Report No. FHWA-RD-76-114

PREFABRICATED STRUCTURAL MEMBERS FOR CUT-AND-COVER TUNNELS

Vol. 2. Three Case Studies

May 1977

Final Report

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FOREWORD

The report summarizes the results of a study by The Consulting Engineers Group, Inc., to determine the applicability of prefabricated structural members to cut-and-cover tunnel construction. Volume 1 (FHWA-RD-76-113) presents concepts for the design and use of prefabricated members. This volume tests the concepts at three sites where transportation tunnels are proposed or under construction. In each case the comparisons were favorable to the designs with prefabricated members.

Sufficient copies of the report are being distributed to provide two copies to each regional office, one copy to each division office, and two copies to each State highway agency. Direct distribution is being made to the division offices.

NOTICE

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

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16. Abstract

This report is the second of two volumes. The design concepts for the use of prefabricated structural members on cut-and-cover tunnels developed in Volume I are tested on three sites where transportation tunnels are being considered. The sites represent a diversity of site conditions, grades and tunnel depths.

The site studies confirm the feasibility of many of the concepts proposed in Report No. FHWA-RD-76-113, "Prefabricated Structural Members for Cut-and-Cover Tunnels, Vol. I, Design Concepts." Cost savings in the order of 7 to 13 percent of the structural costs are indicated. Construction time will usually be saved, and a dramatic difference in surface disruption is shown in Case Study 1, the only site studied where such disruption was an important factor.

The use of prefabricated members for tunnel approaches and other depressed roadways is investigated in Case Study 2.

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This report is the second volume of a study of the use of prefabricated structural members for cut-and-cover tunnels. The study was conducted by The Consulting Engineers Group, Inc., with the assistance of consultants Ben C. Gerwick, Jr. and Soil Testing Services, Inc. It was performed under Contract No. DOT-FH-11-8594 with the Department of Transportation. Contract Administrator was Ms. Ann Pomerantz and the Contract Manager was Mr. J. R. Sallberg.

This volume, designated Task B of the contract, tests the concepts proposed in Volume I on three sites where transportation tunnels are being proposed. The cooperation of the following organizations and individuals, who furnished the site data and preliminary designs for the case studies is gratefully acknowledged:

Case Study 1: Chicago Urban Transportation District; Harold E. Nelson, Executive Director. DeLeuw-Novick, Supervising Consulting Engineers.

Case Study 2: State of Minnesota. Department of Highways; Keith V. Benthin, Bridge Engineer. Van Doren-Hazard-Stallings, Engineers and Architects.

Case Study 3: Commonwealth of Virginia, Department of Highways and Transportation; Fred C. Sutherland, Bridge Engineer. Parsons, Brinkerhoff, Quade and Douglas, Engineers.

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SI CONVERSION FACTORS

The units of measurement used in this report are English. They are shown below with their metric or SI equivalents.

1 in.	= 2.54 cm	= 25.4 mm	
1 ft	= 12 in.	= 0.305 m	
1 lb (force)	= 4.448 N		
1 kip (force)	= 4448.2 N		
1 ton (force)	= 8896.4 N		
1 $lb/in.^2$	= 1 psi	= 6.90 kN/m^2	
1 $kip/in.^2$	= 1 ksi	= 6895 kN/m^2	= 6.90 MPa
1 lb/ft^2	= 1 psf	= 47.88 n/m^2	= 47.88 Pa
1 ton/ft^3 (subg. mod.)	= 31.4 kN/m^3		
1 in.-kip (moment)	= 0.113 N-m		
1 lb (mass)	= 454 g	= 0.454 kg	
1 ton (mass)	= 907.2 kg		
1 lb/ft^3 (unit wt)	= 1.60 kg/m^3		
1 cu yd	= 0.765 m^3		

I. OVERVIEW AND SUMMARY

A. INTRODUCTION

This report is Volume 2 of a two volume report entitled "Prefabricated Structural Members for Cut-and-Cover Tunnels." Volume I explored the possibility of improving cut-and-cover tunnel construction in urban areas by the use of prefabricated structural members. Various shapes and materials were examined and methods of incorporating these shapes into cut-and-cover transportation tunnels were described.

Volume I concluded that the use of prefabricated members, particularly precast concrete members is feasible and offers opportunities for significantly reducing surface disruption time.

In this volume, the concepts and methods proposed in Volume I are tested on three sites in urban areas where transportation tunnels are being considered. One site is a subway station, the other two are highway tunnels.

Actual proposed tunnel sites, as opposed to hypothetical ones, are used as test cases in an attempt to avoid the criticism of selecting site conditions to fit the proposed solution. Also, since in each of the cases, some preliminary work has been done using "conventional" construction methods, a base for comparison has been established that limits the opportunity to "stack the deck" in favor of the proposed method.

In each of the case studies,.a structural system using prefabricated components is selected, and detailed designs of the components, connections, etc., are made. Drawings showing typical sections and details are presented (see Appendix) and cost estimates of the proposed solution using prefabricated members are compared with estimates of methods using more conventional construction. The length of time required for construction is compared using an idealized Critical Path Method (CPM) construction scheduling technique. Only the structural portions of each project that are different are compared. Items such as architectural treatment, ventilation and other functional equipment are not included.

It should be emphasized that the only purpose of these case studies is to test the feasibility of using prefabricated structural members in real situations. There is no intention to second guess or "value engineer" a proposed design prepared by others.

B. OVERVIEW OF CASE STUDY 1

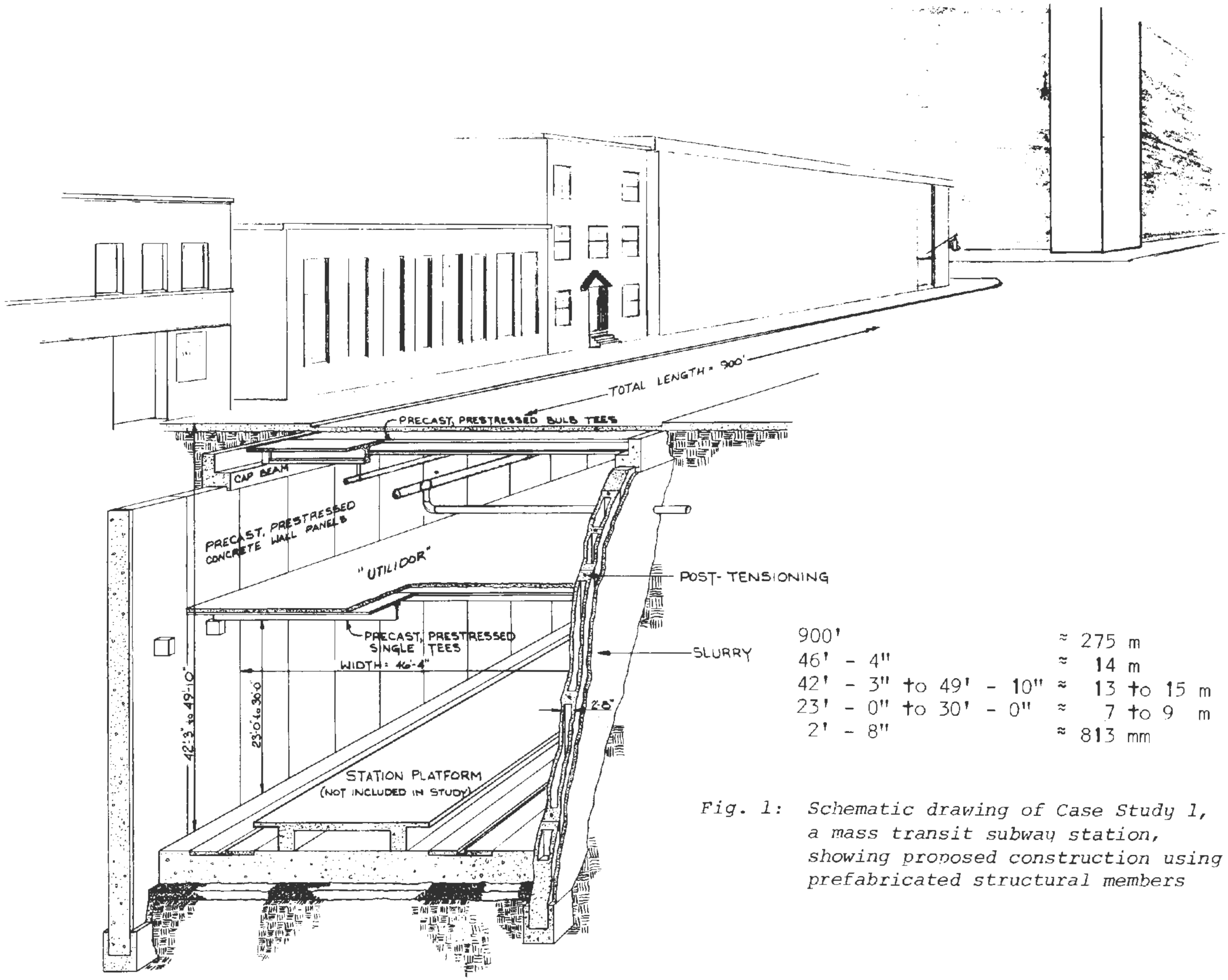
Case Study 1 is a subway station for a metropolitan area urban mass transit system. The site selected is a part of the Chicago, Illinois, Central Area Transit Project being planned by the Chicago Urban Transportation District.

A schematic drawing of the typical tunnel structure using prefabricated components is shown in Fig. 1. Details of the site conditions, components, connections, cost and time comparisons, etc. are in Section II of this report. The proposed construction uses load-bearing precast, prestressed concrete wall panels placed in a slurry trench, with precast, prestressed members used for the tunnel roof and at street level. Underground utilities are placed in a permanently accessible space between the tunnel roof and the street--the "utilidor" concept recommended in Volume I. A major part of the construction is "under the roof", thereby minimizing the time of surface disruption.

The comparison with conventional construction shows the following:

1. Costs: The estimated cost of the structural portion of this project is $7,803 per foot* of length using precast concrete components and $8,932 per foot using conventional construction, a savings of about

*Cost per metre ≈ 3.28 times the cost per foot.



900'	≈ 275 m
46' - 4"	≈ 14 m
42' - 3" to 49' - 10"	≈ 13 to 15 m
23' - 0" to 30' - 0"	≈ 7 to 9 m
2' - 8"	≈ 813 mm

Fig. 1: Schematic drawing of Case Study 1, a mass transit subway station, showing proposed construction using prefabricated structural members

13%, or approximately $1 million on the complete station. It is estimated that the parts of construction compared are about 65% of the total cost, so the net savings on the project would be about 9%.

2. Construction time: There is virtually no difference in total construction time between the precast and conventional method--each would take about 2 years. However, the CPM study shows that the construction method proposed using prefabricated components would allow the street above to be permanently re-opened to traffic only 9 months after the start with virtually no visible evidence of construction after that. The conventional method would require considerable surface disruption for the full 2 year period.

C. OVERVIEW OF CASE STUDY 2

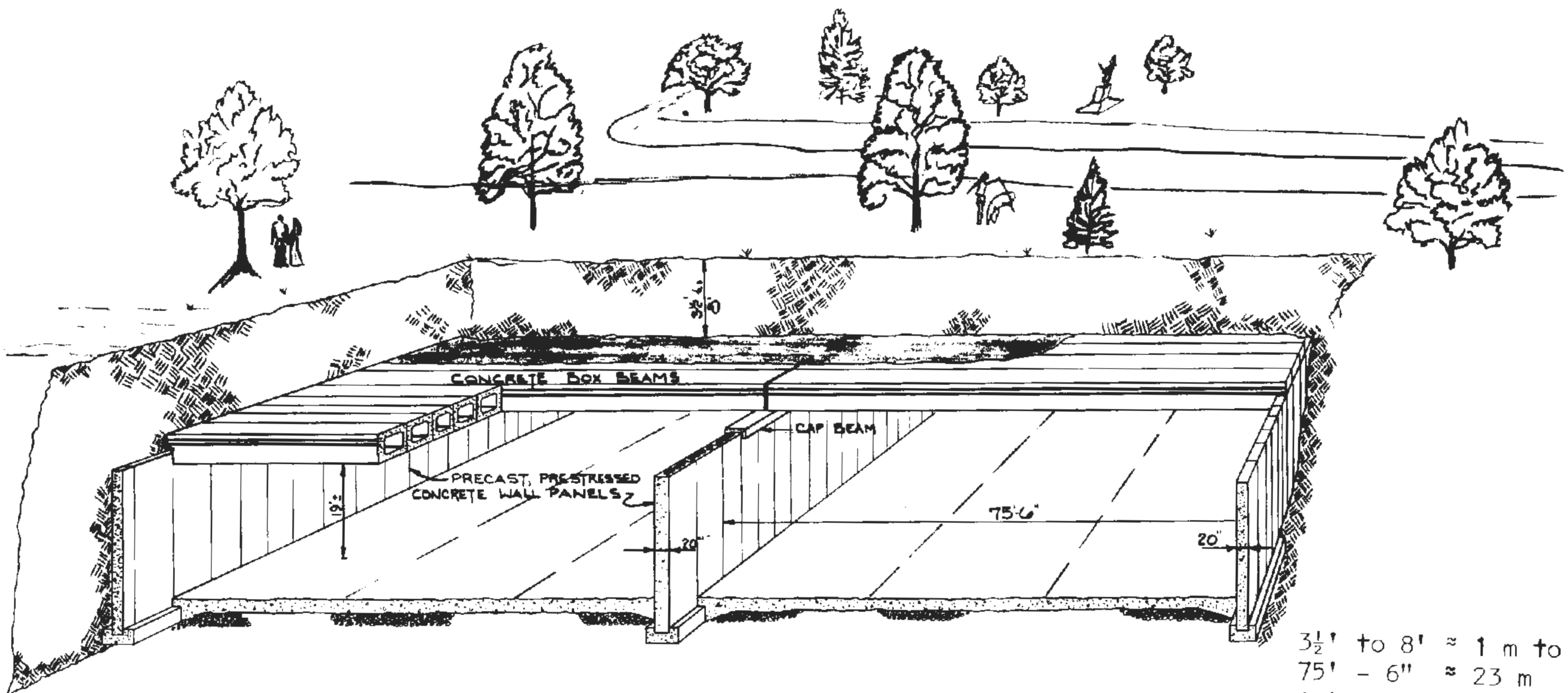
Case Study 2 investigates the use of prefabricated structural elements for a shallow highway tunnel through a public park in the suburbs of a metropolitan area. The project is part of Minnesota Trunk Highway No. 55=116 through Minnehaha Park in Minneapolis.

The proposed tunnel design is shown schematically in Fig. 2 and the detailed description is in Section III of this report.

In this study, surface disruption is not of primary concern, so open excavation is proposed for both the prefabricated and conventional solutions. Part of the excavation is in rock.

For the proposed tunnel construction using prefabricated components, precast, prestressed load-bearing wall units support precast, prestressed box beams.

Two related studies are undertaken in connection with Case Study 2. One is a cost comparison between anchored and gravity tunnel floor slabs. The



3½' to 8'	≈ 1 m to 2.5 m
75' - 6"	≈ 23 m
19'	≈ 6 m
20"	≈ 508 mm

Fig. 2: Schematic drawing of Case Study 2, a highway tunnel through a park, showing tunnel construction using prefabricated structural members

other, includes a design and discussion of the use of prefabricated components in recessed approach construction. The cost comparison discusses the use of ground anchors and establishes some guidelines for choosing an anchored or unanchored design in a series of charts. The recessed approach study presents two alternates for the system using prefabricated components and one for the "conventional" construction method and discusses all three.

Comparisons of costs and construction times showed the following:

1. Costs:

   a. Tunnel construction: The system using prefabricated components is estimated at $9,183 per foot of length compared with $9,828 per foot for the conventional cast-in-place system. The difference in cost, about 7%, is about $600,000 for the total project.

   b. Approach retaining walls: For retaining walls up to about 20 ft (6 m), a cast-in-place cantilever design is the least expensive. For heights above this, a retaining wall, either precast or cast-in-place, supported near the top with horizontal ground anchors, becomes cost effective.

   c. Anchored vs. gravity tunnel floor slabs: The relative cost is dependent on the amount of overburden, height of water table above the slab, span between vertical elements and whether the anchors are in rock or soil. In this case, because of the long span and high water table, the use of anchors would probably save about 7%.

2. Construction time: The CPM study shows that the construction time using prefabricated members would be approximately three months less than the conventional cast-in-place system--11 months vs. 14 months.

D. OVERVIEW OF CASE STUDY 3

Case Study 3 illustrates prefabricated structural components and construction methods which might be applicable for a deep tunnel in poor soil with a high ground water level. The structure investigated is the east approach to the proposed Second Downtown Elizabeth River Tunnel between Portsmouth and Norfolk, Virginia.

Fig. 3 shows a schematic drawing of the proposed construction method, and details of the study are given in Section IV of this report. In this study, cast-in-place slurry walls were chosen over precast because of the extreme depth, up to 90 ft (27 m). For the roof structure, precast concrete 2-hinged arches proved to be economical at the deeper end of the approach, while prestressed box beams were used near the shallower end. Because of the slurry wall tolerance requirements, connection of the precast roof units to the cast-in-place slurry walls does not seem feasible, so a separate framing system is used.

The cast-in-place system in this case study employs three different construction methods: open excavation, soldier piles and lagging, and slurry wall. Therefore, separate cost comparisons are made for each of the three segments, as follows:

1. Cost comparisons: For the segment of the project that used cast-in-place construction with slurry walls, the precast concrete scheme showed a cost savings of nearly 32%. The part that used soldier piles and lagging with the cast-in-place section, the costs are about equal, and for the shallow end where open excavation is feasible, the conventional system saves about 10% compared with the prefabricated method. Overall, the system using precast concrete members indicates approximately 9% savings in cost.

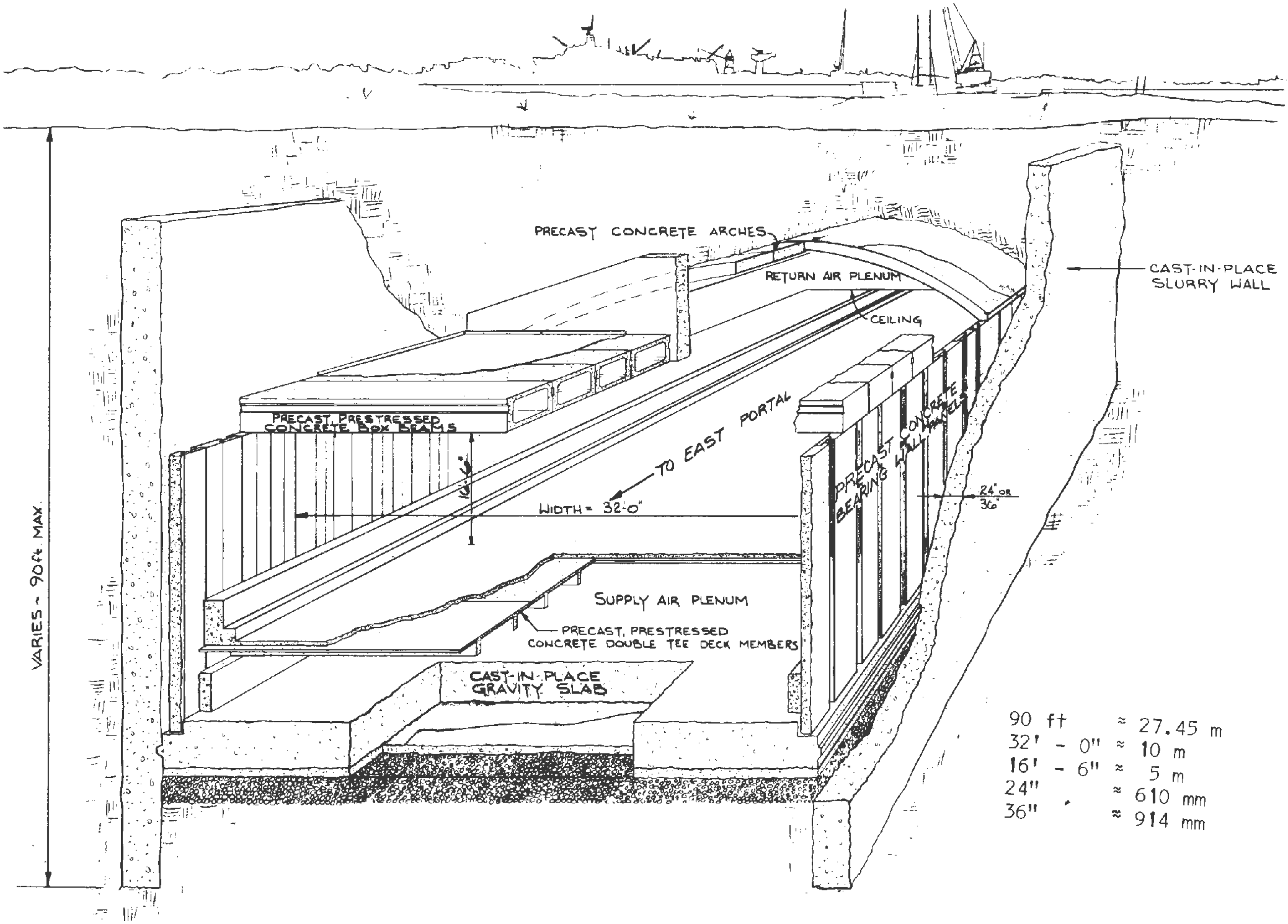


Fig. 3: Schematic drawing of Case Study 3, a cut-and-cover approach to a river tunnel, showing proposed construction using prefabricated structural members.

2. Construction time comparison: The CPM study shows a time saving of about 7-1/2 months for the design using precast concrete components--18-1/2 months vs. 26 months. This time savings appears to be independent of the construction method used for the cast-in-place system.

E. SUMMARY OF THE FINDINGS

The primary conclusion stated in Volume I was confirmed in these case studies; that is, that prefabricated structural members can have a place in cut-and-cover transportation tunnel construction.

Several of the precast structural framing schemes outlined in Volume I proved to be quite efficient. Others were found to be less efficient and still others were not considered because of inappropriate site conditions.

The bearing wall/box beam combination seemed to be one of the best. Besides being cost and time efficient, this combination did not encounter any aesthetic, ventilation, or construction problems that several of the other schemes did. For instance, the king pile wall system becomes inefficient at certain depths and where the size of the flange cannot be changed to improve aesthetics. Another example is the use of stemmed sections for roofs (single tees, double tees, bulb tees, channels). They are efficient shapes, but were not found suitable in Case Study 2 because of ventilation concerns.

