:58

Plate 3
Surface Wave Testing Location Map
Zones 1, 2 and 3

SR-710 Tunnel Technical Study
Los Angeles County, California

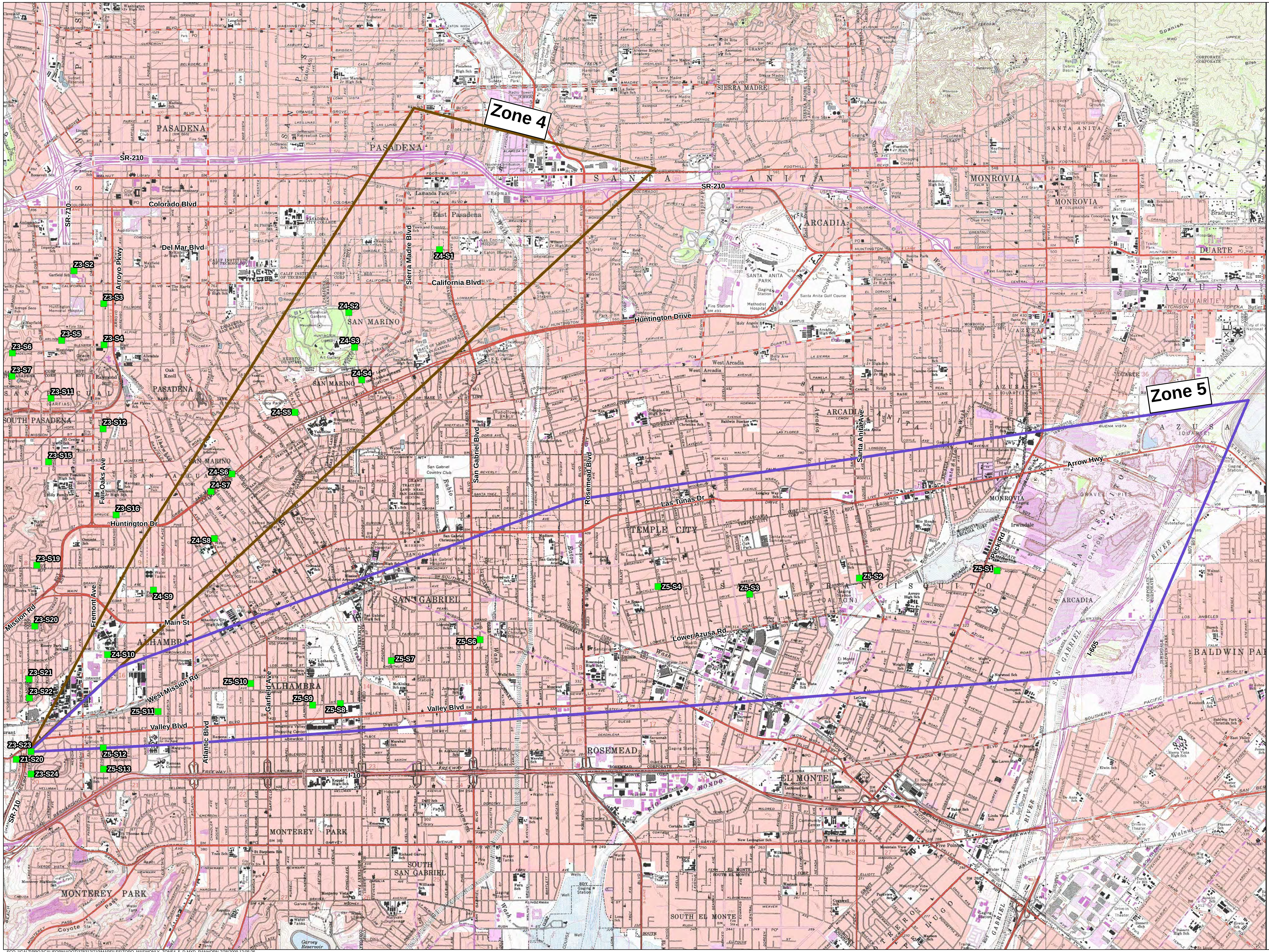
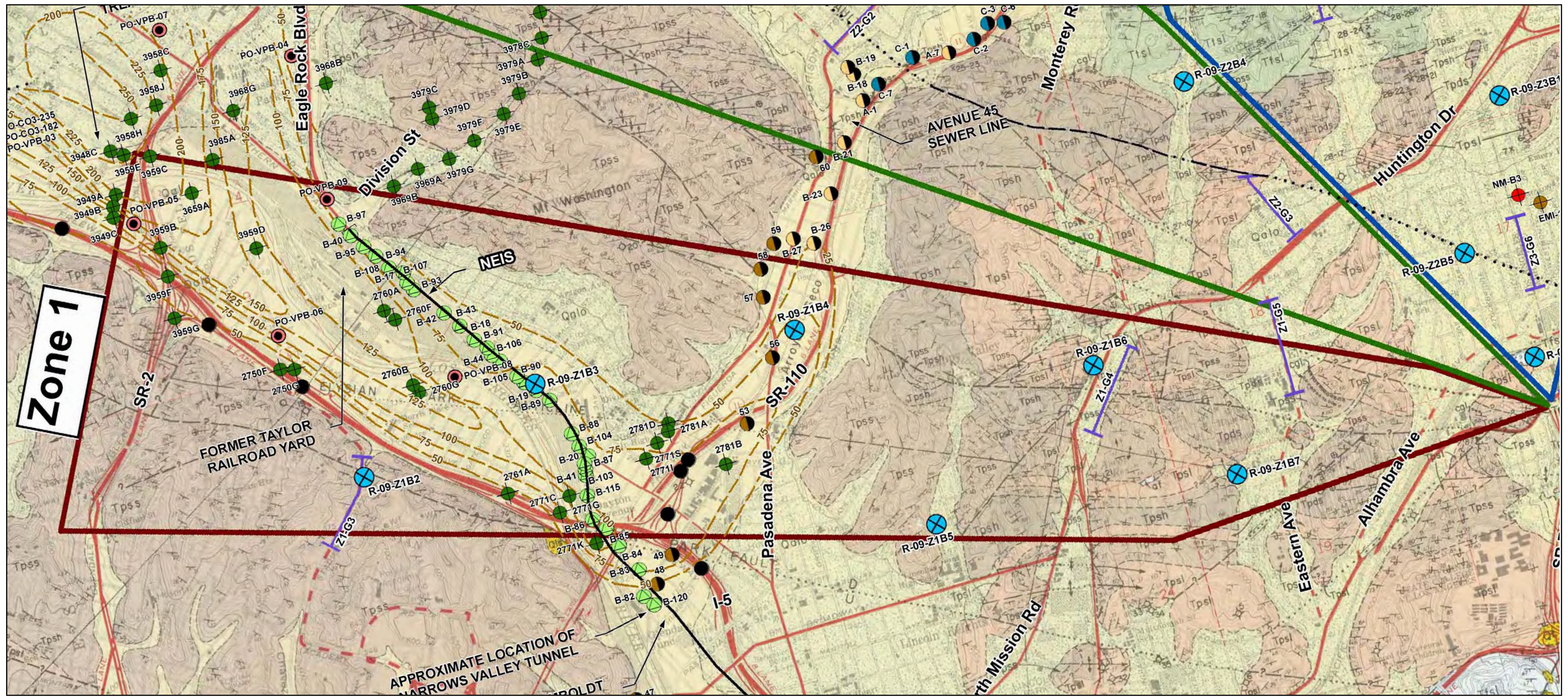


Plate 4
Surface Wave Testing
Location Map
Zones 4 and 5
SR-710 Tunnel Technical Study
Los Angeles County, California

Geotechnical Map



Map Legend

(All Locations are Approximate)

- R-09-Z1B8 — Continuous Core Boring (CH2M HILL, this study)
- W12ASMW2 — Facility Monitoring Well (CH2M HILL, 2009)
- Caltrans As-built LOTB's (Various Locations)
- 4077B — Water Production Well; Location for which only Groundwater Data in Available (LACDPW, 2009)
- EMI-1 — Continuous Core Boring (EMI, 2006)
- A-1 and B-3 — Geotechnical Boring (City of Los Angeles, 2000, 2006a, and 2006b)
- C-1 — Geotechnical Boring (URS, 2006)
- MW-17 — Groundwater Monitoring Well (CH2M HILL, 2006)
- MW1-4 — Groundwater Monitoring Well (CH2M HILL, 2003)
- B-90 — Geotechnical Boring (City of Los Angeles, 2001)
- NM-B1 — Boring (Ninyo and Moore, 1999)
- 80 — Geotechnical Boring (Law/Crandall, 1993)
- PO-103-182 — Monitoring Well, (JMMI, 1992 and CH2M HILL, 2007)
- 2760c — Boring (Yerkes et al, 1977)
- C-65/C-23f — Boring (Caltrans, 1974a)
- ES-1 — Geotechnical Boring (Caltrans, 1974b)
- 9D2 — Water Production Well (CDWR, 1966)
- 200 — Depth to Bedrock in Feet Below Existing Ground Surface (Yerkes et al, 1977)
- 1400 — Structural Contour Line, Elevation at Top of Bedrock in Feet (MSL) (CDWR, 1966 and Geoscience, 2004)
- 220 — Groundwater Elevation in Feet (MSL) (San Gabriel Basin - MSGW, 2006 and Raymond Basin - RBMB, 2006 and 2007)
- Z2-G2 — Seismic Reflection Line (CH2M HILL, this study)
- Zone 1 Limits
- Zone 2 Limits
- Zone 3 Limits
- Northeast Interceptor Sewer (NEIS)
- East Central Interceptor Sewer (ECIS)
- Metro Red Line
- Metro Gold Line Eastside Extension (Tunnel Portion)
- Existing Street, Road, or Highway

