



SR 710 North Study

Preliminary Geotechnical Report

SR 710 North Study

Los Angeles County, California

Prepared for



Metro

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Executive Summary

Introduction

The California Department of Transportation (Caltrans), in cooperation with the Los Angeles County Metropolitan Transportation Authority (Metro), selected the CH2M HILL team to provide alternatives analysis, preliminary engineering, and environmental studies documentation for the State Route (SR) 710 North Study. The SR 710 North Study included geotechnical, geologic, and seismic evaluations for five alternatives proposed within the SR 710 North Study. Results of the CH2M HILL study are summarized in this Preliminary Geotechnical Report (PGR).

The SR 710 North Study includes a No Build Alternative and four alternatives involving transportation improvements: Transportation System Management/Transportation Demand Management (TSM/TDM), Bus Rapid Transit (BRT), Light Rail Transit (LRT), and Freeway Tunnel. A preliminary geologic and geotechnical evaluation was conducted for each alternative and included an assessment of the following:

- Physical Setting
- Regional Geologic Setting
- Stratigraphy and Structure
- Groundwater
- Seismic Hazards
- Non-Seismic Geologic Hazards
- Naturally Occurring Oil and Gas
- Geotechnical Considerations for Design and Construction
- Future Geotechnical Exploration and Investigations

SR 710 North Study Field Exploration Program

A field exploration program was conducted as part of the SR 710 North Study. The No Build, TSM/TDM, and BRT Alternatives propose either no or relatively minimal improvements. Therefore, field explorations focused on the LRT and Freeway Tunnel Alternatives. Thirteen geotechnical explorations were conducted to collect subsurface information in areas along the LRT and Freeway Tunnel Alternatives. A fault exploration was conducted as part of the SR 710 North Study to collect data that would aid in evaluating the location and activity of the Raymond, Eagle Rock, and San Rafael faults in the SR 710 North Study Area. Twelve borings were drilled and sampled for the preliminary fault investigation.

Regional Geology, Faulting, and Seismicity

The SR 710 North Study Area encompasses portions of the San Gabriel Valley, the southern San Rafael Hills, the Elysian Hills, and the Repetto Hills. 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. Table ES-1 presents the generalized stratigraphic column specific to the SR 710 North Study Area, and lists the formations in vertical sequence from youngest to oldest.

TABLE ES-1
Study-Specific Stratigraphic Column

Geologic Unit/ Formation Name	Map Symbol (Plate 2)/ Cross Section Symbol (Plates 3, 4, 8, and 9) ^a	Geologic Epoch (Period)	Approximate Age (Years)	Generalized Description
Young Alluvium	Qw, Qf, Qyf, Qya / 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	Qof, Qoa, Qvoa / Qal	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	Tss, Tsh / Tfcg, Tfsl	Pliocene (Tertiary)	2 to 5 million	Predominantly claystone, siltstone, and mudstone, with some sandstone and conglomerate. Marine deposits.
Puente (includes Monterey, Modelo, and an Unnamed Shale)	Tss, Tsh / Tps, Tpsl	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	Tss, Tsh / Tt, Ttsl	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, Wilson Quartz Diorite	Gr / Wqd	Cretaceous and Pre Cretaceous	120 to 160+ million	Crystalline igneous rocks (diorite, quartz diorite, monzonite, foliated igneous rocks) and layered metamorphic rocks (gneiss).

^a Plates 1 through 9 are provided at the end of the PGR.

The geologic structure of the area is a result of ongoing compressional geologic forces that have resulted in the uplift of the San Gabriel Mountains, and folding of the rocks within the hills present in the SR 710 North Study Area. These compressional forces have yielded active, potentially active, and inactive faults across the SR 710 North Study Area. The only confirmed active fault identified in the SR 710 North Study Area that could produce ground rupture is the Raymond fault. The Raymond fault is considered to be the most significant fault with regard to the potential for causing surface rupture in the area of the alternatives. In addition, two potentially active faults are present in the study area, the Eagle Rock and San Rafael faults. For the purposes of this study, it is assumed that the Eagle Rock and San Rafael faults are also active. The Raymond, Eagle Rock, and San Rafael faults cross the Freeway Tunnel Alternative at tunnel depth. The Raymond and San Rafael faults cross the LRT Alternative at tunnel depth and the BRT Alternative at the surface. Strong ground shaking may occur in the SR 710 North Study Area as the accumulated strain on these and other regional faults is released.

Groundwater

Groundwater levels vary considerably across the SR 710 North Study Area, occurring as deep aquifers and as shallow perched zones. Several of the faults within the study area act as groundwater barriers with different groundwater levels on either side of the fault. A major part of the alluvium is an aquifer. The underlying rock formations contain groundwater but are not aquifers. Perched groundwater might be present within local sandstone beds and faulted and/or fractured zones.

Groundwater conditions within each of the build alternatives are highly variable, ranging from near the ground surface to over 200 feet below the ground surface (bgs):

- The groundwater levels within the overall SR 710 North Study Area are applicable to the TSM/TDM Alternative. Groundwater levels for the overall SR 710 North Study Area range from 10 to 450 feet below ground surface (bgs). Historically highest groundwater levels range from 5 to 200 feet bgs.
- Groundwater levels for the BRT Alternative range from 20 feet bgs near the Raymond fault (near Arroyo Seco Parkway) in South Pasadena to 330 feet bgs in the vicinity of West Main Street in Alhambra.
- Groundwater levels for the LRT Alternative range from approximately 10 feet bgs south of Valley Boulevard to 160 feet bgs immediately south of the Raymond fault zone.
- Groundwater levels for the Freeway Tunnel Alternative range from approximately 10 feet bgs in the vicinity of the southern portal, to over 250 feet bgs at the northern end of the alternative.

Geologic and Geotechnical Evaluation of Alternatives

The geologic setting and geologic hazards along each of the alternatives for SR 710 North Study are summarized in the following sections. The intent of these summaries is to identify conditions that affect the design, construction, and operation of the alternative. Preliminary geotechnical design recommendations are also summarized in the following sections.

No Build Alternative

The SR 710 North Study, No Build Alternative does not include any of the improvements included in the projects Build Alternative. However, the No Build Alternative does include projects/planned improvements through 2035 that are contained in the Federal Transportation Improvement Program, as listed in the Southern California Association of Governments 2012 Regional Transportation Plan/Sustainable Communities Strategy, Measure R, and the funded portion of Metro's 2009 Long Range Transportation Plan. It is possible that the construction of those improvements could result in short-term and/or permanent effects related to geology and seismicity. Those effects would be analyzed and mitigated, if needed, as each of those projects/improvements is advanced for implementation.

TSM/TDM Alternative

The TSM/TDM Alternative consists of strategies and improvements to increase efficiency and capacity for all modes in the transportation system with lower capital cost investments and/or lower potential impacts. In addition to intersection and local street improvements, Intelligent Transportation Systems (ITS), changeable message signs (CMS), Active Traffic Management (ATM), expanded bus service, bus service improvements, and bicycle facility improvements; one new bridge (SR 710 Connector Underpass, Improvement T-1) and one bridge widening (Garfield Avenue Bridge, Improvement I-16) are included in this alternative. All TSM/TDM elements are included in the BRT Alternative with the exception of the reversible lane component of Improvement L-3 and Improvement L-8. All TSM/TDM elements are included in the LRT Alternative and the Freeway Tunnel Alternative with the exception of Improvement T-1 for the LRT Alternative, and Improvements T-1 and T-3 for the Freeway Tunnel Alternative. The TSM/TDM improvements would be designed and constructed in accordance with applicable Caltrans and local (city and county) standards to account for the geologic hazards.

The TSM/TDM improvements are situated primarily within alluvial soils. Areas underlain by artificial fill soils are to be anticipated locally within some of the TSM/TDM improvements. Sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite are present along the TSM/TDM improvements at depth. TSM/TDM Alternative improvements are not expected to be adversely affected by these conditions, as they are the same soil and rock types supporting existing similar developments. Considering the proposed improvements associated with the TSM/TDM Alternative, the primary geologic hazards that could affect the alternative include seismic shaking, liquefaction, groundwater, and expansive materials and compressible soils; these and other potential geologic hazards present along the alternative are summarized in this report.

Within the TSM/TDM Alternative improvements, pavement construction will mainly consist of widening travel lanes or shoulders. The pavement sections for the widening would match the existing pavement sections. Foundation recommendations for the proposed bridges are provided in Structure Preliminary Geotechnical Reports prepared by CH2M HILL for this project (see Section 13 for a full list of reports and references). Two retaining walls are proposed at the SR 110 hook ramp and Fair Oaks Avenue. The proposed retaining walls are Caltrans standard Type-I walls with maximum heights ranging from 8 to 22 feet.

BRT Alternative

BRT Alternative improvements include BRT trunk-line arterial street and station improvements, more frequent bus service, new bus feeder services, and enhanced connecting bus services, as well as the TSM/TDM improvements described above. The BRT Alternative would be designed and constructed in accordance with Metro BRT Design Criteria accounting for potential geologic hazards.

The entire extent of the BRT Alternative is situated within alluvial soils. Areas underlain by artificial fill soils are to be anticipated locally along the alternative. Sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite are present along the alternative at depth. BRT Alternative development is not expected to be adversely affected by these conditions, as they are the same soil and rock types supporting existing transit systems. Considering the proposed improvements associated with the BRT Alternative, the primary geologic hazards that could affect the alternative include seismic shaking, liquefaction, groundwater, and expansive materials and compressible soils; these and other potential geologic hazards present along the alternative are summarized in this report.

Within the BRT Alternative areas, pavement construction will mainly consist of widening travel lanes and overlays. A minimum of 0.15-foot overlay over the widening and existing pavement would be used to eliminate pavement joints for flexible pavement. The preliminary pavement section of 6-inch asphalt concrete on top of 7-inch Class 2 aggregate base over 14-inch Class 1 aggregate sub-base is estimated for the conceptual cost estimate. Concrete bus pads are proposed at each bus station. Based on Caltrans design criteria, the minimum pavement structural section for bus pads is 10-inch jointed plane concrete pavement with dowel bars at transverse joints on top of 6-inch lean concrete base or Type A hot mix asphalt over 6-inch aggregate sub-base. A Type-I retaining wall with a maximum wall height of 10 feet is proposed to accommodate the travel lane widening at Atlantic Boulevard and El Repetto Drive in Monterey Park.

LRT Alternative

The LRT Alternative of the SR 710 North Study involves substantial improvements, including a dedicated guideway and a bored tunnel segment, as well as TSM/TDM improvements described previously. The LRT Alternative is approximately 7.5 miles long, with 3 miles of aerial segments and 4.5 miles of bored tunnel segments. Two-directional tunnels are proposed with tunnel diameters approximately 20 feet each, with the crown of the tunnels located approximately 60 feet bgs along most of the tunnel.

Considering the proposed improvements associated with the LRT Alternative, the primary geologic hazards that could affect the alternative include fault-induced ground rupture, seismic shaking, liquefaction, soil and bedrock variability, slope instability, and groundwater; these and other potential geologic hazards present along the alternative are summarized in this report.

Design and construction of the LRT Alternative would follow Metro Rail Design Criteria for tunneling and deep excavations to account for geologic hazards. The overhead segments of the LRT Alternative also would be designed in accordance with Metro Rail Design Criteria, accounting for the various geologic units at the support locations.

The LRT Alternative is underlain by a variety of geologic units including artificial fill soils, alluvial soils, and sedimentary bedrock (Fernando, Puente, and Topanga Formations). These geologic units would determine foundation requirements for the elevated sections of the LRT Alternative, as well as tunneling design and construction methods within the tunnel segment.

The LRT Alternative crosses one active fault (the Raymond fault) and one potentially active fault (the San Rafael fault). Future studies would be performed to evaluate the activity of the San Rafael fault; however, for planning purposes, this fault is treated as an active fault. Based on Metro Maximum Design Earthquake criteria, preliminary fault rupture displacement estimates have been prepared for the LRT Alternative. A left-lateral fault offset of 1.0 meter and a vertical reverse offset of 0.2 meter are estimated for design of the tunnel at the Raymond fault across a fault zone 25 meters in width. A left-lateral offset of 0.5 meter and a reverse-vertical offset of 0.25 meter are estimated for design of the tunnel at the San Rafael fault across a fault zone 50 meters in width. The potential fault offsets require design features that would allow the tunnel lining to accommodate the anticipated ground displacement. Construction of an oversized vault in conjunction with the installation of a robust lining system, has been recommended as the preliminary design concept for the LRT Alternative fault crossings.

The Upper Elysian Park Blind Thrust fault (UEPBT)-generated Coyote Pass escarpment transects the elevated portion of the LRT Alternative in the vicinity of Corporate Center Drive and Corporate Center Place, just east of I-710 in the city of Monterey Park. Potential ground movements along the elevated segment of the LRT Alternative need to be further evaluated if this alternative is selected, and potential ground movements would have to be taken into consideration during design. This would include evaluating the locations of the guideway supports, and the amount of differential displacement that could be tolerated along the guideway structure.

Unconsolidated and/or water-saturated alluvial soil deposits would likely be encountered in excavations for the portal, the Alhambra Station, and along segments of the LRT tunnel. Open excavation and tunneling in unconsolidated and/or saturated alluvium have the potential for high groundwater inflows and flowing ground conditions at the heading of the excavation, which could potentially result in settlement of the ground surface. Groundwater inflows also are anticipated in the fractured/sheared rock adjacent to faults, which may act as groundwater barriers. During construction, excavation of a tunnel using a pressurized-face tunnel boring machine (TBM) would actively control groundwater inflows at the tunnel heading. To ensure that water flows are controlled at the tunnel heading and behind the TBM and during tunnel operation, a relatively watertight support system may be required, such as a bolted, double gasketed with appropriate cross gaskets, precast concrete segmental lining system. Special care would have to be exercised when tunneling through a fault zone that has a substantial difference in groundwater levels on opposite sides of the fault. In addition, systematic ground improvement measures on a localized basis may be implemented, including a combination of dewatering, permeation grouting, or jet grouting to stabilize the deposits and reduce the loss of ground.

Tunnel excavation for the LRT Alternative would be through several different geologic units. The tunnel excavation methods would need to address a range of geologic conditions including alluvium (soil) and weak sedimentary rocks. This would require the use of tunneling equipment adaptable to the variable range of rock characteristics anticipated, such as rock hardness, tunnel face stability, and muck characteristics or a flexible approach that allows methods to be changed to suit the geology.

The LRT Alternative TBM launching pit excavation may extend approximately 30 to 50 feet bgs. To support the deep excavation, soldier pile walls with lagging and tie-backs are conceptually proposed.

Based on the subsurface conditions, the proposed 8- to 12-foot-diameter cast-in-drilled-hole (CIDH) piles are considered suitable to support the aerial segments of the LRT Alternative. The various CIDH pile diameters are proposed to support the various column sizes. Several retaining walls are proposed to support grade changes, a portion of the LRT guideway, an aerial station, realigned roadways, and a maintenance yard along the LRT Alternative. For preliminary design, Caltrans standard walls and mechanically stabilized earth (MSE) walls can be considered to support the proposed structures. At locations where right-of-way (ROW) is limited, a slurry wall or soldier pile wall can be considered. A soil nail or tieback wall may be considered if a retaining wall supports a relatively high cut slope.

The proposed aerial stations are Civic Center Station and Floral Station, which will be supported by bridge structures. The California State University, Los Angeles Station would be located on cut-and-fill graded ground, which will be supported by retaining walls. The proposed underground stations are Alhambra Station, Huntington Station, South Pasadena Station, and Fillmore Station. These stations would be constructed with the cut-and-cover method with a maximum excavation depth of approximately 80 to 90 feet bgs. Temporary support will be required during initial excavation, such as soldier piles with timber or shotcrete lagging, tangent pile walls, and slurry walls. The groundwater table at Alhambra Station is anticipated at a depth of approximately 45 feet bgs, while the groundwater tables at the other underground stations are deeper than the station base slab levels. If soldier piles and lagging systems are used at Alhambra Station, dewatering operations and/or groundwater control could be required prior to excavation. The permanent station structures would have a gas- and water-proofing barrier system. The remaining underground stations may also require a gas- and water proof barrier system.

Freeway Tunnel Alternative

The Freeway Tunnel Alternative consists of either a single- or dual-bored tunnel approximately 4.2 miles in length, and also includes TSM/TDM improvements described previously. The bored tunnel (either single- or dual-bore) would have an outside diameter of approximately 58.5 feet; the crown of each tunnel would be located approximately 120 to 250 feet bgs along the tunnel. Short segments of cut-and-cover tunnels would be located at the southern and northern termini to provide access via portals to the bored tunnels. Some of the Freeway Tunnel improvements will require engineering and construction techniques similar to the LRT Alternative (as described above).

Considering the proposed improvements associated with the Freeway Tunnel Alternative, the primary geologic hazards that could affect the alternative include fault-induced ground rupture, seismic shaking, soil and bedrock variability, and groundwater; these and other potential geologic hazards present along the alternative are summarized in this report.

Design and construction of the Freeway Tunnel Alternative would follow Federal Highway Administration criteria for tunneling to account for geologic hazards. The surface improvements of the Freeway Tunnel Alternative would be designed in accordance with Caltrans design criteria, accounting for the various geologic units at and near the surface.

The Freeway Tunnel Alternative is underlain by a variety of geologic units including artificial fill soils, alluvial soils, sedimentary bedrock (Fernando, Puente, and Topanga Formations), and igneous and metamorphic bedrock (Wilson Quartz Diorite). The Freeway Tunnel Alternative crosses one active fault (the Raymond fault) and two potentially active faults (the Eagle Rock and San Rafael faults).

Preliminary fault rupture displacement estimates have been prepared for the Freeway Tunnel Alternative. Based on Caltrans Safety Evaluation Earthquake criteria, a left-lateral fault offset of 0.5 meter and a vertical reverse offset of 0.1 meter are estimated for design of the tunnel at the Raymond fault, across a fault zone 25 meters in width. A left-lateral offset of 0.5 meter and a vertical reverse offset of 0.25 meter are estimated for design of the tunnel at the San Rafael and Eagle Rock faults across a fault zone 50 meters in width. The fault rupture mitigation proposed for the LRT Alternative was initially considered for the Freeway Tunnel Alternative. However, the size of the Freeway Tunnel bored tunnel (58.5 feet in diameter) and the anticipated ground conditions in and around the faults raised constructability issues as well as risk, cost, and schedule implications. Subsequently, a vault section utilizing steel segmental lining was determined to be more cost effective and less risky than an oversized vault excavation. Within the Freeway Tunnel Alternative of the SR 710 North Study, two new cut-and-cover tunnels—referred to as the South and North Portal Cut-and-Cover Tunnels—will be constructed at the southern and northern ends of the bored tunnel segment. The cut-and-cover tunnel areas will be used as the TBM launching pits prior to constructing the cut-and-cover tunnels. The TBM launching pit excavation may extend approximately 85 to 100 feet bgs. To support the deep excavation, slurry panel walls with tie-backs are conceptually proposed at the south portal and soldier pile walls with tie-backs are conceptually proposed at the north portal.

Within the Freeway Tunnel Alternative improvements, two new bridge constructions, two bridge widenings, and two bridge replacements are proposed. Foundation recommendations for the advanced planning study are provided in the Structure Preliminary Geotechnical Reports prepared by CH2M HILL. Several retaining walls are proposed to support grade changes and realigned roadways in the Freeway Tunnel Alternative. For preliminary design, Caltrans standard walls and MSE walls can be considered as potential retaining wall types. At the locations where ROW is limited, a slurry wall or soldier pile wall can be considered. A soil nail or tieback wall may be considered if a retaining wall supports a relatively high cut slope.

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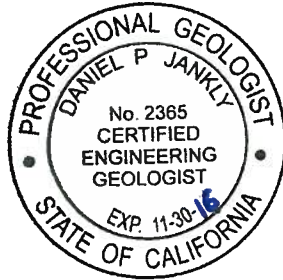
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- G Fault Investigation Technical Memorandum

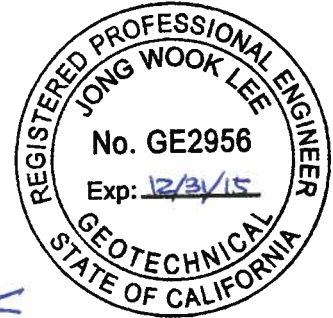
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Acronyms and Abbreviations

°F	degrees Fahrenheit
AASHTO	American Association of State Highway and Transportation Officials
APEQFZ	Alquist-Priolo Earthquake Fault Zone
ARS	acceleration response spectra
ASTM	ASTM International (formerly American Society for Testing and Materials)
ATM	Active Traffic Management
bgs	below ground surface
BRT	Bus Rapid Transit
Cal/OSHA	California Department of Occupational Safety and Health Administration
Cal State LA	California State University, Los Angeles
Caltrans	California Department of Transportation
CDMG	California Division of Mines and Geology
CDOGGR	California Division of Oil, Gas & Geothermal Resources
CDWR	California Department of Water Resources
CGS	California Geological Survey (formerly California Division of Mines and Geology)
CIDH	cast-in-drilled-hole
CMS	changeable message sign(s)
CTM	California Test Method
ECI	Earth Consultants International
EMI	Earth Mechanics, Inc.
EPFT	Elysian Park Fold and Thrust Belt
FHWA	Federal Highway Administration
ft/sec	feet per second
g	acceleration due to gravity
GIS	geographic information system
H:V	horizontal to vertical
I	Interstate
ISA	Initial Site Assessment
ITS	Intelligent Transportation Systems
km	kilometer(s)
L:V	lateral to vertical
LACDPW	Los Angeles County Department of Public Works
LRFD	load and resistance factor design
LRT	Light Rail Transit
MASW	multichannel analyses of surface waves

Metro	Los Angeles County Metropolitan Transportation Authority
M _L	earthquake Richter magnitude
mm/yr	millimeters per year
M _{max}	maximum moment magnitude
M _s	surface wave magnitude
MSE	mechanically stabilized earth
MSGW	Main San Gabriel Watermaster
M _w	earthquake moment magnitude
NAVD 88	North American Vertical Datum 1988
NISZ	Newport-Inglewood Structural Zone
O&M	operations and maintenance
ohm-cm	ohm centimeter(s)
P-wave	compressional wave
pcf	pounds per cubic foot
PDL	potential disturbance limit
PGA	peak ground acceleration
PGR	Preliminary Geotechnical Report
ppm	parts per million
psi	pounds per square inch
RBMB	Raymond Basin Management Board
ReMi	refraction microtremor
ROW	right-of-way
RQD	Rock Quality Designation
S-wave	shear wave
SCEC	Southern California Earthquake Center
SPT	Standard Penetration Test
SR	State Route
TBM	tunnel boring machine
TDM	Transportation Demand Management
Technical Study	<i>Final Geotechnical Summary Report, SR 710 Tunnel Technical Study (CH2M HILL, 2010)</i>
TSM	Transportation System Management
UEPBT	Upper Elysian Park Blind Thrust fault
UPRR	Union Pacific Railroad
USGS	United States Geological Survey
VW	vibrating wire
WRD	Water Replenishment District of Southern California

Introduction

The California Department of Transportation (Caltrans), in cooperation with the Los Angeles County Metropolitan Transportation Authority (Metro), selected the CH2M HILL team to provide alternatives analysis, preliminary engineering, and environmental studies documentation for the State Route (SR) 710 North Study. The SR 710 North Study Area is shown in Figure 1-1. The SR 710 North Study included geotechnical, geologic, and seismic evaluations for five alternatives proposed within the SR 710 North Study Area. Results of the CH2M HILL evaluations are summarized in this Preliminary Geotechnical Report (PGR). Caltrans and Metro will utilize this PGR during evaluations of the technical, operational, and financial feasibility of the SR 710 North Study Alternatives, as described in Section 1.3.

1.1 Objective and Scope

The objective of this PGR is to provide sufficient documentation for geotechnical, geologic, and seismic conditions to support the Caltrans and Metro evaluations. To meet this objective, the scope of work for this PGR included the following:

- Collect and review available information including existing geotechnical, geologic, seismic, and fault-related data.
- Conduct field exploration and laboratory testing programs.
- Evaluate the collected data to characterize the subsurface conditions along the alternatives.
- Prepare this PGR, presenting the findings of the exploration program and preliminary geotechnical design recommendations for the SR 710 North Study Alternatives.

Work was carried out by CH2M HILL geotechnical staff and its primary subconsultant, Earth Consultants International (ECI). ECI provided support by leading the fault characterization for the study.

1.2 Purpose and Need

Due to the lack of continuous north-south transportation facilities in the study area, there is congestion on freeways, cut-through traffic that affects local streets, and low-frequency transit operations in the study area. Therefore, the following project purpose and need have been established.

- The purpose of the proposed action is to effectively and efficiently accommodate regional and local north-south travel demands in the study area of the western San Gabriel Valley and east/northeast Los Angeles, including the following considerations:
 - Improve efficiency of the existing regional freeway and transit networks.
 - Reduce congestion on local arterials adversely affected due to accommodating regional traffic volumes.
 - Minimize environmental impacts related to mobile sources.
- The lack of continuous north-south transportation facilities in the SR 710 North Study Area has the following consequences, which have been identified as the elements of need for the project:
 - Degradation of the overall efficiency of the larger regional transportation system.
 - Congestion on freeways in the SR 710 North Study Area.
 - Congestion on the local streets in the SR 710 North Study Area.
 - Poor transit operations within the SR 710 North Study Area.

1.3 Project Alternatives

There are five alternatives being considered in the SR 710 North Study. These alternatives are listed below and described in the following subsections.

- No Build
- Transportation System Management/Transportation Demand Management (TSM/TDM)
- Bus Rapid Transit (BRT)
- Light Rail Transit (LRT)
- Freeway Tunnel

Figures and plates included in this report display the potential disturbance limit (PDL) of each alternative. In areas where the PDL is outside the project limits, minimal work will be conducted. Major construction will take place within the project limits of each alternative as stated in the project descriptions below.

1.3.1 No Build Alternative

The SR 710 North Study, No Build Alternative does not include any of the improvements included in the projects Build Alternatives. However, the No Build Alternative does include projects/planned improvements through 2035 that are contained in the Federal Transportation Improvement Program, as listed in the Southern California Association of Governments 2012 Regional Transportation Plan/Sustainable Communities Strategy, Measure R, and the funded portion of Metro's 2009 Long Range Transportation Plan. Figure 1-2 illustrates the projects in the No Build Alternative.

1.3.2 Transportation System Management/Transportation Demand Management (TSM/TDM) Alternative

The TSM/TDM Alternative consists of strategies and improvements to increase efficiency and capacity for all modes in the transportation system with lower capital cost investments and/or lower potential impacts. The TSM/TDM Alternative is designed to maximize the efficiency of the existing transportation system by improving capacity and reducing the effects of bottlenecks and chokepoints. Components of the TSM/TDM Alternative are shown in Figure 1-3.

- TSM strategies increase the efficiency of existing facilities (that is, TSM strategies are actions that increase the number of vehicle trips a facility can carry without increasing the number of through lanes). TSM strategies include Intelligent Transportation Systems (ITS) improvements consisting of traffic signal upgrades, synchronization and transit prioritization, arterial changeable message signs (CMS), and arterial video and speed data collection systems; local street and intersection improvements; and Active Traffic Management (ATM) consisting primarily of arterial speed data collection and CMS.
- TDM strategies focus on regional means of reducing the number of vehicle trips and vehicle miles traveled as well as increasing vehicle occupancy. TDM strategies facilitate higher vehicle occupancy or reduce traffic congestion by expanding the traveler's transportation options in terms of travel method, travel time, travel route, travel costs, and the quality and convenience of the travel experience. TDM strategies include reducing the demand for travel during peak periods; reducing the use of motor vehicles; shifting the use of motor vehicles to uncongested times of the day; encouraging rideshare and transit use; eliminating trips (that is, telecommuting); and improving transportation options, as well as expanded bus service, bus service improvements, and bicycle facility improvements.

The TSM/TDM Alternative includes one new bridge (SR 710 Connector Underpass, Improvement T-1) and one bridge widening (Garfield Avenue Bridge, Improvement I-16). All TSM/TDM elements are included in the BRT Alternative with the exception of Improvement L-8, and the reversible lane component of Improvement L-3. All TSM/TDM elements are included in the LRT and Freeway Tunnel Alternatives with the exception of Improvement T-1 for the LRT Alternative, and Improvements T-1 and T-3 for the Freeway Tunnel Alternative.

1.3.3 Bus Rapid Transit (BRT) Alternative

The BRT Alternative would provide high-speed, high-frequency bus service through a combination of new, dedicated, and existing bus lanes, and mixed-flow traffic lanes to key destinations between East Los Angeles and Pasadena. The proposed route length is approximately 12 miles. Figure 1-4 illustrates the BRT Alternative.

The BRT Alternative includes the BRT trunk line arterial street and station improvements, frequent bus service, new bus feeder services, and enhanced connecting bus services. The BRT Alternative would include the same improvements proposed for the TSM/TDM Alternative with the exception of Improvement L-8, and the reversible lane component of Improvement L-3.

The 12-mile route would begin at Atlantic Boulevard and Whittier Boulevard to the south; follow Atlantic Boulevard, Huntington Drive, Fair Oaks Avenue, and Del Mar Boulevard; and end with a terminal loop in Pasadena to the north. Buses operating in the corridor would be given transit signal priority from a baseline transit signal priority project that will be implemented separately by Metro.

A total of 17 BRT stations with amenities would be placed on average, at approximately 0.8-mile intervals at major activity centers and cross streets. Typical station amenities would include new shelters, branding elements, seating, wind screens, leaning rails, variable message signs (next bus information), lighting, bus waiting signals, trash receptacles, and stop markers. Some of these stops will be combined with existing stops; while in some cases, new stops for BRT will be provided.

1.3.4 Light Rail Transit (LRT) Alternative

The LRT Alternative would include passenger rail operated along a dedicated guideway, similar to other Metro light rail lines, as well as operations within a tunnel segment. The LRT Alternative is approximately 7.5 miles long, with 3 miles of aerial segments and 4.5 miles of bored tunnel segments. The LRT Alternative would include the same improvements proposed for the TSM/TDM Alternative with the exception of Improvement T-1. Figure 1-5 illustrates the LRT Alternative.

The LRT Alternative would begin at an aerial station on Mednik Avenue adjacent to the existing East Los Angeles Civic Center Station on the Metro Gold Line. The Alternative would remain elevated as it travels north on Mednik Avenue, west on Floral Drive, north across Corporate Center Drive, and then along the west side of I-710, primarily in Caltrans right-of-way (ROW), to a station adjacent to California State University, Los Angeles (Cal State LA). The Alternative would descend into a tunnel south of Valley Boulevard and travel northeast to Fremont Avenue, north under Fremont Avenue, and easterly to Fair Oaks Avenue. The Alternative would then cross below SR 110 and end at an underground station below Raymond Avenue adjacent to the existing Fillmore Station on the Metro Gold Line.

Two directional tunnels are proposed with tunnel diameters approximately 20 feet each, the crown of the tunnels would be located approximately 60 feet below ground surface (bgs). Supporting tunnel systems include emergency evacuation cross passages, a ventilation system consisting of exhaust fans at each portal and an exhaust duct along the entire length of the tunnel, fire detection and suppression systems, communications and surveillance systems, and 24-hour monitoring, similar to the existing LRT system.

Seven stations would be located along the LRT Alternative at Mednik Avenue in East Los Angeles, Floral Drive in Monterey Park, Cal State LA, Fremont Avenue in Alhambra, Huntington Drive in South Pasadena, Mission Street in South Pasadena, and Fillmore Street in Pasadena. The Fremont Avenue Station, the Huntington Drive Station, the Mission Street Station, and the Fillmore Street Station would be underground stations. New Park-and-Ride facilities would be provided at all of the proposed stations except the Mednik Avenue, Cal State LA, and Fillmore Street stations.

A maintenance yard to clean, maintain, and store light rail vehicles would be located on both sides of Valley Boulevard at the terminus of SR 710. A track spur from the LRT mainline to the maintenance yard would cross above Valley Boulevard.

1.3.5 Freeway Tunnel Alternative

The Freeway Tunnel Alternative starts at the existing southern stub of SR 710 in Alhambra, just north of Interstate (I)-10, and connects to the existing northern stub of SR 710, south of the I-210/SR 134 interchange in Pasadena. The Freeway Tunnel Alternative would include the same improvements proposed for the TSM/TDM Alternative with the exception of Improvements T-1 and T-3.

The Freeway Tunnel Alternative has two design variations: a dual-bore tunnel and a single-bore tunnel. The dual-bore design variation includes two tunnels that independently convey northbound and southbound vehicles. The single-bore design variation includes one tunnel that carries both northbound and southbound vehicles. Figure 1-6 illustrates the dual-bore and single-bore tunnel design variations for the Freeway Tunnel Alternative; a typical single-bore tunnel cross section is illustrated in Figure 1-7. Each of these design variations is summarized below.

- **Dual-Bore Tunnel:** The dual-bore tunnel variation is approximately 6.3 miles long, with 4.2 miles of bored tunnel, 0.7 mile of cut-and-cover tunnel, and 1.4 miles of at-grade segments. This tunnel variation would consist of dual two-level bored tunnels with two lanes on each level and in each direction. Each bored tunnel would have an outside diameter of approximately 58.5 feet; and the crown of each tunnel would be located approximately 120 to 250 feet bgs along most of the tunnel. Vehicle cross passages would be provided throughout this tunnel variation that would connect one tunnel to the other tunnel for use in an emergency situation.

Short segments of cut-and-cover tunnels would be located at the southern and northern termini to provide access via portals to the bored tunnels. The portal at the southern terminus would be located south of Valley Boulevard. The portal at the northern terminus would be located north of Del Mar Boulevard. No intermediate interchanges are planned for the tunnel.

- **Single-Bore Tunnel:** The single-bore tunnel design variation is also approximately 6.3 miles long, with 4.2 miles of bored tunnel, 0.7 mile of cut-and-cover tunnel, and 1.4 miles of at-grade segments. This tunnel variation would consist of a single, two-level, bored tunnel with two lanes on each level in each direction. The single-bored tunnel would also have an outside diameter of approximately 58.5 feet; and the crown of the tunnel would be located approximately 120 to 250 feet bgs along most of the tunnel. The single-bore tunnel would be in the same location as the northbound tunnel in the dual-bore tunnel design variation.

Both tunnel design variations would include the following tunnel support systems: emergency evacuation for pedestrians and vehicles, air scrubbers, a ventilation system consisting of exhaust fans at each portal, fire detection and suppression systems, communications and surveillance systems, and 24-hour monitoring. Operations and maintenance (O&M) control buildings would be constructed at the northern and southern ends of the tunnel. In addition, both tunnel design variations include roadway improvements outside the north and south portal areas. There would be no operational restrictions for the tunnel, with the exception of vehicles carrying flammable or hazardous materials.

Five operational variations have been identified for the Freeway Tunnel Alternative, including:

- Freeway Tunnel Alternative with Tolls
- Freeway Tunnel Alternative without Tolls
- Freeway Tunnel Alternative with Trucks Excluded
- Freeway Tunnel Alternative with Trucks Excluded and with Tolls
- Freeway Tunnel Alternative with Toll and Express Bus

Pertinent Reports and Investigations

Previous investigations performed within the SR 710 North Study Area were reviewed to develop subsurface profiles and to characterize subsurface conditions for the four build alternatives. Results of this review were used to identify gaps in the existing information. Additional field investigations were subsequently conducted as part of the SR 710 North Study to address these gaps. The locations of the previous and current field explorations are presented in the Boring Location Map (Plate 1) and Geologic Map (Plate 2). Previous and current field exploration details, as well as other pertinent documents reviewed during this study, are summarized in the following subsections.