The precast arch system was shown to be effective when a large amount of backfill is required, although that effectiveness was compromised somewhat in Case Study 3 by the use of support columns made necessary by the construction tolerances required.

The judicious use of slurry wall construction as a temporary as well as a permanent structure is the key to the use of prefabricated wall members. Its many advantages include a water tight excavation, elimination of underpinning of existing structures, and a narrower path of disruption. These advantages can be had even when slurry walls are combined with conventional construction. However, it is not until they are used as a portion of the permanent structure that cost or time savings can be realized, as evidenced in Case Study 3. On the other hand, the use of slurry wall construction where it is not warranted, can result in a more expensive solution. This was assumed when the construction method was selected in Case Study 2, and proven in Case Study 3. Clearly, if the site conditions permit open excavation, it will usually prove less expensive.

The choice between precast and cast-in-place slurry walls is another consideration. As stated in Volume I, prefabrication of the walls will not result in a savings in time or cost, and the opposite may be true. However, if a finished wall surface is required or perhaps greater attention to construction tolerances demanded, the precast wall might be a good choice provided the size does not become a problem as it did in Case Study 3.

As suspected, the presence of heavy cross utilities, as frequently encountered at street intersections may make slurry walls impractical. This was illustrated in Case Study 1, where after considering several alternatives a modified system using some conventional ideas was selected.

When analyzing the merit of a system using prefabricated components along with the construction methods outlined in Volume I, two things must always be kept in mind. One is that in some areas of a project, there may need to be a cost/time trade-off. One of the key aims of this entire study, which is also a major advantage of the system using prefabricated components, is the savings in time and disruption. If these are primary considerations, the importance of any cost differential may be lessened.

Second, is that the use of prefabricated components alone will not guarantee a substantial cost savings. The use of these materials must be integrated with construction methods discussed in Volume I. Only then, can a substantial savings be realized in both time and money. This total integration cannot be stressed too greatly. The permanent structure must also serve as the temporary retaining and support structure when one is required. This means the designer of the permanent structure must also specify the construction methods. In addition, he must monitor the time sequence which is essential in the savings of time and at least a factor in the area of costs.

Some concerns have been expressed that the concepts proposed in this study will meet with some opposition from the labor unions, contractors, designers, owners, and others involved with these types of projects. Acceptance of a new idea, even one which merely incorporates already accepted concepts and practices, often comes slowly. It may, therefore, be beneficial to test these ideas in the design and construction industry through the building of trial portions on selected conventional jobs.

There is no reason to anticipate unusual problems from the labor unions. Jurisdiction of the construction trades involved in the manufacture and erection of precast concrete, while it varies geographically, has generally been established for above-ground structures.

General contractors who specialize in this type of construction may have reservations about the concepts illustrated in this study. Such reservations would, of course, be reflected in bid prices on the first jobs. There also would likely be some resistance to the specifying of construction methods, if the present procedures of bidding are followed.

Designers and owners may also resist these concepts because of the risks involved in any innovation. The schemes proposed in this study require that the designer or owner assume additional risks by specifying construction methods.

Many of the objections could be eliminated, or at least significantly reduced by the letting of design-build contracts. This is probably not possible in its purest form in public works construction in the United States today. However, there have been some cases where alternates have been bid on a design-build basis. Also, some innovation has been introduced by the so-called "value engineering" encouraged by many Federal and State agencies in recent years.

The greatest technical objection that designers may have is related to the stability of this type of construction. In conventional continuous cast-in-place construction, there is a structural redundancy, meaning that failure of a single component will not cause total failure of the system. Much of this redundancy has been eliminated with the use of separate pieces and mostly simple span framing. However, because of the confinement that exists from the surrounding soil, adequate stability is achieved.

Another concern, which stems from the first, is the response of the structure to earthquakes. Up until now, very little has been done on the study of underground structures and their response to earthquakes. It was merely noted that no severe problems have ever been encountered. While it is felt by many that this remains the case with the designs proposed in this study, it is an area that might warrant future research.

Of the three cases studied, it is apparent that the ideas conceived in Volume I are most applicable to the conditions encountered in Case Study I, the subway station in Chicago. This is perhaps fortunate because there is more emphasis on such mass transportation facilities than on highway tunnels. While it is obviously not possible to anticipate all conditions that might be encountered, there is enough variety in the conditions studied to illustrate the versatility of construction using prefabricated members.

II. CASE STUDY NO. 1

SUBWAY STATION FOR A METROPOLITAN AREA URBAN MASS TRANSIT SYSTEM

A. PROJECT DESCRIPTION

1. Purpose of the study: Case Study No. 1 is intended to illustrate the applicability of prefabricated structural elements for a typical subway station located in a large metropolitan area.

2. Location of the project: The subway station studied is a part of the Chicago, Illinois, Central Area Transit Project being planned by the Chicago Urban Transportation District. It is located on the Franklin line under the intersection of Chicago Avenue and Larrabee Street on the near north side of Chicago, approximately 200 feet (61 m) east of the North Branch of the Chicago River. The station is intended to serve the Montgomery Ward - Marcor Corporation complex as well as a large public housing area situated nearby. See Fig. 16 (Appendix).

3. Dimensions: The area considered in this study is limited to the station itself, and does not include any of the subway line. The north end, approximately 900 ft (275 m) long, which houses the loading platforms and two train tracks, is typically 46'-4" (14 m) wide, and varies in height 23 to 30 ft (7 to 9 m) within the station. The tunnel floor varies from 42'-3" to 49'-10" (13 to 15 m) below ground surface. The southern end, approximately 250 ft (76 m) contains the fare collection area, access escalators and other ancillary space. This area is 63 ft (19 m) wide above a mezzanine level, requiring two-span structural framing.

4. Soil and groundwater characteristics: A typical soil boring log from

the area is shown in Fig. 17. This soil boring is actually a composite, or average of several borings in the area used for design purposes.

Most of the excavation will be in stiff clays typical of the Chicago area. These clays, while appearing quite stiff and hard initially, become soft and sticky when standard rubber-tired vehicles drive on them, making it virtually impossible to use such equipment for excavation without stabilization. This is an important consideration in determining the method and cost of excavation.

For design purposes the water table is assumed at eight feet (2.4 m) below ground surface.

5. Items considered in the study: The purpose of this study is to compare construction using prefabricated elements with conventional methods of construction. For this reason, only the structural elements of the tunnel construction were considered. It was determined that items such as the mezzanine, station platform, escalator and other architectural features as well as all mechanical and electrical work would be the same for both construction methods. Therefore, these items were neglected in this study.

6. Critical areas of concern: The following items required special consideration in determining the type of structure and the methods of construction:

   a. Traffic maintenance. Chicago Avenue is a primary east-west thoroughfare crossing the Chicago River. Alternate routes are available for both crossing the river and access to the Montgomery Ward building and other industrial buildings in the area. However, closing of Chicago Avenue would be a considerable inconvenience to the public and this study has assumed that at least one lane would be open except for very short periods of time at night.

Larrabee Street is of less importance to the general public, but does have some effect on the industry in the immediate vicinity. This study has allowed the closing of Larrabee Street as required by the construction method.

b. Underground utilities: This is always a major concern in construction facilities in urban areas. Existing utilities are shown in Figs. 18 through 22. It was determined that most of the utility lines can be temporarily supported and remain in place during construction, but some would have to be relocated before construction is started. Those to be relocated are:

(1) The 5'0" x 6'-10½" (1.5 x 2.1 m) MSD (sewer) line. This line interferes with the final structure. Relocation is a major project, and it was assumed that it would be done prior to the start of construction, regardless of the construction method. Therefore, this relocation was not considered part of this project.

(2) The 24" (610 mm) PG (gas) line. Safety regulations will usually prohibit the maintenance of gas lines within an open excavation, so relocation is considered in the construction time study.

(3) The 6 DCE (electrical) and 2DIBT (telephone) lines. North of Chicago Avenue, these lines run roughly parallel to, and along the line of excavation. There would appear to be a great danger of hitting these lines with any construction

method, so they should be relocated prior to the start of construction.

With these lines relocated, there are no major utility lines crossing the excavation except at Chiago Avenue. Since the cross utilities at that point are quite heavy, the slurry trench and prefabricated wall method is probably not feasible, so a different method of construction is proposed. (See Section B following).

c. Railroad track: The surface railroad that serves the Montgomery Ward Catalog Sales Warehouse and other warehouses on Kingsbury will have to be closed during certain phases of construction at and south of Chicago Avenue. This track is used infrequently, but closing will be an inconvenience and probably cause some expense to those businesses. North of Chicago Avenue at least one track can be kept open during the tunnel construction, but movement along the track would probably have to be restricted to periods when there is little construction activity on the west side of Larrabee. This would probably not be an inconvenience as the track is now used only at night. With the "conventional" construction, it is probable that the excavation would be too close to the track for any use.

d. Pedestrian tunnel: The pedestrian tunnel connection Marcor Corporation building and the Montgomery Ward Administration building would have to be removed and replaced during the construction of the station south of Chicago Avenue. With the proposed prefabricated method of construction, special construction procedures are required around the pedestrian tunnel. While there may be other alternatives, this study assumes that construction around this tunnel opening would be handled in a method similar to that used at Chicago Avenue where the heavy cross utilities present a similar problem.

e. Adjacent structures: Fig. 16 shows the proximity of buildings to the tunnel project. The major structures, i.e., the Marcor Catalog Sales and Parking Garage are founded on either piles or caissons which bear well below the invert of the tunnel. Therefore, underpinning of these structures is not necessary. Also, lowering of the water table is not likely to cause structural damage except for the possible minor settlements of slabs on grade. However, lowering of the water table would only be necessary to the dept of the fill material because of the very impervious nature of the clays below that. With slurry wall construction, even this would not be required.

The other buildings near the north end of the project are quite old and run-down. With slurry-wall construction, these would not need to be underpinned, and even with the "conventional" method, it would probably be less expensive to risk damage than to underpin. Therefore, underpinning was not considered part of the project under either method.

B. CONSTRUCTION USING PREFABRICATED COMPONENTS

1. Structural framing method: The various structural framing schemes outlined in Volume I of this study were considered for this Case Study.

a. Typical section: Approximately 80% of the length of the station is ideal for precast, prestressed load-bearing wall panels placed in a slurry trench with precast, prestressed roof units. This scheme was chosen for that 80%, and is illustrated in Fig. 25 of the drawings. This scheme seemed particularly well suited because:

(1) There are few cross utilities.

(2) The rigid diaphragm wall would enable at least partial operation of the surface railroad during construction.

(3) Larrabee Street can be closed for limited periods of time, but extended times would be inconvenient to the businesses in the area.

(4) The "utilidor" concept would work very well along Larrabee, and few utilities would have to be relocated.

b. Special framing at intersection: At Chicago Avenue, relatively heavy cross utilities are encountered. The typical framing method is not feasible because excavation of a slurry trench by conventional methods is virtually impossible, as is placement of prefabricated panels around the utilities.

Volume I of this study suggests different ways to handle this situation. It is believed that equipment could be developed to excavate slurry trenches under these heavy cross utilities, in this type of soil. One such method would use high pressure directional water jets located vertically along a pipe which is lowered into a drilled hole. Given the proper incentive, other methods could probably be developed by contractors.

However, insertion of precast concrete wall panels, or even reinforcing cages would appear to be impractical. Use of a variation of the Soldier Pile Tremie Concrete (SPTC) wall is suggested as a possibility. However, it would be necessary to develop sufficient flexural strength in the concrete to span between soldier piles unreinforced. If this cannot be done with conventional concrete, fiber reinforced or polymer modified concrete as described in Section XIII of Volume I could be employed.

Another alternative, and the method selected for use in this case is to form and pour a reinforced concrete wall between soldier piles after the tunnel has been excavated. In this case, conventional timber lagging is used between the soldier piles. This lagging remains in place and serves as the outside form for the concrete wall. The concrete and structural steel are designed to act compositely in the final condition.

The precast, prestressed members are still used as struts at both the roof and street levels. Steel wide flange sections are connected to the soldier piles to act as supporting members for the horizontal members and as wales to take the horizontal loads. A section through this area is shown in Fig. 26.

2. Products and design: An eight foot (2.4 m) module was selected because:

(1) Architectural drawings show a vaulted ceiling with ribs on 8 foot centers.

(2) The weight of the eight foot wide units approach the maximum for handling.

(3) This is a common module for precast, prestressed concrete products, so existing equipment in a precasting plant could be used.

No continuity between horizontal and vertical members is assumed.

a. Wall units: The wall units are shown in Fig. 27. They are designed to be manufactured in an off-site precasting plant. The typical section is prestressed with 32 pretensioning strands and

24 post-tensioned strands. The pretensioning is designed to carry all handling and temporary loads, with a temporary strut placed as shown in Fig. 25. The post-tensioning is done after the bottom slab is in place, and before the temporary struts are removed.

The weight of each unit is about 55 tons (50,000 kg) This would require special permits for hauling, but use of units this size is not unusual.

b. Horizontal members: The precast, prestressed street level and tunnel roof members are shown in Fig. 27. The street level members are not designed to act compositely with the cast-in-place concrete slab because of the construction equipment loads which must be carried before the slab is cast.

The tunnel roof members will also not act compositely with the cast-in-place concrete because of the waterproofing membrane placed directly on the precast unit. The single-tee configuration was selected to simulate the vaulted ceiling shown on the preliminary architectural drawings.

c. Connections: The tunnel roof members bear on a concrete encased steel wide flange member. The pocket for the wide flange is cast in the plant, and plugged. After excavation to that level, the plug is removed, the steel member welded into place, and the concrete cast around it. The concrete encasement serves the dual purpose of protecting the steel member and providing the necessary elevation tolerance. Horizontal loads from the walls are transmitted through shims to the horizontal members. The shims are accurately placed so that the load is at the centroid of the member. The joint is then grouted for protection.

At the street level, the horizontal members rest on a cap beam cast over the top of the precast wall units. Horizontal loads are again transmitted through properly placed shims. Connection details are shown in Fig. 25.

d. Foundations: Cast-in-place concrete or grout is tremied or pumped to the bottom of the excavation as soon as practical after the precast units are placed, before the cement-bentonite slurry has set. This concrete or grout is of sufficient strength to transmit the vertical loads to the bearing material. The cement-bentonite slurry has adequate strength, after setting, to transmit the horizontal loads.

3. Construction sequence: Construction of the station is assumed to start at the north end and progress continuously southward. The following assumptions and decisions were made regarding the sequence of operations:

   a. Succeeding operations are kept approximately 100 ft (30 m) apart to avoid interference, e.g., placement of precast, horizontal units is 100 feet behind excavation. (Note: this does not apply to placement of the wall units in the slurry trench, as the slurry trench cannot be held open unsupported more than about 20 feet (6.1 m) ahead of the placement of the wall units.)

   b. Slurry trench excavation and placement of wall units is done one side at a time so that Larrabee Street can be held open to at least one-way traffic.

   c. Post-tensioning of the wall units is done as the last structural operation. The post-tensioning tendons are located for the final loading condition. If the post-tensioning is done earlier, unfavorable stress conditions would result.

d. Certain operations at the intersection with Chicago Avenue, such as placement of the soldier piles, could be done at the same time as the slurry trench operations.

e. Access to the excavation, after placement of the street level horizontal members is at the location of the north entrance (See Fig. 24). This would necessitate the purchase and removal of the existing buildings at that location earlier than might otherwise be required. This property, or another vacant lot near there could also be used for the slurry handling equipment and other construction storage. It may also be desirable to use the parking lot south of the Wards Administration Building for the slurry equipment when operations are at that end of the site.

f. The structural design of the walls requires a temporary strut to be placed approximately 12 ft (3.7 m) above the bottom of the excavation. This strut must remain in place until the base slab is cast and the wall units post-tensioned. After the 4 ft (1.2 m) thick base slab is cast, there is insufficient clearance for trucks to operate on the slab. Therefore, with a single access to the tunnel, all excavation must be completed before casting of the base slab begins.

4. A precedence diagram showing the relationship of the various construction operations is shown in Fig. 29. A detailed description of each operation is shown in Table 1. These operations are used as the input to a Critical Path Method (CPM) computer program. The output of this program is shown as Table 2.

Table 1. Case Study 1: Construction sequence using prefabricated structural elements

(See Fig. 29 for Precedence Diagram)

Operation Number	Description of Operations
1-3	Initializing operation necessary for computer input.
4	Plug abandoned Metropolitan Sanitary District pipe to avoid loss of slurry where slurry trench and pipe cross. Abandoned MSD pipe is because of necessity to relocate outside of main tunnel.
5	Construct access to tunnel from off-street site to be used during construction phases occurring after permanent restoration of street.
6	Relocate utilities such as gas lines completely off of the construction site. Relocate other necessary utilities that are in or near line of slurry trench or interfere with placement of soldier piles across intersection. See page 3 for explanation.
7	Construct a temporary railroad spur farther away from excavation limits to allow continued use and minimize surcharge effect on excavation.
8	Erect side walk barricade to separate pedestrians from construction activities.
10	Close one side of street to traffic to allow construction activities while retaining single-lane traffic on other side.
12-14	See Operations 8-10.
16	Clean-up, remove barricades, and generally restore side of street currently closed off to accept traffic while other side is closed down.
18	Close street completely to all traffic.
20, 22	See Operation 10.
21	See Operation 16.
24	Block off Montgomery Ward pedestrian tunnel during construction operations. Pedestrian tunnel will be rebuilt later in project.
26-28, 32-34	See Operations 8-10
30	See Operation 6.

Table I. Case Study 1: Construction sequence using prefabricated structural elements (continued)

Operation Number	Description of Operations
36-38	See Operations 16-18.
50	Initialization of precasting operations necessary for computer input.
51	Shop drawings for wall units and their approval.
52	Preliminary work required before casting of precast units.
53-561	Casting and shipping of precast wall units.
61-66, 71-75	See Operations 51, 51, 53-56. Similar, but for different precast units.
100-102	Construct a guide trench to be used for accuracy of slurry trench. construction and alignment and temporary suspension of precast wall units.
104-106	Construct a slurry trench, place and temporarily suspend precast wall units, and pour continuous wall footing by the tremie method.
108-110	Cast a continuous concrete cap beam to be a ledger beam and support the precast horizontal members at the street level.
120	Excavate, mostly by hand, to the bottom of the utilities so all utilities are exposed and can be suspended later from the horizontal precast members at the street level. If utility depths are irregular, some may need to be lowered and others supported on some kind of temporary chair. It is anticipated that this operation will be expedited to minimize the time the street is closed. Round-the-clock operation if necessary.
122	Place precast street tees in position and secure flanges together by welding.
124	Suspend utilities at intervals required by any means suitable to last until more permanent pipe racks, etc. can be installed later in the construction sequence.
126	Cast concrete topping at appropriate slope for drainage and finish top surface suitable for permanent traffic.
128	Allow concrete to cure to desired strength.

Table I. Case Study 1: Construction sequence using prefabricated Structural elements (continued)

Operation Number	Description of Operations
130	Excavate to bottom of final excavation and set two levels of temporary streets as excavation progresses.
132	Construct haunch in accordance with design at the center web of each precast wall unit and finish to appropriate height to allow placement of tunnel roof level precast members.
134	Remove upper level of temporary struts, place precast tunnel roof tees and secure flanges by welding.
136	Build-up waterproofing and allow to set.
138	Similar to Operation 126.
140	Restore utilities on permanent racks, color code, inspection and replacement, maintenance, etc.
142	Lay a new gravel base if old base has been embedded in clay by trucks and construction equipment. Form, pour and finish 4 ft. deep base slab.
144	Stress post-tensioning tendons in the precast wall units and remove second level of temporary struts.
146	Caulk wall joints to retard seepage.
200	Hand dig a trench on line of soldier piles down to utilities to accurately locate them and allow the drilling operation to proceed unobstructed.
202	Drill shaft, place and align soldier pile and secure into position by backfilling or setting slurry.
204-212	See associated operation from 120-126.
214	Permanently restore all railroad tracks to original position.
216	See Operation 128.
220-236	Side 2 same as side 1.
240	See Operation 130.

Table I. Case Study 1: Construction sequence using prefabricated structural elements (continued)

Operation Number	Description of Operations
242	Erect permanent steel beams between soldier piles to support precast members at the tunnel roof level. Erect wales to transfer the horizontal force between the permanent soldier piles and the precast members which will permanently brace the walls when the struts are removed.
244	See Operation 134.
246-248	Place waterproofing mats against lagging in preparation for cast-in-place wall which will be poured against lagging.
250-252	Place cast-in-place reinforcement and secure in front of lagging acting as a back form.
254-256	Erect formwork and pour cast-in-place wall and haunch as shown in drawings.
258	Place gravel base, erect necessary formwork, place reinforcement and pour a slab on grade for escalators, etc. located in short span of 2-span area.
260	Strip cast-in-place wall forms and patch or sandblast as required to obtain a permanent finish.
262-268	See associated operations from 136-142.
300-350	Except for additional operations listed below, see associated operations from 100-146.
301, 303	Similar to Operation 202, but at pedestrian tunnel location.
331	See Operation 242.
342	Combination of operations similar to those from 246-256.
344	See Operation 260.
470-500	Non-functional operations designating completion.