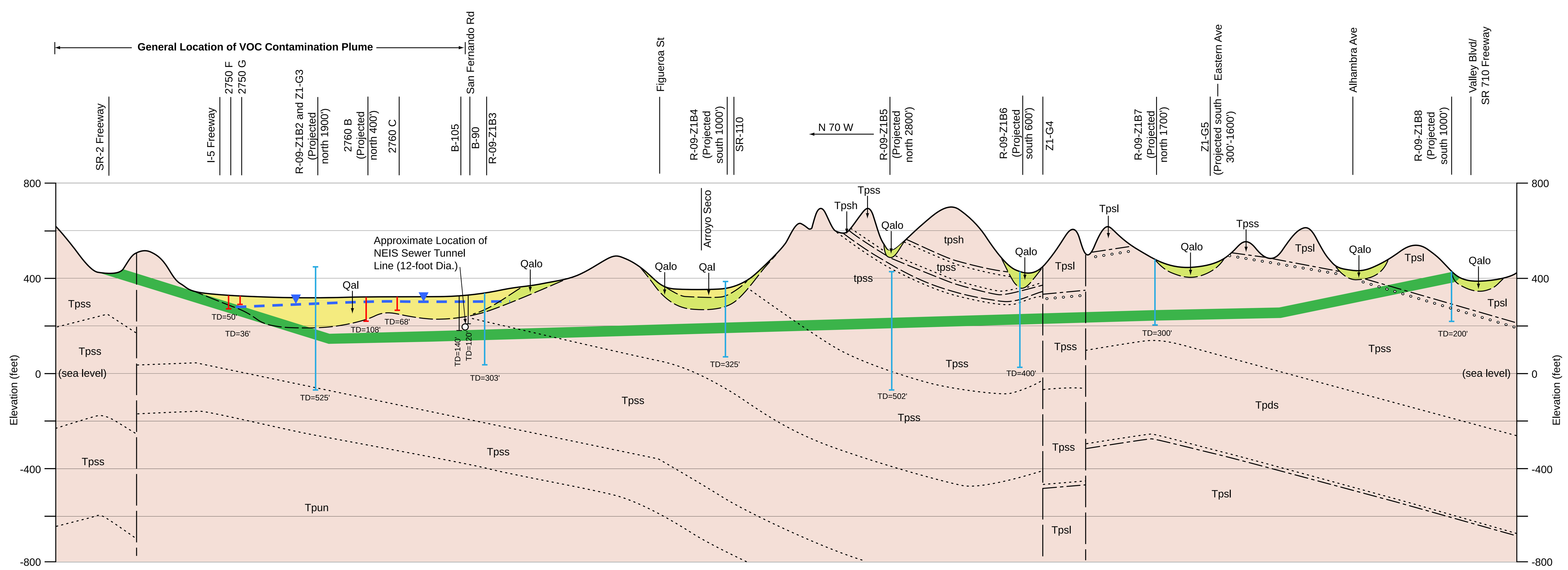
Source of Base Map: Lamar, 1970

North

0 2,000 4,000 Feet

0 750 1,500 Meters

Representative Geologic Profile for Zone 1



EXPLANATION

HORIZONTAL GRAPHIC SCALE

2,000 0 1,000 2,000

Data Sources:

- CDMG (1998d)
- CH2M HILL (2007)
- City of Los Angeles (2001)
- JMMI (1992)
- Lamar (1970)
- Yerkes, et al (1977)

UNITS (from Lamar, 1970)

Quaternary Deposits

- Qal — Alluvium: silt, sand and gravel
- Qalo — Old Alluvium: silt, sand and gravel forming dissected alluvial plain and alluvial terrace deposits

Puente Formation (Late Miocene)

- Tpsl — Siltstone: well bedded, light brown and light gray
- Tpsh — Shale: well bedded, light gray, siliceous
- Tpds — Diatomaceous Shale: punky, dull white
- Tpss — Sandstone: well bedded, medium-to-coarse-grained, light brown to gray
- Tpun — Undifferentiated siltstone, shale, sandstone and conglomerate

SYMBOLS (All locations are approximate)

- Typical Tunnel Profile
- Historically Highest Groundwater Level (CDMG, 1998d)
- Recent Groundwater Level (CH2M HILL, 2007)
- Inactive Fault
- Active Fault
- Geologic Contact, dashed where inferred or indefinite
- R-09-Z1B3 — Continuous Core Boring (CH2M HILL, this study)
- 2760 B — Boring (Yerkes et al, 1977)
- B-105 — Boring (City of Los Angeles, 2001)
- Z1-G2 — Seismic Reflection Line (CH2M HILL, this study)

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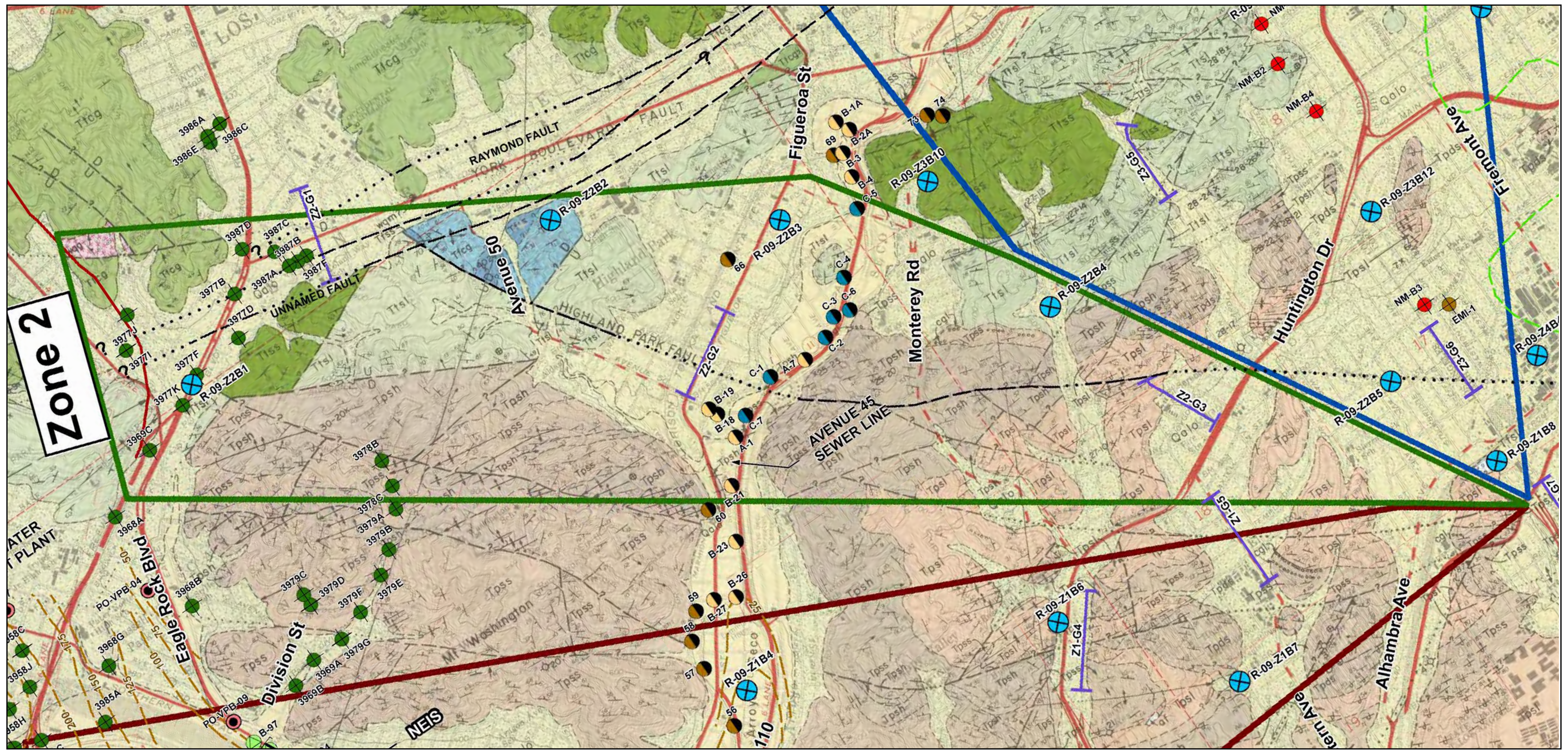
PLATE 5
Representative Geologic Profile and Geotechnical Map for Zone 1
SR-710 Tunnel Technical Study
Los Angeles County, California