2.1 Pertinent Reports

A review of readily available reports and publications from various public and private files addressing the surface and subsurface conditions in the SR 710 North Study Area was conducted. The objective of this task was to develop an initial understanding of the geologic, faulting, hydrogeologic, and geotechnical considerations along each of the SR 710 North Study Alternatives.

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

- United States Geological Survey (USGS)
- Caltrans
- California Geological Survey (CGS), formerly the California Division of Mines and Geology (CDMG)
- California Division of Oil, Gas & Geothermal Resources (CDOGGR)
- Southern California Earthquake Center (SCEC)
- 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
- Water Replenishment District of Southern California (WRD)

Geologic and fault conditions within the central and western portions of the SR 710 North Study Area were evaluated using “Geology of the Elysian Park-Repetto Hills Area,” a report published by the CGS (Lamar, 1970), and geologic maps published by the Dibblee Foundation for the Los Angeles, Hollywood, Pasadena, Mount Wilson, Azusa, El Monte, and Baldwin Park Quadrangles (Dibblee, 1989a, 1989b, 1991, 1998, and 1999). The Geologic Compilation of Quaternary Surficial Deposits in the Los Angeles 30’ by 60’ Quadrangle (CGS, 2012) was used to present the previous and SR 710 North Study boring locations (Plate 2) in geographic information system (GIS) format.

2.2 Previous CH2M HILL Investigations: SR 710 Tunnel Technical Study

The *Final Geotechnical Summary Report, SR 710 Tunnel Technical Study* (Technical Study; CH2M HILL, 2010) describes preliminary investigations performed to evaluate the feasibility of constructing a tunnel within five study zones selected during that study. The five study zones were located in the same general area as the SR 710 North Study, as described in Section 1. The exploration program for the study was conducted to characterize the subsurface materials and determine the general engineering properties of the soil and rock within the five selected study zones. The field investigations included rotary wash core borings, in situ testing, and geophysical testing. The following three subsections summarize the work completed as part of the Technical Study field investigation.

2.2.1 Drilling and Sampling Program

Ten boring locations investigated as part of the Technical Study provide useful subsurface information applicable to the SR 710 North Study alternatives. The locations of these Technical Study borings are shown in Plates 1 and 2. The boring types, locations, and depths are summarized in Table 2-1; the associated boring logs are presented in Appendix A.2.

Rotary wash and continuous core drilling methods were utilized to allow collection of soil and rock samples from each of the exploration locations. Samples collected from the drilling and sampling program were classified in the field, and then transported to testing laboratories for further evaluation. The laboratory test results from the 10 Technical Study borings are presented in Appendix D.3.

TABLE 2-1
SR 710 Tunnel Technical Study Borings (CH2M HILL, 2010) Utilized in the SR 710 North Study

Exploration No.	Type of Exploration	Northing ^a	Easting ^a	Ground Surface Elevation ^b (feet)	Depth of Exploration (feet)
R-09-Z1B8	Rotary Wash/Wireline Coring	1850582.92	6512724.74	419.6	200
R-09-Z2B5	Rotary Wash/Wireline Coring	1853050.81	6511831.88	452.4	300
R-09-Z3B2	Rotary Wash/Wireline Coring	1872415.69	6514868.39	781.4	275
R-09-Z3B3	Rotary Wash/Wireline Coring	1870194.48	6514774.44	802.0	275
R-09-Z3B4	Rotary Wash/Wireline Coring	1870813.73	6516733.49	768.0	276
R-09-Z3B6	Rotary Wash/Wireline Coring	1868062.70	6516722.28	750	326
R-09-Z3B8	Rotary Wash/Wireline Coring	1860993.95	6514198.81	594.3	275
R-09-Z3B11	Rotary Wash/Wireline Coring	1858032.01	6517296.60	533.1	275
R-09-Z3B12	Rotary Wash/Wireline Coring	1856063.15	6513380.17	501.0	275
R-09-Z4B4	Rotary Wash/Wireline Coring	1851895.71	6514496.46	454.4	277

^a California Coordinate System, Zone 5, U.S. Survey Feet

^b The elevations are based on North American Vertical Datum 1988 (NAVD 88).

2.2.2 In Situ Testing and Downhole Logging

In situ testing and downhole logging was performed within the borings drilled and sampled during the Technical Study. A brief discussion of the tests is presented below.

2.2.2.1 Downhole Geophysical Testing and Logging

The in situ testing and downhole logging conducted during the Technical Study were completed in selected borings to determine the physical characteristics and engineering properties of the in-place soil/rock units. These tests/surveys included caliper tests; acoustic televiwer, downhole compression and shear-wave velocity measurements; natural gamma logging; and resistivity or conductivity logging.

The results of this testing and logging were used in combination with boring logs to aid in the identification of rock type, geologic structure, and the engineering properties of the rock mass. The downhole geophysical tests were performed in accordance with ASTM International (ASTM) D5753, Standard Guide for Planning and Conducting Borehole Geophysical Logging. Results of the in situ testing and downhole logging relevant to the SR 710 North Study are provided in Appendix B.1.1.

2.2.2.2 Pressuremeter Testing

To characterize each of the formational materials, a pre-bored mono-cell pressuremeter was used during the Technical Study 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. Results of pressuremeter tests are presented in Appendix B.2.

2.2.3 Geophysical Testing

The objective of the geophysical testing conducted during the Technical Study was to characterize the subsurface geology, structure, and geotechnical conditions. Three types of geophysical tests were performed as part of the Technical Study exploration program: seismic reflection testing, multichannel analyses of surface waves (MASW), and refraction microtremor (ReMi) testing. The locations of the geophysical tests utilized during the SR 710 North Study are shown in Plates 1 and 2.

2.2.3.1 Seismic Reflection Testing

Seismic reflection testing was conducted during the Technical Study to identify the location and orientation of selected active and inactive faults, the contact between alluvium and bedrock, and depth to groundwater by collecting compressional wave (P-wave) velocity data. P-wave reflection data were acquired along each profile using an IVI MiniBuggy vibratory source. Typical length of the seismic line was approximately 1,600 to 1,900 feet. The locations of the seismic reflection lines utilized during the SR 710 North Study are shown in Plates 1 and 2. The seismic-reflection testing results of these lines are presented in Appendix B.1.2.

2.2.3.2 MASW and ReMi Testing

MASW and ReMi testing was conducted during the Technical Study to obtain information on the depth of alluvium and the dynamic characteristics of the underlying material. These testing methods involved collection of shear wave (S-wave) velocity data using the MASW and ReMi testing methods. The MASW uses an active source to obtain S-wave velocity data, while the ReMi procedure uses ambient vibration data to collect S-wave velocities. These techniques were used for 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 from the MASW and ReMi surveys were used for site characterization, including correlation of seismic properties between boreholes; for estimating depth to bedrock where there was sufficient contrast in velocity between bedrock and overlying sediments; and for estimation of excavatability or rippability of rock.

The locations of the MASW and ReMi tests utilized during the SR 710 North Study are shown in Plates 1 and 2. Test results are presented in Appendix B.1.2.

2.3 Previous Investigations by Others

In addition to the Technical Study (CH2M HILL 2010), reports prepared by Caltrans (1974a and 1974b), Earth Mechanics, Inc. (EMI) (2006), and Ninoy & Moore (1999) for previously proposed alignments within the SR 710 corridor between Alhambra and Pasadena were also reviewed. Some of the previously conducted borings provided relevant subsurface data to the SR 710 North Study, and have been incorporated into this report. The types, locations, and depths of these previous borings are summarized in Table 2-2; the associated boring logs are presented in Appendix A.2. The boring locations are shown in Plates 1 and 2.

TABLE 2-2
Previous Geotechnical Explorations Utilized in the SR 710 North Study

Exploration No.	Type of Exploration	Latitude	Longitude	Depth of Exploration (feet)	Ground Surface Elevation ^a (feet)	Reference
C-24a	Unknown	N/A - See Location in Plate 2		195	758	Caltrans (1974a)
ES-1	Wireline Coring	N/A - See Location in Plate 2		351	725	
ES-2	Wireline Coring	N/A - See Location in Plate 2		304	745	Caltrans (1974b)
ES-3	Wireline Coring	N/A - See Location in Plate 2		304	700	
EMI-1	Rotary Wash/ Wireline Coring	N 34.086139°	E -118.157278°	201.1	455	
EMI-2	Rotary Wash/ Wireline Coring	N 34.115111°	E -118.166111°	201.1	650	EMI (2006)
EMI-3	Rotary Wash/ Wireline Coring	N 34.129028°	E -118.154972°	204.1	790	
NM-B1	Hollow-Stem Auger	N/A - See Location in Plate 2		51.5	594	
NM-B2	Hollow-Stem Auger	N/A - See Location in Plate 2		26.0	676	Ninyo & Moore (1999)
NM-B4	Hollow-Stem Auger	N/A - See Location in Plate 2		50.5	545	

^a As noted on the boring logs presented in Appendix A.2.

N/A – Survey data not available

2.4 SR 710 North Study Field Exploration Program

A supplemental field exploration program was conducted as part of the SR 710 North Study. The purpose of the field exploration program was two-fold:

1. Gather geotechnical data along the SR 710 North Study Alternatives relevant to the alternative evaluations, as previously described.
2. Preliminarily investigate the locations and activity of faults in the SR 710 North Study Area that pose, or potentially pose, a surface rupture hazard (Raymond, Eagle Rock, and San Rafael faults, as discussed in Section 4.2.5).

Considering the improvements proposed within the five alternatives of the SR 710 North Study, an exploration program was developed utilizing the previously conducted, relevant reports and explorations as discussed in Sections 2.1, 2.2, and 2.3. The CH2M HILL team also utilized relevant existing information from Caltrans logs of test borings for structures in the vicinity of the SR 710 North Study Alternatives.

2.4.1 Scope of Field Exploration Work

The No Build, TSM/TDM, and BRT Alternatives for the SR 710 North Study would involve either no subsurface work, as in the case of the No Build Alternative, or relatively limited subsurface work, as in the case of the TSM/TDM and BRT Alternatives. In contrast, both the LRT and Freeway Tunnel Alternatives would involve tunnels, the feasibility of which is dependent on geologic and geotechnical conditions along the tunnel alignments. As such, the SR 710 North Study geotechnical explorations focused on collecting subsurface information in areas along the LRT and Freeway Tunnel Alternatives where large data gaps were present. Thirteen explorations were drilled and sampled to meet this objective.

The scope of the field exploration program for the SR 710 North Study also included a focused assessment of the potential for active faulting along the LRT and Freeway Tunnel Alternatives. This fault assessment included the drilling, logging, and sampling of additional borings. The SR 710 North Study fault exploration was designed to collect data that would aid in evaluating the location and activity of the Raymond, Eagle Rock, and San Rafael

faults in the SR 710 North Study Area. Two north-south boring transects were conducted for the SR 710 North Study, one across the Raymond and Eagle Rock faults, and one across the San Rafael fault. The fault exploration borings were plotted on cross sections developed along the LRT and Freeway Tunnel Alternatives in the areas of these faults. These cross sections were used as the basis for the fault evaluation as discussed in Section 4.2.5. Twelve explorations were drilled and sampled for this purpose.

Prior to commencement of the exploration program for the SR 710 North Study, the proposed boring locations were reviewed by Caltrans Geotechnical Services. A summary of the type, location, depth, and purpose of the explorations conducted for the SR 710 North Study exploration program is presented in Table 2-3.

TABLE 2-3
Summary of SR 710 North Study Geotechnical and Fault Exploration Program

Exploration No.	Type of Exploration	Northing ^a	Easting ^a	Ground Surface Elevation ^b (feet)	Depth of Exploration (feet)	Purpose
A-13-001	Hollow-Stem Auger	1839403.75	6511403.50	344.1	105.4	Geotechnical
RC-13-002	Hollow-Stem/ Wireline Coring	1843137.78	6511686.47	349.24	85.1	Geotechnical
RC-13-003	Hollow-Stem/ Wireline Coring	1847540.09	6512456.89	388.78	100.5	Geotechnical
RC-13-004	Hollow-Stem/ Wireline Coring	1848742.92	6512894.91	393.35	109.0	Geotechnical
RC-13-005	Hollow-Stem/ Wireline Coring	1849587.82	6512879.80	425.01	225.0	Geotechnical
R-13-006	Hollow-Stem/Rotary Wash	1855165.01	6515308.63	505.56	120.8	Geotechnical
RC-13-007	Hollow-Stem/ Wireline Coring	1854421.60	6512778.17	493.12	271.0	Geotechnical
A-13-008	Hollow-Stem Auger	1862835.52	6515983.73	615.45	96.5	Geotechnical
RC-13-009	Hollow-Stem/ Wireline Coring	1863312.23	6514073.24	650.91	267.0	Geotechnical
O-13-010	Sonic Drilling	1865277.86	6514376.75	693.46	272.0	Geotechnical/ Faulting
A-13-015	Hollow-Stem Auger Coring	1868621.79	6514906.45	778.26	103.6	Faulting
A-13-016	Hollow-Stem Auger Coring	1869322.87	6514854.40	785.38	65.0	Faulting
A-13-017	Hollow-Stem Auger Coring	1869613.60	6514849.25	788.70	100.0	Faulting
A-13-020	Hollow-Stem Auger	1873733.86	6514763.20	799.91	149.8	Geotechnical
A-13-021	Hollow-Stem Auger	1859621.30	6515914.19	577.93	110.8	Geotechnical
A-13-022	Hollow-Stem Auger Coring	1865463.63	6514130.55	696.34	110.0	Faulting
O-13-023	Sonic Drilling	1865552.07	6514135.20	698.11	270.0	Geotechnical/ Faulting
A-13-024	Hollow-Stem Auger Coring	1865992.79	6514138.52	715.59	125.0	Faulting
A-13-025	Hollow-Stem Auger Coring	1866058.78	6514139.21	720.94	125.0	Faulting
A-13-026	Hollow-Stem Auger Coring	1866214.01	6514140.84	736.07	110.0	Faulting
A-13-027	Hollow-Stem Auger Coring	1866484.70	6514134.81	751.89	100.0	Faulting
A-13-034	Hollow-Stem Auger Coring	1869179.67	6514864.10	783.71	85.0	Faulting
A-13-035	Hollow-Stem Auger Coring	1869478.77	6514848.72	787.19	73.0	Faulting

^a California Coordinate System, Zone 5, U.S. survey feet

^b The elevations are based on NAVD 88.

2.4.2 Drilling Methodology

Twenty-three borings were drilled during the SR 710 North Study. The borings were continuously observed and logged by engineers and geologists from CH2M HILL and ECI. Drill cuttings were contained in 55-gallon drums and disposed of offsite.

Multiple drilling methods were employed during the investigation, as described below.

- **Hollow-Stem Auger:** Four 8-inch-diameter hollow-stem auger borings (A-13-001, A-13-008, A-13-020, and A-13-021) were drilled using CME-75 and CME-95 truck-mounted drill rigs. Standard penetration tests (SPTs) were conducted using a 140-pound automatic hammer falling 30 inches in general accordance with ASTM (2011a) D1586. Samples were collected at 5-foot intervals by driving either a standard 1.4-inch-diameter SPT (split-spoon) sampler or a 2.5-inch-diameter modified California sampler. At the completion of drilling, a vibrating wire piezometer was installed in sonic boring A-13-020 to monitor groundwater variations; the remaining hollow-stem auger boreholes were grouted.
- **Hollow-Stem Auger Coring:** Ten 8.5-inch-diameter hollow-stem auger borings (A-13-015, A-13-016, A-13-017, A-13-022, A-13-024, A-13-025, A-13-026, A-13-027, A-13-034, and A-13-035) were drilled using a CME-75 truck-mounted drill rig. These borings were continuously sampled using a 3-inch-diameter, 5-foot-long split-spoon type core barrel sampler. Depending on the material and relative difficulty in drilling, each drill run (sample) was either 2.5 or 5 feet long. These continuously sampled borings were conducted along the fault exploration boring transects to identify sediment layer correlations between borings, as described in Section 4.2.5. At the completion of drilling, the boreholes were grouted.
- **Sonic Drilling:** Two sonic borings (O-13-010 and O-13-023) were advanced using a 600T Rotosonic truck-mounted rig utilizing a 6-inch-diameter casing. The sonic borings were also continuously sampled for use in the fault boring transects. These borings were drilled using two different sample collection methods. Within the upper 100 feet of each sonic boring, the soil was sampled using 5-foot-long, 4-inch-diameter polyvinyl tubes. Below 100 feet, the soil was sampled using polyvinyl bags with variable run lengths, some as long as 19 feet. At the completion of drilling, a vibrating wire piezometer was installed in sonic boring O-13-010 to monitor groundwater variations; the second sonic borehole was grouted.
- **Rotary Wash:** One boring (R-13-006) was drilled primarily via rotary wash. The truck-mounted CME-75 used a 3.8-inch-diameter drill bit. SPTs were conducted using a 140-pound automatic hammer falling 30 inches. Soil samples were collected at 5-foot intervals by driving either a standard 1.4-inch-diameter split-spoon sampler or a 2.5-inch-diameter modified California sampler. After the drilling was completed, the borehole was grouted.
- **Wireline Coring:** Six rotary wash/wireline core borings (RC-13-002, RC-13-003, RC-13-004, RC-13-005, RC-13-007, and RC-13-009) were drilled using CME-75, CME-85, and CME-95; IR-8400; and Guspech Brut 22R truck-mounted drill rigs. The borings were drilled using the hollow-stem auger method described above, until bedrock or groundwater was encountered. The drilling method was then switched to wireline coring. SPTs were conducted within soils above rock using a 140-pound automatic hammer falling 30 inches. Soil samples were collected at 5-foot intervals by driving either a standard 1.4-inch-diameter split-spoon sampler or a 2.5-inch-diameter modified California sampler. Rock cores were collected using a triple-tube HQ (2.5-inch-diameter) core method. At the completion of drilling, vibrating wire piezometers were installed in four borings to monitor groundwater variations; the remaining boreholes were grouted.

Six borings advanced during the SR 710 North Study exploration program were converted to piezometers, as discussed in Section 5.1.2. The piezometers were constructed using vibrating wire (VW) piezometers with automatic data loggers to monitor the depth of groundwater over time. Additional drilling and sampling details, along with the SR 710 North Study field exploration boring logs, are provided in Appendix A.1. Photographs of the cores recovered during the exploration are presented in Appendix A.3.

2.5 Laboratory Testing

The engineering characteristics of soil and rock within the SR 710 North Study Area were estimated based on existing information from previous exploration programs reviewed as part of the SR 710 North Study and from laboratory testing, in conjunction with the rock mass properties obtained during in situ testing and logging, conducted as part of the SR 710 North Study.

2.5.1 Existing Laboratory Data

The existing laboratory data were obtained from the following sources:

- CH2M HILL. 2010. *Final Geotechnical Summary Report for SR 710 Tunnel Technical Study, Los Angeles County, California*. April.
- EMI. 2006. *Technical Data Report for the Proposed 710 Freeway Tunnels Feasibility, Task 3.1 – Soil Boring Program*. March 20.
- Ninyo and Moore, Inc. 1999. *Phase II Geotechnical Feasibility of the Proposed Interstate 710 Freeway Extension through the Monterey Hills, Los Angeles County California*. March 25.

The previous laboratory test data utilized during the SR 710 North Study are presented in Appendix D.3.

2.5.2 Laboratory Tests Conducted during SR 710 North Study

Laboratory testing was conducted as part of the SR 710 North Study field exploration to supplement existing data. Laboratory tests were performed on soil and rock samples selected by CH2M HILL geotechnical staff to verify field classifications and evaluate the geotechnical engineering properties of the soil and rock. Selected soil and rock samples were tested for classification, moisture content and density, compressibility, strength, rock characteristic, corrosion potential, and petrographic analysis. Samples were selected for testing based on soil and formational type, rock weathering and hardness, sample depth related to the proposed structures, and sample quality.

All testing was performed in general accordance with the applicable ASTM standards or California Test Methods (CTMs). The types of tests performed on the soil and rock samples are summarized in Table 2-4. The laboratory test results from the SR 710 North Study field exploration program are presented in Appendix D.2. A summary of laboratory test results for various materials present along the LRT and Freeway Tunnel Alternatives is included in Appendix D.1.

TABLE 2-4
Summary of Laboratory Test Methods

Laboratory Test	Test Method	Reference
Moisture and Dry Density	ASTM D2937	ASTM, 2010c
Moisture Content	ASTM D2216	ASTM, 2010b
Grain Size Distribution	ASTM D422	ASTM, 2007a
Atterberg Limits	ASTM D4318	ASTM, 2010d
Expansion Index	ASTM D4829	ASTM, 2011d
Consolidation	ASTM D2435	ASTM, 2011b
Direct Shear (Consolidated Drained)	ASTM D3080	ASTM, 2011c
Unconsolidated Undrained Triaxial Compressive Strength	ASTM D2850	ASTM, 2007b
Cerchar Abrasivity Index	N/A	N/A
Petrographic Thin Section Analysis	N/A	N/A
Slake Durability	ASTM D4645	ASTM, 2008a
Point Load Index	ASTM D5731	ASTM, 2008b
Elastic Moduli with Compressive Strength	ASTM D7012	ASTM, 2013
Unconsolidated Undrained Triaxial Shear	ASTM D2850	ASTM, 2007b
Corrosion Suite (Sulfate, Chloride, pH, Resistivity)	CTM 417, 422 and 643	Caltrans, 2007, 2013d, and 2013e

N/A – not applicable

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Physical Setting

This section provides a brief description of the physical setting for the SR 710 North Study Area. The discussions cover general climate, topography and drainage considerations, prior land use, and human-made and natural features of engineering and construction significance. These conditions will influence the design, construction, and operation of the SR 710 North Study Alternatives.

3.1 Climate

The following climate summary was obtained from the Western Regional Climate Center (2013) Web site for the Los Angeles Civic Center (<http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca5115>), located roughly 1 mile west of the southwestern edge of the SR 710 North Study Area:

- Between April 1, 1906, and March 31, 2013, the average monthly temperature high was 83 degrees Fahrenheit (°F) occurring in the month of August; and the average temperature low was 66 °F occurring in the month of January.
- Average annual rainfall was roughly 15 inches; rainfall averages were greater than 2 inches per month in December through March, with the highest monthly rainfall average in February at 3.4 inches.

3.2 Topography and Drainage

The SR 710 North Study Area primarily consists of two areas: (1) a western half that includes Mount Washington, Monterey Park Hills, and the Montebello Hills, as well as several unnamed hills along the western edge of the San Gabriel Valley; and (2) an eastern half within the San Gabriel Valley that 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 topography of the SR 710 North Study Area is shown on Plate 2.

- **Western Area:** The western half of the SR 710 North Study Area includes the Repetto Hills, a group of small hills and valleys between the Santa Monica Mountains on the west and the Puente Hills on the southeast. Elevations within the Repetto Hills range from approximately 870 feet between Monterey Road and SR 110, to 200 feet at the western toe of the hills near Rosemead Boulevard. The San Rafael Hills are located between the Repetto Hills and the Verdugo Hills, and border the SR 710 North Study Area on the northwest. Elevations in the San Rafael Hills portion of the SR 710 North Study Area range from approximately 1,000 feet near SR 134 and Arroyo Seco, to 600 feet in the vicinity of SR 110 and the Arroyo Seco.
- **Eastern Area:** The eastern half of the SR 710 North Study Area 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 (Lamar, 1970). 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 repeated displacements by the Raymond fault.

Major drainages in the SR 710 North 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 20,000 years ago). The SR 710

North Study Area and surface water features are shown in Figure 3-1. Rainfall runoff from the ground surface flows into drainage structures and alluvial soils.

3.3 Prior Land Use

Portions of the SR 710 North Study Area have been developed since the 1800s. Past site usage is addressed in the Phase I Initial Site Assessment (ISA) (CH2M HILL, 2014a).

3.4 Human-Made and Natural Features of Engineering and Construction Significance

Abundant developments are present within the SR 710 North Study Area including residential, commercial, and industrial properties, as well as associated improvements such as roadways, sidewalks, and utilities. See Sections 8.1, 9.1, 10.1, and 11.1 for a summary of the features of engineering and construction significance to the SR 710 North Study Alternatives.

Geologic Setting

The data sources discussed in Section 2 were used to describe the general geologic setting in the SR 710 North Study Area. The description includes regional geology, active and potentially active faulting, and seismicity. This section also identifies potential seismic hazards within the SR 710 North Study Area. These potential hazards could result in loading conditions that would affect the design and operations of the BRT, LRT, and Freeway Tunnel Alternatives.

4.1 Regional Geology

The SR 710 North Study Area encompasses portions of the San Gabriel Valley, the southern San Rafael Hills, the Elysian Hills, and the Repetto Hills. 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. The regional geology is particularly relevant to methods that will be used to tunnel through the formations, as well as to long-term operational issues related to tunnels. Regional geology also defines the seismic environment within the SR 710 North Study Area.

4.1.1 Stratigraphy

Regional geologic maps (Lamar, 1970; CGS, 2012; Dibblee, 1989a, 1989b, 1991, 1998, and 1999; Yerkes and Campbell, 2005; Morton and Miller, 2003) indicate that the SR 710 North Study Area is underlain by nonmarine Quaternary-age (approximately less than 2 million years old) alluvium, marine Tertiary-age (approximately 2 to 16 million years old) sedimentary rocks, and Cretaceous and Pre-Cretaceous (120 to 160+ million years old) crystalline basement complex of igneous and metamorphic rocks. Table 4-1 presents the generalized stratigraphic column specific to the study area and lists the formations in vertical sequence from youngest to oldest. The primary geologic units making up the stratigraphic column include:

- Quaternary-age alluvium consisting of silt, clay, sand, and gravels with scattered cobbles and boulders.
- Tertiary-age sedimentary rocks underlying the alluvial deposits. The Tertiary-age rocks crop out in the 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. The Fernando Formation overlies the Puente Formation with both conformable and unconformable contacts, and the Puente Formation unconformably overlies the Topanga Formation.
- Tertiary-age formations and/or Quaternary-age alluvium are underlain by basement complex rocks in the northern portion of the SR 710 North Study Area. These basement complex rocks are composed of Cretaceous and pre-Cretaceous igneous intrusive rocks (diorite, quartz diorite, and quartz monzonite). These igneous rocks commonly have weak secondary metamorphism in the form of aligned dark minerals (foliation). The basement complex rocks contain pre-Cretaceous metamorphic rocks (for example, gneiss).

Rock quality designations (RQD) are included on the boring logs prepared for this study and the SR 710 Tunnel Technical Study (CH2M HILL, 2010), see Appendix A. There is a wide range of RQDs observed along the Alternatives. RQD values provided are based on the sum of intact core pieces that were 4 inches or greater in length between 2 natural discontinuities. Core discontinuities created as a result of the drilling process (drill breaks) are not considered in determination of the RQD. The majority of core samples obtained during the SR 710 North Study are soft and weak and commonly do not meet the “sound core” definition for the ASTM International standard RQD method (ASTM D 6032). However, these RQD values can provide a useful indication of the overall rock quality. There are numerous factors that affect the RQD, including: the proximity of the borehole to faults (both active and inactive), resultant shears and fractures, and bedding/foliation separation and spacing. The low RQD values observed in the borings drilled along the Freeway Tunnel and LRT Alternatives are a result of the presence of active and inactive faults in proximity to the borings, and the bedding plane separations and spacing within the Puente and Topanga Formations.

The subsections following Table 4-1 summarize the characteristics of the geologic formations encountered within the SR 710 North Study Area. The bedrock descriptions presented in this section (including rock hardness and bedding spacing) are based on the Caltrans *Soil and Rock Logging, Classification, and Presentation Manual*, 2010 Edition (Caltrans, 2010). The surficial distribution of earth units within the SR 710 North Study Area is shown in Plate 2.

TABLE 4-1
Study-Specific Stratigraphic Column

Geologic Unit/ Formation Name	Map Symbol (Plate 2)/ Cross Section Symbol (Plates 3, 4, 8, and 9)	Geologic Epoch (Period)	Approximate Age (Years)	Generalized Description
Young Alluvium	Qw, Qf, Qyf, Qya / 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	Qof, Qoa, Qvoa / Qal	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 Formation	Tss, Tsh / Tfcg, Tfsl	Pliocene (Tertiary)	2 to 5 million	Predominantly claystone, siltstone, and mudstone, with some sandstone and conglomerate. Marine deposits.
Puente Formation (includes Monterey, Modelo, and an Unnamed Shale)	Tss, Tsh / Tpss, Tpsl	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 Formation	Tss, Tsh / Tt, Ttsl	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, Wilson Quartz Diorite	Gr / Wqd	Cretaceous and Pre Cretaceous	120 to 160+ million	Crystalline igneous rocks (diorite, quartz diorite, monzonite, foliated igneous rocks) and layered metamorphic rocks (gneiss).

4.1.1.1 Quaternary (Young and Old) Alluvium

Quaternary alluvial materials are encountered throughout the SR 710 North Study Area. The alluvial materials consist of interbedded lenses and/or discontinuous layers of fine-grained sediment (clay and silt) and coarse-grained materials (sand and gravel) that generally increase in strength with depth. These materials are generally divided into Young and Old Alluvium.

- The Young Alluvium is limited to shallow depths in active drainage channels that currently carry runoff across the area. This includes the drainage (Dorchester Channel) that is located along the existing SR 710, generally south of Valley Boulevard.
- The Old Alluvium crops out at the surface as alluvial fans and uplifted terrace deposits dissected by the active drainage channels. Old alluvial materials also underlie Young Alluvium and are observed at deeper depths.

Hard to very hard cobble-size rocks are common within the Young and Old Alluvium; some hard to very hard boulders also may be scattered throughout the unit. Within the Old Alluvium, the cobbles and boulders are moderately hard to hard, and much



Exhibit 4-1. Alluvium. The three cores show a variety of sandy and gravelly alluvium. The core on the left is coarse sand and fine gravel; the core in the middle is coarse gravel; the core on the right is sand and gravel.

more weathered than in the Young Alluvium. Exhibit 4-1 shows alluvial material encountered in the SR 710 North Study Area.

From a geologic perspective, the alluvial soils are considered unconsolidated because the soils lack cementation typically associated with rock formations. 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 erosion into older deposits. Based on the previous field exploration program (CH2M HILL, 2010), shear-wave velocities range from 450 to 1,820 feet per second (ft/sec) within the upper 50 feet of the tested alluvium, and from 580 to 3,140 ft/sec for tested depths greater than 50 feet.

Lamar (1970) has mapped the alluvial soils located north of the Raymond fault as Terrace Deposits. Based on the data reviewed during the SR 710 North Study, there is a noticeable difference in composition of the alluvial soils north and south of the Raymond fault. In general, the soils south of the fault have a higher fines constituent and a lesser coarse-grained constituent versus the alluvial soils north of the fault. The laboratory test summary and gradation curves of the alluvial soils are presented in Appendix D.1.

4.1.1.2 Fernando Formation

The Siltstone and Conglomerate Members of the Pliocene-age Fernando Formation are present within the SR 710 North Study Area.

- The Siltstone Member consists primarily of dark gray to black, massive, very soft to moderately soft, marine claystone and siltstone. Scattered, hard concretions and very thin to thin hard layers, occur within the Siltstone Member. The Siltstone Member grades upward into the white-to-brick red Conglomerate Member, which is composed of 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. Exhibit 4-2 shows Fernando Formation siltstone encountered in the SR 710 North Study Area.
- The gravel- to cobble-sized rocks of the Conglomerate Member consist of moderately hard to hard, well-rounded igneous rocks and up to 40 percent angular fragments of hard sandstone, limestone, and shale similar to the underlying sedimentary rocks in the area. The Conglomerate Member is fine- to coarse-grained, poorly consolidated, massive, very soft to moderately soft, and micaceous with scattered gravel-sized moderately hard to hard-rocks.

The Fernando Formation overlies the Puente Formation with both conformable and unconformable contacts. According to Lamar (1970), the Siltstone Member and Conglomerate Member can be over 4,300 and 1,500 feet thick, respectively. Due to the limited exposure of the Conglomerate Member in the SR 710 North Study Area, sufficient samples of the unit were not available for laboratory testing during the previous or current studies. The preliminary engineering properties of the Fernando Formation Siltstone Member are estimated based on laboratory and in situ test results. According to the Technical Study (CH2M HILL, 2010), the shear wave velocity of the Siltstone Member ranges from 900 to 1,300 ft/sec; and the initial and unload/reload shear moduli estimated from the pressuremeter tests range from 1,600 to 20,000 and from 3,600 to 32,000 pounds per square inch (psi), respectively.



Exhibit 4-2. Fernando Formation. Core from SR 710 North Study Area, showing consistent nature of the unbedded Siltstone Member.

The engineering properties of the Fernando Formation Siltstone Member, based on current and previous laboratory test results, are summarized in Table 4-2. The laboratory test summary, engineering property plots, and gradation curves are presented in Appendix D.1.

TABLE 4-2
Typical Engineering Properties of the Fernando Formation

Properties	Siltstone Member (Tfsl)	
	Maximum	Minimum
Moisture Content (%)	29	12
Dry Unit Weight (pcf)	117	92
Liquid Limit	63	44
Plastic Limit	29	17
Plastic Index	42	22
Fine Contents (%)	99	80
Unconfined Compression (psi)	533	48
Slake Durability (%)	87	0.6
Elastic Modulus (psi)	47,332	1,329
Point Load (psi)	34	11
Minimum Resistivity (ohm-cm)	1,720	269
pH	8	4.6
Sulfate Content (ppm)	3,942	21
Chloride Content (ppm)	60	20

pcf – pounds per cubic foot

psi – pounds per square inch

ohm-cm – ohm centimeter(s)

ppm – parts per million

4.1.1.3 Puente Formation

The deep-water marine rocks of the late Miocene Puente Formation are present within the SR 710 North Study Area. 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, these sedimentary rocks within the SR 710 North 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, the Puente Formation is divided into several members as follows (from older to younger): sandstone, shale, diatomaceous siltstone/shale, and siltstone units.

- The Sandstone Member consists predominantly of thickly to very thickly bedded fine-grained, very soft to moderately hard 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 consists predominantly of thinly bedded to laminated and fissile, soft to moderately hard shales with thin interbeds to laminations of fine-grained sandstone and siltstones.
- The Diatomaceous Siltstone/Shale Member is represented by thin-bedded to laminated, very soft to moderately soft diatomaceous siltstones.
- The Siltstone Member generally consists of thinly bedded to laminated, very soft to moderately hard siltstones with medium to thick interbeds to laminations of fine-grained sandstone.

Exhibit 4-3 shows Puente Formation Siltstone and Sandstone Members encountered in the SR 710 North Study Area.

The degree of weathering in these rocks decreases with increasing depth from decomposed to fresh. The rocks have locally hard to very hard, strongly cemented interbeds and concretions. These cemented zones were not over 3 feet in thickness and are not anticipated to be laterally continuous over long distances. According to Lamar (1970), the thickness of the sandstone, shale, diatomaceous siltstone, and siltstone units in the Repetto Hills is over 800, 300, 950, and 2,700 feet, respectively.

The preliminary engineering properties of the Puente Formation are estimated based on laboratory and in situ test results. According to the Technical Study (CH2M HILL, 2010), the shear wave velocity of this formation ranges from 1,300 to 3,400 ft/sec; and the initial and unload/reload shear modulus results estimated from the pressuremeter tests range from 4,000 to 56,000 and from 20,000 to 250,000 psi respectively. The engineering properties for the Puente Formation Sandstone Member and Siltstone Member, based on current and previous laboratory test results, are summarized in Table 4-3. The laboratory data summary, engineering property plots, and gradation curves are presented in Appendix D.1.