Table 2. Case Study 1: Computer output of CPM program for construction using prefabricated structural elements

P R Ø J E C T   S C H E D U L E

FRØM JAN 1, 1977 TØ FEB 27, 1979 - SØRTED BY SEQ

CUTD - LARRABEE STREET STATIØN   APR 27, 1977

	DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
	1	START NØRTH LARRABEE	0	1JAN77	3JAN77	3JAN77	3JAN77	0
	2	START INTERSECTIØN	0	1JAN77	3JAN77	18MAY78	18MAY78	352
	3	START SØUTH LARRABEE	0	1JAN77	3JAN77	2JUN78	2JUN78	362
*	4	PLUG MSD	20	3JAN77	28JAN77	3JAN77	28JAN77	0
	5	CØN CØNSTRUCTIØN ENT	20	3JAN77	28JAN77	22JUL77	18AUG77	142
*	6	REL UTIL NØ ØF CHG	40	3JAN77	25FEB77	3JAN77	25FEB77	0
*	7	CØN TEMP RR TRK	20	3JAN77	28JAN77	3JAN77	28JAN77	0
	8	ER SDWK BARR SD 1 NØ	5	3JAN77	7JAN77	24JAN77	28JAN77	15
	10	CUT ØFF TRAF SD 1 NØ	0	7JAN77	7JAN77	31JAN77	2MAR77	37
	12	ER SDWK BARR SD 2 NØ	5	3JAN77	7JAN77	5MAY77	11MAY77	88
	14	CUT ØFF TRAF SD 2 NØ	0	11MAY77	11MAY77	12MAY77	12MAY77	0
*	16	REST & ØPEN SD 1 NØ	4	6MAY77	11MAY77	6MAY77	11MAY77	0
	18	CLØSE NØRTH LARRABEE	0	18AUG77	18AUG77	19AUG77	19AUG77	0
	20	CUT ØFF TRAF SD 1 IN	0	3JAN77	3JAN77	18MAY78	18MAY78	352
	21	REST & ØPEN SD 1 INT	0	28MAR77	28MAR77	23JUN78	23JUN78	316
	22	CUT ØFF TRAF SD 2 IN	0	28MAR77	28MAR77	23JUN78	23JUN78	316
	24	BLK ØFF PED TUNN	10	3JAN77	14JAN77	16JUN78	29JUN78	372
	26	ER SDWK BARR SD 1 SØ	2	3JAN77	4JAN77	28JUN78	29JUN78	380
	28	CUT ØFF TRAF SD 1 SØ	0	4JAN77	4JAN77	30JUN78	30JUN78	380
	30	REL UTIL SØ ØF CHG	20	3JAN77	28JAN77	2JUN78	29JUN78	362
	32	ER SDWK BARR SD 2 SØ	2	3JAN77	4JAN77	24JUL78	25JUL78	397
	34	CUT ØFF TRAF SD 2 SØ	0	24JUN77	24JUN77	26JUL78	26JUL78	275
	36	REST & ØPEN SD 1 SØ	2	23JUN77	24JUN77	24JUL78	25JUL78	275
	38	CLØSE SØUTH LARRABEE	0	18JUL77	18JUL77	16AUG78	16AUG78	275
	50	PRECAST CØ0TRACT	0	1JAN77	3JAN77	5JAN77	5JAN77	2
	51	SH DRWGS WALLS	20	3JAN77	28JAN77	5JAN77	1FEB77	2
	52	BED SET-UP WALLS	10	3JAN77	14JAN77	19JAN77	1FEB77	12
	53	CAST WALLS SD 1 NØ	42	31JAN77	29MAR77	2FEB77	31MAR77	2
	54	CAST WALLS SD 2 NØ	42	30MAR77	26MAY77	16MAY77	14JUL77	33
	55	CAST WALLS SD 1 SØ	6	27MAY77	6JUN77	27JUN78	5JUL78	275
	56	CAST WALLS SD 2 SØ	6	7JUN77	14JUN77	21JUL78	28JUL78	286
	61	SHØP DRWGS STR TEES	30	3JAN77	11FEB77	8JUL77	18AUG77	132
	62	BED SET-UP STR TEES	10	3JAN77	14JAN77	5AUG77	18AUG77	152
	63	CAST STR TEES NØ	16	14FEB77	7MAR77	19AUG77	12SEP77	132
	64	CAST ST TEES SD 1 IN	1	8MAR77	8MAR77	2JUN78	2JUN78	316
	65	CAST ST TEES SD 2 IN	1	15MAR77	15MAR77	10JUL78	10JUL78	336
	66	CAST ST TEES SØ	2	22MAR77	23MAR77	14AUG78	15AUG78	356
	71	SHØP DRWGS RØØF TEES	30	3JAN77	11FEB77	30SEP77	10NØV77	191
	72	BED SET-UP RØØF TEES	10	3JAN77	14JAN77	28ØCT77	10NØV77	211
	73	CAST RØØF TEES NØ	16	14FEB77	7MAR77	11NØV77	5DEC77	191
	74	CAST RØØF TEES INT	2	8MAR77	9MAR77	12ØCT78	13ØCT78	409
	75	CAST RØØF TEES SØ	2	15MAR77	16MAR77	19ØCT78	20ØCT78	409
*	100	CØN GDE TR SD 1 NØ	30	31JAN77	11MAR77	31JAN77	11MAR77	0
*	102	CØN GDE TR SD 2 NØ	30	12MAY77	23JUN77	12MAY77	23JUN77	0
*	104	CØN WALL SD 1 NØ	60	9FEB77	3MAY77	9FEB77	3MAY77	0
*	106	CØN WALL SD 2 NØ	60	23MAY77	16AUG77	23MAY77	16AUG77	0
*	108	CAST CAP BM SD 1 NØ	20	8APR77	5MAY77	8APR77	5MAY77	0
*	110	CAST CAP BM SD 2 NØ	20	22JUL77	18AUG77	22JUL77	18AUG77	0
*	120	EXCAVATE EL 1 NØ	20	19AUG77	16SEP77	19AUG77	16SEP77	0
*	122	SET STR TEES NØ	16	26AUG77	19SEP77	26AUG77	19SEP77	0

Table 2. Case Study 1: Computer output of CPM program for construction using prefabricated structural elements (continued)

P R Ø J E C T   S C H E D U L E

FRØM JAN 1, 1977 TØ FEB 27, 1979 - SØRTED BY SEQ

CUTD - LARRABEE STREET STATIØN   APR 27, 1977

NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
* 124	TEMP SUSP UTIL NØ	16	29AUG77	20SEP77	29AUG77	20SEP77	0
126	PAVE STR NØ	10	12SEP77	23SEP77	7FEB79	20FEB79	359
128	CURE PAVING NØ	5	26SEP77	30SEP77	21FEB79	27FEB79	359
* 130	EXC & SET STRTS NØ	225	31AUG77	19JUL78	31AUG77	19JUL78	0
132	CAST HAUNCH SUP NØ	205	6ØCT77	26JUL78	15NØV77	2SEP78	28
134	SET RØØF TEES NØ	205	11ØCT77	31JUL78	18NØV77	8SEP78	28
136	WATERPRØØF RØØF NØ	30	1AUG78	12SEP78	9SEP78	19ØCT78	28
138	CAST TØPPING RØØF NØ	20	13SEP78	9ØCT78	20ØCT78	16NØV78	28
140	PERM REST UTIL NØ	70	10ØCT78	18JAN79	17NØV78	27FEB79	28
* 142	CAST BASE SLAB NØ	50	8DEC78	19FEB79	8DEC78	19FEB79	0
* 144	PT & REM TEMP STRTS	30	12JAN79	22FEB79	12JAN79	22FEB79	0
* 146	SEAL WALL JØINTS NØ	25	24JAN79	27FEB79	24JAN79	27FEB79	0
200	UNCØVER UTIL SD 1 IN	2	3JAN77	4JAN77	18MAY78	19MAY78	352
202	SØLD PILES SD 1 INT	10	5JAN77	18JAN77	22MAY78	5JUN78	352
204	EXC EL 1 SD 1 INT	3	19JAN77	21JAN77	6JUN78	8JUN78	352
206	CAST CAP BM SD 1 INT	2	19JAN77	20JAN77	7JUN78	8JUN78	353
208	SET STR TEES SD 1 IN	2	15MAR77	16MAR77	9JUN78	12JUN78	316
210	TEM SUS UTIL SD 1 IN	1	17MAR77	17MAR77	13JUN78	13JUN78	316
212	PAVE SD 1 INT	2	18MAR77	21MAR77	14JUN78	15JUN78	316
214	REST RR TRK SD 1 INT	2	18MAR77	21MAR77	21JUN78	22JUN78	321
216	CURE PAVING SD 1 INT	5	22MAR77	28MAR77	16JUN78	22JUN78	316
220	UNCØVER UTIL SD 2 IN	2	29MAR77	30MAR77	23JUN78	26JUN78	316
222	SØLD PILES SD 2 INT	10	31MAR77	13APR77	27JUN78	11JUL78	316
224	EXC EL 1 SD 2 INT	3	14APR77	18APR77	12JUL78	14JUL78	316
226	CAST CAP BM SD 2 INT	2	14APR77	15APR77	13JUL78	14JUL78	317
228	SET STR TEES SD 2 IN	2	19APR77	20APR77	17JUL78	18JUL78	316
230	TEM SUS UTIL SD 2 IN	1	21APR77	21APR77	19JUL78	19JUL78	316
232	PAVE SD 2 INT	2	22APR77	25APR77	19FEB79	20FEB79	465
234	REST RR TRK SD 2 INT	2	22APR77	25APR77	26FEB79	27FEB79	470
236	CURE PAVING SD 2 INT	5	26APR77	2MAY77	21FEB79	27FEB79	465
* 240	EXC & SET TEMP STRTS	25	20JUL78	23AUG78	20JUL78	23AUG78	0
242	ERECT BMS & WALES	2	24AUG78	25AUG78	19ØCT78	20ØCT78	40
244	SET RØØF TEES INT	1	28AUG78	28AUG78	23ØCT78	23ØCT78	40
246	WATRPRFNG-WALLS SD 1	2	24AUG78	25AUG78	20ØCT78	23ØCT78	41
248	WATRPRFNG-WALLS SD 2	2	28AUG78	29AUG78	31ØCT78	1NØV78	46
250	PLACE CIP REIN SD 1	3	29AUG78	31AUG78	24ØCT78	26ØCT78	40
252	PLACE CIP REIN SD 2	4	1SEP78	7SEP78	2NØV78	7NØV78	44
254	F A P WALLS SD 1	8	1SEP78	13SEP78	27ØCT78	7NØV78	40
256	F A P WALLS SD 2	10	14SEP78	27SEP78	8NØV78	21NØV78	40
* 258	CAST SIDE SLAB	2	22NØV78	24NØV78	22NØV78	24NØV78	0
* 260	STRIP FMS & FIN WALL	4	27NØV78	30NØV78	27NØV78	30NØV78	0
* 262	CAST BASE SLAB INT	5	1DEC78	7DEC78	1DEC78	7DEC78	0
264	WTRPRF RØØF INT	3	29AUG78	31AUG78	11DEC78	13DEC78	73
266	CAST TØPPING RØØF IN	2	1SEP78	2SEP78	14DEC78	15DEC78	73
268	PERM REST UTIL INT	50	6SEP78	13NØV78	18DEC78	27FEB79	73
300	CØN GDE TR SD 1 SØ	3	31JAN77	2FEB77	30JUN78	5JUL78	362
301	SØL PIL-PED TUN SD 1	2	3FEB77	4FEB77	18JUL78	19JUL78	370
302	CØN GDE TR SD 2 SØ	3	27JUN77	29JUN77	26JUL78	28JUL78	275
303	SØL PIL-PED TUN SD 2	2	30JUN77	1JUL77	10AUG78	11AUG78	283
304	CØN WALL SD 1 SØ	10	7JUN77	20JUN77	6JUL78	19JUL78	275

Table 2. Case Study 1: Computer output of CPM program for construction using prefabricated structural elements (continued)

P R Ø J E C T S C H E D U L E

FRØM JAN 1, 1977 TØ FEB 27, 1979 - SØRTED BY SEQ

CUTD = LARRABEE STREET STATIØN APR 27, 1977

			EARLIEST		LATEST		TØTAL
NUMBER	DESCRIPTIØN	DUR	START	FINISH	START	FINISH	FLØAT
306	CØN WALL SD 2 SØ	10	30JUN77	14JUL77	31JUL78	11AUG78	275
308	CAST CAP BM SD 1 SØ	2	21JUN77	22JUN77	20JUL78	21JUL78	275
310	CAST CAP BM SD 2 SØ	2	15JUL77	18JUL77	14AUG78	15AUG78	275
320	EXCAVATE EL 1 SØ	3	19JUL77	21JUL77	16AUG78	18AUG78	275
322	SET STR TEES SØ	2	22JUL77	25JUL77	21AUG78	22AUG78	275
324	TEMP SUSP UTIL SØ	1	26JUL77	26JUL77	23AUG78	23AUG78	275
326	PAVE STREET SØ	2	27JUL77	28JUL77	19FEB79	20FEB79	399
328	CURE PAVING SØ	5	29JUL77	4AUG77	21FEB79	27FEB79	399
* 330	EXC & SET STRUTS SØ	40	24AUG78	18ØCT78	24AUG78	18ØCT78	0
331	ER SUP FRAMING SØ	1	19ØCT78	19ØCT78	25ØCT78	25ØCT78	4
* 332	CAST HAUNCH SUP SØ	5	19ØCT78	25ØCT78	19ØCT78	25ØCT78	0
* 334	SET RØØF TEES SØ	2	26ØCT78	27ØCT78	26ØCT78	27ØCT78	0
336	WTRPRF RØØF SØ	5	30ØCT78	3NØV78	19JAN79	25JAN79	56
338	CAST TØPPING RØØF SØ	3	6NØV78	8NØV78	26JAN79	30JAN79	56
340	PERM REST UTIL SØ	20	9NØV78	7DEC78	31JAN79	27FEB79	56
* 342	CØN CIP WALLS SØ	5	30ØCT78	3NØV78	30ØCT78	3NØV78	0
* 344	CURE WALLS-REM FMS	4	6NØV78	9NØV78	6NØV78	9NØV78	0
* 346	CAST BASE SLAB SØ	8	10NØV78	21NØV78	10NØV78	21NØV78	0
348	PT & REM TEMP STRTS	5	22NØV78	29NØV78	15FEB79	21FEB79	58
350	SEAL WALL JØINTS SØ	4	30NØV78	5DEC78	22FEB79	27FEB79	58
470	ØPEN NØRTH LARRABEE	0	30SEP77	30SEP77	28FEB79	28FEB79	359
480	ØPEN CHG AVE	0	2MAY77	2MAY77	28FEB79	28FEB79	465
490	ØPEN SØUTH LARRABEE	0	4AUG77	4AUG77	28FEB79	28FEB79	399
500	END ØF PRØJECT	0	27FEB79	27FEB79	28FEB79	28FEB79	0

C. COMPARISON WITH CONVENTIONAL CONSTRUCTION

For comparative purposes, the following "conventional" construction method was assumed:

1. A temporary retaining structure is constructed using steel soldier piles placed in drilled holes. Driven sheet piling was not considered feasible due to noise and vibration. This type of temporary structure is being used in subway construction in Washington, D. C. and New York City.

   Timber lagging is placed between soldier piles as excavation proceeds.

   While closing of the street will be permitted for limited periods of time, temporary street decking is required during the construction.

2. The permanent structure is a cast-in-place reinforced concrete tube as shown in Fig. 28.

3. A precedence diagram showing the relationship of the various construction operations is shown in Fig. 30. In this case the operations were assumed to start at the north end of the project and continue sequentially to the south end. It was assumed that materials, equipment, and men could enter or be removed from the excavation by removing sections of the temporary timber deck, as well as through the access at the north end.

   CPM output for the conventional method is shown as Table 3.

Table 3. Case Study 1: Computer output of Critical Path Method (CPM) program for construction using conventional methods

P R Ø J E C T   S C H E D U L E

FRØM JAN 1, 1977 TØ FEB 5, 1979 - SØRTED BY SEQ

CUTD - LARRABEE STREET STATIØN   APR 27, 1977

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
1	START	0	1JAN77	3JAN77	3JAN77	3JAN77	0
4	CØNST TEMP RR TRACK	20	3JAN77	28JAN77	17JAN77	11FEB77	10
6	CØN CØNSTRUCTIØN ENT	20	3JAN77	28JAN77	21FEB77	18MAR77	35
* 100	ER SDWK BARR	10	3JAN77	14JAN77	3JAN77	14JAN77	0
* 102	RELØCATE UTILITIES	40	17JAN77	11MAR77	17JAN77	11MAR77	0
* 104	SØLDIER PILES	120	14FEB77	2AUG77	14FEB77	2AUG77	0
* 110	EXCAVATE EL 1	103	14MAR77	5AUG77	14MAR77	5AUG77	0
* 112	SET DK BMS & DK	103	17MAR77	10AUG77	17MAR77	10AUG77	0
* 114	TEMP SUSP UTIL	103	18MAR77	11AUG77	18MAR77	11AUG77	0
* 116	EXC,LAG & SET STRTS	340	21MAR77	19JUL78	21MAR77	19JUL78	0
* 118	F A P BASE SLAB	185	3NØV77	26JUL78	3NØV77	26JUL78	0
* 120	F A P WALLS	200	10NØV77	23AUG78	10NØV77	23AUG78	0
* 122	F A P RØØF	200	9DEC77	21SEP78	9DEC77	21SEP78	0
124	WATERPRØØF WALLS	185	9DEC77	30AUG78	5JAN78	23SEP78	17
* 126	WATERPRØØF RØØF	185	10JAN78	28SEP78	10JAN78	28SEP78	0
128	BACKFILL EL 3	183	16DEC77	2SEP78	12JAN78	28SEP78	17
* 130	BACKFILL EL 2	185	17JAN78	4ØCT78	17JAN78	4ØCT78	0
* 132	BACKFILL EL 1	24	27ØCT78	30NØV78	27ØCT78	30NØV78	0
* 134	RESTØRE UTILITIES	200	31JAN78	8NØV78	31JAN78	8NØV78	0
* 136	REMØVE DECK	12	25ØCT78	9NØV78	25ØCT78	9NØV78	0
* 138	REMØVE SØLDIER PILES	60	31ØCT78	25JAN79	31ØCT78	25JAN79	0
* 140	PAVE STREET	16	8JAN79	29JAN79	8JAN79	29JAN79	0
* 142	CURE PAVING	20	9JAN79	5FEB79	9JAN79	5FEB79	0
144	REST RR TRACK	20	9NØV78	7DEC78	9JAN79	5FEB79	40
500	END ØF PRØJECT	0	5FEB79	5FEB79	6FEB79	6FEB79	0

D. COST ESTIMATES

Comparative estimated costs for the two construction methods are shown on pages 34-42. These comparative costs are only for the "typical" part of the project, because this comprises about 80% of the job. The atypical parts, i.e., the intersection, ends, framing around pedestrian tunnel, etc., are not included, since construction methods for these parts would be, or could be, very similar.

Table 4. Case Study 1: Construction cost estimate of system using prefabricated components (Total Cost Per Foot of Tunnel Length)

Item	Performed by	Cost to Gen. Contr. (Dollars/ft)	G. C. OH & P (%)	Cost to Owner (Dollars/ft)
1. Guide Trench	Sub	50	10	55
2. Slurry trench excavation	Sub	2480	10	2728
3. Precast wall panels	Sub	1640	10	1804
4. Foundation tremie concrete	G. C.	50	25	63
5. Cap beams	G. C.	180	25	225
6. Hand excavation	G. C.	260	25	331
7. Street level deck members	Sub	425	10	468
8. Street paving	G. C.	70	25	88
9. Machine excavation - under roof	G. C.	444	25	555
10. Temporary struts	G. C.	130	25	163
11. Haunches	G. C.	25	25	31
12. Roof tees	Sub	214	10	235
13. Waterproofing	Sub	112	10	123
14. Concrete topping (roof)	G. C.	90	25	112
15. Floor slab	G. C.	315	25	394
16. Post-tensioning	Sub	375	10	413
17. Joint treatment	G. C.	12	25	15
				$7,803/ft

Cost per metre ≈ 3.28 x cost per ft.

Table 5. Case Study 1: Construction cost estimate system using prefabricated components

(Costs to General Contractor per Foot of Tunnel Length)

Item No.	Item	Costs to G. C. (Dollars/ft)
1.	Guide trench - usually subcontracted by slurry trench contractor:	
	Excavation - 1.8 c.y./ft x $1.10 = 1.98	
	Forming - 8 s.f./ft $1.25 = 10.00	
	Reinf - 3# /ft $0.25 = .75	
	Concrete -0.25 c.y./ft x $30.00 = 7.50	
	20.23 x 2 =	
	$40.46	
	add sub O.H. & Profit	50
2.	Slurry trench excavation. Soil information indicates relatively easy digging - few cross utilities. Cost information from ICOS:	
	$20/S.F. x 62 ft x 2 sides (includes sub O.H. & P)	2480
3.	Precast, prestressed concrete wall panels. Includes placing post-tensioning ducts, but does not include P-T strand or labor (see detailed breakdown)	1640
4.	Foundation tremie concrete (see drawings)	
	Approx. 0.35 c.y. per side x 2 x $70	50
5.	Cap beams - $100/cu yd includes forming and reinforcing (light reinforcing). 0.9 cu yd per side	180
6.	Hand excavation to bottom of utilities. Includes digging around utilities. Between slurry walls	
	46.33 x 8 ÷ 27 = 13 cu yd x $20	260
7.	Street level deck members (see detailed breakdown)	425
	Approx. 52' x $12.00/sq yd	70

Cost per metre ≈ 3.28 x cost per ft.

Table 5. Case Study 1: Construction cost estimate system using prefabricated components (continued)

(Costs to General Contractor per Foot of Tunnel Length)

Item No.	Item	Costs to G. C. (Dollars/ft)
9.	Machine excavat under roof. Front end loaders to trucks	
	74 cu yd/ft x $6.00	444
10.	Temporary struts - 1 level x W14x87	
	87#/ft x 46.33/8 x $0.26	130
11.	Haunches - includes placing steel, welding, forming and pouring cover (see drawing) $100 each	
	100 x 2/8	25
12.	Roof tees (see detailed breakdown)	214
13.	Waterproofing on roof	
	$2.40/S.F. x 46.33	112
14.	Concrete topping at roof level (4" thick)	
	$2.00/S.F.	90
15.	Floor slab, 4 ft thick, minimum reinforcing Machine finish (paving methods)	315
16.	Post-tensioning - includes material and labor at	
	$1.10/lb x 1344 lb = $1500/panel $1500 x 2/8	375
17.	Joint treatment - caulking and sealing wall panel joints	
	$1.50/ft	12

See summary sheet on page 34 for overhead and profit.

Table 6. Case Study 1: Precast concrete estimate

1. WALL PANEL

Price per cu yd
Assume 2 panels per bed

8' wide - 56' long each panel
29.3 cu yd per panel
6000 psi concrete

Item		Cost/cu yd	
Concrete (6000 psi)		$33.00	
Strand - 32 strands x 62' long x $0.21/ft	÷ 29.3	14.22	
Reinforcing Steel - 1900 lb x $0.20/lb	÷ 29.3	12.97	
Embedded Steel Items - $150/panel	÷ 29.3	5.12	
Cardboard Forms $150/panel	÷ 29.3	5.12	
Misc. Handling Devises, etc.		2.00	
TOTAL MATERIAL		72.43	
On Line Labor - 10 men x 10 hrs x $8 (Avg.) ÷ (2 x 29.3)		13.65	
Off-Line Labor (Est)		5.00	
Labor Overhead @ 250%		46.63	
TOTAL LABOR		65.28	
Equipment Write-off			
Forms - 2-sets, self stressing			
240 L.F. @ $125 = $30,000	÷ (275 x 29.3) =	3.72	
Curing & Misc. Equip. = $50,000	÷ (275 x 29.3) =	6.21	
Handling Equip. - $600/Day	÷ (4 x 29.3) =	5.12	
TOTAL EQUIPMENT		15.05	
SUB TOTAL			$152.76
+ 35% O. H. & Profit			53.47
FOB PLANT			$206.23
Haul - Truck & Driver @ $30/hr, 1 Panel/Day = 30 x 8 ÷ 29.3 =			8.19
Crane - 1/2 Day = $500; 5 Man crew @ $18/hr = $360	Set 3 per 1/2 Day = 860 ÷ (3 x 29.3)		9.78
			$224.20/c.y.