CH2MHILL

Geotechnical Map



Map Legend

(All Locations are Approximate)

- R-09-Z1B8 — Continuous Core Boring (CH2M HILL, this study)
- W12ASMW2 — Facility Monitoring Well (CH2M HILL, 2009)
- Caltrans As-built LOTB's (Various Locations)
- 4077B — Water Production Well; Location for which only Groundwater Data in Available (LACDPW, 2009)
- EMI-1 — Continuous Core Boring (EMI, 2006)
- A-1 and B-3 — Geotechnical Boring (City of Los Angeles, 2000, 2006a, and 2006b)
- C-1 — Geotechnical Boring (URS, 2006)
- MW-17 — Groundwater Monitoring Well (CH2M HILL, 2006)
- MW1-4 — Groundwater Monitoring Well (CH2M HILL, 2003)
- B-90 — Geotechnical Boring (City of Los Angeles, 2001)
- NM-B1 — Boring (Ninyo and Moore, 1999)
- 80 — Geotechnical Boring (Law/Crandall, 1993)
- PO-103-182 — Monitoring Well, (JMMI, 1992 and CH2M HILL, 2007)
- 2760c — Boring (Yerkes et al, 1977)
- C-65/C-23f — Boring (Caltrans, 1974a)
- ES-1 — Geotechnical Boring (Caltrans, 1974b)
- 9D2 — Water Production Well (CDWR, 1966)
- 200 — Depth to Bedrock in Feet Below Existing Ground Surface (Yerkes et al, 1977)
- 1400 — Structural Contour Line, Elevation at Top of Bedrock in Feet (MSL) (CDWR, 1966 and Geoscience, 2004)
- 220 — Groundwater Elevation in Feet (MSL) (San Gabriel Basin - MSGW, 2006 and Raymond Basin - RBMB, 2006 and 2007)
- Z2-G2 — Seismic Reflection Line (CH2M HILL, this study)
- Zone 1 Limits
- Zone 2 Limits
- Zone 3 Limits
- Northeast Interceptor Sewer (NEIS)
- East Central Interceptor Sewer (ECIS)
- Metro Red Line
- Metro Gold Line Eastside Extension (Tunnel Portion)
- Existing Street, Road, or Highway

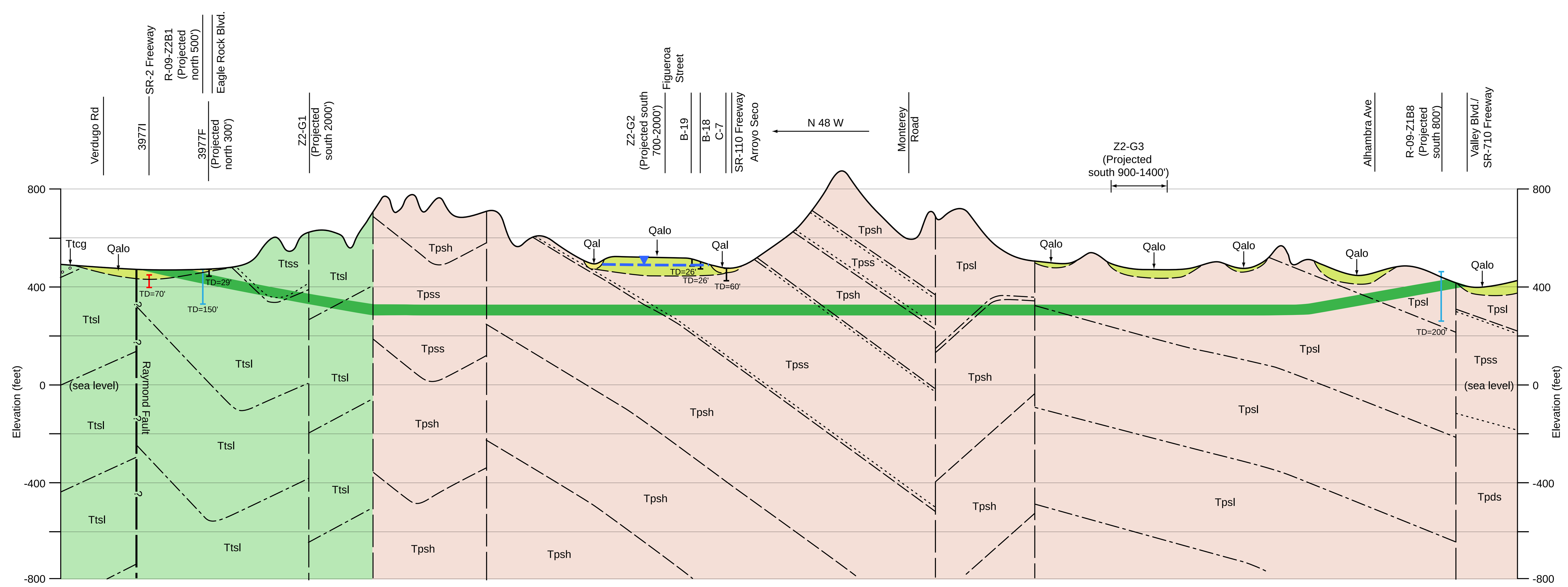
Source of Base Map: Lamar, 1970

North

0 2,000 4,000 Feet

0 750 1,500 Meters

Representative Geologic Profile for Zone 2



EXPLANATION

UNITS (from Lamar, 1970)

Quaternary Deposits

- Qal — Alluvium: silt, sand and gravel
- Qalo — Old Alluvium: silt, sand and gravel forming dissected alluvial plain and alluvial terrace deposits

Puente Formation (Late Miocene)

- Tpsl — Siltstone: well bedded, light brown and light gray
- Tpsh — Shale: well bedded, light gray, siliceous
- Tpds — Diatomaceous Shale: punky, dull white
- Tpss — Sandstone: well bedded, medium-to-coarse-grained, light brown to gray

Topanga Formation (Middle Miocene)

- Ttss — Sandstone: Well bedded, medium- to coarse-grained, brown
- Ttcg — Conglomerate: Massive to well bedded, light brown
- Ttsl — Siltstone: Well bedded, medium to dark brown

SYMBOLS (All locations are approximate)

- Typical Tunnel Profile
- Historically Highest GW Level (CDMG, 1998d)
- Inactive Fault
- Active Fault
- Geologic Contact, dashed where inferred or indefinite
- R-09-Z1B3 — Continuous Core Boring (CH2M HILL, this study)
- 2760 B — Boring (Yerkes, et al, 1977)
- B-105 — Boring (City of Los Angeles, 2001)
- Z1-G2 — Seismic Reflection Line (CH2M HILL, this study)

HORIZONTAL GRAPHIC SCALE

2,000 0 1,000 2,000

Data Sources:

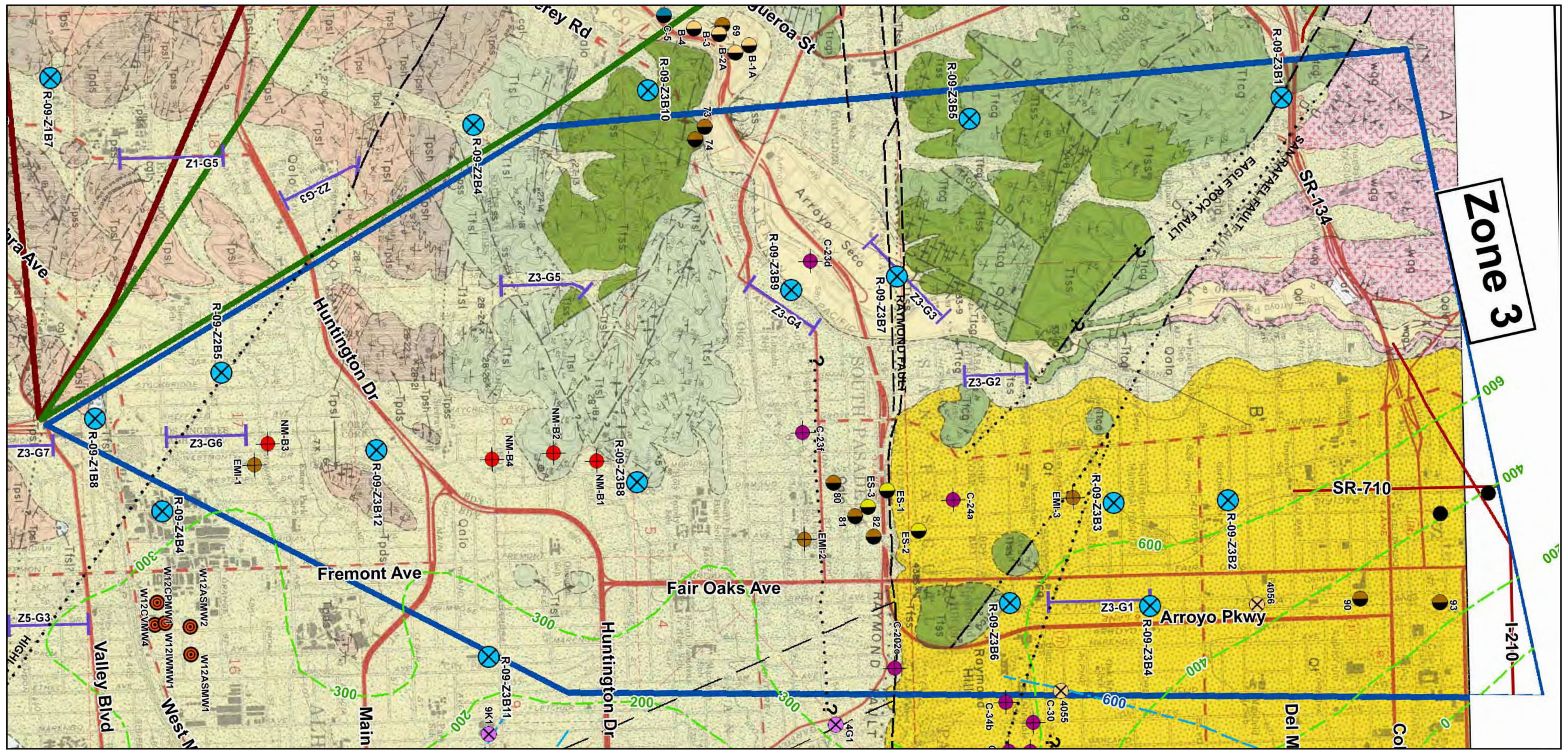
CDMG (1998d)
City of Los Angeles (2001)
JMMI (1992)
Lamar (1970)
Yerkes, et al (1977)

PLATE 6
Representative Geologic Profile and Geotechnical Map for Zone 2
SR-710 Tunnel Technical Study
Los Angeles County, California

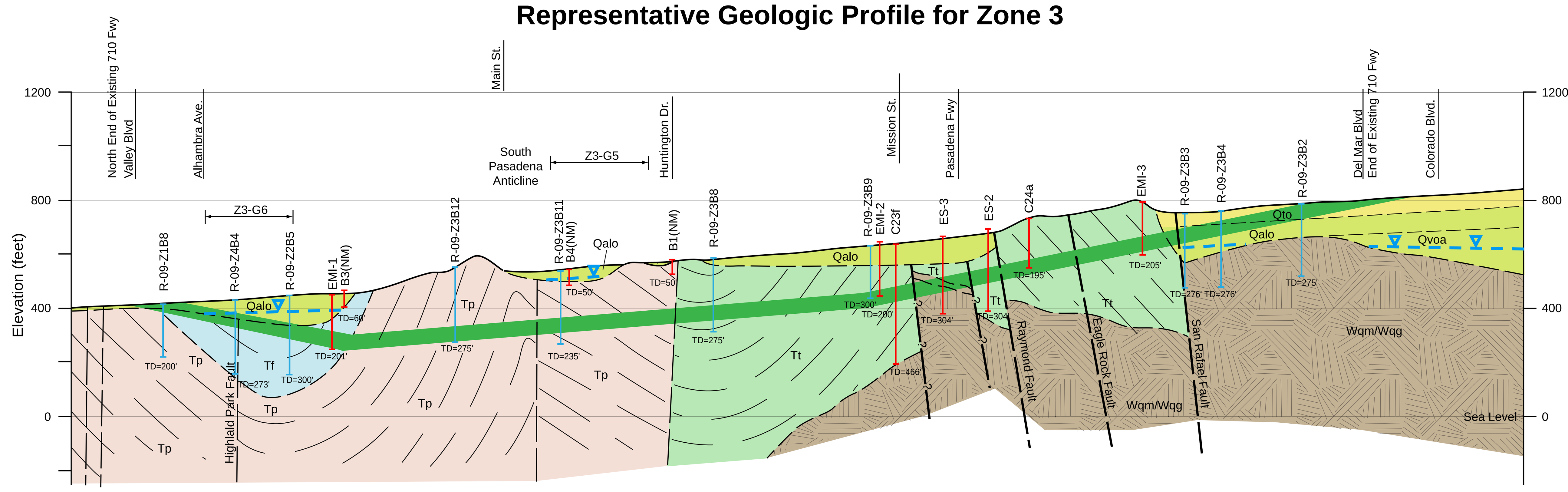
CH2MHILL

ES022009005SCO378312.04.10.01 zone_2_large_rev6.ai 3/10

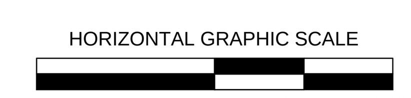
Geotechnical Map



Representative Geologic Profile for Zone 3



EXPLANATION



Data Sources:

CDMG (1998d)
CDWR (1966)
CH2M HILL (2009)
EMI (2006)
Dibblee (1989b)
Dibblee (1999)
Geoscience (2004)
Lamar (1970)
MSGW (2006)
Morton and Miller (2003)
Tan (2000b)

UNITS (from Lamar, 1970)

Quaternary Deposits

- Qto — Old Terrace and fan alluvium: primarily sand and gavel
- Qalo — Old Alluvium, sand and gravel
- Qvoa — Very Old Alluvium: primarily cobbles and coarse gravel

Fernando Formation (Pliocene; Undifferentiated)

- Tf — Siltstone: massive

Puente Formation (Late Miocene)

- Tp — Interbedded Siltstone, claystone, mudstone, shale and sandstone, brown, gray, and black

Topanga Formation (Middle Miocene)

- Tt — Predominantly sandstone and conglomerate with abundant interbeds of siltstone and mudstone; brown, dark gray, and black.

Crystalline Basement Rocks (Mesozoic)

- Wqm Wqg — Primarily Diorite and gneiss; generally highly fractured

SYMBOLS (All locations are approximate)

- R-09-Z4B4 — Continuous Core Boring (CH2M HILL, this study)
- 14D1 — Water Production Well (CDWR, 1966)
- Z5-G2 — Seismic Reflection Line (CH2M HILL, this study)
- C23f — Caltrans Boring (1974a)
- B4(NM) — Ninyo and Moore (1999)
- EMI-2 — Continuous Core Boring (EMI, 2006)
- ES-2 — Caltrans Boring (1974b)
- Typical Tunnel Profile
- Historically Highest Groundwater Level (CDMG, 1998f, 1998d)
- 2006 Groundwater Level (MSGW, 2006 and RBMB, 2006)
- Inactive Fault
- Active Fault
- Geologic Contact, dashed where inferred or indefinite

Map Legend

(All Locations are Approximate)

- R-09-Z1B8 — Continuous Core Boring (CH2M HILL, this study)
- W12ASMW2 — Facility Monitoring Well (CH2M HILL, 2009)
- Caltrans As-built LOTB's (Various Locations)
- 4077B — Water Production Well; Location for which only Groundwater Data in Available (LACDPW, 2009)
- EMI-1 — Continuous Core Boring (EMI, 2006)
- A-1 and B-3 — Geotechnical Boring (City of Los Angeles, 2000, 2006a, and 2006b)
- C-1 — Geotechnical Boring (URS, 2006)
- MW-17 — Groundwater Monitoring Well (CH2M HILL, 2006)
- MW1-4 — Groundwater Monitoring Well (CH2M HILL, 2003)
- B-90 — Geotechnical Boring (City of Los Angeles, 2001)
- NM-B1 — Boring (Ninyo and Moore, 1999)
- 80 — Geotechnical Boring (Law/Crandall, 1993)
- PO-103-182 — Monitoring Well, (JMMI, 1992 and CH2M HILL, 2007)
- 2760c — Boring (Yerkes et al, 1977)
- C-65/C-23f — Boring (Caltrans, 1974a)
- ES-1 — Geotechnical Boring (Caltrans, 1974b)
- 9D2 — Water Production Well (CDWR, 1966)
- 200 — Depth to Bedrock in Feet Below Existing Ground Surface (Yerkes et al, 1977)
- 1400 — Structural Contour Line, Elevation at Top of Bedrock in Feet (MSL) (CDWR, 1966 and Geoscience, 2004)
- 220 — Groundwater Elevation in Feet (MSL) (San Gabriel Basin - MSGW, 2006 and Raymond Basin - RBMB, 2006 and 2007)
- Z2-G2 — Seismic Reflection Line (CH2M HILL, this study)
- Zone 1 Limits
- Zone 2 Limits
- Zone 3 Limits
- Northeast Interceptor Sewer (NEIS)
- East Central Interceptor Sewer (ECIS)
- Metro Red Line
- Metro Gold Line Eastside Extension (Tunnel Portion)
- Existing Street, Road, or Highway