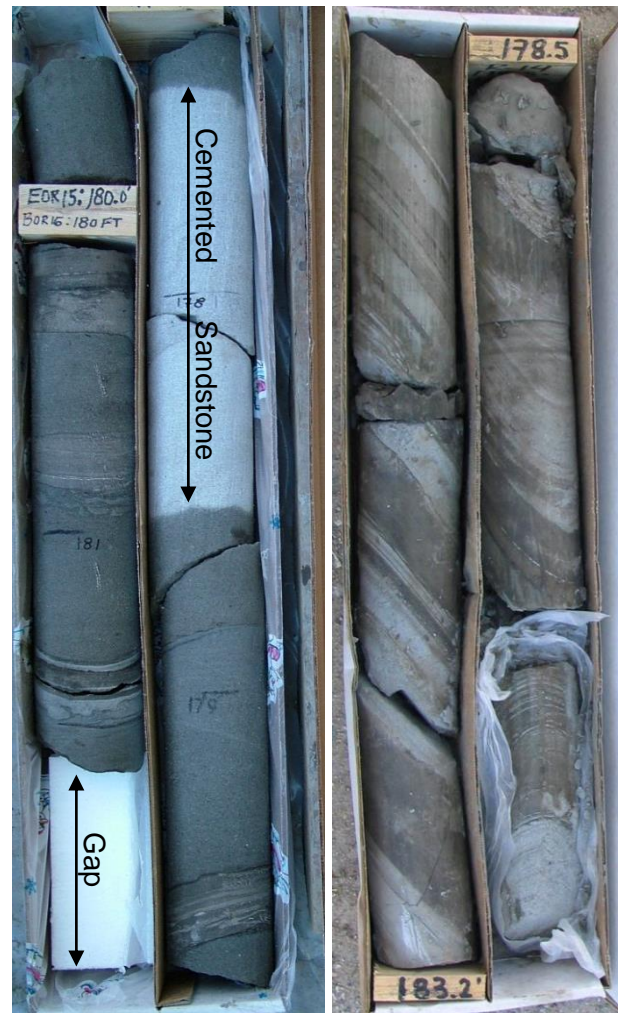


Exhibit 4-3. Puente Formation. The two cores on the left show predominantly thick bedded to thin bedded sandstone with siltstone laminations; the light gray material is hard calcareous-cemented sandstone. The two cores on the right show predominantly thin bedded to laminated siltstone and sandstone.

TABLE 4-3
Typical Engineering Properties of the Puente Formation

Properties	Sandstone Member (Tpss)		Siltstone Member (Tpsl)	
	Maximum	Minimum	Maximum	Minimum
Moisture Content (%)	26	4.5	32	16
Dry Unit Weight (pcf)	118	93	114	88
Liquid Limit	36	NP	60	47
Plastic Limit	17	NP	28	18
Plastic Index	19	NP	38	19
Fine Contents (%)	31	10	98	93
Unconfined Compression (psi)	2158	102	519	35.5
Slake Durability (%)	2.5	---	96	0
Elastic Modulus (psi)	199,000	---	31,910	1,292
Point Load (psi)	136	7	32	23
Minimum Resistivity (ohm-cm)	1154	---	2,645	343
pH	7.9	---	8	6.2
Sulfate Content (ppm)	60	---	1,156	18
Chloride Content (ppm)	61	---	76	10

NP – non-plastic

4.1.1.4 Topanga Formation

The middle-Miocene-age Topanga Formation occurs as three separate units within the SR 710 North Study Area (Lamar, 1970). These units include a lower Siltstone Member, middle Sandstone Member, and upper Conglomerate Member. The rocks of the Topanga Formation tend to be coarser-grained north of the Raymond fault.

- The Siltstone Member consists of thinly bedded to laminated and fissile, very soft to moderately hard siltstones and shales, with fine- to coarse-grained sandstone interbeds that present a rhythmically bedded sequence typical of turbidity current deposits. Beds of tuff and tuffaceous sandstones were noted in the upper portion of the unit (Lamar, 1970). The rocks of this unit are commonly very similar to those of the Siltstone Member of the Puente Formation; some geoscientists, in fact, have mapped them as Puente Formation (Dibblee, 1989a; Weber, 1980).
- The Sandstone Member consists of laminated to moderately bedded, medium- to coarse-grained, very soft to moderately hard sandstone with thin interbeds and laminations of fine-grained sandstone, siltstone, and/or shale with some conglomerate beds. Individual beds and intervals of these rocks are friable, weakly cemented, and susceptible to softening in the presence of water. Exhibit 4-4 shows the Topanga Formation encountered in SR 710 North Study Area.



Exhibit 4-4. Topanga Formation. Core on right is conglomerate with sandstone matrix; core in middle is sandstone with siltstone laminations; core on left is siltstone/ mudstone.

- The Conglomerate Member generally consists of moderately hard to 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 rock 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 cobbles and fine gravel 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.

Localized, strongly cemented, thin calcareous and siliceous concretions were reported as scattered through all units of the Topanga Formation (CH2M HILL, 2010). Additionally, scattered, strongly cemented, very thin to thin beds and lenses were reported throughout the formation. The cemented zones, layers, and concretions 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.

The preliminary engineering properties of the Topanga Formation are estimated based on laboratory and in situ test results. According to the Technical Study (CH2M HILL, 2010), the shear wave velocity of this formation ranges from 800 to 6,700 ft/sec; and the initial and unload/reload shear modulus results estimated from the pressuremeter tests range from 3,000 to 69,000 and from 3,000 to 450,000 psi, respectively. The engineering properties of the Topanga Formation Siltstone Member and Conglomerate Member, based on current and previous laboratory test results, are summarized in Table 4-4. The laboratory data summary, engineering property plots, and gradation curves are presented in Appendix D.1.

TABLE 4-4
Typical Engineering Properties of the Topanga Formation

Properties	Siltstone Member (Ttsl)		Conglomerate Member (Ttcg)	
	Maximum	Minimum	Maximum	Minimum
Moisture Content (%)	30	6	11	2
Dry Unit Weight (pcf)	137	84	154	142
Liquid Limit	59	47	---	---
Plastic Limit	31	21	---	---
Plastic Index	35	19	---	---
Fine Contents (%)	73	37	33	19
Unconfined Compression (psi)	4,898	13.2	1,243	393
Slake Durability (%)	98	14.1	66	---
Elastic Modulus (psi)	268,481	1,957	105,745	31,599
Point Load (psi)	6,960	3,936	4,176	312
Minimum Resistivity (ohm-cm)	1,600	1,287	---	---
pH	8	7.5	---	---
Sulfate Content (ppm)	58	42	---	---
Chloride Content (ppm)	120	35	---	---

4.1.1.5 Basement Complex Rocks

Bedrock within the northern part of the SR 710 North Study Area 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, 1989a; Lamar, 1970). However, these rocks comprise a wide suite of lithologies including diorite, monzonite, quartz diorite, quartz monzonite, and gneissic diorite. These are the same rocks that compose the San Gabriel Mountains north of the SR 710 North Study Area. For SR 710 North Study, this rock unit is referred to as the Wilson Quartz Diorite. Exhibit 4-5 shows quartz diorite and metamorphic rocks encountered in the SR 710 North Study Area.

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 moderately hard to hard with strengths as high as 30,000 psi, they are highly fractured. The fracture density is commonly greater than 10 fractures per foot; 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.

The preliminary engineering properties of basement complex rocks are estimated based on laboratory and in situ test results. According to the Technical Study (CH2M HILL, 2010), the shear wave velocity of this formation ranges from 1,600 to 6,700 ft/sec; and the initial and unload/reload shear modulus results estimated from the pressuremeter tests range from 5,500 to 34,000 and from 47,000 to 590,000 psi, respectively. Wilson Quartz Diorite engineering properties based on current and previous laboratory test results are summarized in Table 4-5 and in Appendix D.1.



Exhibit 4-5. Basement Rocks. Igneous and metamorphic rocks from SR 710 North Study Area. The two cores on right are weathered rocks and the two cores on left are fresh rock.

TABLE 4-5
Typical Engineering Properties of the Basement Complex Rocks

Properties	Wilson Quartz Diorite (Wqd)	
	Maximum	Minimum
RQD (%)	76	0
Moisture Content (%)	6	0
Dry Unit Weight (pcf)	162	139
Unconfined Compression (psi)	1,593	35
Elastic Modulus (psi)	2.07 E6	4,576
Point Load (psi)	4,488	11
Minimum Resistivity (ohm-cm)	11,021	1,090
pH	7.9	7.1
Sulfate Content (ppm)	225	130
Chloride Content (ppm)	226	82

4.1.2 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 SR 710 North Study Area are primarily a result of Quaternary-age folding and uplift. 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).

The faults considered capable of generating seismic activity within the SR 710 North Study Area are described in Section 4.3 and 5.3. Numerous inactive (pre-Holocene), intra-formational faults are present within the SR 710 North Study Area, as shown in the Geologic Map (Plate 2). These faults likely formed as a result of the Miocene-Pliocene tectonic regime (approximately 16 to 2 million years ago).

A northwest-southeast trending intra-formational (Puente Formation) fault has been mapped transecting the northern SR 710 terminus at Valley Boulevard by Lamar (1970). This fault is shown in the Geologic Map (Plate 2) just north of boring RC-13-005. The fault is mapped as queried by Lamar (1970) where it transects the two bedrock knobs situated northwest and southeast of boring RC-13-005. As the fault crosses Valley Boulevard, the fault is mapped as being concealed beneath the older (Pleistocene-age) alluvial soil that blankets the site. An aerial photograph evaluation conducted previously for the study area (CH2M HILL, 2010) did not reveal any lineaments or other features indicative of a fault within the alluvial soils in this area. In addition, a seismic line (Z3-G7) was conducted across the concealed trace of this fault in 2010 (CH2M HILL, 2010). The seismic line indicated the possible presence of a linear feature at depth in this area. The feature could not be traced across seismic marker beds shallower than approximately 125 feet bgs. This fault, if it exists, is considered an intra-formational fault that has not experienced movement in the Holocene Epoch. This fault, if it exists, and similar faults mapped in this area was considered by Lamar (1970) to be pre-Pliocene in age. There is no evidence that would indicate this fault has moved in the Pleistocene or Holocene, and good geologic evidence to show that it has not.

4.2 Faulting

The faults of greatest importance to the study are described below and shown in Figure 4-1. The following subsections discuss the location and activity of regional faults that could affect the project, and the characteristics of the active and potentially active faults in the SR 710 North Study Area. The discussion concludes with a summary of the fault investigation conducted during the SR 710 North Study. SR 710 North Study seismicity is discussed in Sections 4.3 and 5.3.

4.2.1 Classification of Faults within the Study Area

Three types of faults were identified during the SR 710 North Study. These involved active faults, potentially active faults, and inactive faults. Inactive faults are discussed in Section 4.1.2.

- Active Faults:** Within the SR 710 North Study Area, only the Raymond fault is identified as an active fault under the Alquist-Priolo Earthquake Fault Zone (APEQFZ) Act, which implies a potential for surface rupture (Bryant and Hart, 2007). Such a designation indicates the fault is known to have experienced surface offsets in Holocene time (the last 11,000 years) and its location is well defined. Potentially active faults may not be identified as active per the APEQFZ Act simply because their locations are not well defined and/or they have not been confirmed to have surface ruptures in Holocene time. The EPFT also occurs in the study area and is active, but is not considered capable of generating fault-induced ground rupture. An APEQFZ Act designated Earthquake Fault Zone has not been established around the EPFT Zone because its location is not well defined.
- Potentially Active Faults:** Within the SR 710 North Study Area, the San Rafael and Eagle Rock faults (see Plate 2) are considered potentially active. A potentially active fault is defined by the State of California as a fault that has experienced surface displacement within the Quaternary period (the last 1.6 million years), but has not been confirmed to have younger Holocene displacements (Bryant and Hart, 2007). Additional detailed investigation will be required to adequately characterize the recency of activity of the San Rafael and Eagle

Rock faults. For planning purposes, the Eagle Rock and San Rafael faults are considered active, as discussed in the Fault Rupture Evaluation Technical Memorandum for this project (CH2M HILL and ECI, 2013), which is included in Appendix E of this report.

As a part of the SR 710 North Study, a fault investigation was conducted, designed to collect data that would aid in evaluating the location and activity of the Raymond, Eagle Rock, and San Rafael faults in the SR 710 North Study Area, as discussed in Section 4.2.5.

4.2.2 Nearby Active and Potentially Active Regional Faults

The characteristics of nearby active and potentially active regional faults are summarized in the following four sections. These faults serve as sources of ground shaking. Although they do not represent fault rupture hazard to the SR 710 North Study Alternatives, they will affect the level of seismicity that could occur during operations, and therefore are an important consideration to project design.

4.2.2.1 Transverse Ranges Southern Boundary Faults – Malibu Coast, Santa Monica, and Hollywood Faults

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 Transverse Ranges Southern Boundary faults (SCEC, 2001), consists primarily of the Malibu, Santa Monica, Hollywood, and Raymond faults. Although the Raymond fault is included in this fault system, considering the importance of the Raymond fault to the SR 710 North Study Area, the Raymond fault is discussed separately in Section 4.2.3.1.

The Santa Monica Mountains, which form the southern edge of the fault system, 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 (Meigs et al., 1999). Earthquake focal mechanisms and local geologic relationships suggest about equal amounts of reverse faulting with a left-lateral component. It is uncertain whether this is accomplished by strain partitioning on separate faults or oblique slip on one dominant fault.

The Hollywood, Santa Monica, and Malibu faults also have been shown to have ruptured the ground surface within the past 11,000 years, and all have a similar left-lateral reverse sense of slip. Paleoseismic studies of the Hollywood and Santa Monica faults (Dolan et al., 1997, 2000a, and 2000b) suggest that these two faults have recurrence intervals of about 10,000 years, but the Santa Monica fault last broke 1,000 to 3,000 years ago, and the Hollywood fault last ruptured 6,000 to 9,000 years ago. Studies of the Malibu fault also identify it as having Holocene displacements with a recurrence interval of 4,000 to 5,000 years (Drumm, 1992).

The great length of the Transverse Ranges Southern Boundary fault system suggests that the fault is capable of generating a large earthquake (approximately 7.5 magnitude), but the discontinuous nature of faulting and the lack of temporal correlation of the most recent paleoseismic events suggest that the individual fault segments behave independently at least some of the time. Based on their individual lengths, 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 (M_w = earthquake moment magnitude). The earthquake recurrence interval is very long and could be more than 10,000 years. In addition, documented slip rates are only about 0.5 millimeters per year (mm/yr), but this estimate suffers from lack of data and similar inconsistencies between slip accumulation and the timing of its release. Even at 0.5 mm/yr, a 10,000-year recurrence interval would require the release of 5 meters of accumulated strain per earthquake, a value that appears to be improbable, and which leads to concerns that either the slip rate is too high or the earthquake recurrence is more frequent. Caltrans (2013b) assumes a slip rate of 0.3, 1.0, and 0.9 mm/yr and a maximum moment magnitude (M_{max}) of 6.6, 7.0, and 6.6 for the Malibu Coast, Santa Monica, and Hollywood faults, respectively.

The slip kinematics of the Malibu Coast, Santa Monica, and Hollywood faults are similar to the Raymond fault; that is, dominantly left-lateral with a north side up reverse component, which is why they are frequently considered as individual parts of a larger fault system. Currently, the collected paleoseismic data for these faults do not support temporally coincident ruptures, although the data set is small. For analysis purposes, however,

these faults could still be considered as rupturing together with the Raymond fault in various rupture scenarios (CH2M HILL and ECI, 2013)

4.2.2.2 Puente Hills Thrust Fault System

The Puente Hills Thrust fault system is the name currently given to a series of northerly dipping, blind, subsurface thrust faults extending approximately 40 to 45 kilometers (km) along the eastern margin of the Los Angeles Basin. Shaw and Shearer (1999) synthesized oil company data and seismicity to interpret three discrete thrust fault segments underlying the La Brea/Montebello Plain (Los Angeles Segment), Santa Fe Springs Plain (Santa Fe Springs Segment), and Coyote Hills (Coyote Hills Segment). These faults form an en-echelon arrangement from the northern Los Angeles Basin to the southern part of the Puente Hills.

A down-dip projection of the Santa Fe Springs Segment (see Figure 4-2) of the Puente Hills faults extends to the approximate area of the 1987 Whittier earthquake hypocenter, which Shaw and Shearer (1999) relocated to about 16 km in 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 transferred from one segment to the next. Using empirical data on rupture area, magnitude, and coseismic displacement, Shaw et al. (2002) estimated a potential for earthquakes of M_w 6.5 to 6.6 for individual segments, and 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. Caltrans (2013b) assumes a slip rate of 0.9 mm/yr and a M_{max} of 6.9 for the Puente Hills fault – Los Angeles section (the closest segment to the SR 710 North Study Area as shown in Figure 4-2).

The exact geometry and location of the Puente Hills fault system is unclear. The fault system may extend north and underlie the entire SR 710 North Study Area. 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.

4.2.2.3 Alhambra Wash Fault (Elsinore Fault Zone-Whittier Segment)

The Alhambra Wash fault is a short northwest-southeast-trending fault in the southern part of the San Gabriel Valley. The fault is mapped from near SR 60 on the southeast to San Gabriel Boulevard on the northwest (CDMG, 1991; Treiman, 1991; Bullard and Lettis, 1993). This portion of the fault is designated as an APEQFZ and, therefore, is considered to be active.

Several investigators (Yerkes and Campbell, 2005; Dibblee, 1999) have mapped their interpretation of the fault to continue northwest of San Gabriel Boulevard past I-10 into the city of Alhambra and further northwest. 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.

Gath et al. (1994) estimated right-lateral, northeasterly dipping normal oblique slip with a minimum lateral slip rate of about 0.1 to 0.2 mm/yr and a vertical slip rate of about 0.08 mm/yr for the Alhambra Wash fault. The potential for surface displacement on the Alhambra Wash fault is poorly known and 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 M_{max} of an event on the Alhambra Wash fault could be about 6.25, though it is unlikely to rupture separately from the Whittier fault.

The Alhambra Wash fault is not included in the Caltrans (2013b) fault database. However, the Alhambra Wash fault is believed to be a northerly extension of the Elsinore fault zone – Whittier segment. The Whittier segment is a roughly 40-km-long, northeasterly dipping, northwest-southeast-trending, right-lateral strike-slip fault with a minimum slip rate of about 2.5 mm/yr (Gath, et al., 1992; SCEC, 2013a). Caltrans (2013b) assumes the same slip rate of 2.5 mm/yr and a M_{max} of 6.9 for the Whittier segment of the Elsinore fault zone.

4.2.2.4 Additional Active Regional Faults

Three other active fault systems have been recognized in the general Los Angeles basin area. These faults contribute to the overall seismicity of the area.

- The Newport-Inglewood fault zone is a roughly 75-km-long, northwest-southeast-trending, right-lateral strike-slip fault with local reverse slip (SCEC, 2013b). The Newport-Inglewood fault is mapped extending from central Orange County near the coast, to near the foothills of the Santa Monica Mountains in the

Westwood/Beverly Hills area (USGS, 2010). Caltrans (2013b) assumes a slip rate of 1.0 mm/yr and a M_{max} of 7.2 for the Newport-Inglewood fault zone.

- The Sierra Madre fault zone is a roughly 75-km-long, east-west- to northwest-southeast-trending reverse fault (SCEC, 2013c). The Sierra Madre fault is located near the southern toe of the San Gabriel Mountains. Movement along this fault, and the San Andreas fault, located near the northern toe of the San Gabriel Mountains has resulted in the ongoing uplift of the San Gabriel Mountains. Tucker and Dolan (2001) measured a minimum reverse offset of 4 meters in the last event, yielding a reverse slip rate of 0.9 mm/yr with more than 8,000 years since the last rupture. These results imply over 7 meters of accumulated strain, which would result in a M_{max} greater than 7.5 earthquake if released in a single event. Caltrans (2013b) assumes a slip rate of 2.0 mm/yr and a M_{max} of 7.2 for the Sierra Madre fault zone (Strands B and C).
- The Clamshell-Sawpit fault is a roughly 18-km-long, southwest-northeast-trending reverse fault (SCEC, 2013d), that may have been the source for the 1991 M_{max} 5.8 Sierra Madre earthquake (Hauksson, 1994). It is thought to serve as a boundary between two segments of the Sierra Madre thrust (Hauksson, 1994). The Clamshell-Sawpit fault is mapped near the northeastern end of the Raymond fault, within the Angeles National Forest, north of the Monrovia area (USGS, 2010), and may represent the eastern end of the Raymond fault. Caltrans (2013b) considers the Clamshell-Sawpit fault to be a splay of the Sierra Madre fault zone, and assigns a slip rate of 0.5 mm/yr and a M_{max} of 6.6 for the Clamshell-Sawpit splay.

4.2.3 Active Faults within the SR 710 North Study Area

Two active faults have been identified within the SR 710 North Study Area. These include the Raymond fault and the EPFT. Where active faults cross an Alternative, the potential magnitude and consequence of fault rupture is a critical consideration to project design, particularly if the active fault crosses a tunnel. In this case, specific provisions are required to ensure that potential fault rupture does not result in collapse of the tunnel section, where the crossing occurs.

4.2.3.1 Raymond Fault

One of the major faults with regard to the SR 710 North Study Area is the Raymond fault (also known as the Raymond Hill fault); the location of this fault is shown in Plate 2. 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. The length of the fault is roughly 19 to 25 km, depending on which interpretation is accepted. The fault forms a gentle arc, convex toward the south across the alluvial deposits of the San Gabriel Valley, potentially joining with the Clamshell-Sawpit fault at the base of the San Gabriel Mountains to the east and the Hollywood fault to the west. The fault is best expressed in the area of San Marino to South Pasadena, 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 (Chapman and Chase, 1979). However, the westerly continuation of the Raymond fault into the Los Angeles River floodplain is uncertain and the earthquake/rupture histories are very different (Weaver and Dolan, 2000). Others (such as Dolan et al., 1995) have suggested that the Raymond fault may be a tear fault associated with the uplift of the Verdugo Hills via the Eagle Rock and/or San Rafael faults. A discussion of potential rupture scenarios is presented in the Fault Rupture Evaluation (CH2M HILL and ECI, 2013) included in Appendix E.

The most recent major surface rupture on the Raymond fault occurred in Holocene time, most likely around 2,000 years ago but potentially as long as 6,000 years ago (Crook et al., 1987; Weaver and Dolan, 2000). The average recurrence interval for surface rupturing events may be about 3,300 years (Weaver and Dolan, 2000), though temporal clustering has been proposed to both shorten and lengthen that recurrence interval.

The Raymond fault is a north-dipping, east-west-trending fault that has a dominant left-lateral sense of offset (Jones et al., 1990; Weaver and Dolan, 2000), though some north-side-up reverse slip is also likely. The percentage of lateral to vertical slip varies along the trace of the fault; it has been estimated at about 5:1 lateral to vertical (L:V) ratio (see Appendix E).

Currently, there is little consensus on the rate of slip for the Raymond fault. Geological trenching studies across the fault scarp indicate average slip rates between 0.5 and 2.0 mm/yr (Dolan et al., 2000a; SCEC, 2013e). More recently, the rate of slip has been estimated to be as high as 4 +1/-0.5 mm/yr (Yeats, 2012) based on a regional modeling study (Walls et al., 1998).

As discussed above, there remains considerable inconsistency in the published data for the Raymond fault. Caltrans (2013b) currently assumes a slip rate of 2.0 mm/yr and a Mmax of 6.7 for the Raymond fault zone; implying a recurrence interval of 250 to 500 years with an offset of 0.5 to 1.0 meter per event. Additional discussion regarding the various scenarios involving the Raymond fault is presented in the Fault Rupture Evaluation Technical Memorandum (CH2M HILL and ECI, 2013), which is included in Appendix E. See Section 4.2.5 for a discussion of the SR 710 North Study fault investigation as it relates to the Raymond fault. The Raymond fault is mapped crossing the TSM/TDM (Improvements I-18 and T-2), BRT, LRT and Freeway Tunnel Alternatives, as shown in Plate 2.

4.2.3.2 Elysian Park Fold and Thrust Belt (EPFT)

The EPFT was initially described by Davis et al. (1989) who postulated that the Los Angeles area is underlain by a series of deep master detachment faults, probably of Miocene age, and that most of the Quaternary uplift in the region is caused by reverse slip along the reactivated detachments. This north-south convergence results in blind-thrust faulting with folding at bends and kinks in the detachment fault, expressed at the surface as a series of east-west oriented hills. The 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 Blind Thrust (UEPBT).

As shown in Figure 4-3, the concealed trace of the UEPBT has been mapped just north of the I-710/I-10 interchange. The UEPBT is theorized to be bound by the Hollywood fault to the northwest and the Alhambra Wash fault (the northerly extension of the Elsinore/Whittier fault zone) to the southeast (Oskin et al., 2000; Shaw et al., 2002). The UEPBT has been modeled dipping to the north at angles ranging from 30 to 60 degrees from horizontal (Oskin et al., 2000); the actual dip of the fault is unknown at this time.

Shaw and Suppe (1996) estimated earthquake magnitudes associated with these seismic events on the UEPBT ranging from 6.6 to 7.3, with recurrence intervals in the range of 340 to 1,000 years. The CGS, following the lead of Oskin et al. (2000), models the UEPBT as a feature about 18 km long and dipping 50 degrees northeasterly with a slip rate estimate of approximately 1.3 ± 0.4 mm/yr. Caltrans (2013b) assumes a slip rate of 1.9 mm/yr and a Mmax of 6.6 for the UEPBT.

Because the UEPBT does not extend to the surface, it does not meet the criteria of having a well-defined location, a requirement to be considered an active fault as defined by the State of California (Bryant and Hart, 2007). However, movements along the UEPBT have resulted in local coseismic deformation at the surface. Oskin et al. (2000) have identified numerous folds and escarpments (some of which are visible at the surface) that have formed as a result of movement along the UEPBT. As shown in Figure 4-3, these features have been mapped in the area generally south of York Boulevard in northeast Los Angeles, north of SR 60 in East Los Angeles, west of Rosemead Boulevard in the Whittier Narrows area, and east of Van Ness Avenue in the Hollywood area. Of these features, the Coyote Pass escarpment (Figure 4-3) is considered to be the feature of most concern (Oskin et al., 2000). Investigations following the 1994 Northridge earthquake found ground deformation on structures geomorphically similar to the Coyote Pass Escarpment (Hart et al., 1995; Treiman, 1995). The uplift caused by the Northridge blind thrust produced folding, minor (bending moment) faulting, and fracturing of the

ground surface along the northeast flank of the Pico Anticline near Newhall, California. Here, investigators found up to 19 centimeters (7.5 inches) of vertical offset along faults and tensional surface fracturing (Treiman, 1995).

The Coyote Pass escarpment transects the Freeway Tunnel Alternative just north of Floral Drive, and the LRT Alternative in the vicinity of Corporate Center Drive and Corporate Center Place, just east of I-710 in Monterey Park. The very eastern end of the escarpment is mapped transecting the BRT Alternative in the vicinity of Brightwood Street, also in Monterey Park. A deformation study on the Coyote Pass escarpment was conducted at the intersection of Soto Street and First Street in Los Angeles for the Metro Gold Line Soto Station, a subterranean LRT station (ECI, 2001). The Soto Station is located at the toe of the Coyote Pass escarpment. The station is roughly 2.5 miles west of where the escarpment crosses the SR 710 North Study LRT Alternative and 4 miles west of the BRT Alternative. The ECI (2001) study indicated that deformation at the Coyote Pass escarpment (at the Soto Station) has a recurrence interval of 2,800 to 3,900 years; however, no data were available to constrain the timing of the most recent event. Each event was estimated to result in uplift of approximately 60 to 85 centimeters, yielding tightening of the synclinal fold hinge of 0.21 to 0.43 degrees per event. This deformation would result in an estimated 0.3 percent volumetric compressive strain along the axis hinge line over an area approximately 8 meters wide; a second scenario indicated a 0.1 percent volumetric strain along the axis hinge line over an area approximately 23 meters wide (ECI, 2001). The top of the escarpment would also experience uplift, differential tilting, and extensional strains during a UEPBT event. Although this deformation was not quantified by ECI (2001), it would presumably be similar in magnitude to deformation across the synclinal axis, though extensional and potentially more broadly dispersed.

Although the ECI study was 2.5 to 4 miles west of the Build Alternatives, the deformations estimated by ECI (2001) can be hypothesized as also occurring at the Build Alternatives at the Coyote Pass escarpment. Several additional folds related to the UEPBT have been mapped transecting the BRT, LRT, and Freeway Tunnel Alternatives, as shown in Figure 4-3. Based on the available data, it appears that these folds also experience coseismic deformation during an event on the UEPBT; however, the rate of deformation is substantially less than that discussed above for the Coyote Pass escarpment. Bullard and Lettis (1993) indicate that fold deformation has migrated to the south since the late Tertiary (roughly 5 million years ago). This southerly migration indicates that folds present north of the Monterey Park and Montebello Hills are subject to substantially less deformation than those south of the hills. This concurs with the findings of Oskin et al. (2000), which identify the Coyote Pass escarpment (located at the southerly toe of the Monterey Park Hills) as the feature of primary concern. Although minor coseismic deformation may occur on the folds north of the hills, the amount of deformation at or near the surface (if any) would be substantially less than that of the Coyote Pass escarpment.

4.2.4 Potentially Active Faults within the SR 710 North Study Area

The potentially active faults that have been identified within the SR 710 North Study Area are the Eagle Rock and San Rafael faults. Although the risk of a rupture on these faults may be lower than the active faults described above, the potential for fault-induced ground rupture cannot be ruled out. As shown in Plate 2, the San Rafael fault crosses the TSM/TDM, BRT, LRT, and Freeway Tunnel Alternatives, and the Eagle Rock fault crosses only the Freeway Tunnel Alternative. As such, the location and potential for movement along these faults represent important design considerations.

Existing geologic maps (Lamar, 1970; Dibblee, 1989a and 1989b; Yerkes and Campbell, 2005; City of Pasadena, 2002) 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 San Rafael 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, similar to that shown in Plate 2. The Eagle Rock and San Rafael faults do not extend across the Raymond fault but appear to join with it in a relationship that is not well understood. Some

transfer of strain between the Raymond and Verdugo faults may be accommodated along the Eagle Rock and San Rafael faults.

The Eagle Rock/San Rafael fault is generally considered to be the southern continuation of the Verdugo fault (Yeats, 2004). No paleoseismic studies have been published for the Verdugo fault. The Eagle Rock/San Rafael fault zone also has no quantitative investigations, though all three faults are considered to be potentially active. Caltrans classifies the Eagle Rock and San Rafael faults as one fault and as a continuation of the Verdugo fault. According to the Caltrans (2013b) fault database, the Verdugo/Eagle Rock fault is estimated to have a slip rate of 0.6 mm/yr and a M_{max} of 6.8.

The Eagle Rock and San Rafael faults seem to merge just west of Raymond Hill; it is possible that Raymond Hill is being elevated as a result of this strain transfer between the San Rafael and Raymond faults. However, a joint rupture involving these faults cannot be a common event, because the tectonic geomorphology of the Eagle Rock/San Rafael fault is much less developed than that of the Raymond fault, suggesting it has a lower slip rate or longer recurrence interval to refresh it on the landscape. Despite this observation, the tectonic geomorphology of the Raymond fault is much better developed east of Arroyo Seco, near its intersection with the Eagle Rock/San Rafael faults. No data have been published to confirm or refute the presence of Holocene-age offsets on the Eagle Rock/San Rafael faults, nor on the Verdugo fault farther northwest.

Based on the SR 710 North Study, the locations of the Eagle Rock and San Rafael fault where they cross the alternatives are shown in Plates 2, 3, 4, 8 and 9 and Figure 4-3. The San Rafael Fault is mapped crossing the TSM/TDM (Improvements L-1 and T-2), BRT, LRT and Freeway Tunnel Alternatives, as shown in Plate 2 (and Plates 3 and 8 and 4 and 9 for the LRT and Freeway Tunnel Alternatives, respectively). The Eagle Rock Fault is mapped crossing the Freeway Tunnel Alternative, as shown in Plates 2, 4, and 9. The fault locations shown in Figures 4-1 and 4-2 are generalized, based on the regional mapping studies referenced on the figures.

Additional discussion regarding the various fault scenarios involving the Eagle Rock and San Rafael faults is presented in the Fault Rupture Evaluation Technical Memorandum prepared for the project (CH2M HILL and ECI, 2013), which is included in Appendix E. See Section 4.2.5 for a discussion of the SR 710 North Study fault investigation as it relates to the Eagle Rock and San Rafael faults.

4.2.5 SR 710 North Study Fault Investigation

The CH2M HILL team, led by ECI, conducted an investigation to study the Raymond, Eagle Rock, and San Rafael faults and their potential effects on the SR 710 North Study Alternatives. There was substantial uncertainty as to the detailed locations of these faults. In addition, it was unknown whether the Eagle Rock and San Rafael faults are active. Due to these uncertainties, a field investigation was conducted to aid in constraining the locations and activity of these faults. Prior to determining the locations of the proposed explorations, a review of the limited available data on these faults was conducted (see references listed in Section 13). The following summarizes the findings and conclusion of the fault investigation; detailed findings can be found in the SR 710 North Study Fault Investigation Technical Memorandum in Appendix G.

4.2.5.1 Fault Investigation Methodology

Twelve borings were conducted during the SR 710 North Study to evaluate faulting, as described in Section 2.4. The locations of these borings are shown in Plates 1 through 4; detailed logs of the borings are included in Appendix A.1.

To aid in constraining the location of the Raymond, Eagle Rock, and San Rafael faults, geologic cross sections were developed using the exploration data obtained from the current and previous SR 710 North Study Area investigations. The cross sections follow the centerlines of the LRT Alternative (Plate 3) and Freeway Tunnel Alternative (Plate 4) in the area of the faults in question. The borings were projected onto the cross sections parallel to the local structural grain based on information from published geological maps (Lamar, 1970; Dibblee, 1989a and 1989b; Weber, 1980). Between borings, correlations were made along the sections utilizing laterally continuous horizons including the alluvial/bedrock contact, distinctive packages of fine- and coarse-grained alluvium, and pedogenic soil development within the alluvium. The continuity of groundwater levels

between borings along the sections was also utilized. Discontinuities in these correlated markers were utilized to identify potential fault locations.

Given the wide spacing between some borings (see Plates 3 and 4), additional information to constrain fault locations was considered, including faults or shear zones documented during previous explorations, tectonic scarps at the ground surface, and previous surficial mapping by others (Lamar, 1970; Dibblee, 1989a and 1989b; Weber, 1980). Where the location of a fault could not be well constrained, a zone of uncertainty was established around the fault location at tunnel depth, as summarized below and as shown in Plates 3 and 4. The horizontal zones of uncertainty indicated were established from the center of the proposed LRT and Freeway Tunnels. Fault dips were based on information from published maps and reports. For faults that cross the section obliquely, the apparent dip of the fault was indicated on the sections.

4.2.5.2 Fault Investigation Findings

The following conclusions were reached based on the investigation of the active and potentially active faults in the SR 710 North Study Area. These conclusions include a horizontal zone of uncertainty assigned to each fault crossing for the LRT and Freeway Tunnel Alternatives.