224.20 x 29.3 = $6569 Per Panel or $14.66/sq ft
say $820/l.f.

Cost per cu metre ≈ 1.31 x cost per c.y.

Table 6. Case Study 1: Precast concrete members (continued)

2. BULB TEE (STREET LEVEL)

Price per cu yd
Assume 6 units per bed
8' wide, 49'-4" long
12.0 cu yd/unit
6000 psi concrete

Item	Cost/cu yd
Concrete (6000 psi)	$33.00
Strand - 20 strands x 55' long x $0.21/ft ÷ 12 =	19.25
Reinf. Steel - 1800 lb x $0.20/lb ÷ 12 =	30.00
Embedded Steel - $100/unit ÷ 12 =	8.33
Misc.	2.00
TOTAL MATERIAL	92.58
On-Line Labor - 10 men x 10 hrs x $8 (Avg) ÷ (6 x 12)=	11.11
Off-Line Labor (est)	6.00
Labor Overhead @ 250%	42.78
TOTAL LABOR	59.89
Equipment Write-off	
Forms - 320 L.F. @ $125 = $40,000 ÷ (155 x 12)	21.51
Curing & Misc. Equip = $25,000 ÷ (155 x 12)	13.44
Handling Equip. = $250/Day ÷ (6 x 12)	3.47
	38.42
Diaphragms - $100/BM ÷ 12 =	8.50
SUB TOTAL	199.39
+ 35% O. H. & Profit	69.78
	$269.17
Haul - Truck & Driver at $20/hr, 2 per day = 20 x 8 ÷ (2 x 12)	6.67
Crane - $1,000 5 Man Crew @ $18/hr x 8 x 5 = $720 set 20 per day = 1720 ÷ (20 x 12)	7.17
	$283.01/c.y.

283.01 x 12 = $3,396.18 per unit or $8.61/sq ft
say $425/l.f.

Table 6. Case Study 1: Precast concrete members (continued)

3. SINGLE TEE (ROOF LEVEL)

Price per cu yd
Assume 6 units per bed
8' wide, 46'-2" long
6.8 cu yd/unit
6000 psi concrete

Item	Cost/cu yd
Concrete (6000 psi)	$33.00
Strand - 10 Strands x 50' long x $0.21/ft ÷ 6.8 =	15.44
Reinf. Steel 135 lb x $0.23/lb ÷ 6.8 =	4.57
W.W.F. - 400 S.F. x .20 ÷ 6.8 =	11.76
Embedded Steel $50/unit ÷ 6.8 =	7.35
Misc.	2.00
TOTAL MATERIAL	74.12
On-Line Labor 10 men x 8 hrs x $7 ÷ (6 x 6.8) =	13.73
Off-Line Labor (est)	3.00
Labor overhead @ 250%	41.83
TOTAL LABOR	58.56
Equipment Write-off	
Forms - 300 L.F. @ $100 = $30,000 ÷ (150 x 6.8) 29.41 x 50% Write-off	14.71
Curing & Misc. Equip - $15,000 ÷ (150 x 6.8)	14.71
Handling Equip. - $200/Day ÷ (6 x 6.8)	4.90
	34.32
SUB TOTAL	167.00
+ 35% O. H. & Profit	58.45
	$225.45/c.y.
Haul - Truck & Drive @ $20/hr, - 2 per day = 20 x 8 ÷ (2 x 6.8)	11.76
2 - Lift Trucks - $500/Day 4 - Man Crew @ $18/hr x 8 x 4 = 576 Set 12 per Day = 1076 ÷ (12 x 6.8) =	13.96
	$251.17

251.17 x 6.8 = $1,707.96/unit or $4.62/sq ft
say $214/l.f.

Table 7. Case Study 1: Construction cost estimate, conventional system

(Total Cost Per Foot of Tunnel Length)

	Item	Performed by	Cost to Gen. Contr. (Dollars)	G. C. OH & P (%)	Cost to Owner (Dollars)
1.	Drill holes for piles (30")	Sub	140	10	154
2.	Steel soldier piles (material)	Sub	495	10	545
3.	Place in lean concrete	G. C.	465	25	581
4.	Hand excavation	G. C.	340	25	425
5.	Deck supports (Material & Labor)	G. C.	370	25	462
6.	Temporary wood decking	G. C.	370	25	462
7.	Machine excavation (under deck)	G. C.	600	25	750
8.	Timber lagging	G. C.	246	25	308
9.	Wales	G. C.	60	25	75
10.	Temporary struts	G. C.	325	25	406
11.	Structure	G. C.	3059	25	3824
12.	Waterproofing	Sub	336	10	370
13.	Finish walls	G. C.	34	25	42
14.	Backfill	G. C.	330	25	412
15.	Street paving	G. C.	93	25	116
					$8,932/ft

Cost per metre = 3.28 x cost per ft.

Table 8. Case Study 1: Conventional system

Costs to General Contractor

Item No.	Item	Costs to G. C. (Dollars/ft)
1.	Drill holes for piles - 30" to 36" diameter - 62' deep @ 8' o.c. casing req'd top 15 ft 2 x 62 ÷ 8 = 15.5 l.f. @ $9/ft = 77.50 (Unit price assume 25% sub OH & P)	$140
2.	Steel soldier piles - W27x145 - material only delivered to site 15.5 x 145 = 2250 lb x $0.22/lb (not removed)	495
3.	Place soldier pile. Concrete below tunnel floor, lean concrete above. $30 per foot estimate based on Wash. D. C. experience $30 x 15.5 = 465	465
4.	Hand excavation to bottom of utilities. Includes digging around utilities - 60 ft wide by 8 ft deep = 17 c.y. @ $20	340
5.	Deck supports W36x182 Length = 46.33 + 16 = 62.33' x 182 ÷ 8 = 1420#/ft Material & Labor = 36¢/lb less 10¢/lb salvage 1420 x .26 = 369.20	370
6.	Temporary wood deck - 12 x 12 Timbers 62.33 sq ft/ft = 0.74 MFBM Material & Labor = $600/MFBM less $100 salvage =	370
7.	Machine excavation under the temporary wood deck. Load buckets with front-end loaders lift to surface with drag line. Haul to disposal site. Includes remove and replace sections of temp. deck as required 100 c.y./ft @ $6/cu yd	600
8.	Timber lagging - 102 s.f. of 4" lagging per ft - not removed 0.41 MFBM/ft x 600	246
9.	Steel wales - 2 levels W30x116 2 x 116 x 0.26 = 60.32	60
10.	Temporary struts - 2 levels W14x87 (46.33 + 11) x 87 x 2 ÷ 8 = 1250#/ft 1250 x .26	325

Cost per metre ≈ 3.28 x cost per ft.

Table 8. Case Study 1: Conventional system (continued)

Costs to General Contractor

Item No.	Item	Cost to G. C. (Dollars/ft)
11.	Structure	
	Concrete	
	Walls = 2 (28 + 9)(4) = 296 C.F.	
	Floor = 46.33 (4) = 185	
	Roof = 46.33 $\frac{450}{144}$ = = 145	
	626 C.F. = 23.2 c.y. x \$45 = 1044	
	Reinforcing	
	4700 lb x 30¢ = 1410	
	Formwork	
	Walls =(32 + 28) 2 = 120 S.F. x \$3.50 = 420	
	Roof = 46.33 x 4.00 = 185 = 605	3059
12.	Waterproofing of walls and roof	
	Subcontracted at \$2.80/S.F. x [(2 x 33) + 54.33]	336
13.	Finish walls (to provide comparable finish to precast)	
	Remove & patch ties, rub - 60¢/S.F. x 56	34
14.	Backfill - includes compaction, but does <u>not</u> include bedding for utilities or other work in restoring utilities	
	30 c.y. x \$11	330
15.	Street paving - 8" concrete paving with curbs, sidewalk repair as required - prepare base	
	\$13.50/s.y. x 62/9	93

See summary sheet on page 40 for overhead and profit.

E. SUMMARY COMPARISON

The following compares the time spans and dates that have a significant affect on surface activity in the area:

1. Larrabee Street closed to traffic north of Chicago Avenue:

   a. Precast Concrete construction method: 6 weeks near the beginning of the project during excavation to the bottom of the utilities setting street members and repaving.

   b. Conventional construction method: 4 weeks total time near the beginning during excavation to the bottom of utilities and setting of temporary deck. This would be intermittent over a period of 15 weeks. An additional 4 weeks, intermittent over a period of 13 weeks at the end during backfill, removal of temporary deck and repaving.

2. Larrabee Street, north of Chicago Avenue partially disrupted, i.e., some major construction activities in process on the surface:

   a. Precast method: 9 months.

   b. Convention method: 24 months.

3. Chicago Avenue partially disrupted, i.e., single lane traffic or temporary decking:

   a. Precast method: 4 months.

   b. Conventional method: 11 to 19 months, depending on discretionary sequencing of operations.

4. Larrabee Street closed to traffic south of Chicago Avenue:

   a. Precast method: 2½ weeks.

   b. Conventional method: One week at the beginning intermittently over a six week period; one more week at end intermittently over a two week period.

5. Larrabee Street, south of Chicago Avenue partially disrupted:

   a. Precast method: 6 months.

   b. Conventional method: 10 to 20 months.

6. Date the street is permanently re-opened, assuming construction operations started on January 1, 1977:

   a. Precast method: October 3, 1977.

   b. Conventional method: February 6, 1979

7. Project completion date (primary structure as considered in this study):

   a. Precast method: February 21, 1979.

   b. Conventional method: February 7, 1979

8. Costs: The cost estimates on pages 34-42 indicate that the precast method is approximately 13% less costly for the phases of construction considered. It is estimated that the parts of construction compared represents about 65% of the total cost, so the net savings on the project is indicated to be about 9%.

III. CASE STUDY NO. 2

HIGHWAY TUNNEL THROUGH AN ENVIRONMENTALLY SENSITIVE AREA

Case Study No. 2 investigates the use of prefabricated structural elements for a shallow highway tunnel through a public park in the suburbs of a metropolitan area. It was chosen because the site conditions are very different from the other Case Studies and represents a growing trend toward building transportation facilities with a minimum of environmental disruption.

This project is part of Minnesota Trunk Highway No. 55=116. It goes through Minnehaha Park in Minneapolis. Concept Plans for the project were prepared for the Minnesota Department of Highways in 1974 by Van Doren-Hazard-Stallings, Engineers and Architects of Topeka, Kansas. Figs. 31 through 35 (Appendix) show the layouts and preliminary structural system as presented in those concept plans.

This Case Study is presented in two parts. Part A concerns the tunnel structure. It presents designs and details of tunnel construction using prefabricated components, and compares this method of construction with the conventional cast-in-place structure shown on the Concept Plans.

Part B investigates the use of prefabricated wall members for the retaining walls of the tunnel approaches. These designs were then compared with cast-in-place cantilever walls as shown schematically in the Concept Plans.

In the comparisons, every attempt was made to compare equal quality of construction. It is not the purpose of the study to second-guess or "value engineer" an existing design, but merely to determine the feasibility of using prefabricated members for this type of project.

PART A TUNNEL CONSTRUCTION

1. DESCRIPTION

a. Dimensions: The tunnel is approximately 1000 ft (305 m) long, 150 ft (46 m) wide and carries 3 lanes of traffic in each direction. Top of structural slab to underside of roof structure is approximately 19 ft (5.8 m) except at the south portal where it is 27 ft (8.2 m). There is between 3-1/2 (1 m) and 8 ft (2.4 m) of fill on the structure with the average being about 6 ft (1.83 m). (See Fig. 35)

b. Soil and groundwater characteristics: Soils data for the site is shown in Fig. 31. Approximately one-half of the excavation is in glacial drift and the other half in Platteville limestone.

The water table varies but for purposes of design it is assumed at elev. 805.0.

c. Items considered in the study: As in Case Study No. 1, the study is limited to the structural elements. Items such as lighting, barricades, cross-overs, portal entrance facades and all other architectural concerns are not considered.

An alternate design for the base slab is presented in Section A-6 but is not considered in the cost comparison nor in the construction time comparison.

d. Environmental concerns: Preservation of Minnehaha creek and Minnehaha park as a public use area is the sole reason for the tunnel, in lieu of a surface highway. The creek crosses over the tunnel as well as running alongside a portion of the north approach. The creek must be diverted while the cross-over is constructed and then returned to its original location. The creek must also be permanently contained where it runs close to the north approach.

This area of the park can be closed during construction, but a minimum length of time of disruption would result in the most favorable environmental impact. It is assumed that the structure will be built first, allowing for the restoration of the park upon completion of the tunnel portion of the project.

It is assumed that for any method of construction, traffic on Minnehaha Parkway can be rerouted for a short period of time while construction operations take place at that location.

2. PROPOSED TUNNEL CONSTRUCTION METHOD USING PREFABRICATED COMPONENTS

a. Structural framing: Two framing schemes described in Volume I of this study were considered, but a cost comparison led to early rejection of a scheme employing king piles.

The tunnel structure has precast, prestressed load-bearing wall panels supported on cast-in-place footings. These panels span vertically between a cast-in-place base slab and precast, prestressed roof units. The roof units are supported by the wall panels and also act as permanent struts for lateral loads. The framing scheme is shown in detail in Fig. 37..

b. Products and design: All elements are designed as simple span members; no continuity is assumed. An eight foot module was selected because it is a common module for precast, prestressed concrete products thereby allowing much of the existing equipment in a plant to be used.

(1) Wall units: The wall units are shown in Figs. 36 through 38. They are designed to be manufactured in an off-site precasting plant.

The center wall panels separating the northbound and southbound traffic are 20 in. (508 mm) thick and each unit has six-12 in. (305 mm) round voids. The panels are designed as prestressed concrete columns. The only moment they carry is from dead load eccentricity, which is minimal, and therefore only the minimum prestressing to qualify as prestressed columns is provided; 14 prestressing strands.

The outer wall panels are also 20 in. (508 mm) thick, but have no voids. This is to keep the shear stresses low enough that shear reinforcement is not required. There are two reinforcing designs for these wall panels. One has 27 prestressing strands and is designed for the typical 18 ft (5.5 m) clear tunnel section as shown in Fig. 37. The other has 37 prestressing strands and is designed for the 26.5 ft (8.1 m) high south portal and sloping transition to the more typical height. The weight of a typical solid wall panel is about 22 tons (20,000 kg).

(2) Horizontal members: The precast, prestressed box girders are also shown in Figs. 36 through 38. They are designed to span between wall panels and also act as a strut for lateral loads. They are designed to carry the equivalent of eight feet of fill over their entire length.

(3) Cap beams: To facilitate production and placement, the wall panels are all the same length over the typical tunnel section. The footings are stepped to accommodate grade changes, resulting in steps at the top of the wall. A continuous cast-in-place cap beam of varying depth is placed on top of the wall panels to affect the transition between the steps and the

smooth flowing roof line desired. It will be lightly reinforced and conform to the width of the wall panel. (See Fig. 37.

c. Construction sequence: For the purposes of presenting the construction sequence the 1000 ft (305 m) of tunnel has been divided into four sub-projects as follows:

SP1 - Sta. 223.25 - Sta. 226-25

SP2 - Sta. 227.25 - Sta. 230.25

SP3 - Sta. 230.25 - Sta. 233.25

SP4 - Sta. 226.25 - Sta. 227.25

Construction of the tunnel is assumed to start with the temporary diversion of Minnehaha creek from an area in sub-project SP1 to SP4. The construction will then proceed through SP1, SP2, SP3, and SP4 in order, generally working away from the diverted creek (from North to South in SP1, and from South to North in SP2 and SP3) - See Fig. 4. After SP1 has been completed, the creek can be re-diverted to its final location.

A precedence diagram showing the relationships of the various operations is shown in Fig. 39. A detailed description of each operation is shown in Table 9. These operations are used as input to a Critical Path Method (CPM) computer program. Estimated activity durations and precedences used in establishing the CPM consider not only the required time to complete a given activity, but also reasonable allocation of resources. For example, with the construction sequence shown, it is technically possible to work on subprojects SP1 and SP2 simultaneously. However, this would result in a much higher requirement of manpower and equipment than the remainder of the project, and the economy and efficiency would probably suffer. Therefore, the similar operations on each subproject are sequenced.

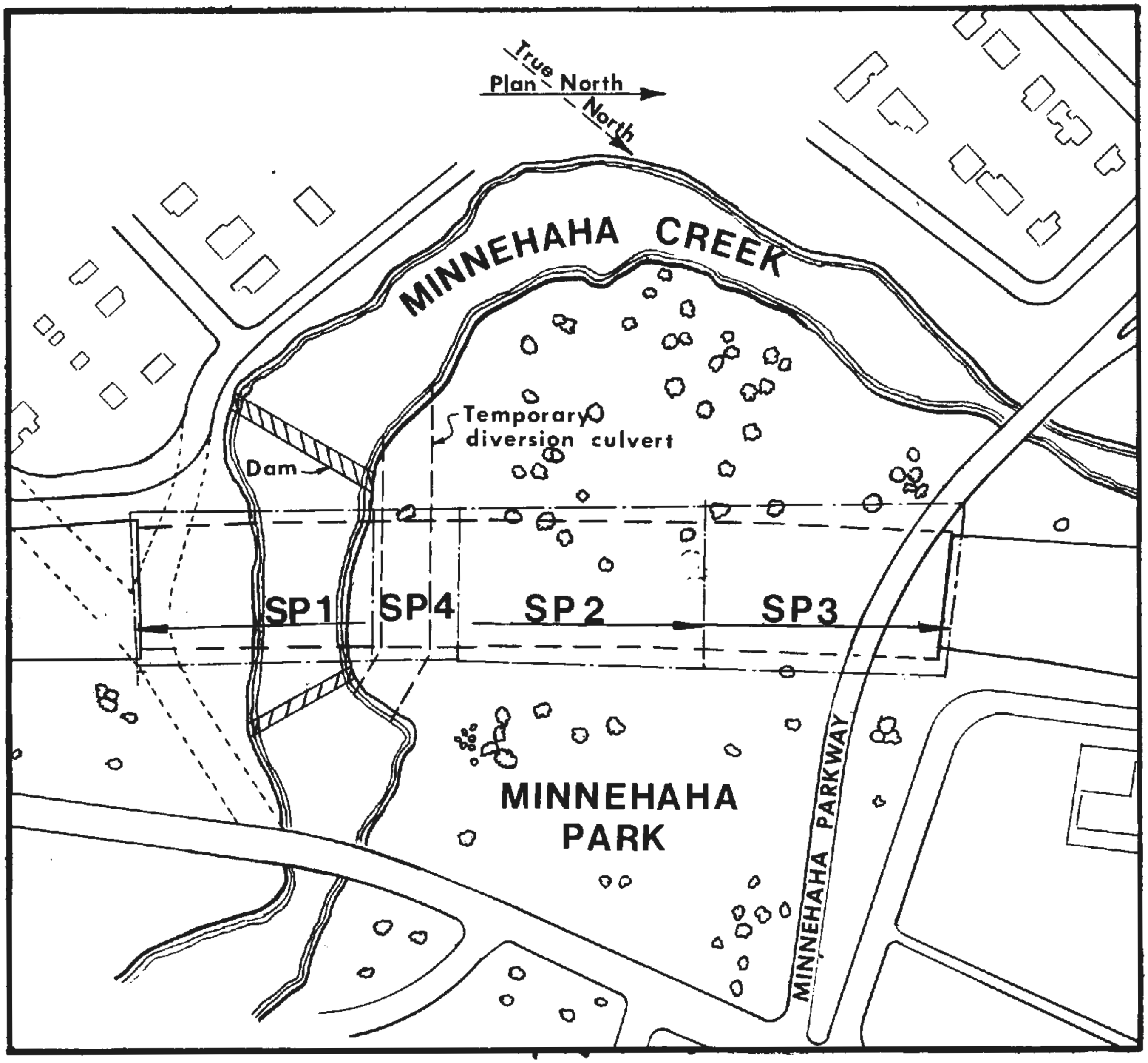


Fig. 4: Plan of tunnel site showing assumed construction sequence

Table 9. Case Study 2: Construction sequence using prefabricated structural elements

(See Fig. 39 for Precedent Diagram)

Last 2 digits of Operation Number	Description of Operations
02	Excavate to rock using draglines and/or front end loaders.
04	Rock excavation to desired depth using explosives, rock rippers, etc.
06	Form and pour cast-in-place footings to receive wall panels.
08	Place and temporarily brace precast wall panels.
09	Construct structural enclosure for accessory buildings at north portal.
10	Seal all joints in wall panels and apply waterproofing to walls.
12	Prepare base and cast base slab.
14	Drill in rock anchors for base slab.
16	Form and pour cap beam on top of wall panels.
18	Place precast roof members.
20	Seal all joints in roof members and apply waterproofing to roof.
22	Cast protective concrete topping over waterproofing on roof of tunnel.
23	Construct creek bed across tunnel roof.
24	Backfill to finish grade.
50	Divert Minnehaha creek temporarily while construction operations take place.
53	Redivert Minnehaha creek to final location.
57	Remove temporary culvert following rediversion of creek.

Table 9. Case Study 2: Construction sequence using prefabricated structural elements (continued)

Last 2 digits of Operation Number	Description of Operations
59	Primary construction completed.
60	Award precast contract.
61	Shop drawings for wall panels.
62	Bed set-up for wall panels.
63-66	Cast wall panels for SP1 to SP4 respectively.
71	Shop drawings for roof members.
72	Bed set-up for roof members.
73-76	Cast roof members for SP1 to SP4 respectively.