Source of Base Map: Lamar, 1970

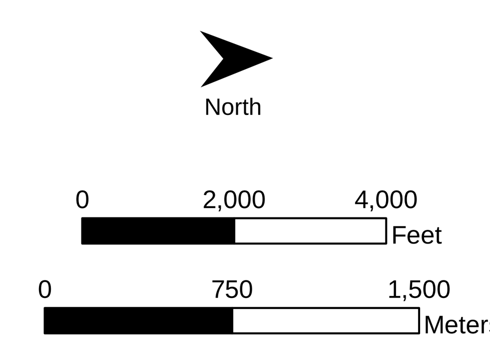
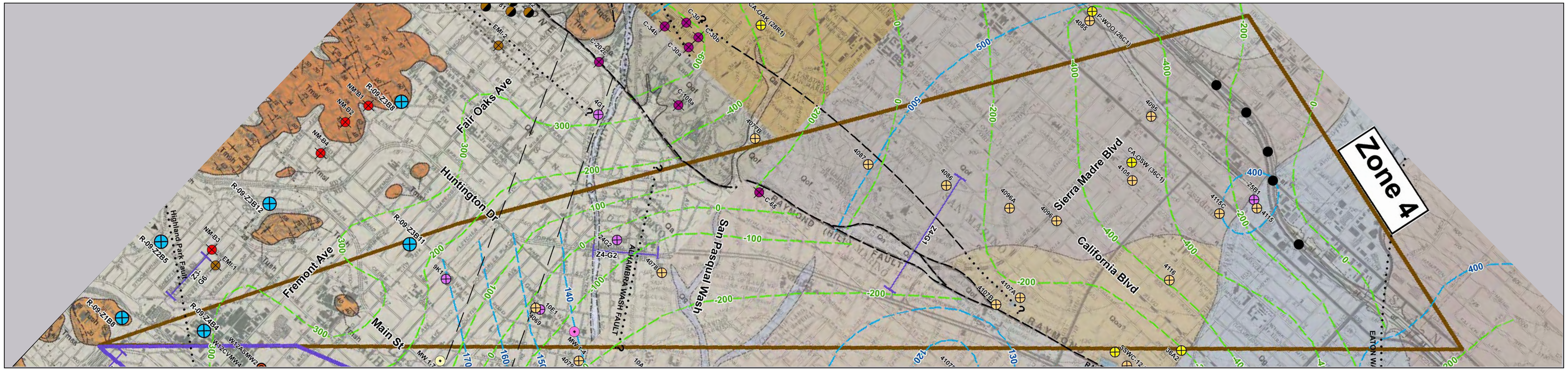


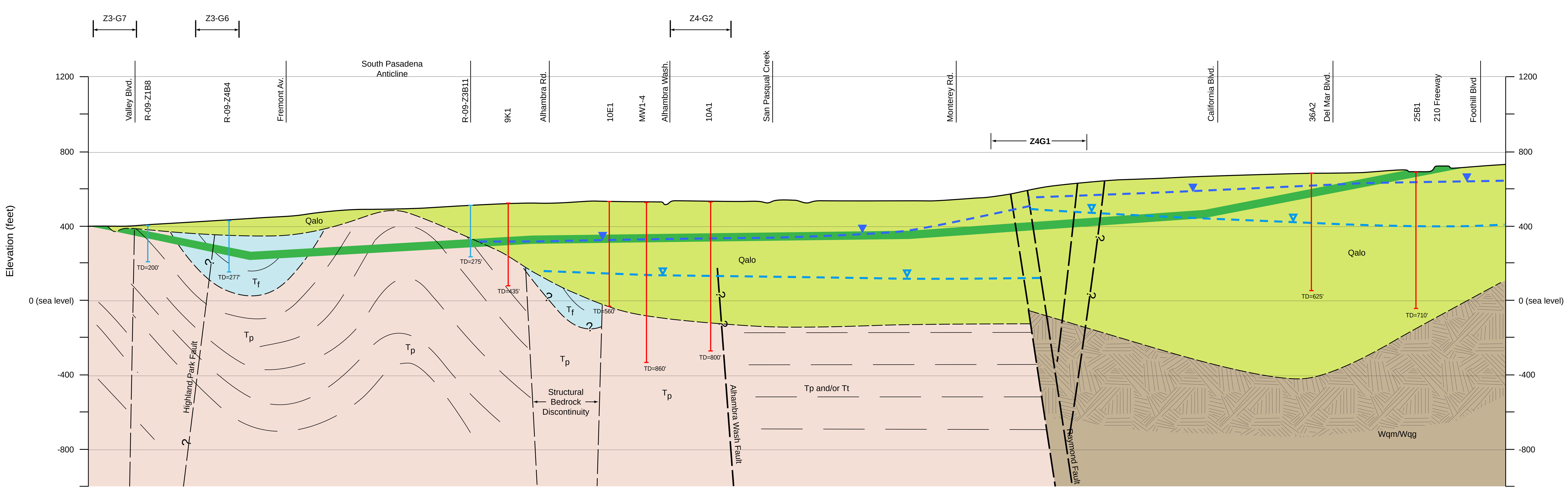
PLATE 7
Representative Geologic Profile and Geotechnical Map for Zone 3
SR-710 Tunnel Technical Study
Los Angeles County, California

CH2MHILL

Geotechnical Map



Representative Geologic Profile for Zone 4



EXPLANATION

HORIZONTAL GRAPHIC SCALE

2,000 0 1,000 2,000

Data Sources:

- CDMG (1998b)
- CDMG (1998d)
- CDWR (1966)
- CH2M HILL (2003)
- CH2M HILL (2006)
- CH2M HILL (2009)
- Dibblee (1989b)
- EMI (2006)
- Dibblee (1999)
- Geoscience (2004)
- Lamar (1970)
- MSGW (2006)
- Yeats (2004)
- Tan (2000b)
- Yerkes and Campbell (2005)

UNITS (from Lamar, 1970)

Quaternary Deposits

Qalo — Old Alluvium, Silt, clay, sand and gravel, fan and valley-fill deposits in poorly bedded, discontinuous lenses

Fernando Formation (Pliocene)

Tf — Siltstone, massive, very dark gray to black

Puente Formation (Late Miocene)

Tp — Siltstone, claystone, mudstone, and fine sandstone; well bedded, brown, gray, black

Topanga Formation (Middle Miocene)

Tt — Primarily Sandstone and conglomerate with abundant siltstone and mudstone interbeds; brown, gray, black

Crystalline Basement Rocks (Mesozoic)

Wqm Wqg — Primarily Diorite and gneiss; generally highly fractured

SYMBOLS (All locations are approximate)

- Typical Tunnel Profile
- Historically Highest Groundwater Level (CDMG, 1998a, 1998b, 1998d)
- 2006 Groundwater Level (MSGW, 2006 and RBMB, 2006)
- Inactive Fault
- Active Fault
- Geologic Contact, dashed where infered or indefinite
- R-09-Z4B4 Continuous Core Boring (CH2M HILL, this study)
- 9k1 Water Production Well (CDWR, 1966)
- MW1-4 Groundwater Monitoring Well (CH2M HILL, 2003)
- Z5-G2 Seismic Reflection Line (CH2M HILL, this study)

ES022009005SCO378312.04.10.01 zone_4_large_rev6.ai 3/10

Map Legend

(All Locations are Approximate)