- **Raymond Fault:** As detailed in Appendix G and shown in Plates 3 and 4, a combined horizontal zone of uncertainty of about 240 feet is established for the three Raymond fault strands anticipated at tunnel depth (fault zone width is anticipated to be similar along both the LRT Tunnel and Freeway Tunnel). Most of this uncertainty (nearly 190 feet) is due to a lack of information on the location of an inferred southern strand of the Raymond fault. A pronounced scarp present at the surface between borings ES-1 and A-13-025 is used to constrain the width of active faulting. Based on this, a horizontal zone of uncertainty of about 70 feet is assigned to the two northern Raymond fault strands at tunnel depth. Variations of the alluvial/bedrock contact north of the Raymond fault zone (see Plates 3 and 4) have been interpreted based on the available data. These variations could be fault induced; if so, the tunnels could intersect additional fault strands for an additional 200 feet north of the main fault zone. However, it is unlikely that the zone of active faulting would extend that far north. Based on geomorphology, it is assumed that the most southerly strand, as shown in Plates 3 and 4, is not active.
- **Eagle Rock Fault:** As shown in Plate 4, the Eagle Rock fault is interpreted to die out or merge with the Raymond fault west of Fair Oaks Avenue. As such, the Eagle Rock fault would not cross the LRT Alternative. The mapped trace of the Eagle Rock fault (see Plate 2) projects onto the Freeway Tunnel Alternative in the vicinity of Highland Street (just south of boring ES-2, as shown in Plate 4). This generally correlates with the surface projection of a “probable major fault” observed in boring ES-2. The distance between explorations in the vicinity of the Eagle Rock fault is too wide to speculate about the activity of the fault. As such, a queried fault offset at the alluvial/bedrock has been mapped, indicating that the fault could be late Quaternary active. No surficial scarps are present at the projected Eagle Rock fault location. Additional faults and shear zones were observed within boring ES-2, and could be the expression of the Eagle Rock fault splaying into multiple minor fault strands as it dies out to the southeast. Based on the currently available information, an asymmetrical horizontal zone of uncertainty approximately 85 feet wide has been established along the Eagle Rock fault; this zone would encompass the additional faults and shear zones observed in boring ES-2.
- **San Rafael Fault Zone:** As shown in Plates 2, 3, and 4, the San Rafael fault zone is mapped as having a main strand and two potential secondary strands. East of the Arroyo Seco and west of the Freeway Tunnel Alternative, the strands splay from the main trace of the San Rafael fault. As shown in Plates 2, 3, and 4, the mapped surficial trend of the strands splay out toward the southeast. As such, the San Rafael fault zone may affect a larger cross sectional area of the LRT Alternative compared to that of the Freeway Tunnel Alternative. However, similar to the Eagle Rock fault, there are limited data available to evaluate the San Rafael fault zone.
 - Between borings R-09-Z3B3 and A-13-017 bedrock changes from Wilson Quartz Diorite to Topanga Formation and the alluvial/bedrock contact rises in elevation by over 80 feet. The same relation in bedrock exposures in the Arroyo Seco, approximately 3,700 feet to the northwest (along the trend of the faults) marks the main trace of the San Rafael fault. As such, the main strand of the fault is mapped

between these two borings. Continuity of fine-grained alluvial units between boring A-13-017 and borings to the north and south suggests the main San Rafael strand does not disturb the upper roughly 30 feet of alluvium. Although no quantitative age dating of alluvium was done for the SR 710 North Study Area, the soil development in the alluvium suggests the upper alluvial surface is pre-Holocene. A lack of continuity of deeper alluvial units between borings could be the result of faulted alluvium, or lateral facies changes. The zone of uncertainty for the location of the main fault strands at the Freeway Tunnel and LRT Alternatives is shown in Plates 3 and 4 and summarized in Table 4-6.

- South of the main strand, variations of the alluvial/bedrock contact between borings could represent the secondary splays of the San Rafael fault. Between A-13-016 and A-13-034, and A-13-017 and A-13-035, the top of bedrock drops about 25 and 45 feet, respectively. Although these variations could be the expression of a channel margin, the proximity of the variations to the main strand of the San Rafael fault suggests that they could be fault induced. Very limited data are available to refine the spatial location, activity, or even existence of the secondary splays. For preliminary planning purposes, zones of uncertainty around these splays at the Freeway Tunnel Alternative and LRT Alternative are estimated in Plates 3 and 4 and summarized in Table 4-6.

TABLE 4-6
San Rafael Fault: Fault Strand Zone of Uncertainty at Tunnel Depth^a

Strand	Freeway Tunnel Alternative (feet)	LRT Alternative (feet)
Northern (main)	75	260
Central (secondary)	120	100
Southern (secondary)	95	100

^a Summarized from Fault Investigation Technical Memorandum (see Appendix G)

4.3 Seismicity

The SR 710 North 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 and very long baseline interferometry). These data suggest crustal shortening of between 5 and 9 mm/yr across the greater Los Angeles area and extension of less than 2.5 mm/yr in the east-west direction. Crustal shortening of about 6 mm/yr occurs in the study region, but much of this is being accommodated on the Sierra Madre fault zone, north of the SR 710 North Study Area (CH2M HILL, 2010).

The epicenter map for the Los Angeles area shows widespread seismicity throughout the region; earthquakes of M_w 4.0 and greater are shown in Figure 4-4. Although earthquakes shown in Figure 4-4 often occur near known faults, the earthquakes are difficult to directly associate with mapped faults. Part of this difficulty is because the basin is underlain by several subsurface thrust faults (blind faults).

The largest earthquakes in the region were the 1933 Long Beach, 1971 San Fernando, 1987 Whittier, 1988 and 1991 Pasadena, and 1994 Northridge earthquakes (Figure 4-4). Characteristics of these earthquakes are summarized below.

- **1933 Long Beach earthquake:** A major 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 9.6 km below the Huntington Beach-Newport Beach city boundary.
- **1971 San Fernando earthquake:** The 1971 San Fernando earthquake (M_W 6.7, M_S 6.4, M_L 6.4)¹ was of similar size to the 1994 Northridge event (discussed below) 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 15 km 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.
- **1987 Whittier earthquake:** The 1987 Whittier earthquake (M_L 5.9, M_W 5.9) occurred on the Puente Hills Thrust fault, which is a subsurface (blind) fault dipping under the Puente Hills to about 16 km beneath the San Gabriel Basin (Shaw and Shearer, 1999). This event did not rupture the ground surface. The M 5.4 aftershock had an epicenter roughly 8 km from the center of the SR 710 North Study Area and occurred on a northwest trending strike slip fault that correlates well with the Alhambra Wash fault.
- **1988 Pasadena and 1991 Sierra Madre earthquakes:** Two small earthquakes occurred in the Pasadena region in 1988 and 1991. The 1988 earthquake had a magnitude of 5.0 (M_L) (M_W 4.9) and is postulated to have occurred on the Raymond fault at a depth of about 16 km (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 12 km below the San Gabriel Mountains. The focal mechanism indicated pure thrust faulting. This event is believed by Hauksson (1994) to have occurred on the Clamshell-Sawpit splay of the Sierra Madre fault zone.
- **1994 Northridge earthquake:** The 1994 Northridge earthquake had a M_W of about 6.7, a M_S of 6.8, and a M_L of 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 19 km. Earthquake aftershocks clearly defined the rupture surface dipping about 35 degrees southerly from a depth of about 2 to 3 km to 23 km (Hauksson et al., 1995).

¹ M_W = earthquake moment magnitude; M_S = surface wave magnitude; M_L = earthquake Richter magnitude

Geotechnical Conditions

Geotechnical conditions within the SR 710 North Study Area were identified based on a review of past geotechnical information for the region and the SR 710 North Study Area, as well as from explorations carried out as part of the SR 710 North Study Area geotechnical program. These geotechnical conditions include the presence of groundwater, erosion potential, seismic hazards, slope stability, excavation characteristics, and several additional potential geologic hazards. This information forms the basis for assessing geotechnical issues and constraints associated with each of the proposed SR 710 North Study Area Alternatives.

5.1 Groundwater

Groundwater in the region and SR 710 North Study Area will need to be considered for both design and construction of below-ground improvements. Results of the regional groundwater study and groundwater monitoring carried out in the SR 710 North Study Area are summarized below.

5.1.1 Regional Groundwater

The SR 710 North Study Area is located within four alluvial groundwater basins of the South Coast Hydrologic Region. The subject basins include the San Fernando, Raymond, Main San Gabriel, and (Los Angeles) Central basins, which are separated by bedrock upland areas and/or faults. The bedrock units within the SR 710 North Study Area generally do not contain substantial amounts of groundwater; however, groundwater seepages may be present within local sandstone beds and fault and/or fracture zones. The alternatives, groundwater basins, and bedrock upland areas are shown in Figure 5-1. Historic and current groundwater levels for SR 710 North Study Area are discussed in Section 5.1.2.

The groundwater basins contain permeable alluvial materials that can transmit large amounts of groundwater. Groundwater from these basins is a primary source of water supply for the region. A brief description of these basins is provided below (from CDWR, 2003, and 2004a through 2004d).

- The San Fernando 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 SR 710 North 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. TSM/TDM sites are located within this basin, as shown in Figure 5-1.
- 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 western 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 typically unconfined, and dominated by unconsolidated Quaternary alluvial sediments deposited by streams flowing out of the San Gabriel Mountains. A portion of each of the alternatives is located within this basin, as shown in Figure 5-1.
- The Main San Gabriel 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. A portion of each of the alternatives is located within this basin, as shown in Figure 5-1.

- The (Los Angeles) 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 deposited by streams and rivers flowing out of the San Gabriel Mountains and Elysian, Repetto, Merced, and Puente Hills. The Central Basin is historically divided into forebay and pressure areas. In the SR 710 North Study Area, the Los Angeles forebay of the Central Basin has unconfined groundwater conditions. The southern portions of the BRT and LRT Alternatives are located within this basin, as shown in Figure 5-1.

5.1.2 SR 710 North Study Area Groundwater

Eight groundwater monitoring piezometers were installed during the Technical Study (CH2M HILL, 2010) to monitor groundwater elevation fluctuations between July 2009 and September 2013. Groundwater levels observed within these piezometers are summarized in Table 5-1. The 25 borings drilled and sampled during the SR 710 North Study also were monitored for groundwater during drilling; groundwater levels recorded from these borings are presented in Table 5-1.

Six of the borings drilled for the SR 710 North Study were converted to VW piezometers. The VW piezometer uses a vibrating wire pressure transducer grouted in a borehole to record groundwater pressure at the transducer elevation. The VW piezometers (manufactured by DGSi Slope Indicator) were installed to monitor groundwater levels on a daily basis. Automatic data loggers were used to record groundwater levels at 12-hour intervals.

The VW piezometer data were collected from March to September 2013. During this period, groundwater levels dropped approximately 1 foot to 2.7 feet. However, the groundwater level recorded at boring A-13-020, located along SR 710, north of Del Mar Boulevard in Pasadena, rose approximately 1.3 feet. The borings in which the VW piezometers are installed, as well as the recorded groundwater levels, are summarized in Table 5-1.

A summary of the piezometer installations, well diagrams, and groundwater level graphs are presented in Appendix C.

TABLE 5-1
SR 710 North Study Piezometer and Groundwater Summary

Boring Designation	Piezometer Type	Ground Surface Elevation ^a (feet)	Depth of Piezometer (feet)	Groundwater Level ^a (Elevation in feet)			
				July 2009	March 2013 ^b (During Drilling)	March 2013	September 2013
R-09-Z1B8	Stand Pipe	419.6	200	394.6	---	396.2	395.7
R-09-Z2B5	Stand Pipe	452.4	277	441.6	---	440.7	---
R-09-Z3B2	Stand Pipe	781.4	275	637.0	---	672.9	674.4
R-09-Z3B3	Stand Pipe	802.0	276	666.0	---	673.6	674.8
R-09-Z3B4	NA	768.0	---	---	---	---	---
R-09-Z3B6	Stand Pipe	750.0	324	698.8	---	697.8	---
R-09-Z3B8	Stand Pipe	594.3	275	NA	---	563.1	562.6
R-09-Z3B11	NA	533.1	NA	NA	---	---	---
R-09-Z3B12	Stand Pipe	501.0	240	488.2	---	487.3	486.7
R-09-Z4B4	Stand Pipe	454.4	275	408.1	---	387.9	378.1
A-13-001	NA	344.1	NA	NA	NE	---	---
RC-13-002	NA	349.2	NA	NA	317.2	---	---
RC-13-003	NA	388.8	NA	NA	371.8	---	---

TABLE 5-1
SR 710 North Study Piezometer and Groundwater Summary

Boring Designation	Piezometer Type	Ground Surface Elevation ^a (feet)	Depth of Piezometer (feet)	Groundwater Level ^a (Elevation in feet)			
				July 2009	March 2013 ^b (During Drilling)	March 2013	September 2013
RC-13-004	VW	393.4	36.7	NA	383.9	379.2	378.2
RC-13-005	VW	425.0	124.5	NA	372.5	389.4	388.1
R-13-006	NA	505.6	NA	NA	NE	---	---
RC-13-007	VW	493.1	52	NA	448.1	449.7	449.0
RC-13-007	VW	493.1	200	NA	448.1	451.6	449.4
A-13-008	NA	615.5	NA	NA	NE	---	---
RC-13-009	VW	650.9	100	NA	558.9	552.5	551.0
RC-13-009	VW	650.9	199.5	NA	558.9	548.1	546.5
O-13-010	VW	693.5	196	NA	542.5	675.5	676.8
A-13-015	NA	778.3	NA	NA	710.5	---	---
A-13-016	NA	785.4	NA	NA	NE	---	---
A-13-017	NA	788.7	NA	NA	NE	---	---
A-13-020	VW	799.9	147	NA	675.9	544.7	543.7
A-13-021	NA	577.9	NA	NA	NE	---	---
A-13-022	NA	696.3	NA	NA	NE	---	---
O-13-023	NA	698.1	NA	NA	537.1	---	---
A-13-024	NA	715.6	NA	NA	NE	---	---
A-13-025	NA	720.9	NA	NA	NE	---	---
A-13-026	NA	736.1	NA	NA	696.1	---	---
A-13-027	NA	751.9	NA	NA	696.9	---	---
A-13-034	NA	783.7	NA	NA	701.2	---	---
A-13-035	NA	787.2	NA	NA	NE	---	---

^a Elevations are based on NAVD 88.

^b See boring records in Appendixes A.1 and A.2.

NA – not applicable

NE – not encountered

The bedrock upland areas within the SR 710 North Study Area generally do not contain substantial amounts of groundwater; however, groundwater seepages may be present within local sandstone beds and fault and/or fracture zones. Substantial amounts of groundwater inflows are expected locally in alluvial deposits. The Raymond fault is a known groundwater barrier; groundwater levels on the north side of this fault are over 100 feet higher than the levels on the south side of the fault. In addition, the potentially active (Eagle Rock and San Rafael faults) and inactive faults also may act as groundwater barriers.

Historically, highest groundwater levels within the SR 710 North Study Area range from 5 to 200 feet bgs. In the overall study area, groundwater levels vary considerably, ranging from 10 to 450 feet bgs. A groundwater discussion specific to each of the SR 710 North Study Alternatives is presented in Section 8.5, 9.5, 10.5, and 11.5.

No major springs are known to occur in the upland bedrock areas within the SR 710 North Study Area.

5.2 Erosion

Erosion occurs when rock and/or soil surfaces are exposed to weathering. Erosion is a constant ongoing process that can be successfully managed using engineered controls. The potential for erosion varies with soil type, amount of vegetation, and slope steepness. The surficial soil types present in the SR 710 North Study Area are shown in Plate 5; these data were obtained from the 2006 LACDPW Hydrology Manual, and Web-based GIS viewer (<http://ladpw.org/wrd/hydrologygis/>). Soils data from the United States Department of Agriculture Soil Survey are not available for the urbanized SR 710 North Study Area.

The susceptibility to erosion of the surficial soils within the SR 710 North Study Area was delineated based on the Soil Erodibility Factor, or “K-Factor” established by the USGS (1994), as shown in Plate 6. Results indicate that the SR 710 North Study Area is in an area of moderate erosion potential.

5.3 Seismic Hazards

Two types of seismic hazards were considered within the SR 710 North Study Area. The first involved primary hazards from ground rupture and shaking. The second involved secondary hazards, primarily generated by ground shaking.

5.3.1 Primary Seismic Hazards

The primary seismic hazards present within the SR 710 North Study Area include seismic shaking and fault-induced ground rupture.

5.3.1.1 Seismic Shaking

During an earthquake, seismic waves are produced that emanate in all directions from the fault rupture. Seismic waves can produce strong ground shaking that is typically strongest near the fault and attenuates as the waves move away from the source. The severity of ground shaking is controlled by the interaction of magnitude, distance, and the type, thickness, and condition of underlying geologic materials. Areas underlain by unconsolidated recent alluvium or artificial fill may amplify the strength and duration of strong ground motion.

The SR 710 North Study Area will be subject to seismic ground shaking over time. Preliminary seismic design parameters for the SR 710 North Study Area are presented in the Preliminary Earthquake Acceleration Response Spectra (ARS) Technical Memorandum (CH2M HILL, 2013), which is included in Appendix F of this report.

The parameters were obtained from the Caltrans (2013b) ARS Web site, Version 2.2.06

(http://dap3.dot.ca.gov/ARS_Online) and the USGS (2008) ground motion model-interactive Web application (<https://geohazards.usgs.gov/deaggint/2008>).

5.3.1.2 Fault-Induced Ground Rupture

Fault-induced ground rupture could occur where active or potentially active faults cross the alternatives. At these locations, a potential exists for permanent ground displacement along the fault during an earthquake. The nature of the rupture could be vertical movement, horizontal movement, or some combination of vertical and horizontal movement. Displacements could exceed 1 meter, depending on the length of the fault rupture and magnitude of the earthquake. The rate of displacement would be very rapid, giving little time to plan for the event. Since it is very difficult to prevent or control displacements associated with fault-induced ground rupture, at locations where a high risk of rupture is anticipated, special provisions must be taken during design to meet seismic performance objectives relative to collapse, damage, and post-event operations. Based on this study, known active faults (Raymond fault) and potentially active faults assumed to be active (the San Rafael and Eagle Rock faults) that cross the SR 710 North Study Alternatives are shown in Plates 2, 3, 4, 8, and 9, and Figure 4-3. The Raymond, Eagle Rock, and San Rafael faults cross the Freeway Tunnel Alternative at tunnel depth. The Raymond and San Rafael faults cross the LRT Alternative at tunnel depth, and the BRT Alternative at the surface. The Raymond faults crosses TSM/TDM Improvement I-18 and Improvement T-2 at the surface; and the San Rafael fault crosses TSM/TDM Improvement L-1 and Improvement T-2 at the surface.

5.3.2 Secondary Seismic Hazards

A number of geologic hazards can result from a strong ground shaking caused by a seismic event. These hazards range from liquefaction to seismically induced settlements. Brief descriptions of these hazards are provided in the following discussion. The risk of each of these hazards is further discussed within the geotechnical evaluations (Sections 8, 9, 10, and 11) for each of the SR 710 North Study Alternatives.

- Liquefaction:** During strong ground-shaking, loose, saturated, cohesionless soils in the upper 50 to 75 feet bgs can experience a temporary loss of shear strength and ground deformations can occur. This phenomenon is known as liquefaction. 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. Areas identified as having experienced liquefaction during historical times, or where the anticipated geological conditions indicate a potential for liquefaction, are shown in Plate 7.
- Coseismic Deformation:** UEPBT generated paleoseismic deformation has been observed along the Coyote Pass escarpment, as discussed in Section 4.2.3.2. The coseismic deformation was expressed as broad-scale folding parallel to the escarpment axis. The Coyote Pass escarpment, as well as several, additional, less active folds related to the UEPBT have been mapped transecting the BRT, LRT, and Freeway Tunnel Alternatives, as shown in Figure 4-3.
- Seismically Induced Landslides:** The potential for seismically induced landslides will depend on the steepness of the slope, strength and structure of the soil/rock, groundwater depth and extent, and level of ground shaking. Consequences could include adverse loading on structures located on or adjacent to ground that moves. Areas identified as having experienced seismically induced landslides in the past, or where the anticipated geologic conditions indicate a potential for seismically induced landslides, are shown in Plate 7.
- Seismically Induced Settlement:** Loose, unsaturated granular soils are also susceptible to seismically induced settlement. This could include the alluvial soils located above the groundwater table within the SR 710 North Study Area. These settlements can result in total and differential settlement of soils supporting structures, roadways, and utilities. The magnitude of these settlements will depend on the type of structure, the characteristics of the soil below the structure, and the level of ground shaking. Areas most susceptible to seismically induced settlement generally will be the same as those identified as susceptible to liquefaction in Plate 7.
- Seismically Induced Inundation:** Seismically induced inundation occurs when an earthquake causes catastrophic failure of a water-retaining structure, such as a reservoir, dam, or levee; and subsequent flooding occurs due to the release of water from the structure. The County of Los Angeles has prepared a Dam and Reservoir Inundation Routes Map, which includes the SR 710 North Study Area (Los Angeles County, 2012). As shown in Figure 5-2, portions of the SR 710 North Study Area are located within a dam and inundation route.
- Tsunamis and Seiches:** Tsunamis are waves typically generated offshore or within large open bodies of water primarily during subaqueous fault rupture or a subaqueous landslide event. Seiches are waves generated within a large closed body of water, also caused either by subaqueous fault rupture or landslide events, or by ground oscillations from distant earthquakes. Because of the distance between the SR 710 North Study Area and large bodies of water, there is no potential impact to the project due to a tsunami or seiche.

5.4 Slope Stability

The stability of a slope depends on the inclination, geology and geologic structure, soil and rock strength, and ground and surface water conditions within the slope. Hillside areas and the SR 710 North Study Alternatives are shown in Plate 2. Areas with slopes have a potential hazard from slope failures. In addition, excavating, grading, or fill work during construction might introduce temporary slope stability hazards.

5.5 Excavation Characteristics

The excavation characteristics of the earth units anticipated along the tunnel portions of the LRT and Freeway Tunnel Alternatives are discussed in Sections 10.8 and 11.8, respectively. As discussed in Section 4, the sedimentary and igneous/metamorphic bedrock units anticipated within the SR 710 North Study Area exhibit variable geologic and engineering properties. However, in the near subsurface, including the LRT and Freeway Tunnel Alternative portal areas, these units likely can be excavated using conventional equipment. Local cemented layers and/or concretions may require mechanical breaking.

Cobbles and boulders, which may require mechanical breaking, may be encountered in the conglomeratic bedrock units and locally within the alluvial soils in the SR 710 North Study Area.

5.6 Corrosion Characteristics

The general corrosion potential of the earth units present within the SR 710 North Study Area has been evaluated by laboratory testing. Soil laboratory tests for corrosion potential were conducted on 28 samples collected during the current investigation, and during the Technical Study (CH2M HILL, 2010). Soil samples were tested for pH, minimum resistivity, soluble chloride content, and soluble sulfate content using the procedures described in CTM 417, 422 and 643 (Caltrans, 2007, 2013a, and 2013b). The corrosion test results are summarized in Table 5-2.

TABLE 5-2
SR 710 North Study Corrosion Test Data Summary

Boring Number	Sample Number	Depth	Geologic Unit	Minimum Resistivity (ohm-cm)	pH	Soluble Sulfate Content (ppm)	Soluble Chloride Content (ppm)
A-13-001	S-02	5.0	Artificial Fill Soil	1,431	7.7	9	5
RC-13-002	B-01	1 to 5	Artificial Fill Soil	1,142	7.7	380	180
RC-13-003	S-03	10.0	Puente Formation	1,154	7.9	60	61
RC-13-004	B-1	0 to 5	Alluvial Soil	2,541	7.6	101	60
RC-13-004	S-6	25.0	Alluvial Soil	1,853	7.7	137	48
RC-13-005	S-10	45.0	Alluvial Soil	1,137	7.1	23	8
RC-13-005	C-22	99.5	Puente Formation	2,057	7.9	63	21
R-13-006	S15	70.0	Puente Formation	1,614	7.4	18	31
R-13-006	S19	90.0	Puente Formation	2,645	8	29	10
RC-13-007	C-33	157.0	Fernando Formation	690	7.1	1,214	23
RC-13-007	C-42	192.2	Fernando Formation	466	7.4	2,111	24
A-13-008	S-15	70.0	Alluvial Soil	41,125	7.5	30	17
RC-13-009	S-30	142.0	Wilson Quartz Diorite	6,917	7.5	225	181
RC-13-009	C-39	186.5	Wilson Quartz Diorite	11,021	7.9	130	82
O-13-010	O34	143.0	Alluvial Soil	5,501	8	88	65
O-13-010	O41	198.0	Alluvial Soil	11,048	7.8	74	144
A-13-020	S-4	15.0	Alluvial Soil	5,828	7.4	101	52
A-13-020	S-10	45.0	Alluvial Soil	8,435	8	22	18
A-13-021	S-14	65.0	Topanga Formation	1,287	7.7	58	120
A-13-021	S-18	85.0	Topanga Formation	1,290	8	42	35

TABLE 5-2
SR 710 North Study Corrosion Test Data Summary

Boring Number	Sample Number	Depth	Geologic Unit	Minimum Resistivity (ohm-cm)	pH	Soluble Sulfate Content (ppm)	Soluble Chloride Content (ppm)
O-13-023	O32	142.0	Alluvial Soil	9,131	7.6	41	15
O-13-023	O39	200.0	Alluvial Soil	3,821	7.8	43	60
R-09-Z1B8	C-26	120.2	Puente Formation	343	6.18	1,156	59
R-09-Z1B8	C-33	159.6	Puente Formation	410	6.26	720	76
R-09-Z3B3	C52	246.4	Wilson Quartz Diorite	1,090	7.10	200	226
R-09-Z3B8	C-54	218.0	Topanga Formation	1,600	7.50	5,188	64
R-09-Z3B11	C-35	171.5	Topanga Formation	1,240	6.86	91	30
R-09-Z3B12	C-34	164.9	Puente Formation	1,320	7.76	85	41
R-09-Z3B12	C-51	229.2	Puente Formation	600	7.41	798	59
R-09-Z4B4	C-19	97.5	Fernando Formation	1,720	6.57	21	20
R-09-Z4B4	C-38	221.0	Fernando Formation	269	4.63	3,942	60

Caltrans (2012a) considers a site to be corrosive to structural elements if one or more of the following conditions exist:

- Soluble chloride concentration is greater than or equal to 500 ppm.
- Soluble sulfate concentration is greater than or equal to 2,000 ppm.
- The pH is 5.5 or less.

Based on the above corrosion criteria, the earth units tested within the SR 710 North Study Area are predominantly considered noncorrosive toward common construction materials. As shown on Table 5-2, two test results indicated soluble sulfate contents greater than 2,000 ppm.

Additional corrosion testing would be conducted during future phases of the project. During design, a corrosion engineer would review the corrosion data and provide appropriate corrosion design recommendations.

5.7 Other Non-Seismic Geologic Hazards

Potential geologic hazards that may exist within the SR 710 North Study Area under static (gravity) loading conditions are briefly summarized below. The risk of these hazards is further discussed within the geotechnical evaluations (Sections 8, 9, 10, and 11) for each of the SR 710 North Study Alternatives.

- **Ground Settlement and Collapsible Soils:** Ground settlement can occur when new loads are added to soil, or when a change in water levels results in a decrease in pore water pressures within compressible soils. Collapsible soils consist predominantly of sand- and silt-size particles arranged in a loose “honeycomb” structure. This loose structure is held together by small amounts of water-softening cementing agents, such as clay or calcium carbonate. When the soil becomes wet, these cementing agents soften and the honeycomb structure collapses and generates ground settlement. Both conditions could potentially occur within the SR 710 North Study Area.
- **Expansive Materials:** Expansive soils are clay-rich soils that swell and shrink with wetting and drying. The mineralogy and percentage of clay-sized particles present within a soil determine the potential for expansive behavior. The shrink-swell capacity of expansive soils can result in differential movement beneath foundations. Clay-rich soils are locally present within the SR 710 North Study Area. Bedrock units

also can exhibit expansive properties due to the clay content within the bedrock. Potentially expansive bedrock materials anticipated in the SR 710 North Study Area include the claystone and siltstone members within the Fernando, Puente, and Topanga Formations.

- **Regional Subsidence:** Regional subsidence results from the withdrawal of groundwater and/or hydrocarbons from the subsurface. As the groundwater or hydrocarbons are pumped out of the ground, the resultant voids or pores are compressed under the pressures of the soils above. Accumulation of the compression results in subsidence of the ground surface. The potential for this hazard to affect the SR 710 North Study Area is low, because groundwater withdrawal is restricted and managed; and where oil extraction is occurring, the reservoir pressures are compensated by reinjection of water in volumes similar to or greater than what is withdrawn (CDOGGR, 2005 and 2012).
- **Flooding:** The SR 710 North Study would not involve a significant encroachment into the 100-year base floodplain, would not be inconsistent with existing watershed and floodplain management programs, and would not result in incompatible floodplain development (CH2M HILL, 2014b).

SECTION 6

Hazardous Waste and Naturally Occurring Oil and Gas

Two other conditions may affect the design and construction of the SR 710 North Study Area Alternatives, particularly those that involve tunnels. These conditions involve contaminated soils and groundwater and naturally occurring oil and gas.

6.1 Contaminated Soil and Groundwater

Soil and groundwater contamination is addressed in the Phase I ISA for the SR 710 North Study (CH2M HILL, 2014a).

6.2 Naturally Occurring Oil and Gas

Naturally occurring oil, tar seeps, and/or gas were not encountered during any of the current or previous investigations conducted along the SR 710 North Study Alternatives.

Based on information available from the CDOGGR (2005 and 2012), and as shown in Figure 6-1, no abandoned or existing oil wells are located within the immediate vicinity of the alternatives. The information in Figure 6-1 shows that there are nearby oil wells, but the number and density of the wells are such that they are not expected to have an effect on the SR 710 North Study Alternatives.

However, based on experience with the construction of other tunnels in Los Angeles, naturally occurring oil and gas is most likely to be encountered within the Puente Formation. Naturally occurring oil and gas could be encountered in any of the formations in the SR 710 North Study Area.

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SECTION 7

Geotechnical Evaluation – No Build Alternative

The generalized descriptions of the SR 710 North Study Area geologic setting presented in Sections 4, 5, and 6 of this report are applicable to the No Build Alternative. The SR 710 North Study No Build Alternative does not include any of the improvements included in the projects Build Alternatives. However, the No Build Alternative does include projects/planned improvements through 2035 that are contained in the Federal Transportation Improvement Program, as listed in the Southern California Association of Governments 2012 Regional Transportation Plan/Sustainable Communities Strategy, Measure R, and the funded portion of Metro's 2009 Long Range Transportation Plan. It is possible that the construction of those improvements could result in short-term and/or permanent effects related to geology and seismicity. Those effects would be analyzed and mitigated, if needed, as each of those projects/improvements is advanced for implementation.

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Geotechnical Evaluation – TSM/TDM Alternative

The TSM/TDM Alternative includes intersection and local street improvements, ITS, CMS, ATM, expanded bus service, bus service improvements, and bicycle facility improvements. In addition, one new bridge (SR 710 Connector Underpass Bridge, Improvement T-1) and one bridge widening (Garfield Avenue Bridge, Improvement I-16) are proposed in this alternative. The TSM/TDM improvements would be designed and constructed in accordance with applicable Caltrans and local (city and county) standards to account for the geologic hazards. All TSM/TDM elements are included in the BRT Alternative with the exception of Improvement L-8 and the reversible lanes of Improvement L-3; all TSM/TDM elements are also included in the LRT and Freeway Tunnel Alternatives with the exception of Improvement T-1 for the LRT Alternative, and Improvements T-1 and T-3 for the Freeway Tunnel Alternative. A generalized discussion of the geologic setting and potential geologic hazards for the TSM/TDM Alternative, as well as associated preliminary design recommendations, is presented below.

8.1 Human-Made and Natural Features of Engineering and Construction Significance

The TSM/TDM improvements would be located within areas already developed with residential, commercial, and industrial properties, as well as associated improvements such as roadways, sidewalks, and utilities. In many locations, the developments have been in place for over 100 years. Although these existing human-made features will be an important consideration during the implementation of the TSM/TDM Alternative, substantial constructed improvements are not proposed with the TSM/TDM improvements. As such, most of the existing features present along the TSM/TDM Alternative would not be adversely affected by the proposed improvements.

Three existing features would require consideration due to the proposed improvements:

- The Union Pacific Railroad (UPRR) tracks and easement near Mission Road and Concord Avenue (TSM/TDM Improvement T-1)
- The existing Fair Oaks Avenue bridge structure over SR 110, the existing cut slope at the southwest corner of Fair Oaks Avenue and SR 110, and the existing commercial improvements located near the top of the cut slope (TSM/TDM Improvement T-2)
- The Garfield Avenue bridge structure and UPRR tracks and easement (TSM/TDM Improvement I-16)

8.2 Geology

Most of the TSM/TDM improvements are located either at or close to the ground surface. Only the new and widened bridges would involve geology that extends to some depth below the ground surface. Geology would affect the TSM/TDM improvement through the physiography and topography of the area, as well as the stratigraphy supporting the TSM/TDM improvement.

8.2.1 Physiography and Topography

The TSM/TDM improvements are located in the northwestern portion of the Repetto Hills and western San Gabriel Valley. See Section 3 for further discussion of the physiography and topography within the SR 710 North Study Area.

As part of TSM/TDM Improvement T-2 (in the vicinity of Fair Oaks Avenue and SR 110), modifications are proposed to the existing cut slope located between Grevelia Street and SR 110 west of Fair Oaks Avenue. This cut slope was constructed to accommodate the below-grade SR 110 mainlines, as well as the associated SR 110 Fair Oaks Avenue northbound off-ramp. The cut slope ranges in height from approximately 15 to 22 feet. The existing cut slope is proposed to be replaced by an approximately 22-foot-tall, Caltrans standard Type I retaining wall. This area is mapped as being underlain by alluvial soils (Plate 2), anticipated to be over 200 feet thick.

Although regrading of the existing topography would be required, the geology of the area would not preclude these changes required for construction of retaining structures.

8.2.2 Stratigraphy and Structure

The TSM/TDM improvements are situated primarily within alluvial soils as depicted in Plate 2. Areas underlain by artificial fill soils are to be anticipated locally within some of the TSM/TDM improvement limits. Sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite are present below the TSM/TDM improvements at depth.

8.3 Primary Seismic Hazards

The primary seismic hazard for the TSM/TDM improvements is ground shaking. This is an important design consideration for the proposed new bridge (SR 710 Connector Underpass Bridge) and bridge widening (Garfield Avenue Bridge). The relevance of ground shaking and faulting to the TSM/TDM improvements is summarized below.

8.3.1 Seismicity

The potential to experience substantial seismic ground shaking is a common hazard for every project in southern California, and the hazard cannot be avoided. TSM/TDM improvements would be designed and constructed in accordance with applicable Caltrans and local (city and county) standards for seismic ground shaking.

8.3.2 Faulting

Typically, local street improvements (such as those proposed with TSM Improvement I-18, L-1, and T-2) are not protected against fault-induced ground rupture. If the roadway is damaged due to fault rupture, the repairs would typically be minor and quickly facilitated. The two bridge improvement sites (SR 710 Connector Underpass Bridge and Garfield Avenue Bridge), which would potentially be more affected by faulting, are not transected by an active or potentially active fault.

8.4 Secondary Seismic Hazards

A number of secondary seismic hazards would need to be considered for the TSM/TDM improvements. The effect of the secondary seismic hazards depends on the proposed designs, and the soil types and groundwater conditions present in the area of the improvement.

8.4.1 Liquefaction

As shown in Plate 7, the following TSM/TDM improvements are located within an area delineated as a Liquefaction Hazard Zone:

- Improvement I-2, located at the intersection of Eagle Rock Boulevard and York Boulevard
- Improvement L-1, located along Figueroa Street, north and south of SR 134
- Improvement L-5, located along Rosemead Boulevard, north of I-10, between Marshall Street and Lower Azusa Road

TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards, accounting for liquefaction.

8.4.2 Seismically Induced Landslides

The potential for seismically induced landslides will depend on the steepness of the slope, strength and structure of the soil/rock, groundwater depth and extent, and level of ground shaking. As shown in Plate 7, none of the TSM/TDM improvements are located within a seismically induced Landslide Hazard Zone. There are no known landslides mapped within or adjacent to the TSM/TDM Alternative Improvements.