Table 10. Case Study 2: Computer output of Critical Path Method (CPM) program for construction using prefabricated components

P R Ø J E C T S C H E D U L E

FRØM APR 1, 1977 TØ MAR 3, 1978 - SØRTED BY SEQ

DØT-MINN-PRECAST ØCT 29, 1976

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
* 50	DIVERT CREEK TEMP	40	1APR77	26MAY77	1APR77	26MAY77	0
53	REDIVERT CREEK	5	7DEC77	13DEC77	22DEC77	29DEC77	11
57	REMØVE TEMP CULVERT	5	14DEC77	20DEC77	30DEC77	6JAN78	11
* 59	PRIMARY CØNST CØMP	1	3MAR78	3MAR78	3MAR78	3MAR78	0
60	PRECAST CØNTRACT	1	1APR77	1APR77	12MAY77	12MAY77	29
61	SHØP DRWG WALL PANEL	30	4APR77	13MAY77	10JUN77	22JUL77	48
62	BED SET-UP W P	10	4APR77	15APR77	11JUL77	22JUL77	68
63	CAST WALL PANELS SP1	12	16MAY77	1JUN77	25JUL77	9AUG77	48
64	CAST WALL PANELS SP2	12	2JUN77	17JUN77	12SEP77	27SEP77	70
65	CAST WALL PANELS SP3	12	20JUN77	6JUL77	17ØCT77	1NØV77	83
66	CAST WALL PANELS SP4	4	7JUL77	12JUL77	24JAN78	27JAN78	139
71	SHØP DRWG RØØF MEM	30	4APR77	13MAY77	13MAY77	24JUN77	29
72	BED SET-UP RØØF MEM	10	4APR77	15APR77	13JUN77	24JUN77	49
73	CAST RØØF MEM SP1	38	16MAY77	8JUL77	27JUN77	18AUG77	29
74	CAST RØØF MEM SP2	38	11JUL77	31AUG77	19AUG77	12ØCT77	29
75	CAST RØØF MEM SP3	38	1SEP77	25ØCT77	13ØCT77	6DEC77	29
76	CAST RØØF MEM SP4	11	26ØCT77	9NØV77	24JAN78	7FEB78	61
* 102	EARTH EXC SP1	10	27MAY77	10JUN77	27MAY77	10JUN77	0
* 104	RØCK EXC SP1	30	13JUN77	25JUL77	13JUN77	25JUL77	0
106	WALL FØØTINGS SP1	10	26JUL77	8AUG77	27JUL77	9AUG77	1
108	WALL PANELS SP1	10	9AUG77	22AUG77	10AUG77	23AUG77	1
110	WATERPRØØF WALLS SP1	8	23AUG77	1SEP77	21ØCT77	1NØV77	42
112	BASE SLAB SP1	10	23AUG77	6SEP77	7SEP77	20SEP77	10
114	RØCK ANCHØRS SP1	30	7SEP77	18ØCT77	21SEP77	1NØV77	10
116	CAP BEAM SP1	13	23AUG77	9SEP77	24AUG77	12SEP77	1
118	RØØF MEMBERS SP1	13	12SEP77	28SEP77	13SEP77	29SEP77	1
120	WATERPRØØF RØØF SP1	10	29SEP77	12ØCT77	30SEP77	13ØCT77	1
122	PRØTECTIVE CØNC SP1	3	13ØCT77	17ØCT77	14ØCT77	18ØCT77	1
123	CØNST CREEK BED	10	18ØCT77	31ØCT77	19ØCT77	1NØV77	1
124	BACKFILL SP1	25	1NØV77	6DEC77	2NØV77	7DEC77	1
202	EARTH EXC SP2	10	1APR77	14APR77	12JUL77	25JUL77	70
* 204	RØCK EXC SP2	30	26JUL77	6SEP77	26JUL77	6SEP77	0
206	WALL FØØTINGS SP2	10	7SEP77	20SEP77	14SEP77	27SEP77	5
208	WALL PANELS SP2	10	21SEP77	4ØCT77	28SEP77	11ØCT77	5
210	WATERPRØØF WALLS SP2	8	5ØCT77	14ØCT77	28NØV77	7DEC77	37
212	BASE SLAB SP2	10	5ØCT77	18ØCT77	12ØCT77	25ØCT77	5
214	RØCK ANCHØRS SP2	30	19ØCT77	30NØV77	26ØCT77	7DEC77	5
216	CAP BEAM SP2	13	5ØCT77	21ØCT77	13ØCT77	31ØCT77	6
218	RØØF MEMBERS SP2	13	24ØCT77	9NØV77	1NØV77	17NØV77	6
220	WATERPRØØF RØØF SP2	10	10NØV77	23NØV77	18NØV77	2DEC77	6
222	PRØTECTIVE CØNC SP2	3	25NØV77	29NØV77	5DEC77	7DEC77	6
224	BACKFILL SP2	25	7DEC77	12JAN78	8DEC77	13JAN78	1
302	EARTH EXC SP3	10	15APR77	28APR77	23AUG77	6SEP77	90
* 304	RØCK EXC SP3	30	7SEP77	18ØCT77	7SEP77	18ØCT77	0
* 306	WALL FØØTINGS SP3	10	19ØCT77	1NØV77	19ØCT77	1NØV77	0
* 308	WALL PANELS SP3	10	2NØV77	15NØV77	2NØV77	15NØV77	0
309	CØNST SIDE BLDGS	20	16NØV77	14DEC77	5DEC77	3JAN78	12
310	WATERPRØØF WALLS SP3	8	15DEC77	27DEC77	4JAN78	13JAN78	12
* 312	BASE SLAB SP3	10	16NØV77	30NØV77	16NØV77	30NØV77	0
* 314	RØCK ANCHØRS SP3	30	1DEC77	13JAN78	1DEC77	13JAN78	0

Table 10. Case Study 2: Computer output of Critical Path Method (CPM) program for construction using prefabricated components (continued)

PRØJECT SCHEDULE
FRØM APR 1, 1977 TØ MAR 3, 1978 - SØRTED BY SEQ
DØT-MINN-PRECAST ØCT 29, 1976

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
316	CAP BEAM SP3	13	16NØV77	5DEC77	17NØV77	6DEC77	1
318	RØØF MEMBERS SP3	13	6DEC77	22DEC77	7DEC77	23DEC77	1
320	WATERPRØØF RØØF SP3	10	23DEC77	9JAN78	27DEC77	10JAN78	1
322	PRØTECTIVE CØNC SP3	3	10JAN78	12JAN78	11JAN78	13JAN78	1
* 324	BACKFILL SP3	25	16JAN78	17FEB78	16JAN78	17FEB78	0
402	EARTH EXC SP4	3	21DEC77	23DEC77	9JAN78	11JAN78	11
404	RØCK EXC SP4	9	27DEC77	9JAN78	12JAN78	24JAN78	11
406	WALL FØØTINGS SP4	3	10JAN78	12JAN78	25JAN78	27JAN78	11
408	WALL PANELS SP4	3	13JAN78	17JAN78	30JAN78	1FEB78	11
410	WATERPRØØF WALLS SP4	3	18JAN78	20JAN78	15FEB78	17FEB78	20
412	BASE SLAB SP4	3	18JAN78	20JAN78	2FEB78	6FEB78	11
414	RØCK ANCHØRS SP4	9	23JAN78	2FEB78	7FEB78	17FEB78	11
416	CAP BEAM SP4	4	18JAN78	23JAN78	2FEB78	7FEB78	11
418	RØØF MEMBERS SP4	4	24JAN78	27JAN78	8FEB78	13FEB78	11
420	WATERPRØØF RØØF SP4	3	30JAN78	1FEB78	14FEB78	16FEB78	11
422	PRØTECTIVE CØNC SP4	1	2FEB78	2FEB78	17FEB78	17FEB78	11
* 424	BACKFILL SP4	9	20FEB78	2MAR78	20FEB78	2MAR78	0

3. COMPARISON WITH CAST-IN-PLACE CONSTRUCTION

a. Description: For comparison purposes, the cast-in-place structure is designed as a two-span continuous box culvert as shown on Fig. 35.

b. Construction sequence: For the purpose of this study, the following assumptions have been made regarding the construction sequence:

(1) For greater accuracy of concurrent activities, the project has been divided into eleven subprojects of 90 ft (27.5 m) each. A 90 ft section was chosen because it is a multiple of the 30 ft spacing of construction joints shown in the concept plans.

(2) The construction will proceed away from the diverted creek similar to the precast method, as described in Subsection c of Section 2.

(3) Following activities will be kept 90 ft (one subproject) apart.

(4) The forming and casting operations associated with the tunnel structure are the key to the difference between the two methods. The schedule rotation, resource allocation and integration of individual operations and crews were studied in detail. The total duration of a given operation for a given 90 ft subproject reflects this day by day analysis. Although this detailed schedule is not presented, it is felt that a fair appraisal of the cast-in-place construction sequence has been formulated.

(5) No penalty in time or cost has been assessed to the cast-in-place method for winter construction although fewer problems would undoubtedly be encountered with the precast method.

(6) A precedence diagram showing the relationship of the various construction operations is shown in Fig. 40. A CPM output is shown as Table 11.

Table 11. Case Study 2: Computer output of Critical Path Method (CPM) program for cast-in-place construction

P R Ø J E C T   S C H E D U L E

FRØM APR 1, 1977 TØ JUN 2, 1978 - SØRTED BY SEQ

DØT-MINN-CAST IN PLACE OCT 29, 1976

	DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
*	50	DIVERT CREEK TEMP	40	1APR77	26MAY77	1APR77	26MAY77	0
	53	REDIVERT CREEK	5	1APR77	7APR77	30JAN78	3FEB78	210
	57	REMØVE TEMP. CULVERT	5	8APR77	14APR77	6FEB78	10FEB78	210
*	59	PRIMARY CØNST CØMP	1	2JUN78	2JUN78	2JUN78	2JUN78	0
*	102	EARTH EXC SP1	3	27MAY77	1JUN77	27MAY77	1JUN77	0
*	104	RØCK EXC SP1	9	2JUN77	14JUN77	2JUN77	14JUN77	0
*	106	BASE SLAB SP1	18	15JUN77	11JUL77	15JUN77	11JUL77	0
	108	SLAB ANCHØRS SP1	9	12JUL77	22JUL77	17JAN78	27JAN78	131
*	110	WALLS SP1	18	12JUL77	4AUG77	12JUL77	4AUG77	0
*	112	RØØF SP1	18	5AUG77	30AUG77	5AUG77	30AUG77	0
	114	WATERPRØØFING SP1	3	31AUG77	2SEP77	24JAN78	26JAN78	100
	116	PRØTECTIVE CØNC SP1	1	6SEP77	6SEP77	27JAN78	27JAN78	100
	118	BACKFILL SP1	8	7SEP77	16SEP77	30JAN78	8FEB78	100
	202	EARTH EXC SP2	3	2JUN77	6JUN77	23JUN77	27JUN77	15
	204	RØCK EXC SP2	9	15JUN77	27JUN77	28JUN77	11JUL77	9
*	206	BASE SLAB SP2	18	12JUL77	4AUG77	12JUL77	4AUG77	0
	208	SLAB ANCHØRS SP2	9	5AUG77	17AUG77	27JAN78	8FEB78	121
*	210	WALLS SP2	18	5AUG77	30AUG77	5AUG77	30AUG77	0
*	212	RØØF SP2	18	31AUG77	26SEP77	31AUG77	26SEP77	0
	214	WATERPRØØFING SP2	3	27SEP77	29SEP77	3FEB78	7FEB78	90
	216	PRØTECTIVE CØNC SP2	1	30SEP77	30SEP77	8FEB78	8FEB78	90
	218	BACKFILL SP2	8	3ØCT77	12ØCT77	9FEB78	20FEB78	90
	302	EARTH EXC SP3	3	7JUN77	9JUN77	20JUL77	22JUL77	30
	304	RØCK EXC SP3	9	28JUN77	11JUL77	25JUL77	4AUG77	18
*	306	BASE SLAB SP3	18	5AUG77	30AUG77	5AUG77	30AUG77	0
	308	SLAB ANCHØRS SP3	9	31AUG77	13SEP77	8FEB78	20FEB78	111
*	310	WALLS SP3	18	31AUG77	26SEP77	31AUG77	26SEP77	0
*	312	RØØF SP3	18	27SEP77	20ØCT77	27SEP77	20ØCT77	0
	314	WATERPRØØFING SP3	3	21ØCT77	25ØCT77	1FEB78	3FEB78	70
	316	PRØTECTIVE CØNC SP3	1	26ØCT77	26ØCT77	6FEB78	6FEB78	70
	317	CØNST CREEK BED	10	27ØCT77	9NØV77	7FEB78	20FEB78	70
	318	BACKFILL SP3	8	10NØV77	21NØV77	21FEB78	2MAR78	70
	402	EARTH EXC SP4	3	1APR77	5APR77	15AUG77	17AUG77	94
	404	RØCK EXC SP4	9	12JUL77	22JUL77	18AUG77	30AUG77	27
*	406	BASE SLAB SP4	18	31AUG77	26SEP77	31AUG77	26SEP77	0
	408	SLAB ANCHØRS SP4	9	27SEP77	7ØCT77	20FEB78	2MAR78	101
*	410	WALLS SP4	18	27SEP77	20ØCT77	27SEP77	20ØCT77	0
*	412	RØØF SP4	18	21ØCT77	15NØV77	21ØCT77	15NØV77	0
	414	WATERPRØØFING SP4	3	16NØV77	18NØV77	27FEB78	1MAR78	70
	416	PRØTECTIVE CØNC SP4	1	21NØV77	21NØV77	2MAR78	2MAR78	70
	418	BACKFILL SP4	8	22NØV77	2DEC77	3MAR78	14MAR78	70
	502	EARTH EXC SP5	3	6APR77	8APR77	9SEP77	13SEP77	109
	504	RØCK EXC SP5	9	25JUL77	4AUG77	14SEP77	26SEP77	36
*	506	BASE SLAB SP5	18	27SEP77	20ØCT77	27SEP77	20ØCT77	0
	508	SLAB ANCHØRS SP5	9	21ØCT77	2NØV77	2MAR78	14MAR78	91
*	510	WALLS SP5	18	21ØCT77	15NØV77	21ØCT77	15NØV77	0
*	512	RØØF SP5	18	16NØV77	12DEC77	16NØV77	12DEC77	0
	514	WATERPRØØFING SP5	3	13DEC77	15DEC77	9MAR78	13MAR78	60
	516	PRØTECTIVE CØNC SP5	1	16DEC77	16DEC77	14MAR78	14MAR78	60
	518	BACKFILL SP5	8	19DEC77	29DEC77	15MAR78	24MAR78	60

Table 11. Case Study 2: Computer output of Critical Path Method (CPM) program for cast-in-place construction (continued)

P R Ø J E C T   S C H E D U L E

FRØM APR 1, 1977 TØ JUN 2, 1978 - SØRTED BY SEQ

DØT-MINN-CAST IN PLACE OCT 29, 1976

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
602	EARTH EXC SP6	3	11APR77	13APR77	5ØCT77	7ØCT77	124
604	RØCK EXC SP6	9	5AUG77	17AUG77	10ØCT77	20ØCT77	45
* 606	BASE SLAB SP6	18	21ØCT77	15NØV77	21ØCT77	15NØV77	0
608	SLAB ANCHØRS SP6	9	16NØV77	29NØV77	14MAR78	24MAR78	81
* 610	WALLS SP6	18	16NØV77	12DEC77	16NØV77	12DEC77	0
* 612	RØØF SP6	18	13DEC77	9JAN78	13DEC77	9JAN78	0
614	WATERPRØØFING SP6	3	10JAN78	12JAN78	21MAR78	23MAR78	50
616	PRØTECTIVE CØNC SP6	1	13JAN78	13JAN78	24MAR78	24MAR78	50
618	BACKFILL SP6	8	16JAN78	25JAN78	27MAR78	5APR78	50
702	EARTH EXC SP7	3	14APR77	18APR77	31ØCT77	2NØV77	139
704	RØCK EXC SP7	9	18AUG77	30AUG77	3NØV77	15NØV77	54
* 706	BASE SLAB SP7	18	16NØV77	12DEC77	16NØV77	12DEC77	0
708	SLAB ANCHØRS SP7	9	13DEC77	23DEC77	24MAR78	5APR78	71
* 710	WALLS SP7	18	13DEC77	9JAN78	13DEC77	9JAN78	0
* 712	RØØF SP7	18	10JAN78	2FEB78	10JAN78	2FEB78	0
714	WATERPRØØFING SP7	3	3FEB78	7FEB78	31MAR78	4APR78	40
716	PRØTECTIVE CØNC SP7	1	8FEB78	8FEB78	5APR78	5APR78	40
718	BACKFILL SP7	8	9FEB78	20FEB78	6APR78	17APR78	40
802	EARTH EXC SP8	3	19APR77	21APR77	25NØV77	29NØV77	154
804	RØCK EXC SP8	9	31AUG77	13SEP77	30NØV77	12DEC77	63
* 806	BASE SLAB SP8	18	13DEC77	9JAN78	13DEC77	9JAN78	0
808	SLAB ANCHØRS SP8	9	10JAN78	20JAN78	5APR78	17APR78	61
* 810	WALLS SP8	18	10JAN78	2FEB78	10JAN78	2FEB78	0
* 812	RØØF SP8	18	3FEB78	28FEB78	3FEB78	28FEB78	0
814	WATERPRØØFING SP8	3	1MAR78	3MAR78	12APR78	14APR78	30
816	PRØTECTIVE CØNC SP8	1	6MAR78	6MAR78	17APR78	17APR78	30
818	BACKFILL SP8	8	7MAR78	16MAR78	18APR78	27APR78	30
902	EARTH EXC SP9	3	22APR77	26APR77	21DEC77	23DEC77	169
904	RØCK EXC SP9	9	14SEP77	26SEP77	27DEC77	9JAN78	72
* 906	BASE SLAB SP9	18	10JAN78	2FEB78	10JAN78	2FEB78	0
908	SLAB ANCHØRS SP9	9	3FEB78	15FEB78	17APR78	27APR78	51
* 910	WALLS SP9	18	3FEB78	28FEB78	3FEB78	28FEB78	0
* 912	RØØF SP9	18	1MAR78	24MAR78	1MAR78	24MAR78	0
914	WATERPRØØFING SP9	3	27MAR78	29MAR78	24APR78	26APR78	20
916	PRØTECTIVE CØNC SP9	1	30MAR78	30MAR78	27APR78	27APR78	20
918	BACKFILL SP9	8	31MAR78	11APR78	28APR78	9MAY78	20
1002	EARTH EXC SP10	3	27APR77	29APR77	18JAN78	20JAN78	184
1004	RØCK EXC SP10	9	27SEP77	7ØCT77	23JAN78	2FEB78	81
*1006	BASE SLAB SP10	18	3FEB78	28FEB78	3FEB78	28FEB78	0
1008	SLAB ANCHØRS SP10	9	1MAR78	13MAR78	27APR78	9MAY78	41
1009	CØNST SIDE BLDGS	20	1MAR78	28MAR78	6APR78	3MAY78	26
*1010	WALLS SP10	18	1MAR78	24MAR78	1MAR78	24MAR78	0
*1012	RØØF SP10	18	27MAR78	19APR78	27MAR78	19APR78	0
1014	WATERPRØØFING SP10	3	20APR78	24APR78	4MAY78	8MAY78	10
1016	PRØTECTIVE CØNC SP10	1	25APR78	25APR78	9MAY78	9MAY78	10
1018	BACKFILL SP10	8	26APR78	5MAY78	10MAY78	19MAY78	10
1102	EARTH EXC SP11	3	2MAY77	4MAY77	13FEB78	15FEB78	199
1104	RØCK EXC SP11	9	10ØCT77	20ØCT77	16FEB78	28FEB78	90
*1106	BASE SLAB SP11	18	1MAR78	24MAR78	1MAR78	24MAR78	0
1108	SLAB ANCHØRS SP11	9	27MAR78	6APR78	9MAY78	19MAY78	31

Table 11. Case Study 2: Computer output of Critical Path Method (CPM) program for cast-in-place construction (continued)

P R Ø J E C T   S C H E D U L E
FRØM APR 1, 1977 TØ JUN 2, 1978 - SØRTED BY SEQ
DØT-MINN-CAST IN PLACE   ØCT 29, 1976

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
*1110	WALLS SP11	18	27MAR78	19APR78	27MAR78	19APR78	0
*1112	RØØF SP11	18	20APR78	15MAY78	20APR78	15MAY78	0
*1114	WATERPRØØFING SP11	3	16MAY78	18MAY78	16MAY78	18MAY78	0
*1116	PRØTECTIVE CØNC SP11	1	19MAY78	19MAY78	19MAY78	19MAY78	0
*1118	BACKFILL SP11	8	22MAY78	1JUN78	22MAY78	1JUN78	0

4. COST ESTIMATES

Comparative estimated costs for the two construction methods are shown on pages 61-66. These comparative costs are only for the "typical" part of the tunnel construction which comprises about 90% of the tunnel.

Table 12. Case Study 2: Construction cost estimates

(Total cost per foot of tunnel length)

SYSTEM USING PREFABRICATED COMPONENTS

	Item	Performed by	Cost to Gen. Contr. (Dollars)	G. C. OH & P (%)	Cost to Owner (Dollars)
1.	Machine Excavation	G. C.	558	25	698
2.	Rock Excavation	G. C.	2280	25	2850
3.	Footings	G. C.	50	25	63
4.	Wall Panels	Sub	815	10	897
5.	Cap Beams	G. C.	15	25	19
6.	Box Girders	Sub	3125	10	3438
7.	Roof & Wall Waterproofing	Sub	568	10	625
8.	Joint Treatment	Sub	64	10	70
9.	Backfill	G. C.	418	25	523
					$9183/ft

CAST-IN-PLACE SYSTEM

	Item	Performed by	Cost to Gen. Contr. (Dollars)	G. C. OH & P (%)	Cost to Owner (Dollars)
1.	Machine Excavation	G. C.	594	25	743
2.	Rock Excavation	G. C.	2426	25	3033
3.	Structure	G. C.	3771	25	4714
4.	Waterproofing	Sub	568	10	625
5.	Joint Treatment	Sub	17	10	19
6.	Finish Walls	G. C.	23	25	29
7.	Backfill	G. C.	532	25	665
					$9828/ft

Cost per metre ≈ 3.28 x cost per ft.

Table 13. Case Study 2: Construction cost estimate system using prefabricated components

(Costs to General Contractor per Foot of Tunnel Length)

Item No.	Item		Costs to G. C. (Dollars/ft)
1	Machine excavation with front end loaders to truck		
	93 cu yd/ft x $6.00		558
2	Rock excavation using explosives, rippers, etc.		
	76 cu yd/ft x $30.00		2280
3	Form and pour footings		
	Preparation -	1.00	
	Forming - 4 sq ft/ft x $1.50	6.00	
	Reinf. - 3#/ft x $0.25	.75	
	Conc. - .30 c.y./ft x $30.00	9.00	
		3 x 16.75	50
4	Wall panels (see Table 15)		
	2 x $295 + 1 x $225		815
5	Cap beams - $100/cu yd includes forming and rein. (.05 cu yd each x 3)		15
6	Box girders (see detailed breakdown)		3125
7	Waterproofing		
	$2.80/s.f. x (2 x 26.5 + 150)		568
8	Joint treatment @ $1.50/ft =		
	$1.50 (2 x 20 + 2 x 150)/8 =		64
9	Backfill - includes compaction		
	38 cu yd/ft x $11 =		418
			$7893/ft

Cost per metre ≈ 3.28 x cost per ft.