- R-09-Z1B8 — Continuous Core Boring (CH2M HILL, this study)
- W12ASMW2 — Facility Monitoring Well (CH2M HILL, 2009)
- 4077B — Water Production Well; Location for which only Groundwater Data is Available (LACDPW, 2009)
- Caltrans As-built LOTB's, (Various Locations)
- ERP-15 — Groundwater Monitoring Well (CDM, 2008a)
- ERP-16 — Groundwater Monitoring Well (CDM, 2008b)
- EMI-1 — Continuous Core Boring (EMI, 2006)
- ERP-14 — Groundwater Monitoring Well (CDM, 2006)
- MW-17 — Groundwater Monitoring Well (CH2M HILL, 2006)
- CDEM-5 — Groundwater Monitoring Well (Geosyntec, 2006b)
- DCMW-1 — Monitoring Well (Geosyntec, 2006a)
- CA-DSW — Water Production Well (Geoscience, 2004)
- MW 1-6 — Groundwater Monitoring Well (CH2M HILL, 2003)
- NM-B1 — Boring (Ninyo and Moore, 1999)
- MW2-02 — Groundwater Monitoring Well (CDM, 1998)
- 90 — Geotechnical Boring (Law/Crandall, 1993)
- C-65/C-23f — Boring (Caltrans, 1974a)
- ES-1 — Geotechnical Boring (Caltrans, 1974b)
- 9D2 — Water Production Well (CDWR, 1966)
- -1400- Structural Contour Line, Elevation at Top of Bedrock in Feet (MSL) (CDWR, 1966 and Geoscience, 2004)
- -220- Groundwater Elevation in Feet (MSL) (San Gabriel Basin - MSGW, 2006 and Raymond Basin - RBMB, 2006 and 2007)
- Z2-G2 — Seismic Reflection Line (CH2M HILL, this study)
- Zone 4 Limits
- Zone 5 Limits

Source of Base Map: Dibblee, 1989b, 1989c, 1998, 1999

North

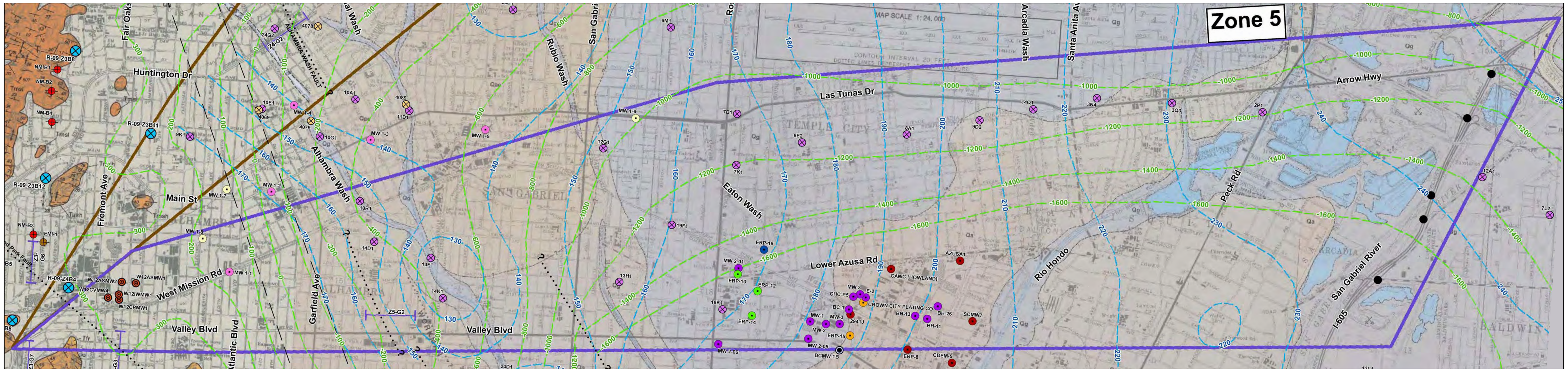
0 2,000 4,000 Feet

0 750 1,500 Meters

PLATE 8
Representative Geologic Profile and Geotechnical Map for Zone 4
SR-710 Tunnel Technical Study
Los Angeles County, California

CH2MHILL

Geotechnical Map



Map Legend

(All Locations are Approximate)

- R-09-Z1B8 — Continuous Core Boring (CH2M HILL, this study)
- W12ASMW2 — Facility Monitoring Well (CH2M HILL, 2009)
- 4077B — Water Production Well; Location for which only Groundwater Data is Available (LACDPW, 2009)
- Caltrans As-built LOTB's, (Various Locations)
- ERP-15 — Groundwater Monitoring Well (CDM, 2008a)
- ERP-16 — Groundwater Monitoring Well (CDM, 2008b)
- EMI-1 — Continuous Core Boring (EMI, 2006)
- ERP-14 — Groundwater Monitoring Well (CDM, 2006)
- MW-17 — Groundwater Monitoring Well (CH2M HILL, 2006)
- CDEM-5 — Groundwater Monitoring Well (Geosyntec, 2006b)
- DCMW-1 — Monitoring Well (Geosyntec, 2006a)
- CA-DSW — Water Production Well (Geoscience, 2004)
- MW 1-6 — Groundwater Monitoring Well (CH2M HILL, 2003)
- NM-B1 — Boring (Ninyo and Moore, 1999)
- MW2-02 — Groundwater Monitoring Well (CDM, 1998)
- 90 — Geotechnical Boring (Law/Crandall, 1993)
- C-65/C-23f — Boring (Caltrans, 1974a)
- ES-1 — Geotechnical Boring (Caltrans, 1974b)
- 9D2 — Water Production Well (CDWR, 1966)
- -1400- Structural Contour Line, Elevation at Top of Bedrock in Feet (MSL) (CDWR, 1966 and Geoscience, 2004)
- -220- Groundwater Elevation in Feet (MSL) (San Gabriel Basin - MSGW, 2006 and Raymond Basin - RBMB, 2006 and 2007)
- Z2-G2 — Seismic Reflection Line (CH2M HILL, this study)
- Zone 4 Limits
- Zone 5 Limits

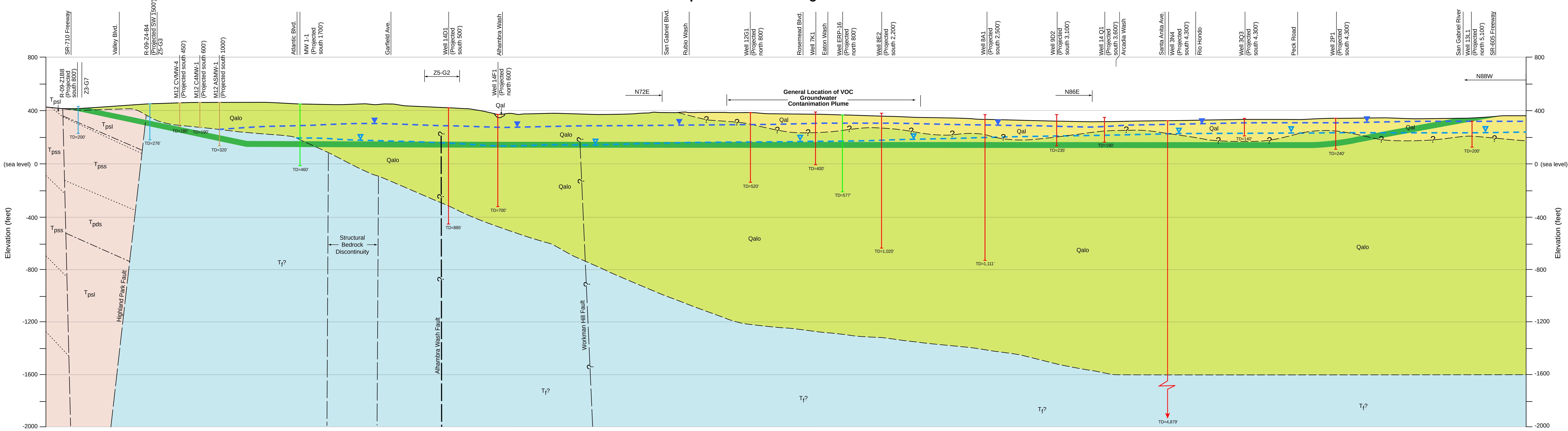
Source of Base Map: Dibblee, 1989b, 1989c, 1998, 1999

North

0 2,000 4,000 Feet

0 750 1,500 Meters

Representative Geologic Profile for Zone 5



EXPLANATION

HORIZONTAL GRAPHIC SCALE

2,000 0 1,000 2,000

Data Sources:

CDWR (1966)	Lamar (1970)
CDMG (1998a)	MSGW (2006)
CDMG (1998b)	Morton and Miller (2003)
CDMG (1998d)	Yeats (2004)
CH2M HILL (2003)	Tan (2000a)
CH2M HILL (2006)	Tan (2000b)
CH2M HILL (2009c)	Yerkes and Campbell (2005)
Dibblee (1999)	
Dibblee (1989b)	

UNITS (from Lamar, 1970)

Quaternary Deposits

- Qal — Alluvium: silt, sand and gravel
- Qalo — Old Alluvium, Silt, sand and gravel forming dissected alluvial plain and alluvial terrace deposits

Fernando Formation (Pliocene; Undifferentiated)

- Tf — Siltstone, sandstone, and conglomerate

Puente Formation (Late Miocene)