8.4.3 Seismically Induced Settlement

Loose, unsaturated granular soils are susceptible to seismically induced settlement. This could include the alluvial soils located above the groundwater table within the SR 710 North Study Area. Where local street improvements and new or widened bridges are proposed, the TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards, accounting for seismically induced settlement.

8.4.4 Seismically Induced Inundation

One TSM/TDM improvement (Improvement I-2, located at the intersection of Eagle Rock Boulevard and York Boulevard) is located within a potential dam inundation area, as shown in Figure 5-2. The Eagle Rock Reservoir, which is located on the north side of SR 134 approximately 1,500 feet west of the SR 134/Figueroa Street interchange, would be the source of the inundation in this area. If seismically induced inundation were to occur during the design life of the improvements, it would be a very rare occurrence. The inundation would be short-lived and the effects of any resultant scour or water inundation could be easily facilitated or accounted for during design and construction. TSM/TDM improvements would be designed and constructed in accordance with applicable Caltrans and local (city and county) standards for scour and water inundation.

8.4.5 Tsunamis and Seiches

The TSM/TDM improvements are not located adjacent to any large bodies of water or at elevations that could be flooded by tsunamis or seiches. As such, there is no potential for a tsunami- or seiche-related impact on the alternative.

8.5 Groundwater

Groundwater levels vary widely within the SR 710 North Study Area. See Section 5.1 for a discussion of groundwater conditions. Surface water within the SR 710 North Study Area generally infiltrates into the ground, or drains by sheet flow into engineered drainage structures. No TSM/TDM improvements cross any major drainages.

Groundwater in the vicinity of the Garfield Avenue Bridge is on the order of 300 feet bgs, no impact to groundwater is anticipated related to this improvement. Shallow groundwater conditions (on the order of 20-25 feet bgs) may be present at the SR710 Connector Underpass Improvement site. The SR710 Connector Underpass would be designed in accordance with Caltrans and local (city and county) standards for accounting for groundwater.

8.6 Hazardous Waste and Naturally Occurring Oil and Gas

The SR 710 North Study included an evaluation of hazardous waste and naturally occurring oil and gas for each Alternative.

8.6.1 Contaminated Soil and Groundwater

Soil and groundwater contamination is addressed in the Phase I ISA for the SR 710 North Study (CH2M HILL, 2014a). Design and construction requirements for areas with soil and/or groundwater contamination will be considered if this alternative is selected.

8.6.2 Naturally Occurring Oil and Gas

Considering the type of improvements proposed and the underlying geologic framework, the potential for naturally occurring oil or gas to be encountered during construction or operation of the TSM/TDM improvements is low. Although a slightly higher risk could occur where deep foundations are used to support the two proposed bridge improvements, geotechnical explorations conducted for design of these bridge foundations would establish whether there is a risk, and if needed, mitigation measures could be taken during construction. Where anticipated, appropriate precautions would be implemented in accordance with Occupational Safety and Health Administration (OSHA) requirements for naturally occurring gases, if the alternative is selected.

8.7 Potential Non-Seismic Geologic Hazards

Where local street improvements and new or widened bridges are proposed, the TSM/TDM improvements would be designed in accordance with Caltrans and local (city and county) standards, accounting for the following potential non-seismic geologic hazards.

8.7.1 Slope Stability

As shown in Plate 2, few of the TSM/TDM improvements are located within or adjacent to hillside areas. Aside from Improvement T-2, no other slopes will be substantially impacted by the TSM/TDM improvements.

8.7.2 Ground Settlement and Collapsible Soils

Localized areas within the SR 710 North Study Area that are underlain by alluvial soils (see Plate 2) may be prone to ground settlement or collapsible soils.

8.7.3 Expansive Materials

Clay-rich expansive soils and bedrock are present locally throughout the SR 710 North Study Area. Potentially expansive materials present in the TSM/TDM area include artificial fill soils, alluvial soils, and the siltstone and/or claystone units of the Fernando, Puente, and Topanga Formations.

8.7.4 Erosion

As shown in Plate 6, the surficial soils present at the TSM/TDM improvements have a moderate susceptibility to erosion. Erosion is a constant ongoing process that can be successfully controlled by implementing engineered designs developed in accordance with applicable Caltrans and local (city and county) standards.

8.8 Geotechnical Considerations for Design and Construction

A number of additional geotechnical design and construction considerations would need to be addressed as part of the TSM/TDM Alternative. These considerations include roadway design, bridge structure design, and retaining wall design. Brief summaries of these design requirements are provided below.

8.8.1 Roadway Design Considerations

Within the TSM/TDM Alternative improvements, pavement construction will mainly consist of widening travel lanes or shoulders. The pavement sections for the widening would match the existing pavement sections. The existing adjacent pavement condition would be investigated to determine if rehabilitation or pavement preservation is required. If required, combining rehabilitation or pavement preservation work with widening is recommended. According to Section 603.2 of the Caltrans Highway Design Manual (Caltrans, 2012b), a 0.15-foot overlay over the widening and existing pavement would be used to eliminate pavement joints for flexible pavement.

New pavement construction is proposed at the SR 710 connector improvement from Valley Boulevard to Mission Road (Improvement T-1). The new pavement section would be designed following the procedures outlined in the Caltrans Highway Design Manual (Caltrans, 2012b).

8.8.2 Bridge Structures

Within the TSM/TDM Alternative improvements, a new SR 710 Connector Underpass Bridge (Improvement T-1) will be constructed between Valley Boulevard and Mission Road and will carry three railroad tracks above the SR 710 connector. In addition, the existing Garfield Avenue Bridge, located adjacent to the intersection of Mission Road and Garfield Avenue in the City of Alhambra, will be widened (Improvement I-16).

Foundation recommendations for the advanced planning study of these bridges are provided in the following reports:

- Structure Preliminary Geotechnical Report for SR 710 Connector Underpass Bridge (CH2M HILL, 2014c)
- Structure Preliminary Geotechnical Report for Garfield Avenue Bridge (Widening) (CH2M HILL, 2014d)

8.8.3 Retaining Walls

Within the TSM/TDM Alternative improvements, two retaining walls are proposed at the SR 110 hook ramp and Fair Oaks Avenue (Improvement T-2). The proposed retaining walls are Caltrans standard Type-I walls with maximum heights ranging from 8 to 22 feet.

Subsurface investigation would be conducted for the design of the walls in a future phase. The retaining wall would be designed in accordance with the load and resistance factor design (LRFD) method as specified in the *AASHTO LRFD Bridge Design Specifications* (American Association of State Highway and Transportation Officials [AASHTO], 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014).

8.9 Future Geotechnical Exploration and Investigations

For the design of the TSM/TDM Alternative improvements, additional subsurface investigations are required. The purpose of the investigations would be to evaluate the subsurface conditions and provide geotechnical information for design and construction of pavements, foundations, and remedial earthwork, if required.

- **Bridges:** For the bridge foundations, subsurface explorations would be provided in accordance with Section 10.4.2 of *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012). A minimum of one exploration for each support is recommended for a structure width less than or equal to 100 feet; a minimum of two explorations for each support is recommended for a structure width greater than 100 feet. The depth of exploration would extend below the foundation tip elevation a minimum of 20 feet, at least three times the pile diameter, or a minimum of two times the pile group dimension, whichever is deeper.
- **Retaining Walls:** For the retaining wall foundation, subsurface explorations would be conducted in accordance with Section 10.4.2 of *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012). A minimum of one exploration for each retaining wall is recommended. For retaining walls more than 100 feet in length, exploration points would be spaced every 100 to 200 feet. The depth of exploration would extend between 1 and 2 times the wall height at minimum.
- **Pavements:** For pavement design, the explorations would be extensive enough to reveal variability in the subsurface condition and engineering properties. The exploration points would be spaced every 500 to 1,000 feet along the proposed new pavement and widening areas. The depth of exploration would extend 10 to 15 feet below the proposed finish grade.

All explorations should extend through unsuitable strata such as soft highly compressible soils, peat, highly organic materials, and loose coarse-grained soils to reach competent material of suitable bearing strata.

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Geotechnical Evaluation – BRT Alternative

BRT Alternative improvements include BRT trunk line arterial street and station improvements, more frequent bus service, new bus feeder services, enhanced connecting bus services, active transportation, and local street and intersection improvements. The BRT Alternative would include the same improvements proposed for the TSM/TDM Alternative with the exception of Improvement L-8 and the reversible lanes of Improvement L-3. The TSM/TDM improvements applicable to the BRT Alternative include the SR 710 Connector Underpass Bridge (Improvement T-1) and the Garfield Avenue Bridge widening (Improvement I-16). A generalized discussion of the geologic setting and potential geologic hazards covering the TSM/TDM Alternative, as well as associated preliminary design recommendations are presented in Section 8 of this report. A generalized discussion of the geologic setting and potential geologic hazards along the BRT Alternative, as well as associated preliminary geotechnical design recommendations are presented below.

9.1 Human-Made and Natural Features of Engineering and Construction Significance

The BRT Alternative traverses areas developed with residential, commercial, and industrial properties, as well as associated improvements such as roadways, sidewalks, and utilities. In many locations, the developments have been in place for over 100 years. Although these existing human-made features will be an important consideration during the implementation of the BRT Alternative, substantial constructed improvements are not proposed with the BRT Alternative, apart from the same improvements as discussed in Section 8 for TSM/TDM Improvement T-2. As such, the existing features present along the alternative would not be adversely affected by the BRT improvements.

9.2 Geology

The BRT Alternative generally involves at-grade improvements. Geology would affect the development of the alternative mainly through the physiography and topography of the BRT Alternative, while stratigraphy plays a role through the supporting characteristics of the geology for the new surface developments. These geology-related impacts are summarized in the following two subsections.

9.2.1 Physiography and Topography

The BRT Alternative commences in the Los Angeles Basin, then extends north across the Repetto Hills and along the western edge of the San Gabriel Valley. Elevations along the alternative vary from 175 feet at Olympic Boulevard in East Los Angeles, to 395 feet near Sevilla Street, to 385 feet near Garvey Avenue in Monterey Park. The Alternative then ascends to roughly 840 feet at its northern terminus near Green Street in Pasadena. These grade changes do not present constraints to the development, as they are consistent with grade already in use by transit systems.

9.2.2 Stratigraphy and Structure

The entire extent of the BRT Alternative is situated within alluvial soils as depicted in Plate 2. Areas underlain by artificial fill soils are to be anticipated locally along the alternative. Sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite are present along the alternative at depth. BRT Alternative development is not expected to be affected by these conditions, as they are the same soil and rock types supporting existing transit systems.

9.3 Primary Seismic Hazards

The primary seismic hazard for the BRT Alternative is ground shaking. This is an important design consideration for the proposed BRT structures (shelters, sign posts, etc.). The relevance of ground shaking and faulting to the BRT Alternative is summarized below.

9.3.1 Seismicity

The potential to experience seismic ground shaking is a common hazard for every project in southern California, and the hazard cannot be avoided. The local street and/or station improvements required for the BRT Alternative would be designed and constructed in accordance with applicable Metro BRT Design Criteria (Metro, 2008) for seismic ground shaking.

The effects of seismic ground shaking can be accommodated by applying geotechnical and structural design recommendations that protect structures from collapse and, where appropriate, from experiencing irreparable amounts of damage based on the anticipated seismic loads.

9.3.2 Faulting

The BRT Alternative would involve at-grade roadway improvements. Typically, roadways constructed at-grade are not protected against fault-induced surface rupture. If the roadway is damaged due to fault rupture, the repairs would be minor and quickly facilitated.

9.4 Secondary Seismic Hazards

A number of secondary seismic hazards could affect the design or operation of the BRT Alternative. The effect of the secondary seismic hazards would depend on the proposed design, locations, soil types, and groundwater conditions. Where these secondary seismic hazards appear to pose either a life-safety issue or risk of damage, standard engineering design methods can be implemented to manage the hazards.

9.4.1 Liquefaction

As shown in Plate 7, the BRT Alternative is not located within an area delineated as a Liquefaction Hazard Zone. However, localized deposits of liquefiable soils could be identified during future investigations. Where local street and/or station improvements are proposed and such conditions exist, the improvements would be designed in accordance with Metro BRT Design Criteria (Metro, 2008), accounting for liquefaction.

Typically, roadway improvements at-grade are not protected against liquefaction. If the improvements are damaged due to liquefaction, the repairs would be minor and quickly facilitated. At the BRT stations, various methods are available to alleviate the effects of potential liquefaction, including removal and replacement of liquefiable soils, the use of ground improvement, or supporting the station with deep foundations. Alternatively, the station can be moved to an area without liquefaction hazards.

9.4.2 Seismically Induced Landslides

The potential for seismically induced landslides will depend on the steepness of the slope, strength and structure of the soil/rock, groundwater depth and extent, and level of ground shaking. As shown in Plate 7, a portion of the BRT Alternative is located within a seismically induced Landslide Hazard Zone, generally between Harding Avenue and Garvey Avenue in Monterey Park. There are no known landslides mapped along the BRT Alternative. The proposed improvements do not require modification of the slopes in this area. Where local street and/or station improvements are proposed, the BRT Alternative would be designed in accordance with Metro BRT Design Criteria (Metro, 2008), accounting for seismically induced landslides.

9.4.3 Seismically Induced Settlement

Loose, unsaturated granular soils are susceptible to seismically induced settlement. This could include the alluvial soils located above the groundwater table along the BRT Alternative. Where local street and/or station improvements are proposed, the BRT improvements would be designed in accordance with Metro BRT Design Criteria (Metro, 2008), accounting for seismically induced settlement.

9.4.4 Seismically Induced Inundation

The BRT Alternative is not located within a potential dam inundation area, as shown in Figure 5-2.

9.4.5 Tsunamis and Seiches

The BRT Alternative is not located adjacent to any large bodies of water. The Alternative is located at a minimum elevation of 175 feet. As such, there is no potential for a tsunami- or seiche-related impact on the alternative.

9.5 Groundwater and Surface Water

Groundwater levels for the BRT Alternative range from 20 feet bgs near the Raymond fault (near Arroyo Seco Parkway) in South Pasadena to 330 feet bgs in the vicinity of West Main Street in Alhambra (MSGW, 2010; RBMB, 2011; WRD, 2013a and 2013b). Historically highest groundwater levels range from 20 feet bgs near the Raymond fault to 200 feet bgs between Huntington Drive and West Main Street (CDMG, 1998b, 1998d, and 1998f).

Where the groundwater elevation is located close to the ground surface, engineering design would account for the effects of groundwater on slope stability, soil bearing capacity, and soil settlement. The proximity of groundwater to the ground surface would also be considered during construction of BRT facilities. However, since the BRT facilities are generally located at or slightly below the ground surface, construction should not be affected by groundwater.

Surface water along the BRT Alternative generally infiltrates into the ground, or drains by sheet flow into engineered drainage structures. The Alternative does not cross any major drainages.

9.6 Hazardous Waste and Naturally Occurring Oil and Gas

The SR 710 North Study included an evaluation of hazardous waste and naturally occurring oil and gas for each Alternative.

9.6.1 Contaminated Soil and Groundwater

Soil and groundwater contamination is addressed in the Phase I ISA for the SR 710 North Study (CH2M HILL, 2014a). Design and construction requirements for areas with soil and/or groundwater contamination will be considered if this alternative is selected.

9.6.2 Naturally Occurring Oil and Gas

The BRT Alternative development involves surface features with very little work extending more than 10 feet below the ground surface. Considering the type of improvements proposed and the underlying geologic framework, the potential for naturally occurring oil or gas to be encountered during construction or operation of the BRT Alternative is low.

9.7 Potential Non-Seismic Geologic Hazards

Where local street improvements are proposed, the BRT improvements would be designed in accordance with Metro BRT Design Criteria (Metro, 2008), accounting for the following potential non-seismic geologic hazards.

9.7.1 Slope Stability

The BRT Alternative will traverse the Repetto Hills (see Plate 2) generally between Brightwood Street and Garvey Avenue in Monterey Park. The Repetto Hills in this area are composed of sedimentary bedrock of the Fernando Formation. The proposed improvements do not require modification of the slopes in this area.

9.7.2 Ground Settlement and Collapsible Soils

Local areas along the BRT Alternative that are underlain by alluvial soils (see Plate 2) may be prone to ground settlement or collapsible soils.

9.7.3 Expansive Materials

Clay-rich expansive soils and bedrock are present locally along the BRT Alternative. Potentially expansive materials present along the alternative include artificial fill soils, alluvial soils, and the siltstone and/or claystone units of the Fernando, Puente, and Topanga Formations.

9.7.4 Erosion

As shown in Plate 6, the surficial soils present along the BRT Alternative have a moderate susceptibility to erosion. Erosion is a constant ongoing process that can be successfully controlled by implementing engineered designs developed in accordance with *Metro BRT Design Criteria* (Metro, 2008).

9.8 Geotechnical Considerations for Design and Construction

A number of additional geotechnical design and construction considerations would need to be considered as part of the BRT Alternative development. These considerations include roadway design and retaining wall design. Brief summaries of these design requirements are provided below.

9.8.1 Roadway Design Considerations

Within the BRT Alternative areas, pavement construction will mainly consist of widening travel lanes and overlays. The existing adjacent pavement condition would be investigated to determine if it is suitable for the overlay. According to Section 603.2 of Caltrans Highway Design Manual (Caltrans, 2012b), a minimum of 0.15-foot overlay over the widening and existing pavement would be used to eliminate pavement joints for flexible pavement.

The pavement sections for the widening would be provided in accordance with the Caltrans Highway Design Manual (Caltrans, 2012b). For preliminary pavement design, a flexible pavement is considered with an assumed subgrade R-value of 15 (Subgrade Type II) and traffic index of 10. The pavement section was estimated using the software CalFP Version 1.1 developed by the Caltrans Office of Pavement Design. The preliminary pavement section of 6-inch asphalt concrete on top of 7-inch Class 2 aggregate base over 14-inch Class 1 aggregate sub-base is estimated for the conceptual cost estimate.

Concrete bus pads are proposed at each bus station. Based on Section 620 of Caltrans Highway Design Manual (Caltrans, 2012b), the minimum pavement structural section for bus pads is 10-inch jointed plane concrete pavement with dowel bars at transverse joints on top of 6-inch lean concrete base or Type A hot mix asphalt over 6-inch aggregate sub-base.

9.8.2 Retaining Walls

The BRT Alternative includes the same T-2 improvements proposed as part of the TSM/TDM Alternative at the SR 110 hook ramp and Fair Oaks Avenue. Two Caltrans standard Type-I retaining walls are proposed with maximum heights ranging from 8 to 22 feet. In addition, a Type-I retaining wall with a maximum wall height of 10 feet is proposed to accommodate the travel lane widening at Atlantic Boulevard and El Repetto Drive in Monterey Park.

Subsurface investigation would be conducted for the design of the walls in a future phase of the project. The retaining wall would be designed based on Metro BRT Design Criteria (Metro, 2008) and in accordance with the LRFD method as specified in the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012) and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014).

9.9 Future Geotechnical Exploration and Investigations

For the design of the BRT Alternative, additional subsurface investigations are required. The purpose of the investigations would be to evaluate the subsurface conditions and provide geotechnical information for the design and construction of pavements, foundations, and remedial earthwork, if required.

- **Retaining Walls:** For the retaining wall foundations, subsurface explorations would be conducted in accordance with Section 10.4.2 of *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012). A minimum of one exploration for each retaining wall is recommended. For retaining walls more than 100 feet in length, exploration points would be spaced every 100 to 200 feet. The depth of exploration would extend between 1 and 2 times the wall height at least.
- **Pavements:** For pavement design, the explorations would be extensive enough to reveal variability in the subsurface condition and engineering properties. The exploration points would be spaced approximately every 500 to 1,000 feet along the proposed new pavement and widening areas. The depth of exploration would extend 10 to 15 feet below the proposed finish grade.

All explorations should extend through unsuitable strata such as soft highly compressible soils, peat, highly organic materials, and loose coarse-grained soils to reach competent material of suitable bearing strata.

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Geotechnical Evaluation – LRT Alternative

The LRT Alternative of the SR 710 North Study includes a dedicated guideway, similar to other Metro light rail lines, as well as a bored tunnel segment. The LRT Alternative is approximately 7.5 miles long, with 3 miles of aerial segments and 4.5 miles of bored tunnel segments. Two-directional tunnels are proposed with tunnel diameters approximately 20 feet each, with the crown of the tunnels generally located approximately 60 feet bgs along most of the tunnel. A profile of the LRT Alternative is shown in Plate 8. The LRT improvements would comply with the applicable Metro Rail Design Criteria (Metro, 2013a). The LRT Alternative would also include the same improvements proposed for the TSM/TDM Alternative with the exception of Improvement T-1. A generalized discussion of the geologic setting and potential geologic hazards covering the TSM/TDM Alternative, as well as associated preliminary design recommendations are presented in Section 8 of this report. A generalized discussion of the geologic setting and potential geologic hazards along the LRT Alternative, as well as associated preliminary design recommendations are presented below.

10.1 Human-Made and Natural Features of Engineering and Construction Significance

The LRT Alternative is located within areas developed with residential, commercial, and industrial properties, as well as associated improvements such as roadways, sidewalks, and utilities. In many locations, the developments have been in place for over 100 years. The proposed LRT Alternative includes both an elevated segment and a bored tunnel segment. These segments would be located either next to or below a wide variety of existing residential, commercial, and industrial improvements. The bored tunnel portion of the alternative would be located below some existing residential, commercial, and industrial improvements.

The following is a list of the existing features that would require consideration due to the proposed improvements:

- An LACDPW detention basin located immediately west of the intersection of Corporate Center Drive and Corporate Place
- Natural and human-made slopes located on the west side of SR 710, from the LRT crossover of SR 710 north to the Cal State LA area—Blanchard Landfill (addressed in the SR 710 North Study Phase I ISA [CH2M HILL, 2014a]), Cal State LA (athletic fields and building structures), and commercial developments situated atop the natural and human-made slopes in this area
- The UPPR tracks and easement immediately south of Mission Road
- All structures and associated improvements located above the tunnel portion of the alternative
- Potential existing deep foundations and/or utilities overlying the tunnel portion of the alternative
- All existing structures located adjacent to the portal area and subterranean stations

10.2 Geology

Geology would affect the LRT Alternative, either through the support required for the elevated sections or the tunneled portion of the LRT. The physiography and topography would affect aboveground portions of the LRT Alternative, while stratigraphy will determine the design and operation of the tunneled section of the LRT Alternative. These geology-related impacts are summarized in the following subsections.

10.2.1 Physiography and Topography

The LRT Alternative commences in the Los Angeles Basin, then extends north across the Repetto Hills and along the western edge of the San Gabriel Valley. As shown in the geologic cross section for the LRT Alternative (Plate 8), elevations along the alternative vary from 275 feet at SR 60, to 340 feet at Ramona Boulevard in Monterey Park, to 440 feet at Cal State LA, to 380 feet near Hellman Avenue. The topography then ascends to

an approximate elevation of 780 feet at the northern terminus of the alternative near California Boulevard in Pasadena.

The LACDPW detention basin is present immediately west of the intersection of Corporate Center Drive and Corporate Place (approximate Station 66+00 on Plate 8). This basin is bounded by the I-710 mainline embankment on the northwest; parking lots and local streets surround the remainder of the basin. The eastern basin embankment is on the order of 30 to 40 feet high and has slopes generally inclined at 1.5:1 to 2:1 (horizontal to vertical [H:V]). This channel is mapped as alluvial soil (Plate 8); however, artificial fill soils likely compose the upper portion of the basin embankment.

Natural and human-made slopes are present along the LRT Alternative. In the area of the Blanchard Landfill (located on the west side of I-710 north of the LRT crossover of I-710), the slopes range in height from 40 to 230 feet and are generally inclined at 1.5:1 to 2:1 (H:V). In the area of Cal State LA, slopes up to 100 feet tall are present, generally inclined at 1.5:1 to 2:1 (H:V). Blanchard Landfill, Cal State LA (athletic fields and building structures), and commercial developments are situated atop the natural and human-made slopes in these areas.

10.2.2 Stratigraphy

The stratigraphy along the LRT Alternative is dominated by three principal geologic units: artificial fills, alluvial soils, and bedrock. These geologic units would determine foundation requirements for elevated sections of the LRT Alternative, as well as tunneling design and construction methods within the tunneled segment. Variations in stratigraphy could have influence on design and construction methods being used; therefore, site characterization along the LRT Alternative, particularly for the tunneled section, is a critical design requirement.

10.2.2.1 Artificial Fill Soils

Artificial fill soils are present at the surface along portions of the LRT Alternative. Where encountered, the fills were generally observed to be fine-grained with some coarse-grained constituents. Cross sectional limits of the larger fills present along the alternative are shown in Plate 8 and are described below:

- From Floral Drive north to roughly I-710, artificial fills on the order of 20 to 40 feet thick are expected; this includes the LACDPW basin discussed in Section 10.2.1. The LRT Alternative is elevated in this area.
- In the vicinity of the I-710 and I-10 interchange, artificial fills on the order of 20 to 40 feet thick are expected. The LRT Alternative is elevated in this area.
- Near the SR 710 terminus at Valley Boulevard, artificial fills on the order of 10 to 40 feet thick are expected. The LRT Alternative transitions from elevated to subterranean in this area.
- Local artificial fills are to be expected in the near subsurface along the LRT Alternative, related to the existing improvements.

10.2.2.2 Alluvial Soils

Alluvial soils are present within the Los Angeles Basin and San Gabriel Valley portions of the LRT Alternative, as well as in local drainages within the Repetto Hills. The alluvial soils are either present at the surface, or buried beneath artificial fill soils. The alluvial soils are described in Section 4.1.1. The approximate limits of the alluvial soils present along the alternative are shown in Plate 8 and described below.

- The LRT Alternative, from its southern terminus north to the I-710 crossover (roughly 1,500 feet north of Corporate Center Drive), is located within the Los Angeles Basin, which includes the LACDPW basin discussed in Section 10.2.1. The alluvial soils in this area thicken from zero feet thick near the LRT/I-710 crossover to on the order of 200 feet thick near SR 60. The LRT Alternative is elevated in this area.
- From the LRT/I-710 crossover point north to Hellman Avenue, the LRT Alternative traverses the Repetto Hills. These hills are composed of sedimentary bedrock with intermittent alluvial drainages that are filled with alluvial soil, as shown in Plate 8. This includes the Dorchester Channel, which generally parallels SR 710 from Valley Boulevard south to the southerly limits of the SR 710 North Study Area near SR 60. The LRT Alternative is elevated in this area. The depth of the alluvial soil within these intermittent drainages is anticipated to be on the order of 10 to 50 feet bgs, locally overlain by artificial fill soils.

- From Hellman Avenue to roughly 1,000 feet north of Alhambra Road, the LRT Alternative traverses the western edge of the San Gabriel Valley. The alluvial soils in this area are on the order of 40 to 80 feet thick. Just south of Valley Boulevard, the alternative transitions from elevated to subterranean. The tunnel in this area is located very close to the alluvial soil-bedrock contact, as shown in Plate 8. The area between roughly 1,000 feet north of Alhambra Road and Huntington Drive is underlain by sedimentary bedrock.
- From Huntington Drive north to the Raymond fault (near Arroyo Seco Parkway [SR 110]), the alluvial soil thickness is expected to be highly variable, as shown in Plate 8. The variability in this area is due to the surrounding topography. In addition, a possible ancient channel of the Arroyo Seco, which has been beheaded by the Raymond fault, may be present in this area, resulting in a relatively deep alluvium-filled channel. The alluvial soils in this area are on the order of 100 to 300 feet thick. The LRT tunnel would be located within the alluvial soil in this area. The area between the Raymond fault and the San Rafael fault (near Glenarm Street) is underlain by sedimentary bedrock.
- From the San Rafael fault to the northern terminus of the LRT Alternative near California Boulevard, the tunnel is located within the Raymond Basin portion of the San Gabriel Valley. The alluvial soils along this portion of the alternative are on the order of 160 to 220 feet thick. The tunnel would be located within the alluvial soil in this area.

10.2.2.3 Bedrock Units

Bedrock is present either at the surface or below the artificial fill and/or alluvial soils along the LRT Alternative. The bedrock units include sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite. These bedrock units are described in Section 4.1.1.

The limits of the bedrock present along the alternative are shown in Plate 8 and described below.

- From approximately Corporate Center Drive south to the southern terminus of the LRT Alternative, the Conglomerate Member of the Fernando Formation is present, concealed below the local artificial fill soils and the alluvial soils. The LRT Alternative is elevated in this area.
- From Corporate Center Drive north, to approximately I-10, the LRT Alternative is underlain by the Siltstone Member of the Fernando Formation. This includes a portion of the natural and manufactured slopes located below the Blanchard Landfill on the west side of I-710. The bedrock is locally concealed by the intermittent drainages within the Repetto Hills. The LRT Alternative is both elevated and at grade in this area.
- From I-10 north to approximately 1,000 feet south of Hellman Avenue, the Siltstone Member of the Puente Formation is present. This includes a portion of the natural and human-made slopes located below Cal State LA on the west side of SR 710. The bedrock is locally concealed by the intermittent drainages within the Repetto Hills. The LRT Alternative is both elevated and at grade in this area.
- From approximately 1,000 feet south of Hellman Avenue north to roughly 1,000 feet south of Valley Boulevard, the Sandstone Member of the Puente Formation is present. The bedrock is locally concealed by the intermittent drainages within the Repetto Hills. The LRT Alternative is elevated in this area.
- From approximately 1,000 feet south of Valley Boulevard north to approximately 1,500 feet south of Meridian Avenue, the Siltstone Member of the Puente Formation is present. The bedrock is concealed by the alluvial soils present within the western edge of the San Gabriel Valley. The LRT Alternative transitions from elevated to subterranean in this area.
- From approximately 1,500 feet south of Meridian Avenue north to Commonwealth Avenue, the Siltstone Member of the Fernando Formation is present. The bedrock is concealed by the alluvial soils present within the western edge of the San Gabriel Valley. The LRT Alternative is subterranean in this area, and is located very close to the alluvial soil/bedrock contact, as shown in Plate 8.

- From Commonwealth Avenue north to approximately 500 feet north of Main Street, the Siltstone Member of the Puente Formation is present. The bedrock is concealed by the alluvial soils present in the western edge of the San Gabriel Valley. The LRT Alternative is subterranean in this area, and is located very close to the alluvial soil/bedrock contact, as shown in Plate 8.
- From approximately 500 feet north of Main Street north to the Raymond fault (near Arroyo Seco Parkway [SR 110]), the Siltstone Member of the Topanga Formation is present. The sedimentary bedrock is either present at the surface, or concealed by the alluvial soils present within the western edge of the San Gabriel Valley. The LRT Alternative is subterranean in this area. Near Alhambra Road, the LRT Alternative is located very close to the alluvial soil/bedrock contact, as shown in Plate 8. From Alhambra Road north to near Huntington Drive, the tunnel traverses through the Siltstone Member of the Topanga Formation. North of Huntington Drive, the tunnel transitions back to alluvial soil, as shown in Plate 8.
- From the Raymond fault north to the San Rafael fault (near Glenarm Street), the Sandstone and Conglomerate Members of the Topanga Formation are present. The LRT Alternative is subterranean in this area and would traverse the Topanga Formation bedrock, as shown in Plate 8. From the San Rafael fault north to the northern terminus of the LRT Alternative near California Boulevard, Wilson Quartz Diorite is present concealed by the alluvial soils within the Raymond Basin. The LRT Alternative is subterranean in this area and would traverse the alluvial soils.

Some inherent variability exists between the sedimentary formations present along the LRT Alternative, including occasional hard to very hard cemented layers and concretions, and the presence of cobbles. Although the rocks of the Wilson Quartz Diorite unit are generally moderately hard to hard, they are highly fractured. The highly fractured nature of the Wilson Quartz Diorite, as observed within the SR 710 North Study Area, yields a rock mass that is generally hard but readily friable.

10.2.3 Structural Geology

As shown in Plate 8, the LRT Alternative is underlain by a variety of geologic units including artificial fill soils; alluvial soils; sedimentary bedrock of the Fernando, Puente, and Topanga Formations; and Wilson Quartz Diorite igneous and metamorphic bedrock. The structure within the Fernando, Puente, and Topanga Formations will be variable, ranging from massively bedded to laminated. Numerous intra-formatinal faults are present within the SR 710 North Study Area, as shown in Plate 2. These faults formed as a result of the past tectonic regime and are considered to be inactive. See Section 10.3.1 for a discussion of the active faults present along the LRT Alternative.

Based on the surface mapping by Lamar (1970), the geologic structure (bedding) within the sedimentary formations along the LRT Alternative from the I-710 crossover north to near Hellman Avenue is expected to be neutral to slope and the proposed improvements (bedding within the formations dips to the north and south). North of Hellman Avenue, the alternative is underlain by alluvial soil; the alternative transitions to subterranean south of Valley Boulevard.

10.3 Primary Seismic Hazards

The primary seismic hazards for the LRT Alternative would be faulting and ground shaking. These issues represent important design considerations for any development within the SR 710 North Study Area. The relevance of faulting and ground shaking to the LRT Alternative is summarized below.

10.3.1 Faulting

As shown in Plate 2, the LRT Alternative crosses one active fault (the Raymond fault) and one potentially active fault (the San Rafael fault). The LRT Alternative does not cross the Eagle Rock fault. Future studies would be performed to evaluate the activity of the San Rafael fault; however, for planning purposes, this fault is treated as an active fault.

The invert of the LRT tunnel in the vicinity of these faults would be located roughly 70 to 100 feet bgs. Preliminary fault rupture displacement estimates have been prepared for the LRT Alternative, as summarized in the Fault Rupture Evaluation Technical Memorandum (CH2M HILL and ECI, 2013) included in Appendix E.

Results of the fault evaluation suggest that the magnitude and distribution of fault displacement for each fault are as follows, based on Metro Maximum Design Earthquake criteria (Metro, 2013b):

- A left-lateral fault offset of 1.0 meter and a vertical reverse offset of 0.2 meter are estimated for the design of the tunnel at the Raymond fault across a fault zone 25 meters in width.
- A left-lateral offset of 0.5 meter and a reverse-vertical offset of 0.25 meter are estimated for the design of the tunnel at the San Rafael fault across a fault zone 50 meters in width.

As discussed in Section 4.2.3.2, the UEPBT-generated Coyote Pass escarpment transects the elevated portion of the LRT Alternative in the vicinity of Corporate Center Drive and Corporate Center Place, just east of I-710 in Monterey Park (Figure 4-3). The Coyote Pass escarpment is considered the primary concern with regard to potential coseismic deformation during an earthquake on the UEPBT. Additional study of the Coyote Pass escarpment would provide estimates of the amount of coseismic deformation anticipated where this feature crosses the LRT Alternative.

10.3.2 Seismicity

The potential to experience seismic ground shaking is a common hazard for every project in southern California, and the hazard cannot be avoided. Details on the levels of ground shaking estimated along the LRT Alternative are presented in the Preliminary Earthquake ARS Technical Memorandum (CH2M HILL, 2013; included in Appendix F). As detailed in the ARS technical memorandum, the calculated peak ground accelerations (PGAs) for a return period of 2,500 years range from 0.90g to 1.18g (g = acceleration due to gravity) along the LRT Alternative.

10.4 Secondary Seismic Hazards

A number of secondary seismic hazards could affect the design or operation of the LRT Alternative. The significance of these hazards would depend on the specific location, soil types, and groundwater conditions. Where these secondary seismic hazards appear to pose either a life-safety issue or risk of damage, standard engineering design methods can be implemented to manage the hazards.