Table 14. Case Study 2: Construction cost estimate

Cast-in-Place system

(Costs to General Contractor per Foot of Tunnel Length)

Item No.	Item		Costs to G. C. (Dollars/ft)
1	Machine excavation with front end loaders to trucks		
	99 cu yd/ t x $6.00		594
2	Rock excavation using explosives, rippers, etc.		
	81 cu yd/ft x $30.00		2430
3	Structure (excluding base slab)		
	concrete - 29.0 cu yd x $45	1305	
	reinforcing - 5900 plf x $0.25	1475	
	form work		
	walls - 2 x 26.5 + 2 x 19 + 2 x 15 = 121 S. F. x $3.50	423	
	roof - 142 x $4.00	568	3771
4	Waterproofing		
	$2.80 x (2 x 26.5 + 150)		568
5	Joint treatment @ $1.50		
	$1.50 x (2 x 20 + 2 x 150)/29.67		17
6	Finish walls to provide comparable finish to precast)		
	Remove and patch ties, rub - $0.60/S.F. x 2 x 19		23
7	Backfill		
	48 cu yd/ft x $11		528
			$7931/ft

Cost per metre ≈ 3.28 x cost per ft.

Table 15. Case Study 2: Precast concrete estimate

1. 20" SOLID WALL PANEL (TYPICAL)

Assumes 5 panels per bed
8' wide x 21'-0 (avg)
10.37 cu yd/unit
6000 psi concrete

Item	Cost/cu yd
Concrete (6000 psi)	33.00
Strand - 27 x 130 x $0.21/ft ÷ (5 x 10.37)	14.22
Rein. steel - 150 lb x $0.20 ÷ 10.37	2.89
Embedded steel $75/unit ÷ 10.37	7.23
Misc.	2.00
TOTAL MATERIAL	59.34
On line labor - 12 men x 8 hrs x $8/h (avg)/ (5 x 10.37)	14.81
Off line labor (est)	4.00
Labor overhead @ 250%	47.03
TOTAL LABOR	65.84
Equipment write-off	
Forms - 4 x 120 L.F. @ $125 x 0.4 of job (approx) ÷ (240 x 10.37)	9.65
Curing and misc. equip. @ $100,000 x 0.33 of job ÷ (240 x 10.37)	13.26
Handling equip - $600/day ÷ (10 x 10.37)	5.78
TOTAL EQUIPMENT	28.69
SUB TOTAL	153.87
+35% O.H. & PROFIT	53.85
F.O.B. PLANT	207.72
Haul - truck & deliver @ $20/hr 2 panels/day = $20 x 8 ÷ (2 x 10.37)	7.71
Crane @ $750/day 5 man crew @ $18/hr = (5 x 8 x 18) = $720 Set 12 per day 1470 ÷ (12 x 10.37)	11.81
	$227.24/c.y.

$227.24 x 10.37 = $2356/panel
say $295/l.f.

Cost per cu metre ≈ 1.31 x cost per c.y.

Table 15. Case Study 2: Precast concrete estimate (continued)

2. 20" VOIDED WALL PANEL (CENTER)

Assumes 5 panels/bed
8' wide x 20'-0 (avg)
6.39 cu yd/panel
6000 psi concrete

Item	Cost/cu yd
Concrete (6000 psi)	33.00
Strand - 14 strand x 130 x $0.21/ft ÷ (5 x 6.39)	11.96
Embedded steel - $75/panel ÷ 6.	11.74
Cardboard forms - $150/panel ÷ 6.	23.47
Misc.	2.00
TOTAL MATERIAL	82.17
On line labor - 8 men x 8 hrs x $8 (avg) ÷ (5 x 6.39)	16.03
Off line labor (est)	5.00
Labor overhead @ 250%	52.56
TOTAL LABOR	73.59
Equipment write-off	
Forms - 4 x 120 L.F. @ $125 x .12 of job ÷ (120 x 6.39)	9.39
Curing and misc. equip. @ 100000 x .12 ÷ (120 x 6.39)	15.65
Handling equip. $600/day ÷ (10 x 6.39)	9.39
TOTAL EQUIPMENT	34.43
SUB TOTAL	190.19
+35% O.H. & PROFIT	66.57
F.O.B. PLANT	256.76
Haul - truck & driver @ $20/hr 4 panels/day = 20 x 8 ÷ (4 x 6.39)	6.26
Crane - $750/day 5 man crew @ $18/hr = (5 x 8 x $18) = $720 Set 12 per day = 1470 ÷ (12 x 6.39)	19.17
	$282.19/c.y.

$282.19 x 6.39 = $1803.00/panel
say $225/l.f.

Table 15. Case Study 2: Precast concrete estimate (continued)

3. BOX GIRDER

48" wide x 75'-0
Assume 4 units per bed
22.25 cu yd/unit
6000 psi concrete

Item	Cost/cu yd
Concrete (6000 psi)	33.00
Strand - 54 strand x 80' long x $0.21/ft ÷ 22.25	40.77
Reinf. steel - 1970 lb x $0.20/lb ÷ 22.25	17.71
Embedded steel - $150/unit ÷ 22.25	6.74
Cardboard forms $350/unit ÷ 22.25	15.73
Misc.	2.00
TOTAL MATERIAL	115.95
On line labor - 12 men x 10 hrs x $8 (avg) ÷ (4 x 22.25)	10.79
Off line labor (est)	5.00
Labor overhead @ 250%	39.48
TOTAL LABOR	55.27
Equipment write off	
Forms 2 x 320 L.F. @ $125 x 50% = $40000 ÷ (480 x 22.25) =	3.75
Curing & misc. equip. = $50000 ÷ (480 x 22.25) =	4.68
Handling equip. $600/day ÷ (4 x 22.25)	6.74
	15.17
Diaphragms - $100/BM ÷ 22.25	4.49
SUB TOTAL	$190.88
+35% O. H. & PROFIT	66.81
	$257.69
Haul - Truck & Driver @ $30/hr, 1 per day 30 (8) ÷ (1 x 22.25) =	10.79
2 cranes @ $750 - $1500 5 man crew @ $18/hr = (5 x 8 x 18) = $720 Set 8 per day 2220 ÷ (8 x 22.25)	12.47
TOTAL	$280.95/c.y.

$280.95 x 22.25 = $6251 per unit or $20.84/sq ft
= $3125/l.f.

5. SUMMARY COMPARISON OF TUNNEL CONSTRUCTION

a. Construction time: From the CPM outputs, one sees that the total project time for the precast method is about 11 months versus 14 months for the cast-in-place method. It should be noted that the total project times are shorter than the actual times would be. This is because in this study, only optimum conditions are assumed. There were no allowances made for severe weather construction, learning time in the early stages of the project, or construction of those parts of the project purposely excluded as listed in Subsection c of section I of this study. Nevertheless, the precast method does show a slight savings in time.

b. Costs: The cost estimates on pages 61-66 indicate that the precast method is slightly less costly for the phases of construction considered. However, the cost difference is less than 10%, and may not be within the accuracy of the estimate.

6. ALTERNATE DESIGN FOR BASE SLAB

In Vol. I of this study (Sect. VIII-B), several methods of reducing or resisting hydrostatic uplift on tunnels were suggested. This is particularly relevent to this study because with the solution proposed, there often is less dead weight available to resist the uplift. Some of the reasons for this are:

a. In many of the concepts explored in Vol. I, and in Case Study I, the backfill was eliminated.

b. Precast concrete components, especially when prestressed, are usually lighter.

c. The use of prefabricated vertical members often makes transfer of the vertical loads to the base slab difficult and more costly.

Not anticipated in Vol. I, but the situation encountered in this case study presents additional reasons for considering a method of resisting the uplift other than dead weight of the structure.

a. The tunnel is relatively shallow, therefore, relatively less backfill is available to resist the uplift.

b. The tunnel is wide, approximtely 75 feet span between supports. Thus, if the full hydrostatic pressure bears on the floor slab, it must be designed to carry this load as a one-way slab.

c. The floor of the tunnel is below rock. Therefore, if the required additional dead load is provided by concrete in the floors, the excavation to provide this additional thickness is a very significant cost item.

One of the most effective methods to resist this uplift would seem to be with the use of vertical rock or soil anchors. (Note: For a more detailed discussion on ground anchors, See Part B-2.)

Such use is shown in the Concept Plans for the approach slab, but is not shown for the tunnel floor. In order to help determine if this use of ground anchors is feasible a computer model was established which calculated the costs of the tunnel floor with and without ground anchors. The results of this analysis is shown graphically in Figs. 5 through 10.

The computer model was set up so that the following items could be varied:

a. Magnitude of the vertical uplift (shown as the height of the water table above the tunnel floor).

b. The amount of overburden (structure plus backfill), expressed in pounds per square foot.

c. The span, or distance between supports.

d. (1) The tunnel floor and ground anchors are in rock.

   (2) The tunnel floor and ground anchors are in soil.

e. (1) The floor slab is continuous with the walls, as in cast-in-place construction.

   (2) The floor slab is supported by, but not continuous with the walls, as in construction using prefabricated members.

It was necessary to establish several fixed assumptions in order to make a meaningful comparison. These assumptions follow:

a. The uplift pressure is the full value of the water head.

b. The minimum slab thickness of the gravity slab is that which is required to resist the total uplift, in combination with the overburden, and with a load factor of 1.4.

c. An arbitrary upper limit of reinforcement in the gravity slab was assumed at 3.0 square inches per square ft (this is equivalent to #9 bars at 4 in. (100 cm) on center). If the design indicated more reinforcement required, the slab thickness was increased. Minimum reinforcement of 0.0018bt = 0.0216t per square foot (t = slab thickness) was provided in each direction.

d. The anchored slabs are designed as flat plates, using the "direct design" method of Section 13.2 of the "Building Code Requirements for Reinforced Concrete" (ACI 318-71) of the American Concrete Institute. Minimum reinforcement is 0.0018bt at the middle strips and 0.0054bt at the column strips. This gives 75% of the moment resisting capacity to the column strip, as required by ACI 318-71. Slab thickness is that required to resist the applied loads with this amount of reinforcement.

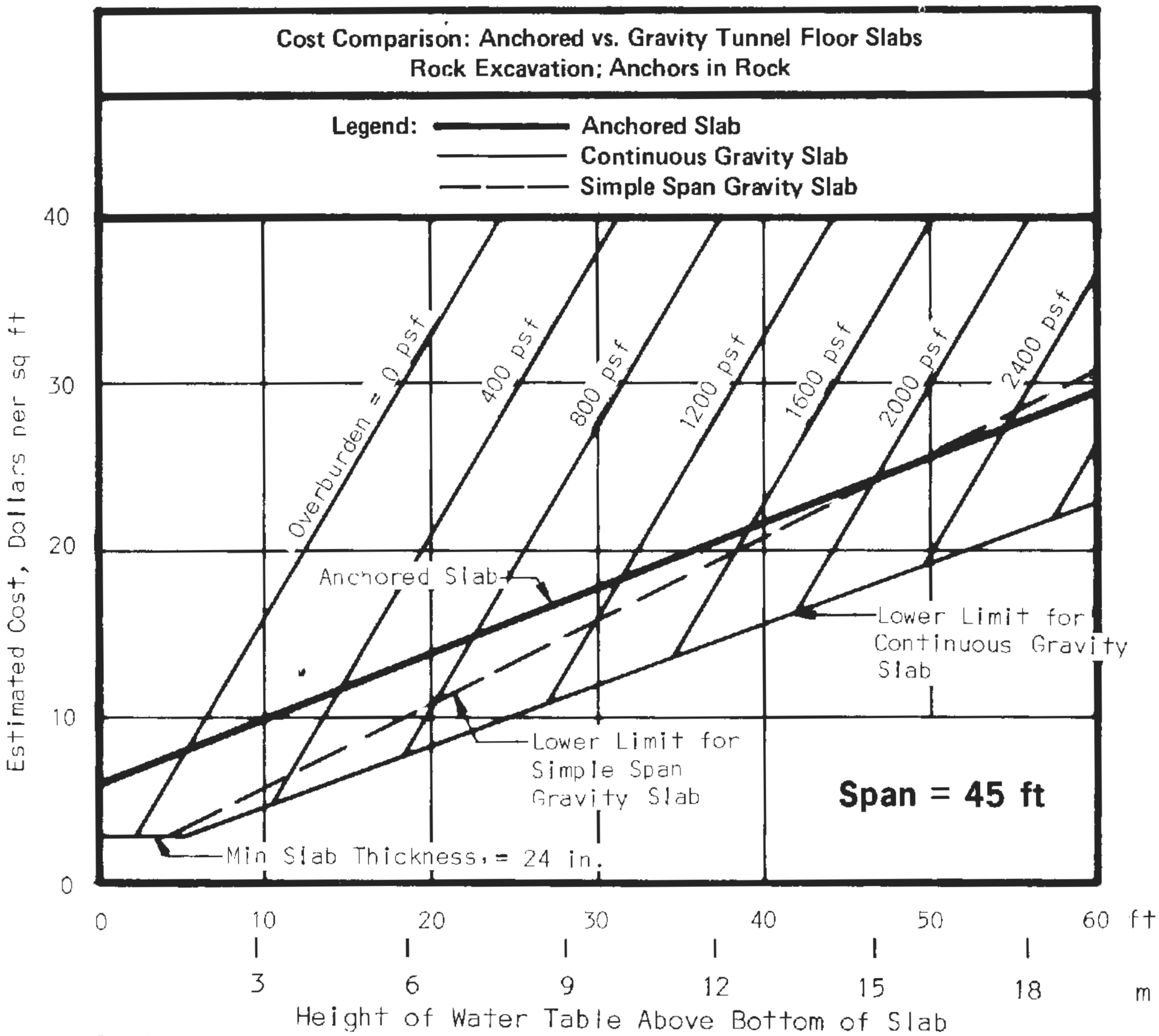
e. Ground anchors are assumed to have a service load capacity of 50 tons, and are located in a square grid at the spacing required to resist the uplift.

f. Unit costs used were as follows:

Excavation - rock	=	\$30/cu yd
soil	=	\$ 6/cu yd
Concrete in place	=	\$45/cu yd
Reinforcement in place	=	\$0.25/lb
Anchors in rock	=	\$700 each
Anchors in soil	=	\$900 each

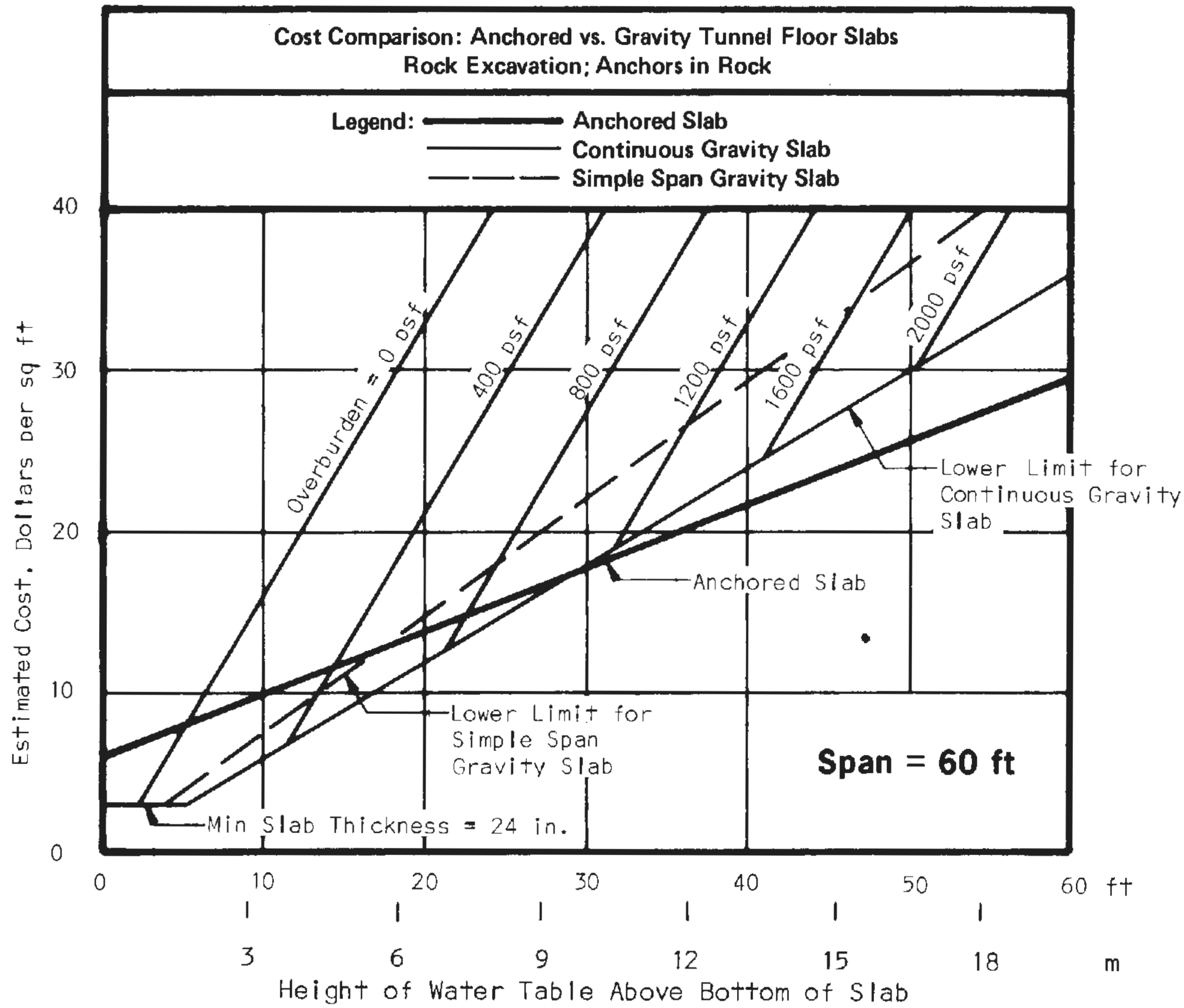
It is apparent that different design parameters and unit costs would result in somewhat different results, but Figs 5 through 10 can be used as a general guide for determining the feasibility of an anchored base slab.

Cost per cu metre ≈ 1.31 x cost per cu yd.



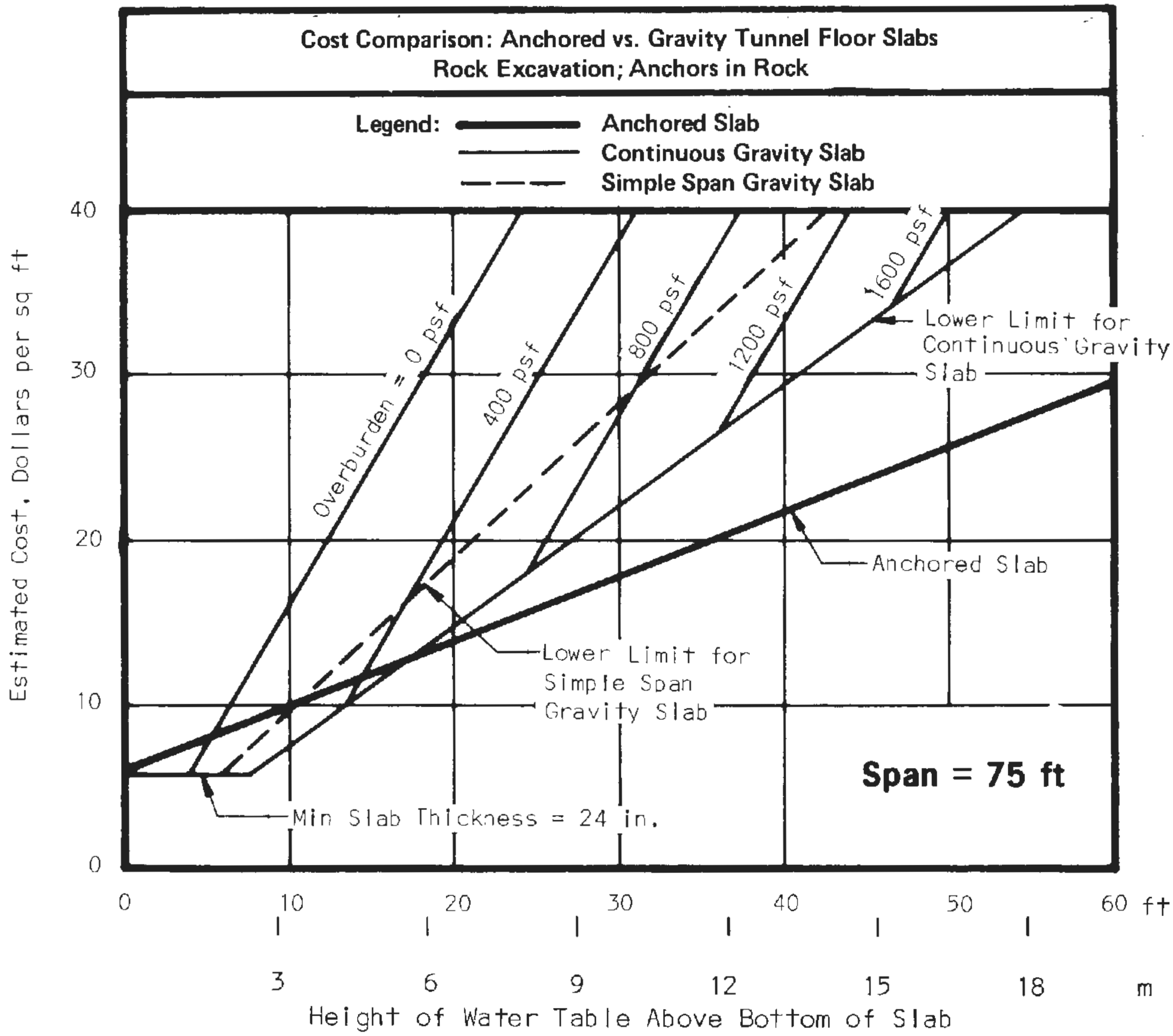
24 in. ≈ 610 mm
45 ft ≈ 13.7 m
1 psf ≈ 47.9 Pa
\$10 per sq ft ≈ \$108 per m^2

Fig. 5: Costs of anchored, continuous gravity, and simple span gravity slabs for a 45-ft span in rock.