- Tpsl — Siltstone: well bedded, light brown and light gray
- Tpsh — Shale: well bedded, light gray, siliceous
- Tpds — Diatomaceous Shale: punky, dull white
- Tpss — Sandstone: well bedded, medium-to-coarse-grained, light brown to gray

SYMBOLS (All locations are approximate)

- Typical Tunnel Profile
- Historically Highest Groundwater Level (CDMG, 1998a, 1998b, 1998d)
- 2006 Groundwater Level (MSGW, 2006)
- Inactive Fault
- Active Fault
- Geologic Contact, dashed where inferred or indefinite
- R-09-Z4B4 — Continuous Core Boring (CH2M HILL, this study)
- CRP-16 — CH2M HILL (2003, 2006, 2008b) and USEPA (2006)
- 14D1 — Water Production Well (CDWR, 1966)
- MW12CVMW-9 — Facility Monitoring Well (CH2M HILL, 2009c)
- Z5-G2 — Seismic Reflection Line (CH2M HILL, this study)

PLATE 9
Representative Geologic Profile and Geotechnical Map for Zone 5
SR-710 Tunnel Technical Study
Los Angeles County, California

CH2MHILL

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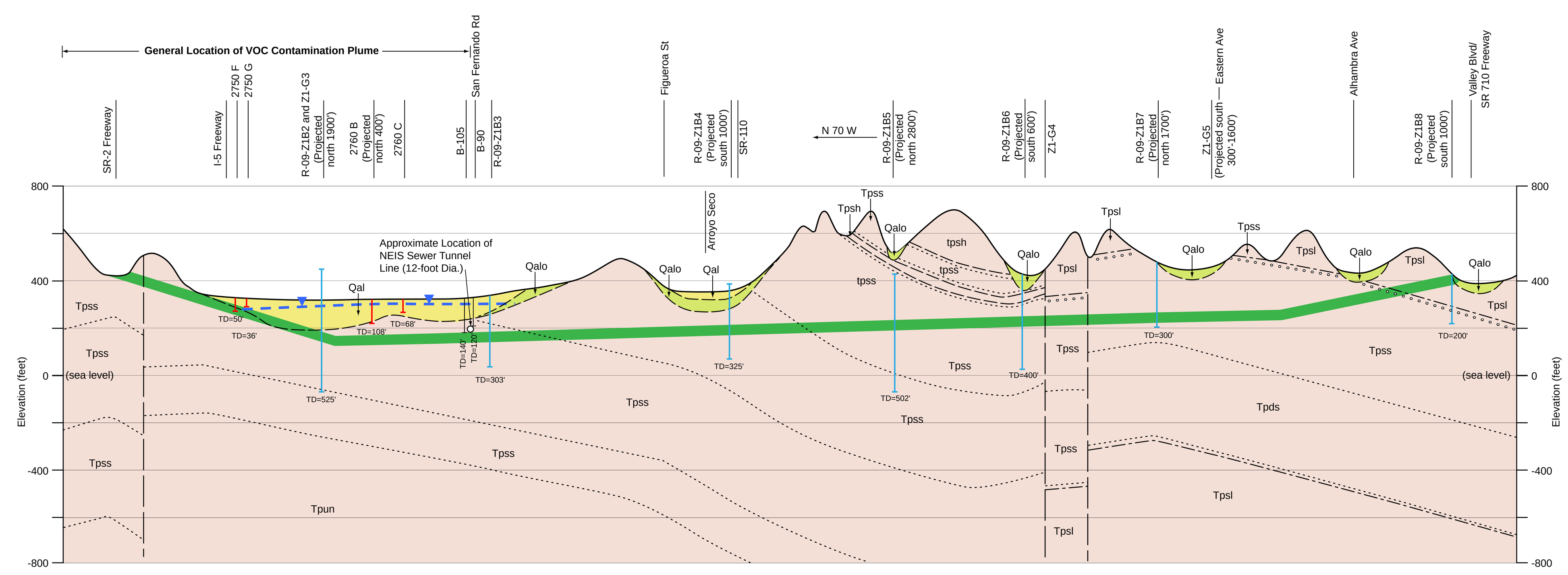
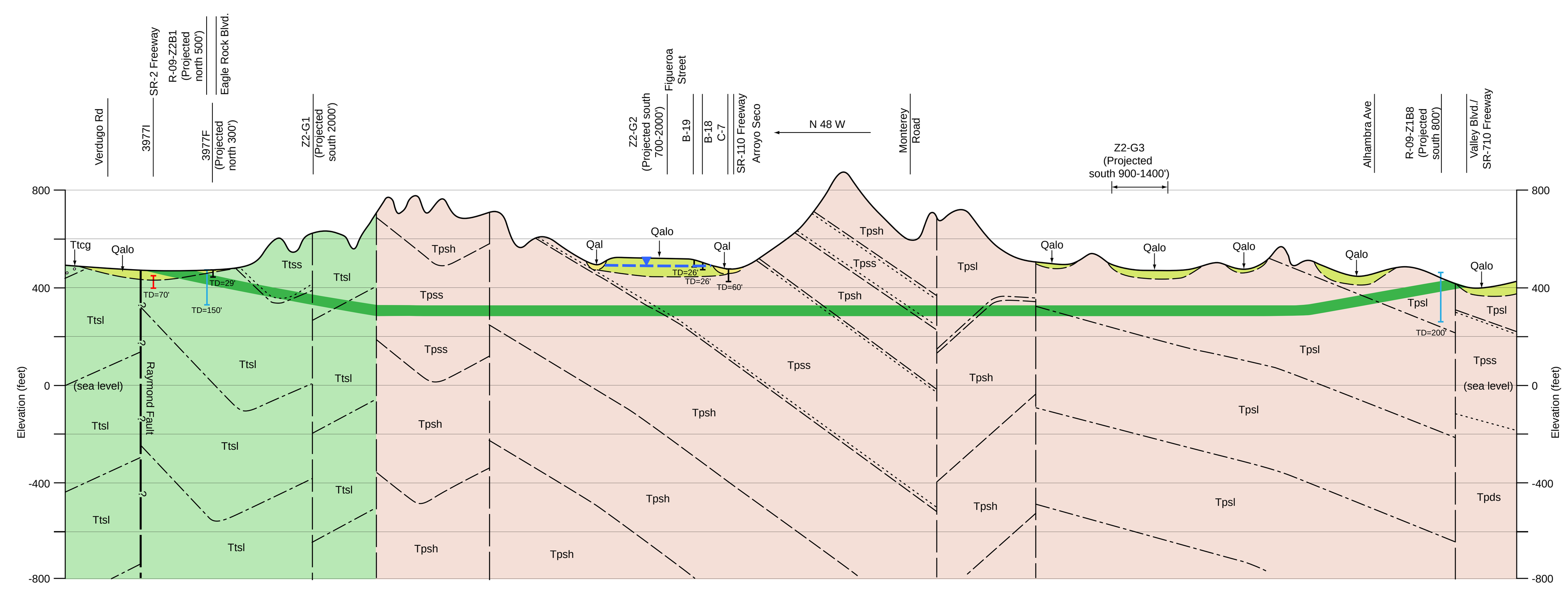
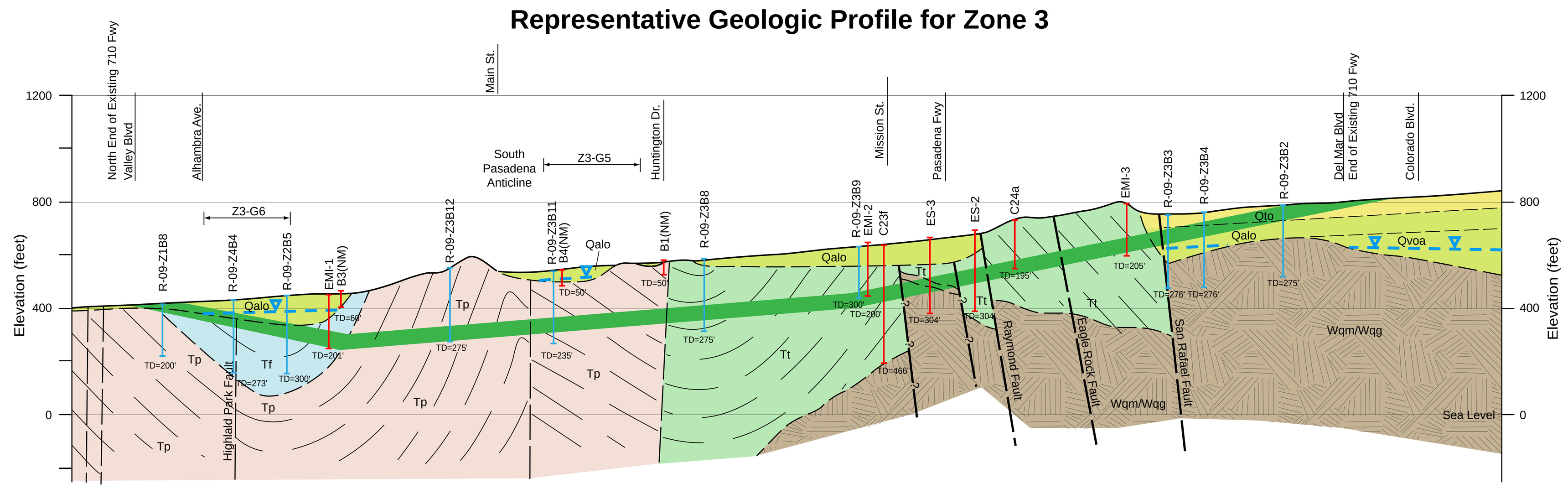
Representative Geologic Profile for Zone 1