10.4.1 Liquefaction

As shown in Plate 7, the LRT Alternative, primarily in the vicinity of I-10 and west of Corporate Place, is located within a Liquefaction Hazard Zone. Key features of this alternative (aboveground or bored tunnel) would be designed for liquefaction and its associated hazards. Where these hazards are identified outside the bored tunnel limits, various methods can be implemented to alleviate this potential hazard. Design and construction of the LRT Alternative would follow Metro Rail Design Criteria (Metro, 2013a) for liquefaction.

The occurrence of liquefaction could lead to loss in foundation support, reduction in lateral support of deep foundations, flow and lateral spreading, and liquefaction-induced settlement. Where these mechanisms could result in unacceptable soil or structural response, ground improvements such as dynamic compaction, stone columns, jet grouting, cement deep soil mixing, and compaction grouting, among others, would reduce the potential for liquefaction.

10.4.2 Seismically Induced Landslides

The potential for seismically induced landslides will depend on the steepness of the slope, strength and structure of the soil/rock, groundwater depth and extent, and level of ground shaking. As shown in Plate 7, the LRT Alternative, generally from Corporate Place north to I-10, is located within a Landslide Hazard Zone. One of the most likely causes of landslides in this zone would be seismically induced ground shaking. Based on the mapping by Lamar (1970) the geologic structure (bedding) within the sedimentary formations in this area is expected to be neutral to slope and the proposed improvements (bedding within the formations dips to the north and south). There are no known landslides mapped along the LRT Alternative. The aboveground segments of the LRT Alternative would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for potential landslides.

If seismically induced slope stability issues are identified outside the bored tunnel limits of the LRT Alternative, there are numerous geotechnical methods available to address this hazard. This can include the construction of buttress fills or shear keys, drainage systems, and the installation of deep foundations or retaining wall systems, among others.

10.4.3 Seismically Induced Settlement

Loose, unsaturated granular soils are susceptible to seismically induced settlement. This could include the alluvial soils located above the groundwater table in areas outside the bored tunnel limits of the LRT Alternative. The settlement issue could be critical at the portal for the tunnel and ground improvements. Ground improvements similar, those used to address liquefaction could be implemented to address settlement concerns. These improvements would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for seismically induced settlement.

10.4.4 Seismically Induced Inundation

The LRT Alternative in the immediate vicinity of I-10 is located within a potential dam inundation area, as shown in Figure 5-2. The inundation zone identified is related to seismically induced failure of the Laguna Regulating Basin (approximate Station 127+00 on Plate 8). The Laguna Regulating Basin is an ungated basin (CH2M HILL, 2014e) intended to collect sediment from runoff entering the basin. The LACDPW has no record of the Laguna Regulating Basin ever being filled to capacity since its construction in 1967 (CH2M HILL, 2014e). During the rare occurrences where inflow exceeds outflow within the basin, the amount of time the runoff would be pooled within the basin would be limited because the basin is allowed to runoff freely.

If the Laguna Regulating Basin was to be filled and a seismic event caused failure of the basin, the inundation would be short-lived. The LRT Alternative in this area would be elevated approximately 80 feet above existing grade (see Plate 8), supported on bridge piers. Potential scour of the ground surface around structural elements such as bridge foundations would be addressed via applicable Metro design standards for scour.

The LRT portal is located over 4,500 feet north of the identified inundation zone, and is situated over 50 feet higher than the top of the Laguna Regulating Basin embankment. As such, the potential for seismically induced inundation from the Laguna Regulating Basin to affect the tunnel portion of the LRT Alternative is very low.

10.4.5 Tsunamis and Seiches

The LRT Alternative is not located adjacent to any large bodies of water and is located at a minimum elevation of 275 feet. As such, there is no potential for a tsunami- or seiche-related impact on the LRT Alternative.

10.5 Groundwater

Historically highest groundwater levels (CDMG, 1998b, 1998d, and 1998f) along the LRT Alternative range from 40 feet bgs near the Raymond fault in South Pasadena to 200 feet bgs near West Main Street in Alhambra and near Caesar Chavez Avenue in Monterey Park.

The bedrock units along the LRT Alternative generally do not contain substantial amounts of groundwater; however, groundwater seepages may be present within local sandstone beds and fault and/or fracture zones. The Raymond fault is a known groundwater barrier; groundwater levels on the north side of this fault are significantly higher than the levels on the south side of the fault. In addition, the potentially active (Eagle Rock and San Rafael faults) and inactive faults may also act as groundwater barriers. Special care would have to be exercised when tunneling through a fault zone that has a substantial difference in groundwater levels on opposite sides of the fault.

Estimated groundwater depths for the alternative are shown in Plate 8. The groundwater depths presented below (and in Plate 8) for the LRT Alternative are based on review of existing information (MSGW, 2010; RBMB, 2011; and WRD, 2013a and 2013b), and the groundwater levels documented during previous and current SR 710 North Studies.

- From the southern terminus of the LRT Alternative near Mednik Avenue and 3rd Street, north to Corporate Center Drive, groundwater depths are on the order of 110 to 130 feet bgs. The LRT Alternative is elevated in this area.
- From Corporate Center Drive north to the southbound SR 710 ramp to westbound I-10, the LRT Alternative is primarily underlain by bedrock or alluvial soil situated above the water table. The LRT Alternative is both elevated and at grade in this area.
- From the southbound SR 710 ramp to westbound I-10, north to Valley Boulevard, groundwater is present at depths of 10 to 40 feet bgs, perched on bedrock. The LRT portal would be partially situated below the water table.
- North of Valley Boulevard to Commonwealth Avenue, groundwater is present at depths ranging from 20 to 70 feet bgs. The LRT tunnel would be situated below the water table in this area.
- From Commonwealth Avenue north to Huntington Drive, the LRT Alternative is underlain by bedrock or alluvial soil situated above the water table which is present to the south.
- From Huntington Drive north to the Raymond fault (near Arroyo Seco Parkway [SR 110]), groundwater levels are 80 to 150 feet bgs. The LRT tunnel would be above the water table in this area. However, in the vicinity of Mission Street, the tunnel invert would be situated within 5 to 10 feet of the groundwater table.
- Between the Raymond fault and the San Rafael fault (near Glenarm Street), the LRT Alternative is underlain primarily by bedrock. However, an alluvial wedge is anticipated between the Raymond fault and Raymond Hill to the north. Groundwater on the order of 10 to 30 feet bgs should be expected within this alluvial wedge. The tunnel would be situated below the water table between the Raymond fault and Raymond Hill.
- From the San Rafael fault north to the northern terminus of the LRT Alternative in the vicinity of California Boulevard, groundwater increases in depth from approximately 100 to 130 feet bgs. The tunnel would be situated above the water table in this area.

Surface water along the LRT Alternative generally either infiltrates into the ground, or drains by sheet flow into engineered drainage structures. The LRT Alternative does not cross any major drainages. Temporary lowering of the water table in alluvial areas due to potential dewatering from construction activities associated with the LRT Alternative would not affect the surface water features because groundwater is below the bottom of the local and regional surface water features.

10.6 Hazardous Waste and Naturally Occurring Oil and Gas

The SR 710 North Study included an evaluation of hazardous waste and naturally occurring oil and gas for each Alternative.

10.6.1 Contaminated Soil and Groundwater

Soil and groundwater contamination is addressed in the Phase ISA for the SR 710 North Study (CH2M HILL, 2014a). Design and construction requirements for areas with soil and/or groundwater contamination will be considered if this alternative is selected.

10.6.2 Naturally Occurring Oil and Gas

As shown in Plate 8, a portion of the tunnel segment of the LRT Alternative is anticipated to be constructed within Puente Formation bedrock. There is a low-to-moderate potential of encountering naturally occurring oil and/or gas within the Puente Formation or fault zones along the subterranean portion of the LRT Alternative. Naturally occurring oil and/or gas also could be found within any of the geologic formations within the SR 710 North Study Area. If encountered, the tunnel could be classified by the California Department of Occupational Safety and Health Administration (Cal/OSHA) as a “Gassy or Potentially Gassy Operation,” and, if so designated, compliance with Cal/OSHA guidelines for tunneling in gassy conditions would be required.

The presence of naturally occurring oil and gas is not unusual, especially in the Los Angeles region. Special tunneling equipment, air monitoring, ventilation methods, and safety procedures have been developed to allow tunnel construction in a safe manner. These techniques have been successfully applied to numerous subterranean projects completed in the Los Angeles region.

Between I-10 and the portal area south of Valley Boulevard, the LRT Alternative elevated guideway drilled shafts would be founded in Puente Formation bedrock. The potential for encountering natural gas during construction of the drilled shafts for this structure is considered low to moderate. To adequately characterize the potential to encounter naturally occurring oil and gas along the LRT Alternative, detailed geotechnical investigations would be conducted during final design. Where anticipated, appropriate precautions would be implemented in accordance with Cal/OSHA requirements for naturally occurring gases.

10.7 Potential Non-Seismic Geologic Hazards

The LRT Alternative would have to consider the effects of non-seismic geologic hazards such as slope stability, ground settlement and collapse, expansive soils, and erosion. The LRT Improvements would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for the following potential non-seismic geologic hazards.

10.7.1 Slope Stability

The LRT Alternative traverses hillside areas, as shown in Plate 2. In areas where improvements may affect existing slopes and/or developments atop existing slopes, detailed evaluations of the geologic units and geologic structure of these slopes would be conducted. These evaluations would yield the appropriate data required to conduct analyses and provide the geotechnical recommendations needed for the design and construction of the proposed hillside improvements.

The portions of the LRT Alternative that are located outside the bored tunnel and are proposed on or adjacent to hillside areas would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for slope instability.

10.7.2 Ground Settlement and Collapsible Soils

Local areas along the LRT Alternative that are underlain by alluvial soils (see Plate 8) may be prone to ground settlement or collapsible soils. Where improvements are proposed on alluvial soils, the improvements would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for ground settlement and collapsible soils.

Ground settlement can also occur as a result of ground loss during deep excavations, such as tunneling. Ground loss would be actively controlled at the tunnel heading, as discussed in Section 10.8.

10.7.3 Expansive Materials

Clay-rich expansive soils and bedrock are present locally along some of the surficial improvement areas and portions of the bored tunnel of the LRT Alternative. Potentially expansive materials present along the alternative include artificial fill soils, alluvial soils, and the siltstone and/or claystone units of the Fernando, Puente, and Topanga Formations. Where expansive materials are identified, the improvements would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for expansive materials.

10.7.4 Erosion

As shown in Plate 6, the surficial soils present along the LRT Alternative have a moderate susceptibility to erosion. Erosion is a constant ongoing process that can be successfully controlled by implementing engineered designs developed in accordance with Metro Rail Design Criteria (Metro, 2013a).

10.8 Geotechnical Considerations for Design and Construction

A number of additional geotechnical design and construction considerations would need to be considered as part of the LRT Alternative development. These considerations would involve the bored tunnel and portal, as well as the elevated segments, retaining walls, and stations. A brief summary of these considerations is provided in the following subsections.

10.8.1 Bored Tunnel and Portal

Design considerations for the bored tunnel and portal include excavations in alluvial soil, in bedrock, at fault crossings, and in areas near or below the groundwater table; as well as naturally occurring oil and gas considerations. With proper planning and implementation of appropriate construction methods, these considerations can be managed.

10.8.1.1 Design Consideration for Alluvial Soil

Unconsolidated and/or water-saturated alluvial soil deposits would likely be encountered in excavations for the portal, the Alhambra Station, and along segments of the LRT tunnel. Open excavation and tunneling in unconsolidated and/or saturated alluvium have the potential for high groundwater inflows and flowing ground conditions at the heading of the excavation, which could result in loss of ground and settlement of the ground surface. Groundwater inflows are also anticipated in the fractured/sheared rock and adjacent to fault zones, which may act as groundwater barriers. During construction, excavation of a tunnel using a pressurized-face tunnel boring machine (TBM) would actively control groundwater inflows at the tunnel heading. Special care must be exercised when tunneling through a fault zone that has a substantial difference in groundwater levels on opposite sides of the fault. Groundwater control methods are discussed in Section 10.8.1.4.

Tunneling methods are available to handle saturated alluvium conditions. Pressure face TBMs generally utilize either earth-pressure balance (EPB) or slurry methods to provide active face control to limit ground loss while excavating. Such machines have been used successfully on previous tunneling projects in Los Angeles, and this technology could be applied to the LRT Alternative. To limit ground loss, the construction contractor could be required to use a pressurized-face TBM, have a robust excavated material monitoring system, and employ a grouting system along the shield of the TBM. While a pressurized face TBM would likely be required for the project, evaluation of whether it can or will be used in open mode would be evaluated in the future. Comprehensive real-time monitoring with geotechnical-tunnel data management software and implementation of observational approach to construction management would be implemented during construction of the LRT Alternative tunnel.

10.8.1.2 Design Consideration for Bedrock

The tunnel excavation for the LRT Alternative would be through several different geologic units. The tunnel excavation methods would need to address a range of geologic conditions including alluvial soil and weak sedimentary rocks. This would require the use of tunneling equipment adaptable to the variable range of rock characteristics anticipated, such as rock hardness, tunnel face stability and muck characteristics or a flexible approach that allows methods to be changed to suit the geology. It would 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.

Regardless of the excavation methods, special provisions will be necessary to address the inherent variability of the Fernando, Puente, and Topanga Formations, such as the cemented layers and concretions, the variability between conglomerate, sandstone, siltstone, claystone, mudstone, and shale, and potential fault gouge. This variability would be considered in the design of tunnel excavation equipment. TBMs can be designed to handle this wide range of ground conditions. The LRT Alternative would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for the structure of the geologic units along the alternative.

The Fernando, Puente, and Topanga Formations are expected to require immediate support in the tunnel excavations proposed for this study. If the tunnel is excavated by a full-face TBM, a precast concrete segmental

lining system 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 these formations. Timely installation of effective ground supports is also required to control loss of ground and ground surface settlement.

10.8.1.3 Design Consideration for Active Faults

Tunneling through faults will require the excavation of fractured rock and control of groundwater, and may involve excavation of clay gouge formed by prior fault movements. Specialized TBMs would be able to complete this work without major difficulty, but with slower progress.

As discussed in Section 10.3.1, the estimated lateral and vertical offsets are 1.0 meter and 0.2 meter, respectively, for the Raymond fault and 0.5 meter and 0.25 meter, respectively, for the San Rafael fault.

For fault displacements such as those anticipated for the Raymond and San Rafael faults, 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 (FHWA, 2009). 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 and backfilled with crushable materials. This vault would be large enough to accommodate the movement of the fault. This method, utilizing a robust lining system has been recommended as the preliminary design concept for the LRT Alternative fault crossings (Jacobs Associates and CH2M HILL, 2014).

At the fault crossings, where clay gouge may be present, squeezing ground may lead to 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. Specialized TBMs would be able to excavate through the clay gouge without major difficulty, but with slower progress, and the tunnel lining would be designed to account for these higher ground loads.

10.8.1.4 Design Consideration for Groundwater

Groundwater inflows could occur while tunneling below the groundwater table, especially in the saturated alluvium. This inflow would be controlled during construction of a tunnel utilizing a pressurized-face TBM to limit groundwater infiltration at the tunnel heading. To ensure that water flows are controlled behind the TBM a relatively watertight support system would be required (such as a bolted, double gasketed with appropriate cross gaskets, precast concrete segmental lining system) when tunneling in saturated alluvium. Supplemental grouting operations may be used in conjunction with the bolted, double rubber gasketed with appropriate cross gaskets, precast concrete segmental lining system to control both water and gas inflows in the temporary and permanent condition. The LRT Alternative would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for groundwater inflows during tunneling.

Groundwater inflows could also occur during construction of the LRT Alternative portal for launching the TBM and also at the Alhambra Station, where construction may take place below the groundwater table. Based on the available information, the groundwater table at the site of the three other underground stations is deeper than the base slab level of the stations. The portal area and Alhambra Station may be temporarily dewatered prior to excavation to facilitate construction if the excavation support system is not watertight (such as the proposed soldier piles and lagging systems). The dewatering or the excavation wall system would be designed such that the groundwater table would experience minimal temporary drawdown. The LRT Alternative would be designed in accordance with Metro Rail Design Criteria (Metro, 2013a), accounting for groundwater inflows at deep excavation.

10.8.1.5 Design Consideration for Naturally Occurring Oil and Gas

Geotechnical investigations would be conducted to adequately characterize the potential for encountering naturally occurring oil and gas, if the LRT Alternative is selected. Where anticipated, appropriate precautions will be necessary in accordance with Cal/OSHA requirements for dealing with potential naturally occurring oil and gas during tunnel and station excavation and/or during construction of the deep foundations for the proposed LRT Alternative guideway supports.

10.8.2 Aerial Guideway

The LRT Alternative includes 3 miles of aerial guideway, which will be supported by deep foundations. Foundations supporting the aerial guideways would be designed based on the latest Metro Rail Design Criteria and in accordance with the LRFD method as specified in the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014).

Based on the subsurface conditions present along the LRT aerial alignment, 8- to 12-foot-diameter cast-in-drilled-hole (CIDH) piles are considered suitable to support the aerial segments. The various CIDH pile diameters are proposed to support the various column sizes. Spread footings do not appear to be suitable for the proposed structure because of difficulties in meeting seismic loading demands for uplift from overturning forces and from lateral demand at support locations. The subsurface conditions at the proposed foundation areas were interpreted based on the limited subsurface information available. Additional, detailed subsurface investigation and testing will be required for final design if this alternative is selected.

As discussed in Section 4.2.3.2, the UEPBT-generated Coyote Pass escarpment transects the LRT Alternative (Figure 4-3). The portion of the elevated LRT guideway proposed at the Coyote Pass escarpment crossing may require design to accommodate potential deformations. Additional study of the Coyote Pass escarpment would provide estimates of the amount of coseismic deformation anticipated where this feature crosses the LRT Alternative. Potential ground movements along the elevated segment of the LRT Alternative would have to be designed for. This would include evaluating the locations of the guideway supports, and the amount of differential displacement that could be tolerated along the guideway structure.

10.8.3 Retaining Walls

According to Advanced Conceptual Engineering Plans for SR 710 North Study – LRT Alternative (AECOM, 2014), multiple retaining walls are proposed to support grade changes (including the portal area), aerial guideways, aerial stations, realigned roadways, and a maintenance yard along the LRT Alternative. The proposed retaining walls are summarized in Table 10-1. Foundation-supporting LRT retaining walls would be designed based on the latest Metro Rail Design Criteria and in accordance with the LRFD method as specified in the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014).

For preliminary design, Caltrans standard walls and mechanically stabilized earth (MSE) walls appear to be suitable for supporting the proposed structures. At the locations where ROW is limited, a slurry wall or soldier pile wall can be considered. A soil nail or tieback wall may be required where a retaining wall supports a relatively high cut slope.

Subsurface conditions at the proposed wall locations were interpreted based on the subsurface information available at this time. Additional, detailed subsurface investigation and testing will be required for final design, if this alternative is selected.

TABLE 10-1
Proposed Retaining Walls and Sound Walls for LRT Alternative

Type	Location	Length (feet)	Maximum Height (feet)	Cut/Fill Wall	Supporting Structure
RW	Floral Station	583	26	Cut	Parking Lot
RW	West of I-710	1162	10	Fill	Guideway
RW	West of I-710	1171	25	Cut	Guideway
RW	Cal State LA Station	375	17	Fill	Cal State LA Station
RW	Cal State LA Station	386	28	Cut	Circle Drive
RW	Proposed SR 710 Off-Ramp	1421	7	Fill	SR 710 Off-Ramp
RW	Proposed SR710 Off-Ramp	473	38	Fill	SR 710 Off-Ramp

TABLE 10-1
Proposed Retaining Walls and Sound Walls for LRT Alternative

Type	Location	Length (feet)	Maximum Height (feet)	Cut/Fill Wall	Supporting Structure
RW	Portal Access	127	14	Cut	Portal Access
RW	Portal Access	80	22	Cut	Portal Access
SW	West of Existing SR 710 Off-Ramp	712	18	N/A	N/A
RW	South of Maintenance Yard	24	31	Fill	Maintenance Yard
RW/SW	South of Maintenance Yard	129	31	Fill	Maintenance Yard
RW	South of Maintenance Yard	96	29	Fill	Maintenance Yard
RW/SW	West of Maintenance Yard	884	29	Fill	Maintenance Yard
RW	North of Maintenance Yard	391	23	Fill	Maintenance Yard
RW/SW	East of Maintenance Yard	965	25	Fill	Maintenance Yard
RW	East of Maintenance Yard	203	17	Fill	Maintenance Yard
RW/SW	Southeast of Maintenance Yard	119	19	Fill	Maintenance Yard
SW	East of Existing SR 710 Off Ramp	790	8	N/A	N/A

RW – retaining wall
 SW – sound wall
 N/A – not applicable

10.8.4 LRT Stations

The LRT Alternative consists of seven stations including two aerial stations, one at-grade station, and four underground stations.

10.8.4.1 Aerial and At-Grade Stations

The proposed aerial stations are Civic Center Station and Floral Station, which will be supported by bridge structures. The preliminary geotechnical recommendations for the aerial stations are the same as those provided in Section 10.8.2 for the aerial guideways. The at-grade Cal State LA Station would be located on cut-and-fill graded ground, supported by retaining walls. The preliminary geotechnical recommendations for the retaining walls are provided in Section 10.8.3. Station buildings not directly supported off the aerial guideway would be designed in conformance with the requirements of the latest California Building Code.

10.8.4.2 Underground Stations

The proposed underground stations are Alhambra Station, Huntington Station, South Pasadena Station, and Fillmore Station. These stations would be constructed using the cut-and-cover method with a maximum excavation depth of approximately 80 to 90 feet bgs.

During the initial excavation, temporary support will be required such as soldier piles with timber or shotcrete lagging, tangent pile walls, or slurry walls. To minimize temporary support movement, a tight bracing system, internal system of walers, struts, or a combination of these methods would also be required for lateral support. The excavation can be supported with tiebacks where feasible.

The groundwater table at the Alhambra Station is shown in the geologic cross section (Plate 8) at a depth of approximately 45 feet bgs, while the groundwater tables at the other underground stations are deeper than the station base slab levels. To account for seasonal variations in groundwater levels, the groundwater table should be considered to vary 5 feet above and below the level shown on the geologic cross section (Plate 8). If soldier

piles and lagging systems are used at the Alhambra Station, dewatering operations and/or groundwater control would be required prior to excavation. Provisions must be implemented to prevent the piping of fines from the alluvial soils and, if a relatively impermeable lagging (such as shotcrete) is used, effective drainage must be provided.

Underground station structures would consist of a reinforced concrete structure constructed within excavations. The structures may have a gas- and water-proofing barrier system to prevent leakage into the stations. The structure would be designed for the specific geologic conditions present at each station location.

To account for seismic demand due to racking deformations, the stations would be designed based on Metro Supplementary Seismic Design Criteria (Metro, 2013b).

10.9 Future Geotechnical Exploration and Investigations

For the design of the LRT Alternative, additional subsurface investigations are required. The purpose of the investigations is to evaluate the subsurface conditions and provide geotechnical information for design and construction of structure foundation, tunnel, portal, station, and remedial earthwork, if required.

Proposed explorations for the LRT Alternative are summarized below.

- **Tunnel Explorations:** The proposed field investigation for the tunnel would consist of borings, sampling, in situ testing, geophysical investigations, and laboratory testing. The borings would be generally spaced at intervals of 300 to 500 feet. The proposed borings would extend at least 1.5 tunnel diameter below the proposed tunnel invert. The borings proposed at LRT stations would extend at least 1.5 times the depth of the station for design of the shoring system. The field investigation should be carried out in phases to obtain the subsurface information necessary at each stage of the project in a cost-efficient manner.
- **Bridge Foundations:** For the bridge foundations, subsurface explorations would be conducted in accordance with Metro Rail Design Criteria (Metro, 2013a). According to Metro Rail Design Criteria, a minimum of 50 percent of the bent locations would be investigated for aerial guideway designs. In addition, a minimum of one exploration for each abutment support is recommended. The depth of exploration would extend below the foundation tip elevation a minimum of 20 feet, at least 3 times the pile diameter, or a minimum of 2 times the pile group dimension, whichever is deeper.
- **Retaining Walls:** For the retaining wall foundation, subsurface explorations would be conducted in accordance with Metro Rail Design Criteria (Metro, 2013a). A minimum of one exploration for each retaining wall is recommended. For retaining walls more than 100 feet in length, exploration points would be spaced every 100 to 200 feet. The depth of the exploration would extend at least 1 to 2 times the wall height. For anchored and soil-nailed walls, additional exploration points in the anchorage zone space are recommended at a distance of 1.0 to 1.5 times the height of the wall behind the wall face and spaced at 100 to 200 feet.
- **Cut Slopes:** For cut slopes, a minimum of one exploration point would be spaced every 200 to 400 feet of slope length. At critical locations, such as maximum slope heights, a minimum of three exploration points in the transverse direction are recommended to define the existing subsurface conditions for stability analyses. The exploration depth would be a minimum of 30 feet below the lowest elevation of the cut, and extend below the toe of the slope. In addition, the exploration depth would be advanced enough to fully penetrate through soft strata into competent material and to determine the depth of underlying pervious strata if the base of the cut is below groundwater level.
- **Active Faulting:** To further evaluate the location and activity details for the Raymond and San Rafael faults, detailed investigations will be required. Trenching is the ideal method to evaluate a fault. However, constraints to the placement of the trenches are abundant along the alternative, and the trenches may need to be emplaced outside the limits of the alternative. This may be the only realistic way to gather the necessary detailed geologic and paleoseismic data needed for these faults. To better locate the Raymond and San Rafael fault crossings along the LRT Alternative, a series of continuously cored boreholes would be emplaced across the fault zones. In addition, seismic lines can be utilized to provide additional subsurface information relevant

to faulting. Further evaluation of the UEPBT fault-generated Coyote Pass escarpment will be required as well. An investigation would be similar to that indicated for the Raymond and San Rafael faults.

All geotechnical explorations should extend through unsuitable strata such as soft highly compressible soils, peat, highly organic materials, and loose coarse-grained soils to reach competent material of suitable bearing strata.

Geotechnical Evaluation – Freeway Tunnel Alternative

The Freeway Tunnel Alternative consists of either a single- or twin-bored tunnel approximately 4.2 miles in length. Each bored tunnel would have an outside diameter of approximately 58.5 feet; the crown of each tunnel would be located approximately 120 to 250 feet bgs along most of the tunnel. Short segments of cut-and-cover tunnels would be located at the southern and northern termini to provide access via portals to the bored tunnels. The portal at the southern terminus would be located south of Valley Boulevard. The portal at the northern terminus would be located north of Del Mar Boulevard. Both tunnel design variations include roadway improvements outside the north and south portal areas. The Freeway Tunnel Alternative would also include the same improvements proposed for the TSM/TDM Alternative with the exception of Improvements T-1 and T-3. A generalized discussion of the geologic setting and potential geologic hazards covering the TSM/TDM Alternative, as well as associated preliminary design recommendations are presented in Section 8 of this report. A generalized discussion of the geologic setting and potential geologic hazards along the Freeway Tunnel Alternative, as well as associated preliminary design recommendations are presented below.

11.1 Human-Made and Natural Features of Engineering and Construction Significance

The Freeway Tunnel Alternative is located within areas developed with residential, commercial, and industrial properties, as well as associated improvements such as roadways, sidewalks, and utilities. In many locations, the developments have been in place for over 100 years. The bored tunnel portion of the alternative would be located below many of these existing residential, commercial, and industrial improvements.

The following is a list of existing features that would require consideration due to the proposed improvements:

- The natural and human-made slopes in the vicinity of Cal State LA, on the west side of SR 710
- The Laguna Regulating Basin, located northeast of the I-10 and SR 710 interchange
- The Hellman Avenue Bridge structure over SR 710
- The UPPR tracks and easement immediately south of Mission Road
- All structures and associated improvements located above the tunnel portion of the alternative
- Potential existing deep foundations and/or utilities overlying the tunnel portion of the alternative
- All the existing structures located adjacent to the portal areas
- The bridge structures over SR 710, including the Del Mar Boulevard, Green Street, Colorado Boulevard, and Union Street bridges

11.2 Geology

Geology would affect the Freeway Tunnel Alternative at the tunnel portals as well as the bored tunneled portion of the alternative. The physiography and topography of the Freeway Tunnel Alternative would affect aboveground portions of the alternative such as portals and ventilation systems. Stratigraphy would affect the design of the tunneled section of the Freeway Tunnel Alternative. These geology-related impacts are summarized in the following subsections.

11.2.1 Physiography and Topography

The SR 710 North Study Freeway Tunnel Alternative is primarily located along the western edge of the San Gabriel Valley; a small portion of the alternative is located within the Repetto Hills (generally between Moffatt Street and Lyndon Street in South Pasadena). As shown in the geologic cross section for the Freeway Tunnel Alternative

(Plate 9), elevations along the alternative vary from 345 feet at I-10, to 545 feet at Newtonia Drive in Los Angeles, to 740 feet near Flores De Oro within the Repetto Hills, to 650 feet near Monterey Road in South Pasadena. The topography then ascends to an approximate elevation of 800 feet at the northern terminus of the alternative near Del Mar Boulevard in Pasadena.

In the area of Cal State LA, slopes up to 100 feet tall are present, generally inclined at 1.5:1 to 2:1 (H:V). Cal State LA athletic fields and building structures are situated atop the natural and manufactured slopes in this area.

11.2.2 Stratigraphy

As shown in Plate 9, the Freeway Tunnel Alternative is underlain by a variety of geologic units including artificial fill soils; alluvial soils; sedimentary bedrock of the Fernando, Puente, and Topanga Formations; and Wilson Quartz Diorite igneous and metamorphic bedrock.

11.2.2.1 Artificial Fill Soils

Artificial fill soils are present at the surface along portions of the Freeway Tunnel Alternative. Where encountered, the fills were generally observed to be fine-grained with some coarse-grained constituents. The limits of the substantial fills present along the Freeway Tunnel Alternative are shown in Plate 9 and described below:

- In the vicinity of the I-710 and I-10 interchange, artificial fills on the order of 20 to 40 feet thick are expected. The Freeway Tunnel improvements proposed in this area are located at the surface.
- In the vicinity of Valley Boulevard, artificial fills on the order of 10 to 40 feet thick are expected to be present. The Freeway Tunnel south portal is planned in this area.
- Local artificial fills are to be expected at the surface throughout the alternative, and are related to the existing improvements.

11.2.2.2 Alluvial Soils

Alluvial soils are present at the surface along the San Gabriel Valley portions of the Freeway Tunnel Alternative, as well as in local drainages within the Repetto Hills. The alluvial soils are either present at the surface, or overlain by artificial fill soils. The alluvial soils are described in Section 4.1.1.

The approximate limits of the alluvial soils present along the alternative are shown in Plate 9 and are described below.

- From I-10 north to Hellman Avenue, the Freeway Tunnel Alternative traverses the Repetto Hills. These hills are composed of sedimentary bedrock with intermittent alluvial drainages that are filled with alluvial soil, as shown in Plate 9. This includes the Dorchester Channel, which generally parallels SR 710 from Valley Boulevard south to near SR 60. The Freeway Tunnel Alternative improvements proposed in this area are located at the surface.
- From I-10 to approximately Moffatt Street, the Freeway Tunnel Alternative traverses the western edge of the San Gabriel Valley. The alluvial soils in this area are on the order of 40 to 110 feet thick. North of Valley Boulevard, the base of the portal and the subsequent tunnel would be located below the alluvial soil, as shown in Plate 9. The area between Moffatt Street and Lyndon Street is underlain by sedimentary bedrock.
- From Lyndon Street north to the Raymond fault (near Arroyo Seco Parkway [SR 110]), the alluvial soil thickness is expected to be highly variable, as shown in Plate 9. The variability in this area is due to the surrounding topography. In addition, a possible ancient channel of the Arroyo Seco, which has been beheaded by the Raymond fault, may be present in this area, resulting in a relatively deep alluvium-filled channel. The alluvial soils in this area are on the order of 60 to 280 feet thick. The Freeway Tunnel Alternative tunnel would continue within sedimentary bedrock until approximately Monterey Road, where the tunnel transitions into alluvial soil as shown in Plate 9.

- From the Raymond fault north to the San Rafael fault (near Hurlbut Street), the Freeway Tunnel Alternative is located within the Raymond Basin portion of the San Gabriel Valley. The alluvial soils along this portion of the alternative are on the order of 75 to 130 feet thick. The tunneled portion of the alternative would be located below the alluvial soil in this area.
- From the San Rafael fault (near Hurlbut Street) to the northern terminus of the Freeway Tunnel Alternative near Green Street, the alternative continues within the Raymond Basin. The alluvial soils along this portion of the Freeway Tunnel Alternative are on the order of 125 to 200 feet thick. The tunnel, portal, and associated improvements would be located within the alluvial soil in this area.

11.2.2.3 Bedrock Units

Bedrock is present either at the surface or buried beneath the artificial fill and/or alluvial soils along the Freeway Tunnel Alternative. The bedrock units include sedimentary rocks of the Fernando, Puente, and Topanga Formations, and igneous and metamorphic rocks of the Wilson Quartz Diorite. These bedrock units are described in Section 4.1.1.

The limits of the bedrock present along the Freeway Tunnel Alternative are shown in Plate 9 and are described below.

- From I-10 north to approximately 1,000 feet south of Hellman Avenue, the Siltstone Member of the Puente Formation is present. The bedrock is locally concealed by the intermittent drainages (alluvial soil filled), which are located within the Repetto Hills. The Freeway Tunnel improvements proposed in this area are located at the surface and would traverse artificial fill soils, alluvial soils, and the Puente Formation.
- From approximately 1,000 feet south of Hellman Avenue north to roughly 1,000 feet south of Valley Boulevard, the Sandstone Member of the Puente Formation is present. The bedrock is locally concealed by the intermittent drainages (alluvial soil filled) that are located within the Repetto Hills. The Freeway Tunnel improvements proposed in this area are located at the surface and would traverse artificial fill soils, alluvial soils, and the Puente Formation.
- From approximately 1,000 feet south of Valley Boulevard north to approximately 500 feet south of Norwich Avenue, the Siltstone Member of the Puente Formation is present. The bedrock is concealed by the alluvial soils present within the western edge of the San Gabriel Valley. The Freeway Tunnel and the southern portal of the alternative are present in this area and would traverse the Puente Formation.
- From approximately 500 feet south of Norwich Avenue north to Huntington Drive, the Siltstone Member of the Fernando Formation is present. The bedrock is concealed by the alluvial soils present within the western edge of the San Gabriel Valley. The Freeway Tunnel would traverse the Fernando Formation in this area.
- From Huntington Drive north to approximately 500 feet south of Newtonia Drive, the Siltstone Member of the Puente Formation is present. The bedrock is concealed by the alluvial soils present within the western edge of the San Gabriel Valley. The Freeway Tunnel would traverse the Puente Formation in this area.
- From approximately 500 feet south of Newtonia Drive north to Lyndon Street, the Siltstone Member of the Topanga Formation is present. The bedrock outcrops at the surface within roughly half of this area, as shown in Plate 9. The Freeway Tunnel would traverse the Topanga Formation in this area.
- From approximately Lyndon Street north to the Raymond fault (near Arroyo Seco Parkway [SR 110]), Wilson Quartz Diorite is present, concealed by the alluvial soils present within the San Gabriel Valley. The Freeway Tunnel transitions from Wilson Quartz Diorite to alluvial soil in the vicinity of Mission Street, as shown in Plate 9.
- From the Raymond fault north to the San Rafael fault (near Hurlbut Street), undifferentiated Topanga Formation is present. Additional exploration will be required to further differentiate the Topanga Formation in this faulted area. Regional maps indicate that the Topanga Formation in this area is either the Sandstone or Conglomerate Member. The bedrock is concealed by the alluvial soils present within the Raymond Basin. The Freeway Tunnel would traverse the Topanga Formation in this area.