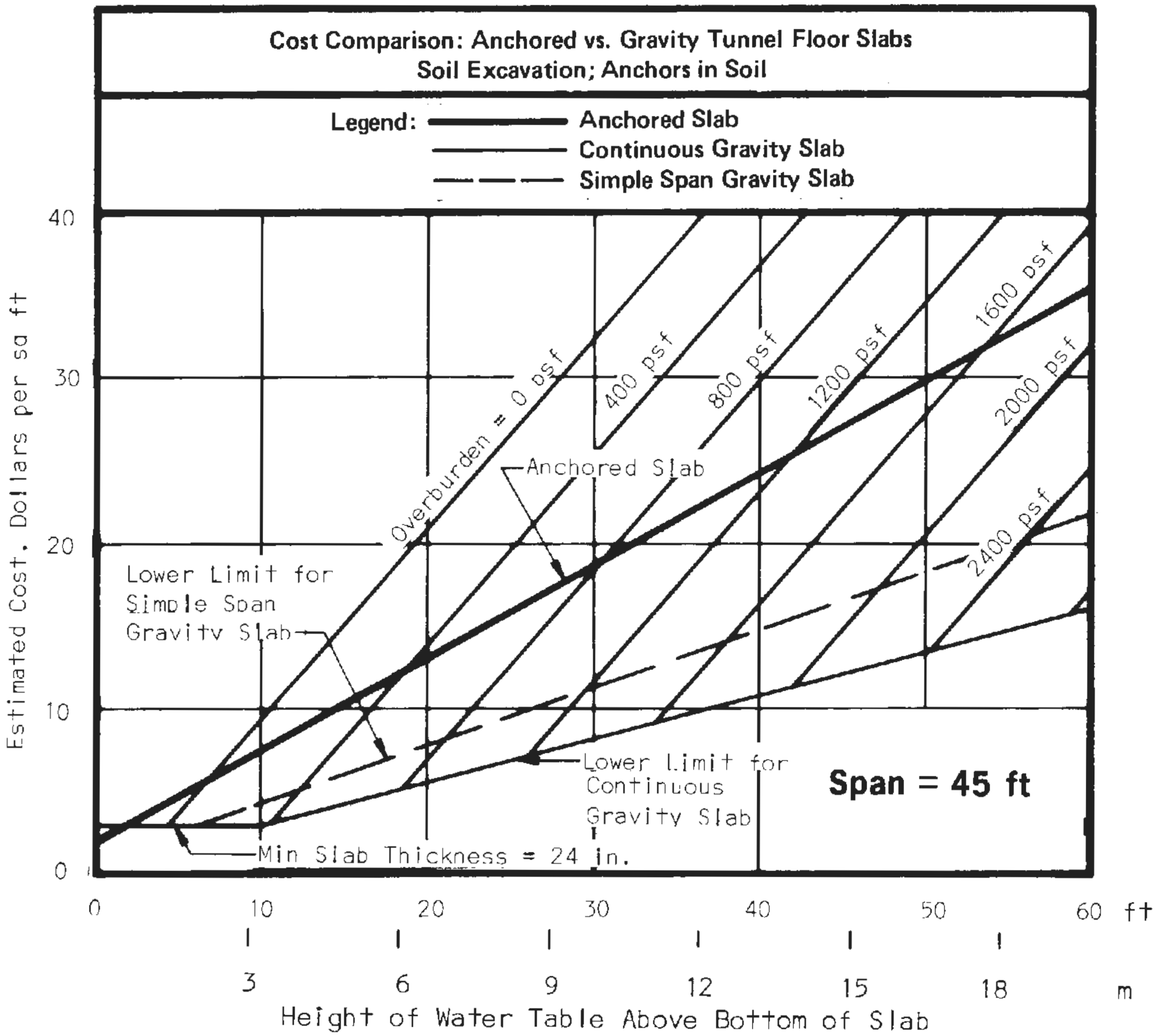
24 in. ≈ 610 mm
60 ft ≈ 18.3 m
1 psf ≈ 47.9 Pa
\$10 per sq ft ≈ \$108 per m^2

Fig. 6: Costs of anchored, continuous gravity, and simple span gravity slabs for a 60-ft span in rock.



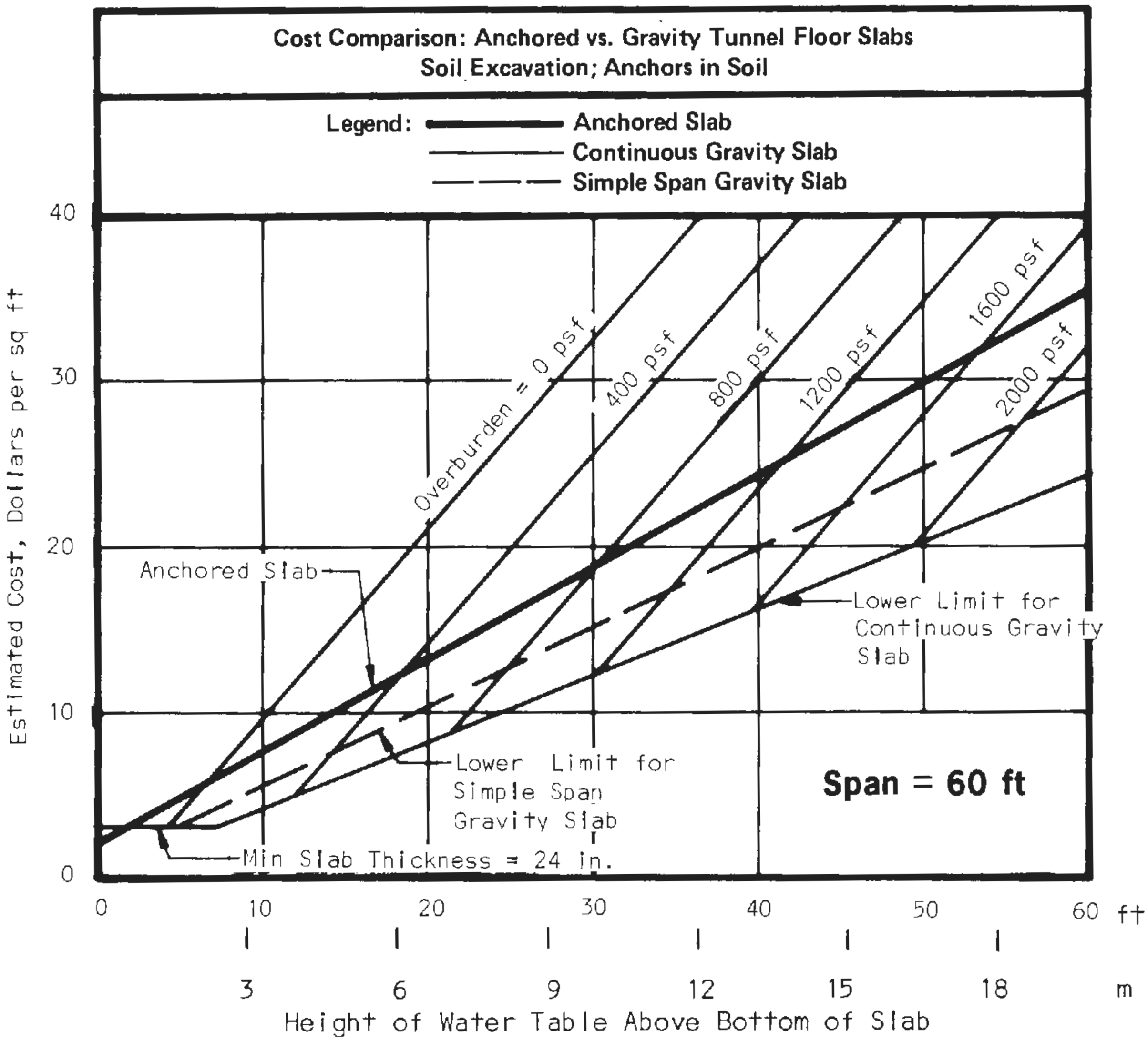
24 in. ≈ 610 mm
75 ft ≈ 22.9 m
1 psf ≈ 47.9 Pa
\$10 per sq ft ≈ \$108 per m^2

Fig. 7: Costs of anchored, continuous gravity and simple span gravity slabs for a 75-ft span in rock.



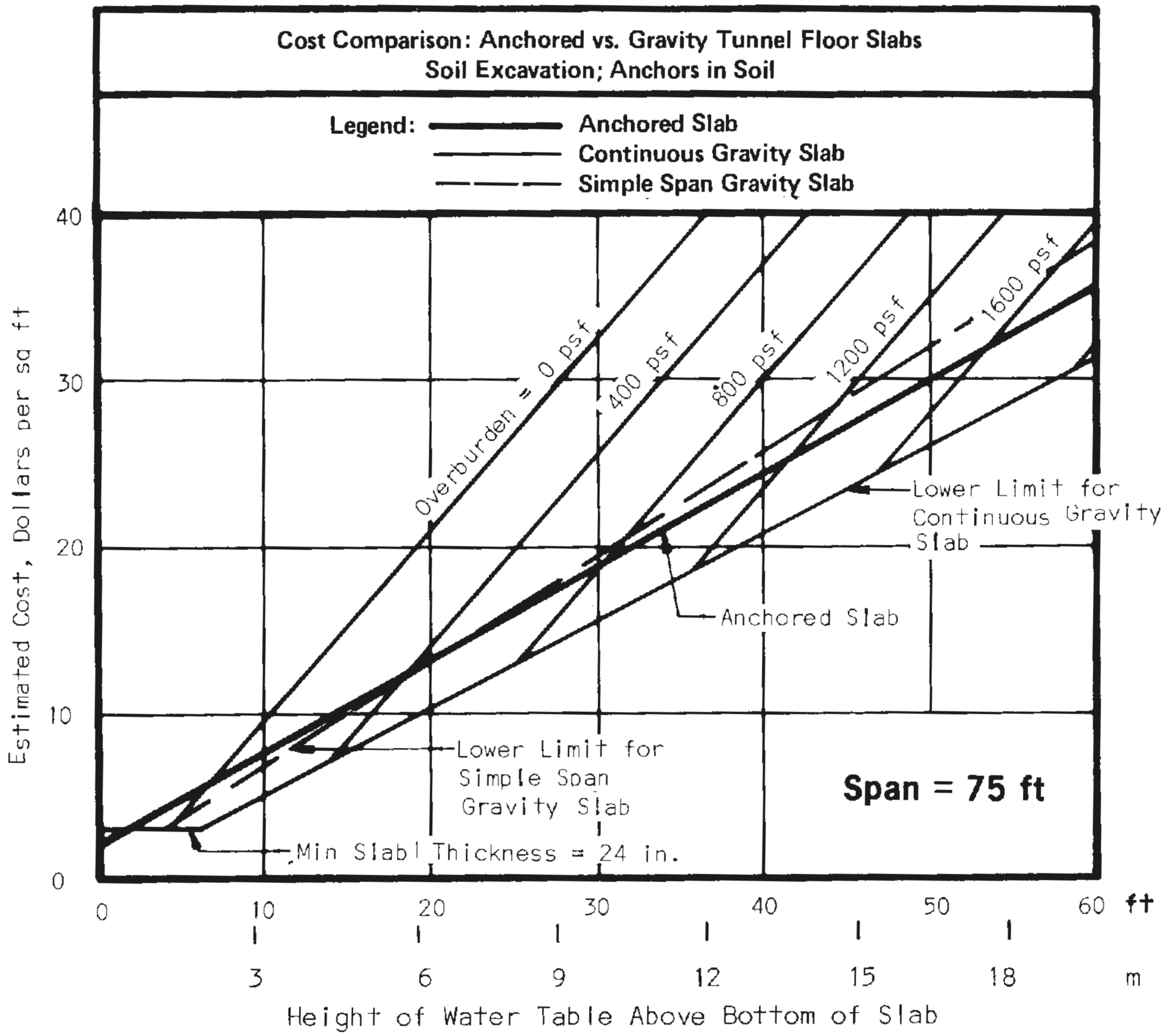
24 in. ≈ 610 mm
45 ft ≈ 13.7 m
1 psf ≈ 47.9 Pa
\$10 per sq ft ≈ \$108 per m^2.

Fig. 8: Costs of anchored, continuous gravity and simple span gravity slabs for a 45-ft span in soil.



24 in. ≈ 610 mm
60 ft ≈ 18.3 m
1 psf ≈ 47.9 Pa
\$10 per sq ft ≈ \$108 per m^2

Fig. 9: Costs of anchored, continuous gravity and simple span gravity slabs for a 60-ft span in soil.



24 in. 610 mm
75 ft 22.9 m
1 psf 47.9 Pa
\$10 per sq ft \$108 per m^2

Fig. 10: Costs of anchored, continuous gravity and simple span gravity slabs for a 75-ft span in soil.

Example of use of Figs. 5 through 10:

In this Case Study, the tunnel floor slab is in rock, the span is about 75 ft and the design water table is approximately 20 ft above the tunnel floor. The minimum fill is about 3.5 ft of 120 pcf soil, and the roof slab weighs 350 lb per sq ft. Therefore, the overburden is 3.5 x 120 + 350 = 770 psf. Reading from Fig. 7 (reproduced as Fig. 11 below) it can be seen that the cost of an anchored slab is about $14 per sq ft, a continuous gravity slab about $15 per sq ft, and a simple span gravity slab about $19 per sq ft. Note that if the overburden is only 400 psf, as is the case near the point where the creek crosses the tunnel, the cost of either a continuous or a simple span gravity slab would be about $21.50 per sq ft.

In this tunnel, then, the use of an anchored slab would be economically advantageous.

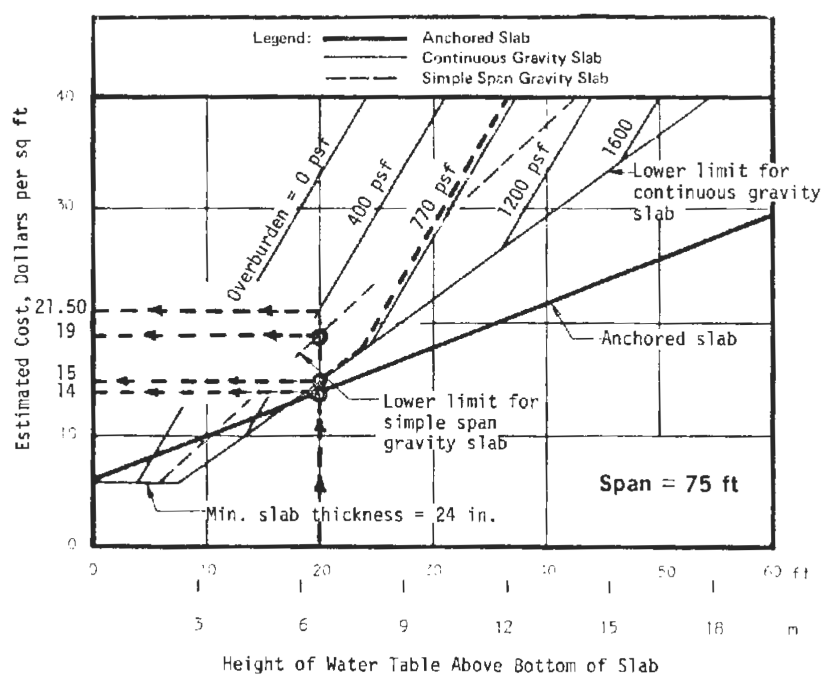
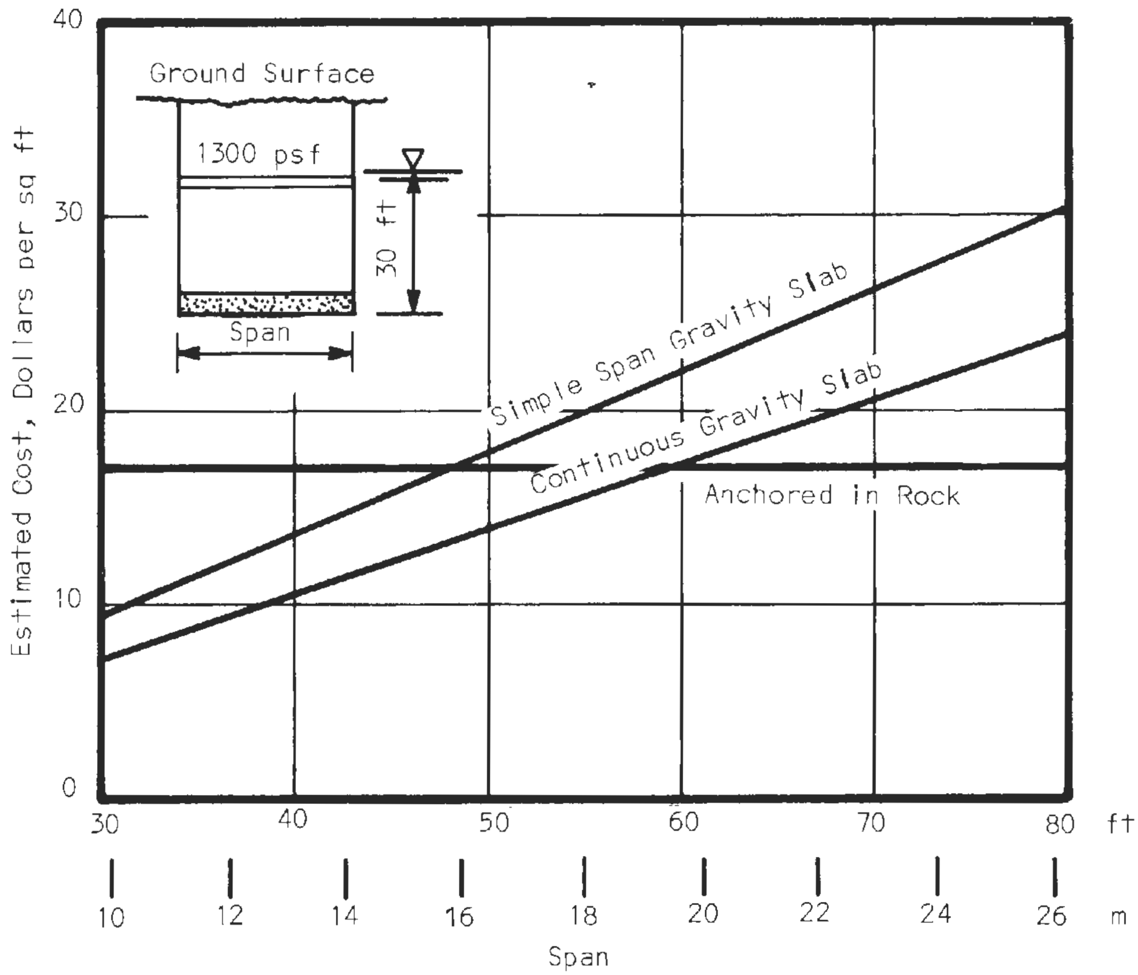


Fig. 11: Example of the use of Figs. 5 through 10.

The previous example shows that anchored slabs are most advantageous when the overburden weight is small, that is, in shallow tunnels. It is also apparent that anchored slabs are most cost effective in wide tunnels. This is illustrated for a specific tunnel depth and water table level in Fig. 12.



30 ft ≈ 9.8 m
1300 psf ≈ 62000 Pa
\$10 per sq ft ≈ \$108 per m^2

Fig. 12: Example of relative costs of gravity and anchored slabs.

PART B CONSTRUCTION OF TUNNEL APPROACHES

When highway tunnels are constructed in essentially level ground, as is the case in most urban areas, the length and cost of the approach to the tunnel may often be as much or more than the tunnel itself. In this case study, for example, the length of approaches, involving a highway cut where retaining walls are required, is about twice the length of the tunnel.

The purpose of this part of this case study is to present methods for using prefabricated components in such retaining walls and to suggest guides for determining the feasibility of such use.

1. DESCRIPTION

a. Dimensions: The portions of the approaches investigated were from about Sta. 210 to 223, the South Portal of the tunnel and from the North Portal, Sta. 233, to about Sta. 240. (See Fig. 31). Within these limits, the height of the wall varies from about 8 ft (24 m) to about 32 ft (9.8 m). In order to gain some economy of repetition, it was determined that all of the walls could be grouped into just three different designs.

b. Loading condition: While the depth of the water table below ground surface varies, it was found that, in general, the designs could be safely assumed to fall into three conditions. These are shown in Fig. 35.

c. Items considered in the study: Only the structural design of the wall was considered. Such things as the base slab, water proofing and the architectural treatment were assumed to be independent entities. This is not entirely true, as the architectural treatment would depend to a great extent on the method of construction chosen, but for any construction method, the architectural treatment can and should be an independent budget item. Also, the thickness of base slab might be different, depending to some extent on the philosophy of the designer.

2. CONSTRUCTION USING PREFABRICATED COMPONENTS

a. Structural framing method

It is very difficult to provide continuity using precast concrete members, particularly when pretensioned steel is used as the primary reinforcing element. It was, therefore, decided that the most feasible concept was to employ permanent soil or rock anchors near the top of the wall to provide support. Bottom support is achieved with the base slab. The precast element is then essentially a simple span member and lends itself to long-line pretensioning. This is illustrated in Section 7 in Fig. 37.

Two structural framing schemes were considered. The first was to use precast, prestressed wall panels, much the same as in the tunnel. The second method was to use precast, mild steel reinforced wall panels separated by king piles. The panels have main reinforcement in both directions and are supported on three sides; across the bottom by the base slab, and on either side by the king piles. Only the king piles need to be supported by ground anchors near the top. This second method is shown in Fig. 13.