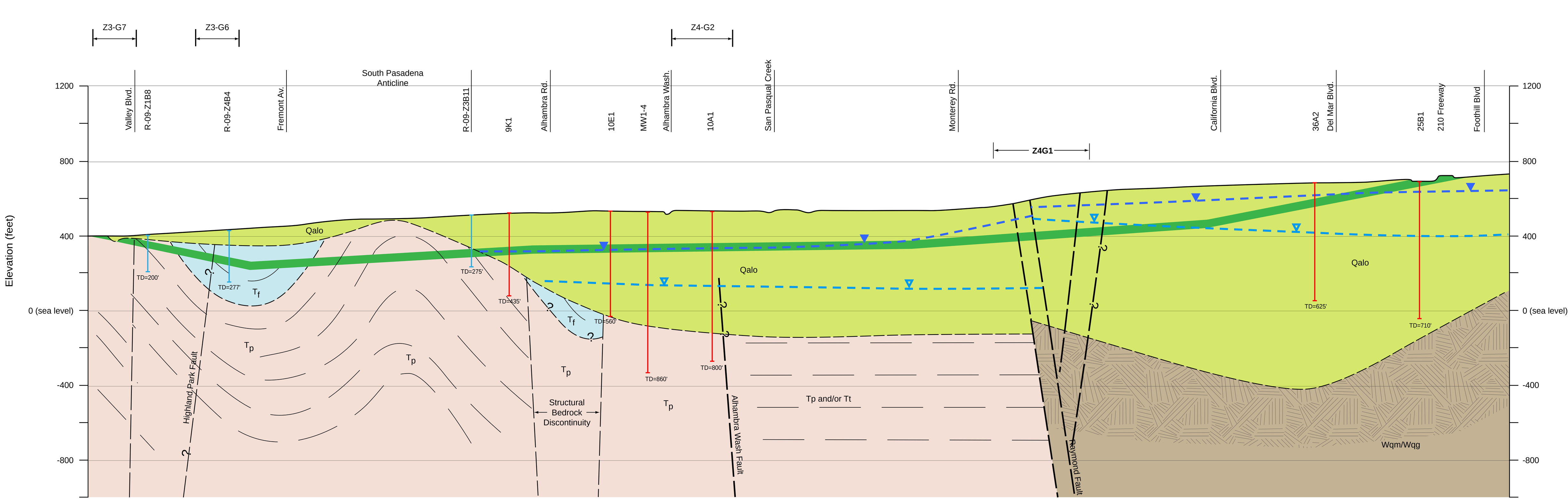
Representative Geologic Profile for Zone 2



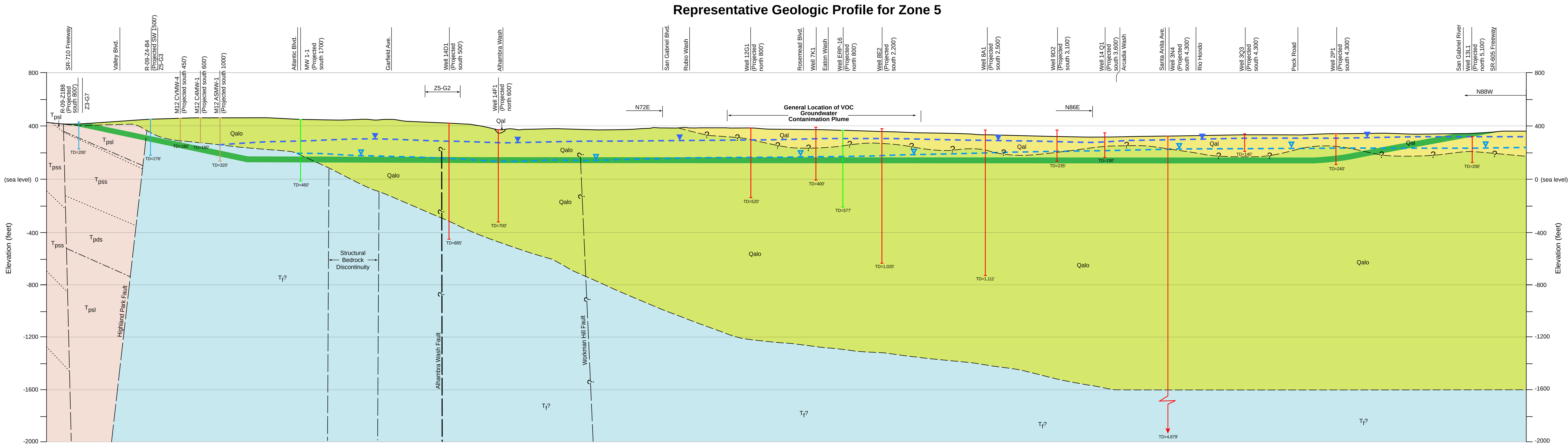
Representative Geologic Profile for Zone 3



Representative Geologic Profile for Zone 4



Representative Geologic Profile for Zone 5



EXPLANATION

HORIZONTAL GRAPHIC SCALE

2,000 0 1,000 2,000

Data Sources:

CDMG (1998a)
CDMG (1998b)
CDMG (1998c)
CDMG (1998d)
CDMG (1998e)
CDMG (1998f)
CDWR (1966)
CH2M HILL (2003)
CH2M HILL (2006)
CH2M HILL (2009c)
City of Los Angeles (2001)
Dibblee (1999)
Dibblee (1989b)
EMI (2006)
JMMI (1992)
Lamar (1970)
MSGW (2006)
Morton and Miller (2003)
RBMB (2006)
Yeats (2004)
Tan (2000a)
Tan (2000b)
Yerkes and Campbell (2005)

UNITS (from Lamar, 1970)

Quaternary Deposits

- Qal — Alluvium
- Qto — Old Terrace and fan alluvium
- Qalo — Old Alluvium
- Qvoa — Very Old Alluvium

Fernando Formation (Pliocene; Undifferentiated)

- Tf — Siltstone: massive

Puente Formation (Late Miocene)

- Tp — Interbedded Siltstone, claystone, mudstone, shale and sandstone, brown, gray, and black
- Tpsl — Siltstone: well bedded, light brown and light gray
- Tpsh — Shale: well bedded, light gray, siliceous
- Tpds — Diatomaceous Shale: punky, dull white
- Tpss — Sandstone: well bedded, medium-to-coarse-grained, light brown to gray
- Tpun — Undifferentiated siltstone, shale, sandstone and conglomerate

Topanga Formation (Middle Miocene)

- Tt — Predominantly sandstone and conglomerate with abundant interbeds of siltstone and mudstone; brown, dark gray, and black.
- Ttss — Sandstone: Well bedded, medium- to coarse-grained, brown
- Ttcg — Conglomerate: Massive to well bedded, light brown
- Ttsl — Siltstone: Well bedded, medium to dark brown

Crystalline Basement Rocks

- Wqm Wqg — Primarily Diorite and gneiss; generally highly fractured

SYMBOLS (All locations are approximate)

- R-09-Z4-B4 — Continuous Core Boring (CH2M HILL, this study)
- 14D1 — Water Production Well (CDWR, 1966)
- Z5-G2 — Seismic Reflection Line (CH2M HILL, this study)
- C23f
- B4(NM)
- 06-2(EMI-2) — Continuous Core Boring (EMI, 2006)
- ES-2
- 4046 and 4045B — Boring (Yerkes et al, 1977)
- B-105 — Boring (City of Los Angeles, 2001)
- MW1-4 — Groundwater Monitoring Well (CH2M HILL, 2003)
- CRP-16 — CH2M HILL (2003, 2006, 2008b) and USEPA (2006)
- Anticipated Tunnel Alignment
- Historically Highest Groundwater Level
- 2006 Groundwater Level (MSGW, 2006)
- Inactive Fault
- Active Fault
- Geologic Contact, queried where uncertain

PLATE 10
Representative Geologic Profile Comparison
SR-710 Tunnel Technical Study
Los Angeles County, California

CH2MHILL

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