- From the San Rafael fault north to approximately the northern terminus of the Freeway Tunnel Alternative near Green Street, Wilson Quartz Diorite is present concealed by the alluvial soils present within the Raymond Basin. The Freeway Tunnel and northern portal of the alternative would traverse the alluvial soils in this area.

Some inherent variability exists between the sedimentary formations present along the Freeway Tunnel Alternative, including occasional hard to very hard cemented layers and concretions, and the presence of cobbles. Although the rocks of the Wilson Quartz Diorite unit are generally moderately hard to hard, they are highly fractured. The highly fractured nature of the Wilson Quartz Diorite, as observed within the SR 710 North Study Area, yields a rock mass that is generally hard but readily friable.

11.2.3 Structural Geology

The generalized geologic structure within the sedimentary units along the Freeway Tunnel Alternative is shown in Plate 9. The structure within the Fernando, Puente, and Topanga Formations will be variable, ranging from massively bedded to laminated. Numerous intra-formational faults are present within the SR 710 North Study Area as shown in Plate 2. These faults formed as a result of the past tectonic regime and are considered to be inactive. See Section 11.3.1 for a discussion of the active faults present along the Freeway Tunnel Alternative.

Based on the surface mapping by Lamar (1970), the geologic structure (bedding) within the sedimentary formations present along the Freeway Tunnel Alternative from I-10 north to near Hellman Avenue is expected to be neutral to slope and the proposed improvements (bedding within the formations dips to the north and south). North of Hellman Avenue, the alternative is underlain by alluvial soil; the alternative transitions to a tunneled alignment near Valley Boulevard.

11.3 Primary Seismic Hazards

The primary seismic hazards for the Freeway Tunnel Alternative would be faulting and ground shaking. These issues represent important design considerations for any development within the SR 710 North Study Area. The relevance of faulting and ground shaking to the Freeway Tunnel Alternative is summarized below.

11.3.1 Faulting

The bored tunnel segment of the Freeway Tunnel Alternative crosses one active fault (the Raymond fault) and two potentially active faults (the Eagle Rock and San Rafael faults), as shown in Plates 2, 4, and 9. Future studies may reveal that the Eagle Rock and San Rafael faults are inactive; however, for planning purposes, these two faults are treated as active faults.

The invert of the tunnel for the Freeway Tunnel Alternative in the vicinity of these faults would be located roughly 160 to over 300 feet bgs. Based on Caltrans design guidelines (Caltrans 2013c), preliminary fault rupture displacement estimates have been prepared for the Freeway Tunnel Alternative as summarized in the Fault Rupture Evaluation Technical Memorandum (CH2M HILL and ECI, 2013) included in Appendix E. Results of the fault evaluation suggest that the magnitude and distribution of fault displacement for each fault are as follows, based on Caltrans Safety Evaluation Earthquake criteria:

- A left-lateral fault offset of 0.5 meter and a vertical reverse offset of 0.1 meter are estimated for the design of the tunnel at the Raymond fault across a fault zone 25 meters in width.
- A left-lateral offset of 0.5 meter and a vertical reverse offset of 0.25 meter are estimated for the design of the tunnel at the San Rafael and Eagle Rock faults across a fault zone 50 meters in width.

Two UEPBT-related features (fold axes) have been mapped by Oskin et al. (2000) transecting the Freeway Tunnel Alternative north of the Montebello Hills (Figure 4-3). Evaluation of these features will be required to determine the potential for coseismic deformation. The amount of deformation anticipated at or near the surface (if any) would be substantially less than that of the Coyote Pass escarpment, as discussed in Section 4.2.3.2.

The UEPBT-generated Coyote Pass escarpment transects the Freeway Tunnel Alternative roughly 700 feet north of Floral Drive, near the southern end of the alternative, south of I-10 (Figure 4-3). No improvements associated with the Freeway Tunnel Alternative single-bore option are proposed south of I-10. The improvements related to the

dual-bore option would be limited to above ground improvements such as striping. As such, the potential movements along the Coyote Pass escarpment will have very low effect on the improvements proposed within the Freeway Tunnel Alternative.

11.3.2 Seismicity

The potential for seismic ground shaking is a common hazard for every project in southern California, and the hazard cannot be avoided. Details on the levels of ground shaking estimated along the Freeway Tunnel Alternative are presented in the Preliminary Earthquake ARS Technical Memorandum (CH2M HILL, 2013; included in Appendix F). As detailed in the technical memorandum, the calculated PGAs for a return period of 1,000 years range from 0.75g to 0.84g along the Freeway Tunnel Alternative.

11.4 Secondary Seismic Hazards

A number of secondary seismic hazards could affect the design or operation of the Freeway Tunnel Alternative. The effect of the secondary seismic hazards would depend on the location of the proposed improvement and geologic conditions. Where these secondary seismic hazards appear to pose either a life-safety issue or risk of damage, standard engineering design methods can be implemented to manage the hazards.

11.4.1 Liquefaction

As shown in Plate 7, a portion of the at-grade segment of the Freeway Tunnel Alternative (generally south of I-10) is located within a Liquefaction Hazard Zone. If needed based on future geotechnical study, key features of the surface improvements along this alternative would be designed for liquefaction and its associated hazards. Where these hazards are identified outside the bored tunnel limits, various methods can be implemented to alleviate this potential hazard. Design and construction of the Freeway Tunnel Alternative would follow the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for liquefaction.

The occurrence of liquefaction could lead to loss in foundation support, reduction in lateral support of deep foundations, flow and lateral spreading, and liquefaction-induced settlement. These issues could be critical at the portals for the tunnel. Where these mechanisms could result in unacceptable soil or structural response, ground improvements such as dynamic compaction, stone columns, jet grouting, cement deep soil mixing, and compaction grouting, among others, would reduce the potential for liquefaction. The liquefaction potential beneath the Freeway Tunnel Alternative bored tunnel segment is considered low.

11.4.2 Seismically Induced Landslides

The potential for seismically induced landslides will depend on the steepness of the slope, strength and structure of the soil/rock, groundwater depth and extent, and level of ground shaking. As shown in Plate 7, the Freeway Tunnel Alternative in the vicinity of I-10 and near Summit Drive in South Pasadena is located within or adjacent to a seismically induced Landslide Hazard Zone. However, there are no known landslides mapped along the Freeway Tunnel Alternative. Surface improvements for the Freeway Tunnel Alternative would be designed in accordance with the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for landslides.

If seismically induced slope stability issues are identified outside the bored tunnel limits of the Freeway Tunnel Alternative, there are numerous geotechnical methods available to address this hazard. These methods can include the construction of buttress fills or shear keys, drainage systems, and the installation of deep foundations or retaining wall systems, among others.

11.4.3 Seismically Induced Settlement

Loose, unsaturated granular soils are susceptible to seismically induced settlement. This could include the alluvial soils located above the groundwater table in areas outside the bored tunnel limits of the Freeway Tunnel Alternative as shown in Plate 9. The settlement issue could be critical at the portals for the tunnel and ground improvements could be implemented to address settlement concerns. Surface improvements for the Freeway Tunnel Alternative would be designed in accordance with the *AASHTO LRFD Bridge Design Specifications*

(AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for seismically induced settlement.

11.4.4 Seismically Induced Inundation

The Freeway Tunnel Alternative in the immediate vicinity of I-10 is located within a potential dam inundation area, as shown in Figure 5-2. The inundation zone identified is related to seismically induced failure of the Laguna Regulating Basin. The Laguna Regulating Basin is an ungated basin (CH2M HILL, 2014e) intended to collect sediment from runoff entering the basin. The LACDPW has no record of the Laguna Regulating Basin ever being filled to capacity since its construction in 1967 (CH2M HILL, 2014e). During the rare occurrences where inflow exceeds outflow within the basin, the amount of time the runoff would be pooled within the basin would be limited because the basin is allowed to runoff freely. Potential scour of the ground surface around structural elements such as bridge foundations would be addressed via *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014) for scour.

The Freeway Tunnel southern portal is located over 4,000 feet north of the identified inundation zone, and is situated over 50 feet higher than the top of the Laguna Regulating Basin embankment. As such, the potential for seismically induced inundation from the Laguna Regulating Basin to affect the tunnel portion of the Freeway Tunnel Alternative is very low.

11.4.5 Tsunamis and Seiches

The Freeway Tunnel Alternative is not located adjacent to any large bodies of water, and the alternative is located at a minimum elevation of 345 feet. As such, there is no potential for a tsunami- or seiche-related impact on the alternative.

11.5 Groundwater

Historically highest groundwater levels (CDMG, 1998b, 1998d, and 1998f) along the Freeway Tunnel Alternative range from 50 feet bgs near the Raymond fault in South Pasadena, to 200 feet bgs near Huntington Drive in Los Angeles. The bedrock units along the LRT Alternative generally do not contain substantial amounts of groundwater; however, groundwater seepages may be present within local sandstone beds and fault and/or fracture zones. The Raymond fault is a known groundwater barrier; groundwater levels on the north side of this fault are significantly higher than the levels on the south side of the fault. In addition, the potentially active (Eagle Rock and San Rafael faults) and inactive faults may also act as groundwater barriers. Special care would have to be exercised when tunneling through a fault zone that has a substantial difference in groundwater levels on opposite sides of the fault.

The Freeway Tunnel Alternative groundwater depths presented below and in Plate 9 are based on review of existing information (MSGW, 2010; RBMB, 2011; WRD, 2013a and 2013b), and the groundwater levels documented during the previous and current studies.

- From the southern terminus of the Freeway Tunnel Alternative at I-10 north to approximately 1,500 feet south of Hellman Avenue, the alternative is underlain primarily by bedrock. Groundwater seepage was observed in this area, within boring RC-13-003 (see Plate 2 and Appendix A.1).
- From approximately 1,500 feet south of Hellman Avenue north to Concord Avenue, groundwater levels range from 10 feet to 40 feet bgs. The Freeway Tunnel Alternative southern portal and subsequent tunnel would be situated below the water table in this area.
- North of Concord Avenue to Huntington Drive, the Freeway Tunnel Alternative groundwater levels range from 30 to 60 feet bgs. The tunnel would be situated below the water table in this area.
- From Huntington Drive north to approximately Monterey Road, the Freeway Tunnel Alternative crosses the western edge of the Repetto Hills. The hills are composed of sedimentary bedrock with intervening drainages filled with alluvial soils. These drainages are expected to have localized perched groundwater tables on the order of 20 to 50 feet bgs. The tunnel would be situated below the localized water tables in this area.

- North of Monterey Road to the Raymond fault (roughly 300 feet north of Arroyo Seco Parkway [SR 110]), groundwater levels along the Freeway Tunnel Alternative increase in depth from 80 to 180 feet bgs. The tunnel would be situated below the water table in this area.
- Between the Raymond fault and the San Rafael fault (approximately 150 feet south of Hurlbut Street), groundwater is present at a depth of 30 to 80 feet bgs, increasing in depth toward the north as a result of a rise in topography along the Freeway Tunnel Alternative. The tunnel would be situated below the water table in this area.
- From the San Rafael fault north to the northern Freeway Tunnel Alternative terminus near SR 134, groundwater is present at depths of 110 feet to over 250 feet bgs. A portion of the tunnel in this area would be located below the water table. The northernmost portion of the tunnel (approximately from California Boulevard north) and the northern portal area would be situated above the water table.

Surface water along the Freeway Tunnel Alternative generally either infiltrates into the ground or drains by sheet flow into engineered drainage structures. The Alternative does not cross any major drainages. Temporary lowering of the water table in alluvial areas due to potential dewatering from construction or O&M activities associated with the Freeway Tunnel Alternative would not affect the surface water features because groundwater is below the bottom of the local and regional surface water features.

11.6 Hazardous Waste and Naturally Occurring Oil and Gas

The SR 710 North Study included an evaluation of hazardous waste and naturally occurring oil and gas for each Alternative.

11.6.1 Contaminated Soil and Groundwater

Soil and groundwater contamination is addressed in the Phase I ISA for the SR 710 North Study (CH2M HILL, 2014a). Design and construction requirements for areas with soil and/or groundwater contamination will be considered if this alternative is selected.

11.6.2 Naturally Occurring Oil and Gas

As shown in Plate 9, portions of the Freeway Tunnel Alternative bored tunnel would be constructed within Puente Formation bedrock. There is a low-to-moderate potential of encountering naturally occurring oil and/or gas within the Puente Formation or fault zones along the tunnel segment of the Freeway Tunnel Alternative. Naturally occurring oil and/or gas could also be found within any of the geologic formations within the SR 710 North Study Area. If encountered, the tunnel could be classified by Cal/OSHA as a “Gassy or Potentially Gassy Operation,” and, if so designated, compliance with Cal/OSHA guidelines for tunneling in gassy conditions would be required.

The presence of naturally occurring oil and gas is not unusual, especially in the Los Angeles region, and special tunneling equipment, air monitoring, ventilation methods, and safety procedures have been developed to allow tunnel construction in a safe manner. These techniques have been successfully applied to numerous subterranean projects completed in the Los Angeles region.

Some of the Freeway Tunnel Alternative improvements that are located outside the bored tunnel limits would be founded in Puente Formation bedrock. The improvements are generally located between I-10 and Valley Boulevard and include the south cut-and-cover tunnel structure, Hellman Avenue bridge replacement, and the Route 710/10 separation widening. The potential for encountering natural gas during construction of the drilled shafts for these structures is considered low to moderate.

To adequately characterize the potential to encounter naturally occurring oil and gas along the Freeway Tunnel Alternative, detailed geotechnical investigations would be conducted during final design. Where anticipated, appropriate precautions would be implemented in accordance with Cal/OSHA requirements.

11.7 Potential Non-Seismic Geologic Hazards

The Freeway Tunnel Alternative would have to consider the effects of non-seismic geologic hazards such as slope stability, ground settlement and collapse, expansive soils, and erosion. Improvements would be designed in accordance with the FHWA Technical Manual (2009), accounting for the following potential non-seismic geologic hazards.

11.7.1 Slope Stability

The Freeway Tunnel Alternative traverses hillside areas as shown in Plate 2. In areas where improvements may affect existing slopes and/or developments atop existing slopes, detailed evaluations of the geologic units and geologic structure of these slopes would be conducted. These evaluations would yield the appropriate data required to conduct analyses and provide the geotechnical recommendations needed for the design and construction of the proposed hillside improvements.

The portions of the Freeway Tunnel Alternative that are located outside the bored tunnel and are proposed on or adjacent to hillside areas would be designed in accordance with the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012) and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for slope instability.

11.7.2 Ground Settlement and Collapsible Soils

Freeway Tunnel Alternative surface improvements that are underlain by alluvial soils (see Plate 9) may be prone to ground settlement or collapsible soils. Where improvements are proposed on alluvial soils, the improvements would be designed in accordance with the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for ground settlement and collapsible soils.

Ground settlement also can occur as a result of ground loss during deep excavations, such as tunneling. To control this type of settlement, ground loss would be actively controlled at the tunnel heading so that ground surface settlement is minimized, as discussed in Section 11.8.

11.7.3 Expansive Materials

Clay-rich expansive soils and bedrock are present locally along the Freeway Tunnel Alternative. Potentially expansive materials present along the alternative include artificial fill soils, alluvial soils, and the siltstone and/or claystone units of the Fernando, Puente, and Topanga Formations. The Freeway Tunnel Alternative would be designed in accordance with the *FHWA Technical Manual for Design and Construction of Road Tunnels - Civil Elements* (FHWA, 2009), *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014), accounting for expansive materials.

11.7.4 Erosion

As shown in Plate 6, the surficial soils present along the Freeway Tunnel Alternative have a moderate susceptibility to erosion. Erosion is a constant ongoing process that can be successfully controlled by implementing engineered designs developed in accordance with Caltrans design standards.

11.8 Geotechnical Considerations for Design and Construction

A number of geotechnical design and construction considerations would need to be considered as part of the Freeway Tunnel Alternative development. These considerations would involve the bored tunnel and portals, as well as the bridge structures, retaining walls, and stations. A brief summary of these considerations is provided in the following subsections.

11.8.1 Bored Tunnel

Design considerations for the bored tunnel include excavations in alluvial soil, in bedrock, at fault crossings, and in areas near or below the groundwater table; as well as naturally occurring oil and gas considerations. With proper planning and implementation of appropriate construction methods, these considerations can be managed.

11.8.1.1 Design Consideration for Alluvial Soil

Unconsolidated and/or water-saturated alluvial soil deposits would likely be encountered in excavations for the portals and along segments of the tunnel for the Freeway Tunnel Alternative. Open excavation and tunneling in unconsolidated and/or saturated alluvium have the potential for high groundwater inflows and flowing ground conditions at the heading of the excavation, which could result in loss of ground and settlement of the ground surface. Groundwater inflows are also anticipated in the fractured/sheared rock and adjacent to fault zones, which may act as groundwater barriers. During construction, excavation of a tunnel using a pressurized-face TBM would actively control groundwater inflows at the tunnel heading. Special care would have to be exercised when tunneling through a fault zone that has a substantial difference in groundwater levels on opposite sides of the fault.

Pressurized-face TBMs generally utilize either EPB or slurry methods to provide active face control to limit ground loss while excavating. Such machines have been used successfully on previous tunneling projects in Los Angeles, and this technology could be applied to the Freeway Tunnel Alternative. To limit ground loss, the construction contractor could be required to use a pressurized-face TBM, have a robust excavated material monitoring system, and employ a grouting system along the shield of the TBM. While a pressurized face TBM would likely be required for the project, evaluation of whether it can or will be used in open mode would be evaluated in the future. Comprehensive real-time monitoring with geotechnical-tunnel data management software and implementation of observational approach to construction management would be implemented during construction of the Freeway Tunnel Alternative tunnel. Design and construction of the Freeway Tunnel Alternative would follow the FHWA *Technical Manual for Design and Construction of Road Tunnels - Civil Elements* (FHWA, 2009) for tunneling and deep excavations in unconsolidated sediments.

11.8.1.2 Design Consideration for Bedrock

The tunnel excavation for the Freeway Tunnel Alternative would be through several different geologic units. The tunnel excavation methods would need to address a range of geologic conditions including alluvial soil and weak sedimentary rocks. This would require the use of tunneling equipment adaptable to the variable range of rock characteristics anticipated, such as rock hardness, tunnel face stability and muck characteristics or a flexible approach that allows methods to be changed to suit the geology. It would 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.

Regardless of the excavation methods, special provisions will be necessary to address the inherent variability of the Wilson Quartz Diorite, Fernando, Puente, and Topanga Formations, such as: cemented layers and concretions, the variability between stronger granitic-type rocks, weaker sedimentary rocks, and potential fault gouge. This variability would be considered in the design of tunnel excavation equipment. The Freeway Tunnel Alternative would be designed in accordance with the FHWA Technical Manual (2009), accounting for the structure of the geologic units along the Freeway Tunnel Alternative.

The Fernando, Puente, and Topanga Formations are expected to require immediate support in the tunnel excavations proposed for this study. If the tunnel is excavated by a full-face TBM, a precast concrete segmental lining system 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 these formations. Timely installation of effective ground supports is also required to control loss of ground and ground surface settlement.

11.8.1.3 Design Consideration for Active Faults

Tunneling through faults will require the excavation of fractured rock and control of groundwater, and may involve excavation of clay gouge formed by prior fault movements. Specialized TBMs would be able to complete this work without major difficulty, but with slower progress.

As discussed in Section 11.3.1, the estimated lateral and vertical offsets are 0.5 meter and 0.1 meter, respectively, for the Raymond fault and 0.5 meter and 0.25 meter, respectively, for the San Rafael/Eagle Rock faults.

These potential offsets require special design features that would allow the tunnel lining to accommodate the anticipated ground displacement.

For fault displacements such as those anticipated for the Raymond, Eagle Rock and San Rafael faults, 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 and backfilled with crushable materials. This vault would be large enough to accommodate the movement of the fault and can be excavated to allow repairs and realignment of the tunnel lining. This method was initially considered for the Freeway Tunnel Alternative. However, the size of the excavation (58.5 feet in diameter) and the anticipated ground conditions in and around the faults raised constructability issues as well as risk, cost and schedule implications while performing the oversized excavation work, and therefore other approaches were evaluated. Subsequently, a vault section utilizing steel segmental lining was determined to be more cost effective and less risky than an oversized vault excavation. This approach is feasible because the magnitude of design fault offsets is relatively small compared to the thickness of the precast concrete segmental lining and therefore recommended as the preliminary design concept for the Freeway Tunnel Alternative fault crossings (Jacobs Associates and CH2M HILL, 2014).

At the fault crossings, where clay gouge may be present, squeezing ground may lead to 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. Specialized TBMs would be able to excavate through the clay gouge without major difficulty, but with slower progress, and the tunnel lining would be designed to account for these higher ground loads.

11.8.1.4 Design Consideration for Groundwater

Groundwater inflows could occur while tunneling below the groundwater table, especially in the saturated alluvium. This inflow would be controlled during construction of a tunnel utilizing a pressurized-face TBM to limit groundwater infiltration at the tunnel heading. To ensure that water flows are controlled behind the TBM, a relatively watertight support system would be required (such as a bolted, double gasketed with appropriate cross gaskets, precast concrete segmental lining system). Supplemental grouting operations may be used in conjunction with the bolted, double gasketed with appropriate cross gaskets, precast concrete segmental lining system to control both water and gas inflows in the temporary and permanent condition. The Freeway Tunnel Alternative would be designed in accordance with the FHWA Technical Manual (2009), accounting for groundwater inflows during tunneling.

Groundwater inflows could also occur during construction of the Freeway Tunnel Alternative portals, where construction may take place below the groundwater table. The excavation support for the south portal could be designed to be watertight, or alternatively, dewatering could be used to lower the groundwater table temporarily. The dewatering or the excavation wall system would be designed such that the surrounding groundwater table would experience minimal, temporary drawdown. Groundwater control does not appear to be an issue for tunnel construction at the north portal due to the relatively deep groundwater table. The Freeway Tunnel Alternative would be designed in accordance with the FHWA Technical Manual (2009), accounting for groundwater inflows at deep excavation.

11.8.1.5 Design Consideration for Naturally Occurring Oil and Gas

To adequately characterize the potential to encounter naturally occurring oil and gas, geotechnical investigations will be conducted if this alternative is selected. Where anticipated, appropriate precautions will be necessary in accordance with Cal/OSHA requirements for dealing with potential naturally occurring oil and gas during tunnel and portal excavations.

11.8.2 Freeway Tunnel Portals (Cut-and-Cover Tunnels)

Within the Freeway Tunnel alternative of the SR 710 North Study, two new cut-and-cover tunnels—referred to as the South and North Portal Cut-and-Cover Tunnels—will be constructed at the southern and northern ends of

the bored tunnel segment, respectively. The cut-and-cover tunnel areas will be used as the TBM launching pits prior to constructing the cut-and-cover tunnels.

The TBM launching pit excavations would extend approximately 80 to 100 feet bgs, and 125 feet bgs for the north and south portals, respectively (CH2M HILL and Jacobs Associates, 2014). To support the deep excavation, soldier pile and timber lagging walls with tiebacks and slurry panel walls with tiebacks were conceptually proposed in the *Tunnel Evaluation Report* (Jacobs Associates and CH2M HILL, 2014) for the north and south portals, respectively.

At the South Portal Cut-and-Cover Tunnel site, the subsurface consists primarily of Puente Formation bedrock, which is generally very soft to soft siltstone, sandstone, and claystone. These materials can generally be excavated using conventional excavation equipment and, hence, no special excavation techniques are anticipated for this tunnel section. The bedrock underlying the tunnel will vary from massively bedded to laminated. In addition, intra-formation faults will likely be encountered, which can act as planes of weakness internal to the formation. The structure of the bedrock will need to be evaluated during future studies and taken into account for the design of the temporary excavation supports. Due to the shallow groundwater conditions present relative to tunnel depth, groundwater control will be an important consideration for the tunnel construction and long-term operations at the South Portal.

At the North Portal Cut-and-Cover Tunnel site, the subsurface consists of alluvium soils, which are generally dense to very dense silty sand and sand with gravel and very stiff to hard sandy silt. Cobbles were also observed within local alluvial soil layers. These materials can generally be excavated using conventional excavation equipment. Because of the relatively deep groundwater elevations compared to the tunnel invert depth, groundwater control does not appear to be a significant issue for tunnel construction and long-term operations at the North Portal.

The advanced planning study foundation recommendations for the south and north portal cut-and-cover tunnel structures are presented in separate Structure Preliminary Geotechnical Reports (CH2M HILL, 2014f and 2014g).

11.8.3 Bridge Structures

Within the Freeway Tunnel Alternative improvements, two new bridge constructions, two bridge widenings, and two bridge replacements are proposed. Foundation recommendations for the advanced planning study are provided in the following:

- Structure Preliminary Geotechnical Report for Green Street Overcrossing (CH2M HILL, 2014h)
- Structure Preliminary Geotechnical Report for Hellman Avenue Overcrossing (CH2M HILL, 2014i)
- Structure Preliminary Geotechnical Report for Laguna Basin Bridge (CH2M HILL, 2014j)
- Structure Preliminary Geotechnical Report for Ramona Boulevard Overcrossing (CH2M HILL, 2014k)
- Structure Preliminary Geotechnical Report for Route 710/10 Separation (Widening) (CH2M HILL, 2014l)
- Structure Preliminary Geotechnical Report for Valley Boulevard Overcrossing (CH2M HILL, 2014m)

11.8.4 Retaining Walls

According to the Freeway Tunnel Alternative Dual-Bore Option and Single-Bore Option plans (CH2M HILL, 2014n), multiple retaining walls are proposed to support grading changes and realigned roadways. The proposed retaining walls are summarized in Tables 11-1 and 11-2. Foundations supporting the retaining walls would be designed in accordance with the LRFD method as specified in the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012), and *California Amendments to AASHTO LRFD Bridge Design Specifications* (Caltrans, 2014).

TABLE 11-1
Proposed Retaining Walls for Dual-Bore Freeway Tunnel Alternative

Location	Approximate Station	Length (feet)	Maximum Height (feet)
South Portal – SB SR 710	“B” 1394+81.82 to “B” 1397+29.81	248	12
WB I-10 to SB SR 710 Connector (Wingwall)	“L” 400+48.02 to “L” 401+30.00	82	17
SB SR 710 to WB I-10 Connector	“F” 405+66.11 to “F” 414+29.47	859	31
SB SR 710 to Busway Connector	“G” 406+40.00 to “SSBT” 1431+76.67	2,537	29
WB I-10 to NB SR 710 Connector (Wingwall)	“D” 417+30 to “D” 417+85.00	55	8
WB I-10 to NB SR 710 Connector	“B” 1418+00.00 to “B” 1427+00.00	900	17
Valley Boulevard Off-Ramp	“SNBT” 1426+81.40 to “V-4” 449+92.48	2,312	33
Hellman Avenue	“HA” 7+58.30 to “HA” 10+55.27	319	9
Hellman Avenue	“HA” 7+58.30 to “HA” 10+34.97	255	11
South Portal – NB SR 710 Bottom	“SNBB” 1429+88.12 to “SNBB” 1439+15.00	936	23
South Portal – SB SR 710 Bottom	“SSBB” 1431+38.15 to “SSBB” 1440+35.00	888	25
South Portal – SB SR 710 Top	“SSBT” 1444+20.00 to “SSBT” 1446+75.00	253	39
South Portal – NB SR 710 Top	“SNBT” 1445+40.00 to “SNBT” 1446+70.00	131	45
North Portal – NB SR 710 Bottom	“C” 1739+81.30 to “C” 1750+46.78	1,066	24
North Portal – SB SR 710 Bottom	“C” 1739+80.00 to “C” 1747+23.45	744	24
WB I-210 to SB SR 710 Connector	“H” 757+28.05 to “H” 763+18.33	590	13
North Portal Parking Lot	“NNBT” 1748+76.36 to “NNBT” 1752+00.58	341	15
B – SR 710C – SR 710	NNBT – SR 710 northbound top level		
D – connector from westbound I-10 to northbound SR 710	SSBB – SR 710 southbound bottom level		
F – connector from southbound SR 710 to westbound I-10	SSBT – SR 710 southbound top level		
G – hot connector from southbound SR 710 to westbound I-10 hot lanes	SNBB – SR 710 northbound bottom level SNBT – SR 710 northbound top level		
H – connector from southbound SR 710 to westbound I-10	TBD – to be determined		
HA – Hellman Avenue	V-4 – northbound off-ramp to Valley Boulevard		
L – connector from westbound I-10 to southbound SR 710			

TABLE 11-2
Proposed Retaining Walls for Single-Bore Freeway Tunnel Alternative

Location	Station	Length (feet)	Maximum Height (feet)
EB I-10 to NB SR 710 Connector	“SNB” 1417+81.21 to “SNB” 1426+80.00	900	20
WB I-10 to NB SR 710 Connector (Wingwall)	“D” 417+30 to “D” 417+85.00	55	8
South Portal – NB SR 710	“SNB” 1426+81.40 to “SNB” 1427+40.00	59	11
South Portal – NB SR 710	“SNB” 1427+40.00 to “SNB” 1438+30.51	1,098	23
South Portal – SB SR 710 Bottom	“SSB” 1431+75.00 to “SSB” 1439+15.00	742	24
Hellman Avenue	“HA” 7+58.30 to “HA” 10+55.27	319	9
Hellman Avenue	“HA” 7+58.30 to “HA” 10+34.97	255	11
Valley Boulevard On-Ramp	“V-3” 442+07.00 to “V-3” 445+37.60	331	21
Valley Boulevard Off-Ramp	“V-4” 438+30.30 to “V-4” 449+92.48	1,155	32

TABLE 11-2
Proposed Retaining Walls for Single-Bore Freeway Tunnel Alternative

Location	Station	Length (feet)	Maximum Height (feet)
South Portal – NB SR 710 Top	“SNB” 1445+40.00 to “SNB” 1446+70.00	131	45
North Portal – SB SR 710 Bottom	“NSB” 1739+80.00 to “NSB” 1740+79.98	100	44
North Portal – NB SR 710	“NNB” 1739+80.02 to “NNB” 1757+41.57	1,761	20
WB I-210 to SB SR 710 Connector	“H” 757+90.00 to “H” 764+20.00	630	21
North Portal Parking Lot	“NNB” 1748+74.52 to “NNB” 1751+93.96	341	15

H – connector from west bound SR-134 to south bound SR 710

HA – Hellman Avenue

NNB – northbound SR 710

NSB – southbound SR 710

SNB – northbound SR 710 top level

SSB – southbound SR 710 bottom level

TBD – to be determined

V-3 – southbound on-ramp from Valley Boulevard

V-4 – northbound off-ramp to Valley Boulevard

For preliminary design, Caltrans standard walls and MSE walls appear to be suitable retaining wall types. At the locations where ROW is limited, a slurry wall or soldier pile wall can be considered. A soil nail or tieback wall may be required where a retaining wall supports a relatively high cut slope.

Subsurface conditions at the proposed wall locations were interpreted based on the subsurface information available at this time. Additional, detailed subsurface investigation and testing will be required for final design, if this alternative is selected.

11.9 Future Geotechnical Exploration and Investigations

For the design of the Freeway Tunnel Alternative, additional subsurface investigations are required. The purpose of the investigations is to evaluate the subsurface conditions and provide geotechnical information for design and construction of structure foundations, tunnel, and remedial earthwork, if required.

Proposed explorations for the different components of the Freeway Tunnel Alternative are summarized below.

- **Tunnels:** The proposed field investigation for the tunnel would consist of borings, sampling, in situ testing, geophysical investigations, and laboratory testing. The borings would be generally spaced at intervals of 300 to 500 feet (FHWA, 2009). The proposed borings would extend at least 1.5 tunnel diameter below the proposed tunnel invert and at least 50 feet below the invert of the cut-and-cover tunnels. The field investigation should be carried out in phases to obtain the subsurface information necessary at each stage of the project in a cost-efficient manner.
- **Bridge Foundations:** For the bridge foundations, subsurface explorations would be conducted in accordance with Section 10.4.2 of *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012). A minimum of one exploration for each support is recommended for a structure width less than or equal to 100 feet; a minimum of two explorations for each support is recommended for a structure width greater than 100 feet. The depth of exploration would extend below the foundation tip elevation a minimum of 20 feet, at least 3 times the pile diameter, or a minimum of 2 times the pile group dimension, whichever is deeper.
- **Retaining Walls:** For the retaining wall foundation, subsurface explorations would be conducted in accordance with Section 10.4.2 of *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2012). A minimum of one exploration for each retaining wall is recommended. For retaining walls more than 100 feet in length, exploration points would be spaced every 100 to 200 feet. The depth of exploration would extend at least between 1 and 2 times the wall height. For anchored and soil-nailed walls, additional exploration points in the

anchorage zone are recommended at a distance of 1.0 to 1.5 times the height of the wall behind the wall, spaced at 100 to 200 feet.

- **Active Faulting:** To further evaluate the location and activity details for the Raymond, Eagle Rock, and San Rafael faults, a detailed investigation will be required. Trenching is the ideal method to evaluate a fault. However, constraints to the placement of the trenches are abundant along the alternative, and the trenches may need to be emplaced outside the limits of the alternative. This may be the only realistic way to gather the necessary detailed geologic and paleoseismic data needed for these faults. To better locate the Raymond, San Rafael, and Eagle Rock fault crossings along the Freeway Tunnel Alternative, a series of continuously cored boreholes should be emplaced across the fault zones. In addition, seismic lines can be utilized to provide additional subsurface information relevant to faulting.

All geotechnical explorations should extend through unsuitable strata such as soft highly compressible soils, peat, highly organic materials, and loose coarse-grained soils to reach competent material of suitable bearing strata.

SECTION 12

Limitations

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

The geotechnical and geological information contained in this report is based on data obtained from review of available sources of information such as geological maps and documents, as-built plans, and previous and current field investigations within the SR 710 North 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. These variations could change some of the hazards discussed and geotechnical recommendations provided in this report. In addition, information about faulting and seismicity is continually being advanced in the Los Angeles area as new scientific work is carried out. These studies could change the level of hazard from faulting and ground shaking, as well as associated hazards, leading to either reduced or increased hazard. As these discoveries are made, the hazard evaluation for each of the alternatives may require updating.

In the event that any change in the nature, design, or location of the SR 710 North Study Alternatives occurs, conclusions and recommendations of this report should not be considered valid unless such changes are reviewed, and the conclusions of this report are modified or verified in writing by CH2M HILL's geotechnical staff. 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.

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SECTION 13

References

- AECOM. 2014. *Advanced Conceptual Engineering Report prepared for the Light Rail Transit Alternative, SR 710 North Study, Los Angeles County, California. February.*
- American Association of State Highway and Transportation Officials (AASHTO). 2012. *AASHTO LRFD Bridge Design Specifications. 2012. 6th Edition.*
- ASTM International. 2007a. *Standard Test Method for Particle-Size Analysis of Soils. ASTM D422. October 15.*
- ASTM International. 2007b. *Standard Test Method for Unconsolidated-Undrained Triaxial Compression on Cohesive Soils. ASTM D2850. September 15.*
- ASTM International. 2008a. *Standard Test Method for Determination of In-Situ Stress in Rock Using Hydraulic Fracturing Method. ASTM D4645. July 1.*
- ASTM International. 2008b. *Standard Test Method for Determination of the Point Load Strength Index of Rock and Application to Rock Strength Classifications. ASTM D5731. January 1.*
- ASTM International. 2010a *Standard Guide for Planning and Conducting Borehole Geophysical Logging. ASTM D5753. May 1.*
- ASTM International. 2010b *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM D2216. July 1.*
- ASTM International. 2010c *Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method. ASTM D2937 March 15.*
- ASTM International. 2010d *Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils. ASTM D4318 January 15.*
- ASTM International. 2011a. *Standard Test Methods Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils. ASTM D1586. November 1.*
- ASTM International. 2011b. *Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading. ASTM D2435/D2435M. May 1.*
- ASTM International. 2011c. *Standard Test Method for Direct Shear Test of Soil Under Consolidated Drained Condition. ASTM D3080/D3080M. November 1.*
- ASTM International. 2011d. *Standard Test Method for Expansion Index of Soils. ASTM D4829. November 1.*
- ASTM International. 2013. *Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens Under Varying States of Stress and Temperature. ASTM D7012. November 15.*
- Benioff, H. 1938. "The Determination of the Extent of Faulting with Application to the Long Beach Earthquake." *Bulletin of the Seismological Society of America*. Vol. 28. pp. 77-84.
- Bryant, W.A. and E.W. Hart. Revised 2007. "Fault-Rupture Hazard Zones in California, Alquist-Priolo Earthquake Fault Zoning Act with Index to Earthquake Fault Zones Maps." State of California, Department of Conservation, Division of Mines and Geology. *Special Publication 42*. Supplements 1 and 2 were added in 1999.
- Bullard, T.F., and W.R. Lettis. 1993. "Quaternary Fold Deformation Associated with Blind Thrust Faulting, Los Angeles Basin, California." *Journal of Geophysical Research*. Vol. 98. pp. 8349-8369.
- California Department of Transportation (Caltrans). 1974a. *Geotechnical Report Route 7*. June.
- California Department of Transportation (Caltrans). 1974b. *LA-07 Pasadena Monterey Road to Columbia, Boring Logs for ES-1, ES-2, and ES-3.*

- California Department of Transportation (Caltrans). 2007. Method for Determining Field and Laboratory Resistivity and pH measurements for Soil and Water. California Test Method 643. June.
- California Department of Transportation (Caltrans). 2010. Soil and Rock Logging, Classification, and Presentation Manual. 2010 Edition.
- California Department of Transportation (Caltrans). 2014. *California Amendments to AASHTO LRFD Bridge Design Specifications*.
- California Department of Transportation (Caltrans). 2012a. *Corrosion Guidelines Version 2.0*. Materials Engineering and Testing Services. November.
- California Department of Transportation (Caltrans). 2012b. *Caltrans Highway Design Manual*. May 7.
- California Department of Transportation (Caltrans). 2013a. Standard Environmental Reference (SER), Chapter 7 (Topography/Geology/Soils/Seismic) Web site Accessed August 27, 2013.
<http://www.dot.ca.gov/ser/vol1/sec2/ch7topography/chap7.htm>.
- California Department of Transportation (Caltrans). 2013b. *Seismic Design Criteria*. Version 2.2.06. Available at http://dap3.dot.ca.gov/ARS_Online/index.php. Accessed on September 3, 2013.
- California Department of Transportation (Caltrans). 2013c. *Fault Rupture, Memo to Designers, MTD 20-10*. January.
- California Department of Transportation (Caltrans). 2013d. Method of Testing Soil and Water for Sulfate Content. California Test Method 417. March.
- California Department of Transportation (Caltrans). 2013e. Method of Testing Soils and Waters for Chloride Content. California Test Method 422. March.
- California Department of Water Resources (CDWR). 2003. *Groundwater Basins in California*. Last Updated June 27.
- California Department of Water Resources (CDWR). 2004a. *California's Groundwater Bulletin 118: California Department of Water Resources, South Coast Hydrologic Region, Coastal Plain of Los Angeles Groundwater Basin, Central Sub-basin (Basin No. 4-11.04)*. Last Updated 2004.
- California Department of Water Resources (CDWR). 2004b. *California's Groundwater Bulletin 118: California Department of Water Resources, South Coast Hydrologic Region, Raymond Groundwater Basin (Basin No. 4-23)*. Last Updated 2004.
- California Department of Water Resources (CDWR). 2004c. *California's Groundwater Bulletin 118: California Department of Water Resources, South Coast Hydrologic Region, San Fernando Valley Groundwater Basin (Basin No. 4-12)*. Last Updated 2004.
- California Department of Water Resources (CDWR). 2004d. *California's Groundwater Bulletin 118: California Department of Water Resources, South Coast Hydrologic Region, San Gabriel Valley Groundwater Basin Groundwater Basin (Basin No. 4-13)*. Last Updated 2004.
- California Division of Mines and Geology (CDMG). 1977a. State of California Special Studies Zones – Los Angeles Quadrangle Official Map. January 1.
- California Division of Mines and Geology (CDMG). 1977b. State of California Special Studies Zones – Mount Wilson Quadrangle Official Map. January 1.
- California Division of Mines and Geology (CDMG). 1982. *Part IV: Mineral Land Classification of the Greater Los Angeles Area: Classification of Sand and Gravel Resource Areas, San Gabriel Valley, Production-Consumption Region*: Special Report 143: Part IV.
- California Division of Mines and Geology (CDMG). 1991. State of California Special Studies Zones – El Monte Quadrangle Official Map. November 1.

- California Division of Mines and Geology (CDMG). 1998a. *Seismic Hazard Zone Report for the Burbank Park 7.5-Minute Quadrangle, Los Angeles, California*. Seismic Hazard Report 016.
- California Division of Mines and Geology (CDMG). 1998b. *Seismic Hazard Zone Report for the El Monte 7.5-Minute Quadrangle, Los Angeles, California*. Open-File Report 98-15.
- California Division of Mines and Geology (CDMG). 1998c. *Seismic Hazard Zone Report for the Hollywood 7.5-Minute Quadrangle, Los Angeles, California*. Open-File Report 98-17.
- California Division of Mines and Geology (CDMG). 1998d. *Seismic Hazard Zone Report for the Los Angeles 7.5-Minute Quadrangle, Los Angeles, California*. Open-File Report 98-20.
- California Division of Mines and Geology (CDMG). 1998e. *Seismic Hazard Zone Report for the Mount Wilson 7.5-Minute Quadrangle, Los Angeles, California*. Seismic Hazard Report 030.
- California Division of Mines and Geology (CDMG). 1998f. *Seismic Hazard Zone Report for the Pasadena 7.5-Minute Quadrangle, Los Angeles, California*. Open-File Report 98-05.
- California Division of Mines and Geology (CDMG). 1999a. State of California Seismic Hazard Zones – Burbank Quadrangle Official Map. March 25.
- California Division of Mines and Geology (CDMG). 1999b. State of California Seismic Hazard Zones – El Monte Quadrangle Official Map. March 25.
- California Division of Mines and Geology (CDMG). 1999c. State of California Seismic Hazard Zones – Pasadena Quadrangle Official Map. March 25.
- California Division of Mines and Geology (CDMG). 1999d. State of California Seismic Hazard Zones – Hollywood Quadrangle Official Map. March 25.
- California Division of Mines and Geology (CDMG). 1999e. State of California Seismic Hazard Zones – Los Angeles Quadrangle Official Map. March 25.
- California Division of Mines and Geology (CDMG). 1999f. State of California Seismic Hazard Zones – Mount Wilson Quadrangle Official Map. March 25.
- California Division of Oil, Gas, & Geothermal Resources (CDOGGR). 2005. Oil and Gas Field Database. Available at ftp://ftp.consrv.ca.gov/pub/oil/Data_Catalog/Oil_and_Gas/Oil_fields/. Accessed September 17, 2013.
- California Division of Oil, Gas, & Geothermal Resources (CDOGGR). 2012. Well Database. Available at <http://conservation.ca.gov//dog/maps/Pages/GISMapping2.aspx>. Accessed September 17, 2013.
- California Geological Survey. (CGS). 2010. *Update of Mineral Land Classification for Portland Cement Concrete-Grade Aggregate in the San Gabriel Valley Production-Consumption Region, Los Angeles County, California*: Special Report 209.
- California Geological Survey. (CGS). 2012. Geologic Compilation of Quaternary Surficial Deposits in Southern California. Special Report 217 (Revised). December.
- CH2M HILL. 2010. *Final Geotechnical Summary Report, SR 710 Tunnel Technical Study, Los Angeles County California*. Prepared for Caltrans. EA-07-187900. April.
- CH2M HILL. 2013. *Preliminary Earthquake Acceleration Response Spectra, SR 710 North Study, Los Angeles County, California*. Technical Memorandum prepared for Los Angeles County Metropolitan Transportation Authority (Metro). December.
- CH2M HILL. 2014a. *Phase I Initial Site Assessment, SR 710 North Study, Los Angeles County, California*. Technical Report prepared for California Department of Transportation (Caltrans) and Los Angeles County Metropolitan Transportation Authority (Metro).

- CH2M HILL. 2014b. *Summary Floodplain Encroachment Report, SR 710 North Study, Los Angeles County, California*. Technical Report prepared for California Department of Transportation (Caltrans) and Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014c. *Structure Preliminary Geotechnical Report, SR 710 Connector Underpass Bridge, SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014d. *Structure Preliminary Geotechnical Report, Garfield Avenue Bridge (Widening), SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014e. *Location Hydraulic Study, SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014f. *Structure Preliminary Geotechnical Report, South Portal Cut-and-Cover Tunnel, SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014g. *Structure Preliminary Geotechnical Report, North Portal Cut-and-Cover Tunnel, SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014h. *Structure Preliminary Geotechnical Report, Green Street Overcrossing, SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014i. *Structure Preliminary Geotechnical Report, Hellman Avenue Overcrossing, SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014j. *Structure Preliminary Geotechnical Report, Laguna Basin Bridge, SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014k. *Structure Preliminary Geotechnical Report, Ramona Boulevard Undercrossing (Widening), SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014l. *Structure Preliminary Geotechnical Report, Route 710/10 Separation (Widening), SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014m. *Structure Preliminary Geotechnical Report, Valley Boulevard Overcrossing, SR 710 North Study, Los Angeles County, California*. Report prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL. 2014n. *Freeway Tunnel Alternative Dual-Bore Option and Single-Bore Option plans, SR 710 North Study, Los Angeles County, California*. Plans prepared for Los Angeles County Metropolitan Transportation Authority (Metro).
- CH2M HILL and Earth Consultants International (CH2M HILL and ECI). 2013. *Fault Rupture Evaluation for the SR 710 North Study, Los Angeles County, California*. Technical Memorandum prepared for Los Angeles County Metropolitan Transportation Authority (Metro). December.
- Chapman, R.H., and Chase, G.W. 1979. *Geophysical investigations of the Santa Monica–Raymond Fault Zone, Los Angeles County, California*. California Division of Mines and Geology Open-File Report 79-16, p. E-1–E-30.

- Crook, R., Jr., C.R. Allen, Kamp, Barclay, C.M. Payne, and R.J. Proctor. 1987. "Quaternary Geology and Seismic Hazard of the Sierra Madre and Associated Fault, Western San Gabriel Mountains." *in* United States Geologic Survey. 1987. *Recent Reverse Faulting in the Transverse Ranges, California*. USGS Professional Paper 1339. pp. 27-63.
- Davis and Namson Consulting Geologists. 1998. *Southern California Cross Section Study, 17 Geologic Cross Sections, Scale 1:250,000*. Available at <http://davisnamson.com/downloads/index.htm>. Accessed October 2013.
- Davis, T.L., J. Namson, and R.F. Yerkes. 1989. "A Cross Section of the Los Angeles Area: Seismically Active Fold and Thrust Belt, The 1987 Whittier Narrows Earthquake, and Earthquake Hazard." *Journal of Geophysical Research*. Volume 9. pp. 9644-9664.
- Dibblee, T.W. 1989a. *Geologic Map of the Los Angeles Quadrangle, Los Angeles County, California: Map, DF-22, Scale 1:1:24,000*.
- Dibblee, T.W. 1989b. *Geologic Map of the Pasadena Quadrangle, Los Angeles County, California: Map, DF-23, Scale 1:1:24,000*.
- Dibblee, T.W. 1991. *Geologic Map of the Burbank (south 1/2) and Hollywood Quadrangles, Los Angeles County, California: Map DF-30, scale 1:24,000*.
- Dibblee, T.W. 1998. *Geologic Map of the Mt. Wilson and Azusa Quadrangles Los Angeles County, California: Map DF-67, Scale 1:24,000*.
- Dibblee, T.W. 1999. *Geologic Map of the El Monte and Baldwin Park Quadrangles, Los Angeles County, California: Map, DF-69, Scale 1:1:24,000*.
- Dolan, J.F., K. Sieh, T.K. Rockwell, R.S. Yeats, J. Shaw, J. Suppe, G. Huftile, and E. Gath. 1995. "Prospects for Larger and More Frequent Earthquakes in Greater Metropolitan Los Angeles, California." *Science*. Volume 267. pp. 199-205.
- Dolan, J.F., K. Sieh, T.K. Rockwell, P. Gupstill, and G. Miller. 1997. "Active Tectonics, Paleoseismology, and Seismic Hazards of the Hollywood Fault, Northern Los Angeles Basin, California." *Bulletin of the Geological Society of America*. Vol. 109. pp. 1595-1616.
- Dolan, J.F., D. Stevens, and T.K. Rockwell. 2000a. "Paleoseismologic evidence for an early to mid-Holocene age of the most recent surface rupture on the Hollywood fault, Los Angeles, California." *Bulletin of the Seismological Society of America*. Volume 90. pp. 334-344.
- Dolan, J.F., M. Marin, R.D. Hartleb, S.A. Christofferson, A.Z. Tucker, and L.A. Owen. 2000b. *2000 SCEC Progress Report, Trench Study of the Slip Rate of the Raymond Fault, San Gabriel Valley*.
- Drumm, P.L. 1992. Holocene Displacement of the Central Splay of the Malibu Coast Fault Zone, Latigo Canyon, Malibu. *Engineering Geology Practice in Southern California: Association of Engineering Geologists Special Publication 4*, p. 247-254.
- Earth Consultants International (ECI). 2001. Coyote Pass Escarpment Study, Eastside Light Rail Transit Project, Soto and First Streets, Los Angeles, California. Project no. 2019.01. Dated August 6.
- Earth Consultants International (ECI). 2013. Preliminary Investigation of the Eagle Rock, Raymond and San Rafael Faults, Freeway Tunnel and Light Rail Transit Alternatives, SR 710 North Study, Los Angeles County, California. Project no. ECI-3202. Dated December 10.
- Earth Mechanics, Inc. (EMI). 2006. *Technical Data Report for the Proposed 710 Freeway Tunnels Feasibility, Task 3.1 – Soil Boring Program*. March 20.
- Federal Highway Administration (FHWA). 2009. *Technical Manual for Design and Construction of Road Tunnels - Civil Elements*. Publication No. FHWA-NHI-10-034. December.

- Gath, E.M., T. Gonzalez, P.L. Drumm, and P. Buchiarelli. 1994. *A Paleoseismic Investigation at the Northern Terminus of the Whittier Fault Zone, in the Whittier Narrows Area, Rosemead, California*. Final Technical Report to the Southern California Earthquake Center.
- Gath, E.M., T. Gonzalez, and T.K. Rockwell. 1992. Evaluation of the late Quaternary rate of slip, Whittier fault, southern California; USGS Final Technical Report, NEHRP Contract No. 14-08-0001-G1696, 24 p., numerous plates.
- Hart, E.W., Treiman, J.A., and Bryant, W.A. 1995. The search for fault rupture after the Northridge earthquake, in Woods, M.C. and Seipie, W.R. (editors), *The Northridge, California, Earthquake of 17 January 1994: California Division of Mines and Geology, Special Publication 116*, pp. 89-101.
- Hauksson, E. 1994. "The 1991 Sierra Madre Earthquake Sequence in Southern California: Seismological and Tectonic Analysis." *Bulletin of the Seismological Society of America*. Volume 84. pp. 1058-1074.
- Hauksson, E., and S. Gross. 1991. "Source Parameters of the 1933 Long Beach Earthquake." *Bulletin of the Seismological Society of America*. Volume 81. pp. 81-98.
- Hauksson, E., L.M. Jones, and K. Hutton. 1995. "The 1994 Northridge Earthquake Sequence in California: Seismological and Tectonic Aspects." *Journal of Geophysical Research*. Vol. 100. pp. 12,335-12,355.
- Jacobs Associates and CH2M HILL. 2014. *Tunnel Evaluation Report. SR 710 North Study*. September 5.
- Jones, L.M., K.E. Sieh, E. Hauksson, and L.K. Hutton. 1990. "The 3 December 1988 Pasadena Earthquake: Evidence for Strike-Slip Motion on the Raymond Fault." *Bulletin of the Seismological Society of America*. Vol. 80, No. 2. pp. 474-482. April.
- Lamar, D.L. 1970. *Geology of the Elysian Park-Repetto Hills Area, Los Angeles County, California*. California Division of Mines and Geology, Special Report 101, Geologic Map Scale 1:24,000.
- Los Angeles County. 2012. Draft General Plan. Available at <http://planning.lacounty.gov/generalplan>, accessed on September 11, 2013.
- Los Angeles County Department of Public Works. 2006. Hydrology Manual. January.
- Los Angeles County Department of Public Works. 2013. Hydrology Map GIS Viewer Application. Web site Accessed September 18, 2013. Available at <http://ladpw.org/wrd/hydrologygis/>.
- Los Angeles County Metropolitan Transportation Authority (Metro). 2008. Metro BRT Design Criteria. November 17.
- Los Angeles County Metropolitan Transportation Authority (Metro). 2013a. Metro Rail Design Criteria, Section 5, Structural/Geotechnical. May 20.
- Los Angeles County Metropolitan Transportation Authority (Metro). 2013b. Metro Supplementary Seismic Design Criteria. Appended to Metro Rail Design Criteria, Section 5, Structural/Geotechnical. May 20.
- Main San Gabriel Watermaster (MSGW). 2010. *Groundwater Contour Map for the San Gabriel Basin*. July.
- Marin, M., J.F. Dolan, R.D. Hartleb, S.A. Christofferson, A.Z. Tucker, and L.A. Owen. 2000. "A latest Pleistocene-Holocene slip rate on the Raymond fault based on 3D trenching, east Pasadena, California." *Eos, Transactions of the American Geophysical Union*. Vol. 78. pp. F702.
- Meigs, A., Brozovic, N., and Johnson, M.L. 1999. "Steady Balanced Rates of Uplift and Erosion of the Santa Monica Mountains, California." *Basin Research*. Vol. 11. pp. 59-73.
- Morton, D.M., and F. Miller. 2003. *Preliminary Geologic Map of the San Bernardino 30' X 60' Quadrangle, Southern California*. United States Geological, Survey Open-File Report 03-293, Version 1.0, Scale 1:100,000.
- Ninyo and Moore, Inc. 1999. *Phase II Geotechnical Feasibility of the Proposed Interstate 710 Freeway Extension Through the Monterey Hills, Los Angeles County California*. March 25.

- Oskin, M., K. Sieh, T. Rockwell, G. Miller, P. Guptill, M. Curtis, S. McArdle, and P. Elliot. 2000. "Active Parasitic Folds on the Elysian Park anticline: Implications for Seismic Hazard in Central Los Angeles, California." *Geological Society of America Bulletin*. Vol. 112. pp. 693-707.
- Pasadena, City of. 2002. *Safety Element of the General Plan*. August.
- Plesch, A., Shaw, J.H., Benson, C., Bryant, W.A., Carena, S., Cooke, M., Dolan, J., Fuis, G., Gath, E., Grant, L., Hauksson, E., Jordan, T., Kamberling, M., Legg, M., Lindvall, S., Magistrale, H., Nicholson, C., Niemi, N., Oskin, M., Perry, S., Planansky, G., Rockwell, T., Shearer, P., Sorlien, M., Süs, M.P., Suppe, J., Treiman, J., Yeats, R. 2007. Community Fault Model (CFM) for Southern California. *Bulletin of the Seismological Society of America*, Vol. 97, No. 6, pp.1793-1802. December.
- Raymond Basin Management Board (RBMB). 2011. *Watermaster Service in the Raymond Basin, Annual Report*. July 1, 2010, to June 30, 2011.
- Shaw, J.H., and Shearer. 1999. "An Elusive Blind-Thrust Fault Beneath Metropolitan Los Angeles." *Science*. Vol. 283. pp. 1516-1518.
- Shaw, J.H., and J. Suppe. 1996. *Earthquake Hazards of Active Blind-Thrust Faults Under the Central Los Angeles Basin California: Journal of Geophysical Research*. Vol. 101, No. B4. pp. 8623-8642.
- Shaw, J.H., A. Plesch, J.F. Dolan, T.L. Pratt, and P. Fiore. 2002. "Puente Hills Blind-Thrust System, Los Angeles, California." *Bulletin of the Seismological Society of America*. Vol. 92. pp. 2946-2960.
- Southern California Earthquake Center - Working Group C (SCEC). 2001. Active Faults in the Los Angeles Metropolitan Region.
- Southern California Earthquake Center (SCEC). 2013a. Information on the Whittier Fault. Web site Accessed September 3, 2013. <http://www.data.scec.org/significant/whittier.html>.
- Southern California Earthquake Center (SCEC). 2013b. Information on the Newport-Inglewood Fault. Web site Accessed September 3, 2013. <http://www.data.scec.org/significant/newport.html>.
- Southern California Earthquake Center (SCEC). 2013c. Information on the Sierra Madre Fault. Web site Accessed September 3, 2013. <http://www.data.scec.org/significant/sierramadre.html>.
- Southern California Earthquake Center (SCEC). 2013d. Information on the Clamshell-Sawpit Fault. Web site Accessed September 3, 2013. <http://www.data.scec.org/significant/clamshell.html>.
- Southern California Earthquake Center (SCEC). 2013e. Information on the Raymond Fault. Web site Accessed September 6, 2013. <http://www.data.scec.org/significant/Raymond.html>.
- Treiman, J.A. 1991. *Whittier Fault Zone, Los Angeles and Orange Counties, California: California Division of Mines and Geology*. Fault Evaluation Report FER-222, 17 Pages and 5 Plates included in California Geological Survey, 2002, Fault Evaluation Reports Prepared Under the Alquist-Priolo Earthquake Fault Zoning Act, Region 2 - Southern California: CGS CD 2002-02, CD R2-06.
- Treiman, J.A. 1995. Surface faulting near Santa Clarita, in Woods, M.C. and Seipie, W.R. (editors), *The Northridge, California, earthquake of 17 January 1994: California Division of Mines and Geology, Special Publication 116*, pp. 103-110.
- Tucker, Allan Z. and James F. Dolan. 2001. Paleoseismologic Evidence for a >8 Ka Age of the Most Recent Surface Rupture on the Eastern Sierra Madre Fault, Northern Los Angeles Metropolitan Region, California; *Bulletin of the Seismological Society of America*, 91, 2, pp. 232-249.
- United States Geological Survey (USGS). 1994. Soils Data for the Conterminous United States Derived from the NRCS State Soil Geographic Database (STATSGO). Accessed August 19, 2013. Available at: <http://water.usgs.gov/GIS/metadata/usgswrd/XML/ussoils.xml>.

- United States Geological Survey (USGS). 2008. National Seismic Hazard Mapping Program 2008 Interactive Deaggregations. Available at <https://geohazards.usgs.gov/deaggint/2008/>. Accessed various dates spring, summer and fall, 2013.
- United States Geological Survey (USGS). 2010. Quaternary Fault and Fold Database of the United States. Accessed September 25, 2013. Available at <http://earthquake.usgs.gov/hazards/qfaults/>.
- Walls, C., T. Rockwell, K. Mueller, Y. Bock, and S. Williams. 1998. Escape Tectonics in the Los Angeles Metropolitan Region and Implications for Seismic Risk; *Nature*, v. 394, p. 356-360.
- Water Replenishment District (WRD). 2013a. *Regional Groundwater Monitoring Report, Central and West Coast Basins, Los Angeles County, California, Water Year 2011-2012*. March.
- Water Replenishment District (WRD). 2013b. Groundwater Level Data. Accessed August 20, 2013. Available at Web site: <http://gis.wrd.org/wrdmap/index.asp>.
- Weaver, K.D., and J.F. Dolan. 2000. "Paleoseismology and Geomorphology of the Raymond Fault, Los Angeles." *Bulletin of the Seismological Society of America*. Vol. 90, No. 6. pp. 1409-1429.
- Weber, F.H. 1980. "Geological Features Related to Character and Recency of Movement Along Faults, North-Central Los Angeles County, California." in California Division of Mines and Geology Open-File Report 80-10 *Earthquake Hazards Associated with the Verdugo-Eagle Rock and Benedict Canyon Fault Zones, Los Angeles County, California*. pp. B1-116.
- Wells and Coppersmith. 1994. "New Empirical Relationships Among Magnitude Rupture Length, Rupture Width, Rupture Area, and Surface Displacement." *Bulletin of the Seismological Society of America*. Vol. 84. pp. 974-1002.
- Western Regional Climate Center Website. 2013. Average Climate Data for Los Angeles Civic Center, available at <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca5115>, accessed on November 1, 2013.
- Yeats, R.S. 2004. *Tectonics of the San Gabriel Basin and Surroundings, Southern California: Geological Society of America*. Vol. 116, No. 9/10. pp. 1158-1182.
- Yeats, Robert S. 2012. *Active Faults of the World*. Cambridge University Press, Cambridge, U.K. 621 p.
- Yerkes, R.F., and R.H. Campbell. 2005. *Preliminary Geologic Map of the Los Angeles 30' x 60' Quadrangle, Southern California*. United States Geological Survey, Version 1.0, Scale 1:100,000.

Figures

Plates

Appendix A
Field Exploration Data (DVD)

Appendix A

Field Exploration Data

Appendix A is provided on the enclosed DVD.

APPENDIX A.1

Current Boring Logs

APPENDIX A.2

Previous Boring Logs

APPENDIX A.3

Soil and Rock Core Sample Photographs

Appendix B
In Situ Test Results (DVD)

Appendix B In Situ Test Results

Appendix B is provided on the enclosed DVD.

APPENDIX B.1

Geophysical Data

APPENDIX B.1.1

Downhole Data

Appendix B.1.1

Downhole Data

The following data reports were prepared for the SR 710 Tunnel Technical Study Final Geotechnical Summary Report (CH2M HILL, 2010). However, only data relevant to the SR 710 North Study are provided herein. To view the reports in their entirety, refer to the Technical Study (CH2M HILL, 2010).

APPENDIX B.1.2

Seismic Reflection and Surface Wave Data

Appendix B.1.2

Seismic Reflection and Surface Wave Data

The following data reports were prepared for the SR 710 Tunnel Technical Study Final Geotechnical Summary Report (CH2M HILL, 2010). However, only data relevant to the SR 710 North Study are provided herein as summarized in Tables B-1 and B-2. The full version of the following appendix is presented in the Technical Study (CH2M HILL, 2010).

TABLE B-1
Summary of Seismic Reflection Testing

Seismic Reflection Line	Approximate Location	City	Purpose/Feature Evaluated
Z3-G1	South Raymond Avenue (N/O E. Glenarm Street)	Pasadena	San Rafael Fault
Z3-G6	Winchester Avenue (N/O Concord Avenue)	Alhambra	Highland Park Fault
Z3-G7	Westmont Drive (S/O, Valley Boulevard)	Alhambra	Unnamed Fault
Z4-G2	Huntington Drive (SW/O N. Granada Avenue)	Alhambra	Alhambra Wash Fault
Z5-G2	East Shorb Street (E/O S. Hildalgo St.)	Alhambra	Alhambra Wash Fault
Z5-G3	Edgewood Drive (S/O W. Valley Blvd.)	Alhambra	Highland Park Fault

Source: CH2M HILL, 2010 (EA-07-187900)

TABLE B-2
Summary of Multichannel Analyses of Surface Waves and ReMi Testing

Number	MASW Line	Approximate Location	City
1	Z1-S20	Highbury Avenue (S/O Valley Boulevard)	Los Angeles
2	Z3-S2	Palmetto Drive (E/O S. Pasadena Avenue)	Pasadena
3	Z3-S3	S. Raymond Avenue, Along Seismic Line Z3-G1	Pasadena
4	Z3-S4	S. Raymond Avenue, Along Seismic Line Z3-G1	Pasadena
5	Z3-S5	Arlington Drive (W/O S. Pasadena Avenue)	Pasadena
6	Z3-S11	Meridian Avenue at Buena Vista Street	South Pasadena
7	Z3-S12	Brent Avenue at Hope Street	South Pasadena
8	Z3-S15	Meridian Avenue (N/O Monterey Road)	South Pasadena
9	Z3-S16	Marengo Avenue at Spruce Street	South Pasadena
10	Z3-S19	Berkshire Avenue (N/O Kendall Avenue)	South Pasadena
11	Z3-S20	Westmont Drive at Keats Street	Alhambra
12	Z3-S21	Winchester Avenue, Along Seismic Line Z3-G6	Alhambra
13	Z3-S22	Winchester Avenue, Along Seismic Line Z3-G6	Alhambra
14	Z3-S23	Westmont Drive, Along Seismic Line Z3-G7	Alhambra
15	Z3-S24	Westmont Drive, Along Seismic Line Z3-G7	Alhambra
16	Z4-S6	E. Huntington Drive, Along Seismic Line Z4-G2	Alhambra
17	Z4-S7	E. Huntington Drive, Along Seismic Line Z4-G2	Alhambra
18	Z4-S8	W. McLean Street (NE/O N. Garfield Avenue)	Alhambra
19	Z4-S9	N. Bushnell Avenue (N/O Larch Street)	Alhambra
20	Z4-S10	S. Date Avenue (S/O W. Commonwealth Avenue)	Alhambra
21	Z5-S10	W. Adams Avenue at S. 2nd Street	Alhambra
22	Z5-S11	Benito Avenue (N/O W. Shorb Street)	Alhambra
23	Z5-S12	Edgewood Drive, Along Seismic Line Z5-G3	Alhambra
24	Z5-S13	Edgewood Drive, Along Seismic Line Z5-G3	Alhambra

Source: CH2M HILL, 2010 (EA-07-187900)

APPENDIX B.2

Pressuremeter Results

Appendix B.2

Pressuremeter Results

The following data reports were prepared for the SR 710 Tunnel Technical Study Final Geotechnical Summary Report (CH2M HILL, 2010). However, only data relevant to the SR 710 North Study are provided herein as summarized in Table B-3. The full version of the following appendix is presented in the Technical Study (CH2M HILL, 2010).

TABLE B-3
Summary of Pressuremeter Tests

Boring Number	Test Number	Date Performed	Test Depth (feet)	Recovery Percent	RQD	Rock Description
R-09-Z3B2	SR710-01	1/16/2009	200.9	17	0	Wilson Quartz Diorite (Wqm)/Granitic-type and Gneissic Rock
R-09-Z3B2	SR710-02	1/16/2009	199.4	17	0	Wilson Quartz Diorite (Wqm)/Granitic-type and Gneissic Rock
R-09-Z3B2	SR710-05	1/17/2009	227	100	0	Wilson Quartz Diorite (Wqm)/Granitic-type and Gneissic Rock
R-09-Z3B2	SR710-06	1/17/2009	225	75	0	Wilson Quartz Diorite (Wqm)/Granitic-type and Gneissic Rock
R-09-Z3B2	SR710-09	1/18/2009	248	50	0	Wilson Quartz Diorite (Wqm)/Granitic-type and Gneissic Rock
R-09-Z3B2	SR710-10	1/18/2009	246.5	92	0	Wilson Quartz Diorite (Wqm)/Granitic-type and Gneissic Rock
R-09-Z3B6	SR710-43	2/20/2009	132	20	8	Topanga Formation(Ttcg)/ Conglomerate
R-09-Z3B6	SR710-47	2/23/2009	166.5	44	0	Topanga Formation(Ttcg)/ Conglomerate
R-09-Z3B6	SR710-48	2/24/2009	188.2	98	30	Topanga Formation(Ttcg)/ Conglomerate

RQD – Rock Quality Designation

Appendix C
Groundwater Data (DVD)

Appendix C

Groundwater Data

Appendix C is provided on the enclosed DVD.

Appendix C

Groundwater Data

Details of vibrating wire (VW) piezometers installed during the SR 710 North Study are shown in this appendix. The VW piezometers were attached to 0.5-inch-diameter polyvinyl chloride (PVC) pipes to place the piezometers at specific depths. The annular space around the VW piezometers was backfilled with No. 3 clean sand. The area above the sand was sealed with bentonite pellets and/or chips. The remaining area to ground surface was filled with cement grout. Each piezometer was completed with a locking cap and traffic-rated well box. The groundwater levels were recorded at 12-hour intervals. The recorded graphs with groundwater elevations versus time are presented in this appendix.

Details of typical piezometer installation during the SR 710 Tunnel Technical Study (CH2M HILL, 2010) are shown in Figure C-1. The piezometers were constructed using 2-inch-diameter PVC Schedule 80 pipe set in the borehole. The bottom of the pipe was slotted and capped; the annular space around the slotted pipe was backfilled with Monterey No. 3 clean sand. Approximately 100 feet of screen interval was used in each piezometer, 25 feet below the invert and 25 feet above the crown of the anticipated tunnel (CH2M HILL, 2010). The area above the sand was sealed with bentonite chips, the remaining annulus was filled with bentonite grout; the annulus within the upper 8 feet was filled with cement grout. Each piezometer was completed with a locking cap and traffic-rated well box, except at boring location R-09-Z3B2, which had a locking cap but no well box where standpipe was used because of grassland at the surface.

TABLE C-1
Piezometer and Groundwater Summary

Boring Designation	Piezometer Type	Ground Surface Elevation ^a (feet)	Depth of Piezometer (feet)	Groundwater Level ^a (Elevation in feet)			
				July 2009	March 2013 ^b (During Drilling)	March 2013	September 2013
R-09-Z1B8	Stand Pipe	419.6	200	394.6	---	396.2	395.7
R-09-Z2B5	Stand Pipe	452.4	277	441.6	---	440.7	---
R-09-Z3B2	Stand Pipe	781.4	275	637.0	---	672.9	674.4
R-09-Z3B3	Stand Pipe	802.0	276	666.0	---	673.6	674.8
R-09-Z3B6	Stand Pipe	750.0	324	698.8	---	697.8	---
R-09-Z3B8	Stand Pipe	594.3	275	NA	---	563.1	562.6
R-09-Z3B12	Stand Pipe	501.0	240	488.2	---	487.3	486.7
R-09-Z4B4	Stand Pipe	454.4	275	408.1	---	387.9	378.1
RC-13-004	Vibrating Wire	393.4	36.7	NA	383.9	379.2	378.2
RC-13-005	Vibrating Wire	425.0	124.5	NA	372.5	389.4	388.1
RC-13-007	Vibrating Wire	493.1	52	NA	448.1	449.7	449.0
RC-13-007	Vibrating Wire	493.1	200	NA	448.1	451.6	449.4
RC-13-009	Vibrating Wire	650.9	100	NA	558.9	552.5	551.0
RC-13-009	Vibrating Wire	650.9	199.5	NA	558.9	548.1	546.5
O-13-010	Vibrating Wire	693.5	196	NA	542.5	675.5	676.8
A-13-020	Vibrating Wire	799.9	147	NA	675.9	544.7	543.7

^a Elevations are based on NAVD 88.

^b See boring records in Appendixes A.1 and A.2.

NA – not applicable; NM – not measured (rotary wash boring)

Appendix D
Laboratory Test Results (DVD)

Appendix D

Laboratory Test Results

Appendix D is provided on the enclosed DVD.

APPENDIX D.1

Summary of Laboratory Test Results

APPENDIX D.2

Current Laboratory Test Results

APPENDIX D.3

Previous Laboratory Test Results

Appendix E

Fault Rupture Evaluation Technical Memorandum

Appendix F
Preliminary Earthquake Acceleration Response
Spectra Technical Memorandum

Appendix G
Fault Investigation Technical Memorandum