After a complete design and cost estimate of each scheme was done for a representative design condition, it was determined that

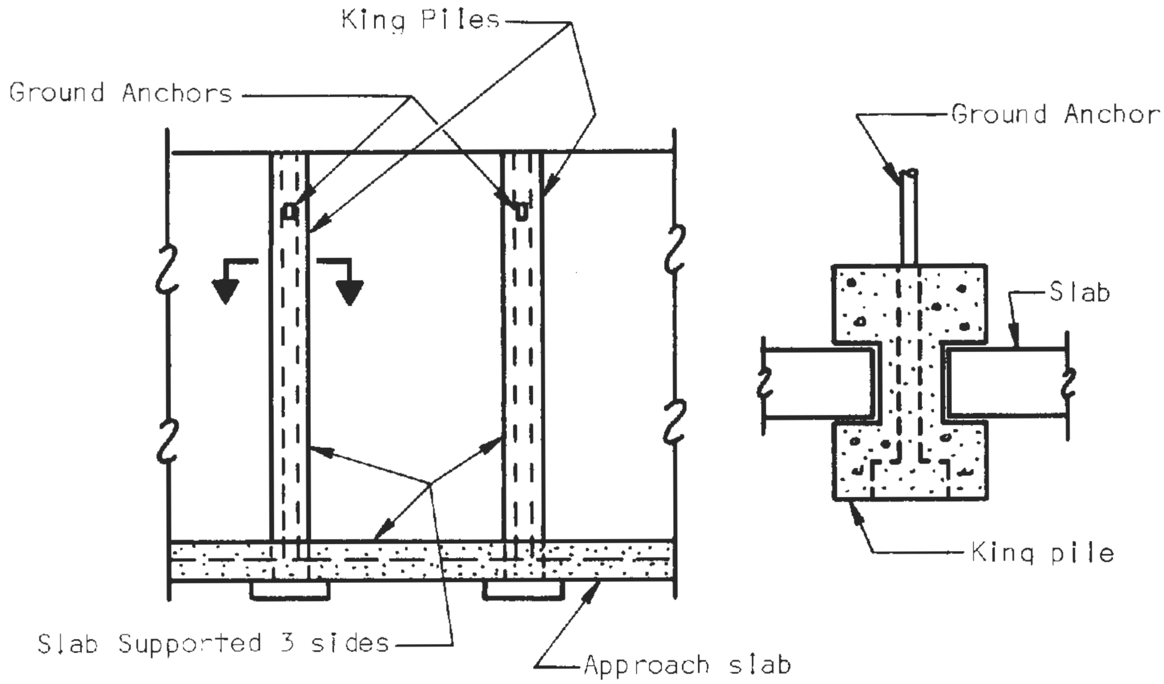


*Fig. 13: **Retaining wall using King-piles.***

the scheme using continuous panels was the most efficient for the project. For the maximum design condition, the one used for comparison, the two schemes were competitive. However, for a variety of reasons, some architectural, it could be seen that Scheme No. 2, using King-piles became inefficient at less than maximum height.

b. Products and Design

(1) Wall units:

The wall units are shown in Fig. 38. They are similar to the wall panels used in the tunnel. All the various design conditions involving the height of the wall, the backfill and the water table have been consolidated into three separate wall panel designs. The maximum height of each design is shown in elevation. The designs are based on zero tension under full load.

(2) Ground anchors: The use of ground anchors for the permanent support of underground walls is not common in this country. There are two very good reasons for this: first is the possibility of corrosion of the anchor and consequent loss of support. In locations where the anchors are inaccessible, or where the loss of support could result in catastrophic failures, as is often the case in such structures as basements of high-rise buildings or subway stations, this is a very real concern. Second, the use of permanent ground anchors in urban areas very often would require a permanent easement under adjacent private property.

Neither of these objections is of great concern here. If an anchor should fail, it would probably only result in ground settlement behind the wall, and could be easily replaced. Given the advancement of corrosion protection methods in recent years, it would seem that the risk is minimal and should not be a deterrent if the use is economically advantageous. Also, the anchors would only extend under public property, so easements are not a problem.

Ground anchors consist of high-tensile strength steel rods or strands, the same as that used in post-tensioning of concrete, placed in a pre-drilled hole. The steel is then anchored to the soil or rock by pumping or placing grout into the hole for a portion of the length to anchor it into the ground by bond. Pre-loading or post-tensioning the anchor also pre-compresses the soil, thus improving the bonding characteristics. For permanent anchors the use of bars rather than strand is usually recommended because of better corrosion resistance.

The design of the anchor obviously must consider the size and strength of the anchor and the bond characteristics of the soil or rock. There are references available [(1)] for estimating the bond values, but these are empirical and should only be used as a guide for determining the size and location of the anchors. Actual anchorage length should be determined by at least one performance test at the project. In addition, each anchor should be proof tested to about 1.5 times the anticipated service load. (This is the value recommended for permanent anchors. Temporary anchors are normally proof tested to about 1.2 times the service load.) After the anchor is jacked to the proof load, the load is backed off to about 60% of the service load and "locked off".[(2)]

Installation and testing of ground anchors are usually performed by specialty contractors. A variety of equipment and materials is used, so specifications should be left open.[(3)]

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(1) Post-tensioning Manual, Chapter 4, "Tentative Recommendations for Prestressed Rock and Soil Anchors", Post-Tensioning Institute, Glenview, IL.

(2) Schnabel, Harry Jr., "Procedures for Testing Earth Tiebacks". Paper presented at the ASEC National Structural Engineering Meeting, Cincinnati, OH, April 22-26, 1974.

(3) Chapman, Ronald K., "Specifications for Earth Tieback Sheeting and Tieback Testing Procedures". The Construction Specifier, June, 1975.

Actual capacity of anchors is largely dependent on soil type. On this project, either the limestone bedrock or the glacial till overburden, which is largely granular, could be effectively used. For the capacity required here, anchoring into the overburden would be more economical. The spacing of the anchors is predetermined by the need to have at least one anchor in each precast element. Since most of the cost is in the drilling and installation, the cost of the anchor is assumed tc be constant, regardless of the required capacity.

(3) Base slab: For purpose of this study the base slab design is taken as that shown in the concept plans. It, therefore, reflects no savings in cost or time when comparing construction methods. A discussion of anchored base slabs vs. gravity slabs is presented in Section III-A-6 of this report.

c. Construction sequence: The construction sequence, presented in a simplified manner, is as follows: Open excavation takes place to the desired depth as with the tunnel construction. The area under the wall footings is then prepared and the footings placed. The wall panels are erected, shimmed and temporarily braced. Following this, three other operations can now take place: 1) a gravel bed is placed, reinforcing laid, the bare slab poured and if necessary vertical ground anchors installed; 2) the panel joints are sealed and the entire back surface of the wall is waterproofed; 3) the ground anchors which support the top of the walls are placed. Following these operations, the areas outside the walls are backfilled and any finishing operations that are necessary take place.

The slowest operation by far will be the excavation. The speed of construction is only limited by the speed of excavation.

3. COMPARISON WITH CONVENTIONAL CONSTRUCTION

a. Retaining wall: For comparison purposes, conventional cast-in-place cantilever retaining walls were designed for the three conditions shown in Fig. 35. These designs are compared with the precast, prestressed walls shown in Figs. 37 and 38.

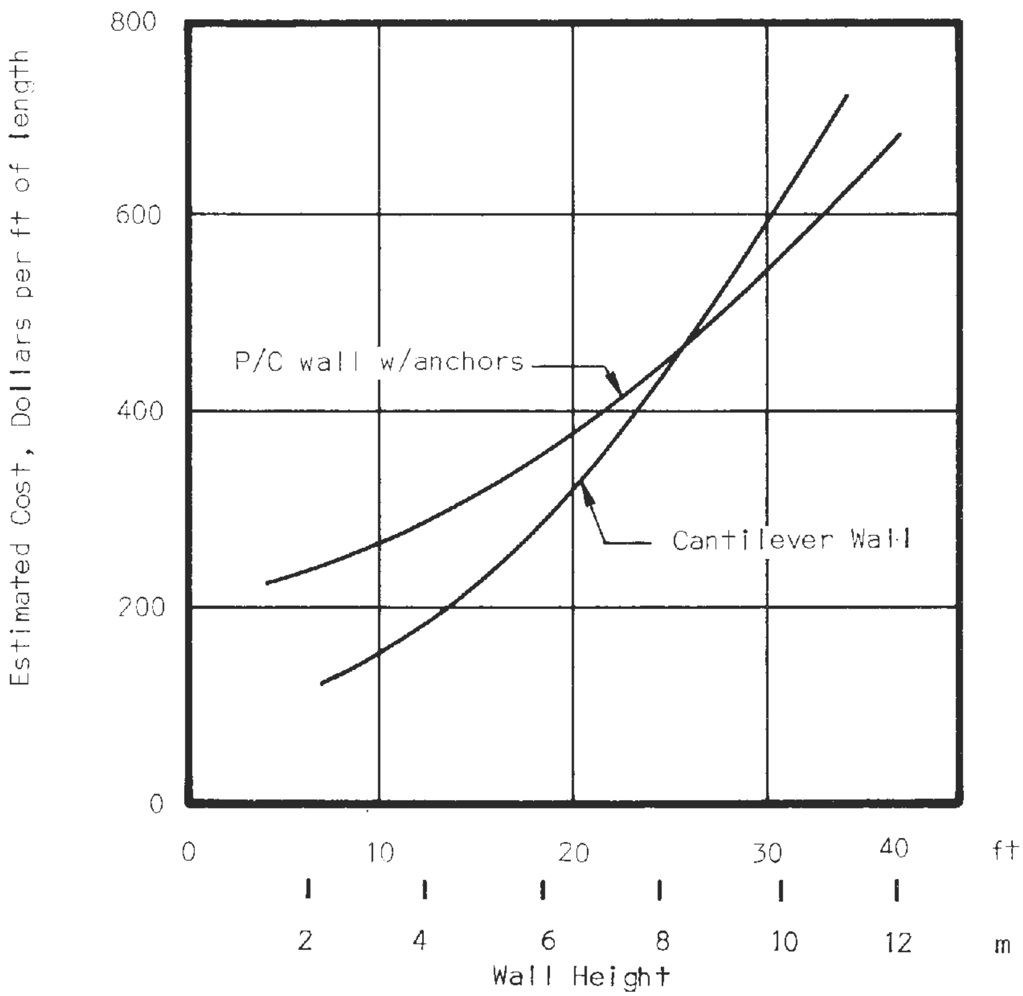
Costs were estimated for the two systems in a manner similar to that of Part A for the tunnel structure. Only the cost of the wall was considered, except for reinforcement required in the conventional design to provide continuity with the wall footing. No credit was given to the prefabricated method for reduced base thickness requirements. The conventional system would require more excavation behind the wall to allow room for forming--this difference in cost is included.

The results of the cost comparison are shown in Fig 14. It should be recognized that this comparison is only for this particular site, and different conditions would require a different analysis. It can probably be generalized, however, that walls less than about 20 feet in height will nearly always be more economical with conventional cast-in-place cantilever construction.

Horizontal wall movements were not a consideration at this site because there were no adjacent structures likely to be damaged. If such conditions do exist, the cost picture could change, especially if it was necessary to provide temporary support, underpinning, etc., during excavation. In this case, the designer should investigate construction methods using slurry walls or steel soldier piles and lagging, as described in Vol I of this study, and in Case Study No. 1.

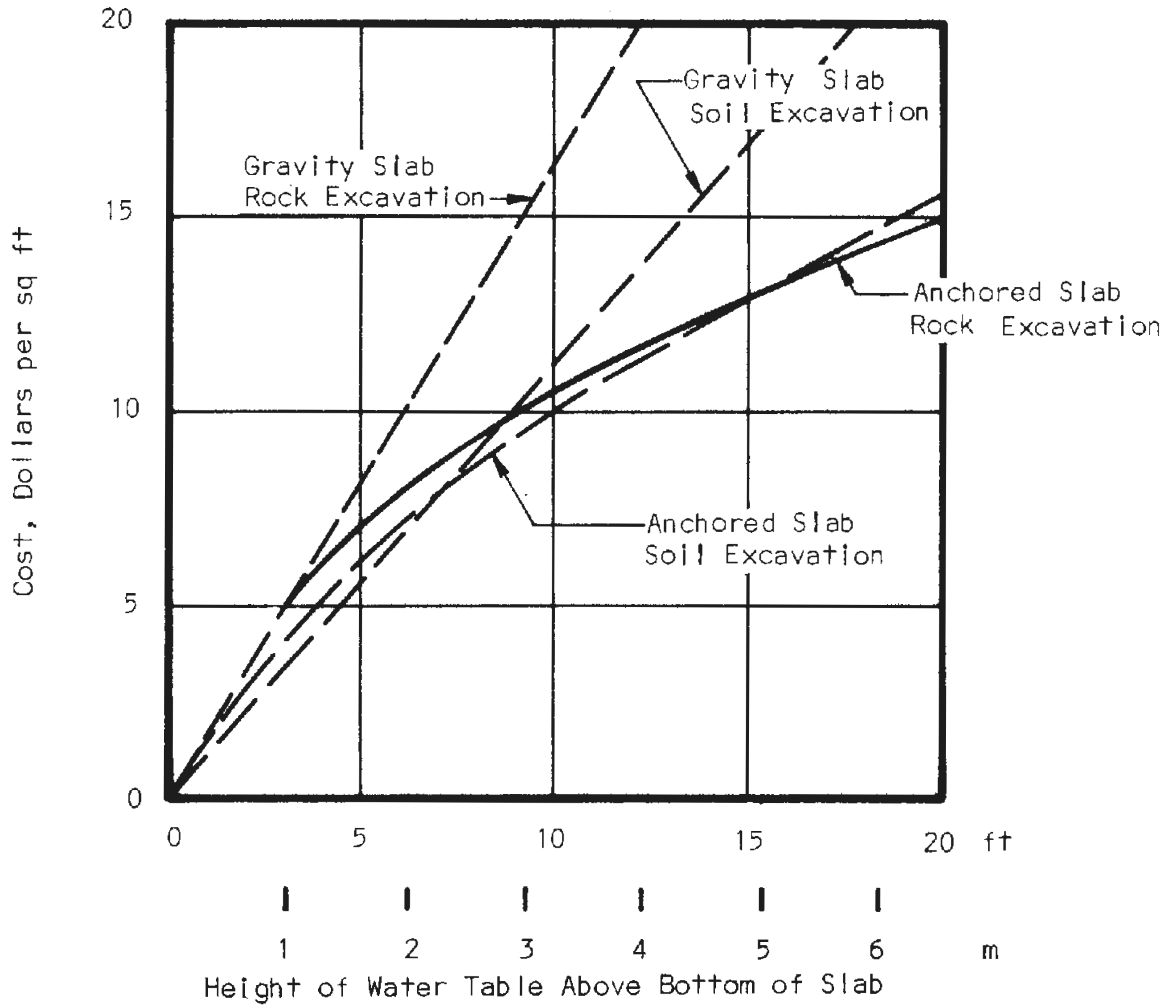
b. Gravity vs. anchored base slab: The use of vertical rock or soil anchors offers opportunities for significant savings in the costs of the pavement slab if the ground water table is much above the bottom of the pavement. It is common practice to resist the uplift pressure caused by the ground water head by the dead weight of the slab. Fig. 15 shows that on this project it is more economical to use an anchored slab if the water table is more than about four feet above the bottom of the slab.

The curves in Fig 9 are calculated using the same assumptions as in Part A-6.



$100 per ft ≈ $328 per metre

Fig. 14: Comparison of costs of precast concrete retaining wall with soil anchors and conventional cantilever retaining wall.



$1 per sq ft ≈ $11 per m^2

Fig. 15: Comparison of costs of anchored and gravity approach slab.

IV. CASE STUDY NO. 3
APPROACH TO A TUNNEL
UNDER A RIVER

A. PROJECT DESCRIPTION

1. Purpose of the study: Case study No. 3 is used to illustrate prefabricated structural components and construction methods which might be applicable to a deep tunnel in poor soil with a high ground water level.

2. Location of the project: The structure investigated in this study is the east approach to the proposed Second Downtown Elizabeth River Tunnel between Portsmouth and Norfolk, Virginia. The site is approximately 200 ft (61 m) south of the present Downtown Tunnel, which was constructed in the early 1950's. When completed, each tunnel will carry two lanes of one-way traffic, and will be incorporated as part of Interstate 264. (See location map in Fig. 41 (Appendix)

3. Preliminary plans: The designs in this study are intended to provide the same functional requirements, i.e., roadway width and clearance, volume of air movement, etc. presented in preliminary plans prepared for the Commonwealth of Virginia Department of Highways and Transportation by Parsons, Brinckerhoff, Quade and Douglas of New York. Construction costs and time of the designs in this study are compared with those of a construction system as presented in those preliminary plans. In the comparisons, every attempt was made to compare equal quality of construction. It is not the purpose of the study to second-guess another design, but merely to determine the feasibility of using prefabricated members for this

type of project.

4. Dimensions: The area considered in this Case Study is limited to the east end of the tunnel, designated as cut-and-cover in the preliminary plans. This portion of the tunnel is 1270 ft (387 m) long, as shown in Fig. 41. 820 ft (250 m) are shown on the preliminary plans as circular in section, and the remaining 450 ft (137 m) are more or less rectangular. The cross-sections proposed in the preliminary plans are shown in Fig. 42. The inside width of the tunnel is 31'-0" (9.8 m). The height from roadway to ceiling is 16'-6" (5.0 m) with space for ventilating air above and below. The depth below ground surface to the roadway varies from approximately 23 ft (7 m) at the east portal to about 77 ft (23.5 m) at the point where the cut-and-cover section joins the sunken tube section. This results in a maximum excavation depth requirement of nearly 90 ft (27 m).

5. Soil and groundwater characteristics: The soil profile assumed for this study is shown graphically in Fig. 41. This is actually based on soil studies used for the design of the first tunnel, but is considered adequate for study purposes. For design purposes, all soils were assumed to have a saturated unit weight of 130 pcf (208 Kg/m^3), with $\phi = 25^{\circ}$. Ground water is assumed at the surface for design purposes.

6. Miscellaneous considerations: The site is in an open area with no underpinning requirements, and groundwater can be safely (if not easily) lowered.

The latest utility plans available were prepared about the time of the construction of the first tunnel. These indicated very few underground lines that would interfere with construction, so this was not an item considered in the study.

A railroad track runs across the tunnel near the east portal. A temporary by-pass would probably have to be provided, although there is a possibility that the line could be abandoned, since it is used infrequently. While this would be a significant cost item and time delay, it was not considered in the cost or time comparisons, under the assumption that the solution would be the same for either construction method.

The transitions between the "box" section and the "circular" section and between the cut-and-cover section and the sunken tube section were not included in the comparisons, as it is assumed approximately equal time and costs would be required for both construction methods.

B. CONSTRUCTION USING PREFABRICATED COMPONENTS

1. Structural framing: The method of framing was dictated primarily by the extremely deep section at the west end of this portion of the project. The use of slurry wall construction is clearly indicated because of the poor soil and high water pressures.

   Cast-in-place slurry walls were chosen over precast concrete wall units as investigated in Vol. I of this study (and used in Case Study 1) for the following reasons:

   a. The extreme depth (over 90 ft (27 m) would make the wall panels very difficult to transport and place. A vertical field splice could be developed, but this would significantly slow down the placing operation, and increase the difficulties involved in alignment.

b. The weight of such precast wall units would mean that the units would be quite narrow, increasing the placing costs, joint treatment, etc.

c. One of the primary advantages of precast wall units is the quality of the interior finish. In this case, a relatively short portion of the wall height is within the exposed part of the tunnel, so the advantage would be minimal.

Near the east end of the project, the tunnel is much shallower and precast wall panels would be more feasible. However, use of two different construction methods would reduce the advantages of both.

The slurry walls are not used to carry the vertical loads as advocated in Vol. I of this study because of the tolerance restrictions this would place on the transverse alignment. By using separate framing, as shown in Fig. 43, normal tolerance (1 in 100) can be allowed.

2. Products and design: Prefabricated elements used in the design include roof units, roadway deck, roof support wall columns and finished wall infill units.

a. Walls: Resistance to lateral earth and water pressure, both temporary during construction and permanent is provided by the cast-in-place slurry walls. The walls are 36 in. (914 mm) thick from Sta. 40 + 80 to Sta. 47 + 80 and 24 in. (610 mm) from Sta. 47 + 80 to the east portal. Reinforcement varies with the depth of the tunnel.

The finished walls of the tunnel and the roof support is provided by precast, prestressed wall-columns as shown in Fig. 43. Temporary lateral support for these columns is achieved by bolting to the slurry wall as shown. Permanent stability is provided by the roof structure. These wall column units are spaced 1'-6" (457 mm) apart because a temporary support is needed within the tunnel until the roof is backfilled. The temporary struts can then be removed, and the wall completed by placing the 6 in. (152 mm) infill panel as shown in Fig. 43.

b. Roof structure: From Sta. 40 + 80 to 49 + 00, the roof structure is composed of precast, reinforced concrete arches, as detailed in Fig. 44. These sections are designed as two-hinged parabolic arches, with the lateral thrust resisted by the passive pressure of the earth. Approximately two-thirds of the total backfill on the arch is necessary to overcome the active pressure of the earth and water, so this much must be provided before the temporary struts can be removed.

Use of these arches is an economical structural solution, and also provides an adequate space for return ventilation air.

From Sta. 49 + 00 to the east portal, the roof section is composed of precast, prestressed box beams, of a standard design as used on highway bridges. The flat roof is necessary because there is insufficient clearance for the arch at the shallower end of the tunnel.

c. Gravity base slab: Uplift caused by ground water pressure acts on the 4'-0" (1.2 m) thick gravity base slab. This uplift load is then resisted by the weight of the slab, the overburden on the roof (transmitted through the wall-columns) and the friction of the slurry walls against the earth, transmitted through a shear key as shown in Fig. 43. Assuming a friction coefficient of 0.3, a factor of safety against floating of more than 1.5 is provided under the conservative assumption of water at ground surface.

d. Roadway deck: The roadway deck members are standard 8 ft (2.4 m) wide precast, prestressed double tees with a 4-in. (102 mm) composite topping. Several other standard members would be feasible, as described in Vol. I of this study.

3. Construction sequence: Construction of this segment of the project is assumed to start at the east portal and proceed westerly toward the river. The following assumptions and decisions were made regarding the sequence of operations:

   a. Excavation would be completed to the bottom of the gravity slab and the gravel fill, before placing the structural members, rather than attempt to excavate "under the roof" as was done on Case Study I. This is because of the necessity for temporary struts within the tunnel, and the fact that there are no surface operations to disrupt.

   b. Succeeding operations are kept approximately 150 feet (46 m) apart to avoid interference.

   c. Precast concrete roof units and wall columns are placed from above with a crane, while the roadway deck units and wall in-fill panels are placed from within the tunnel with a lift truck.

   A precedence diagram showing the relationships of the various operations is shown in Fig. 45. A detailed description of each operation is shown in Table 16. These operations are used as input to a Critical Path Method (CPM) computer program. Estimated activity durations and precedences used in establishing the CPM consider not only the required time to complete the activity, but also a reasonable allocation of resources and use of equipment compatible with space restraints.

Table 16. Case Study 3: Construction sequence using prefabricated structural elements

(See Fig. 45 for Precedence Diagram)

Last 2 digits of Operation Number	Description of Operations
00	Construct a guide trench to be used to align the slurry trench. Operation includes concreting of trench sides.
01	Same as operation 00 for side 2 of the tunnel.
02	Construct a slurry trench and cast-in-place a wall using the tremie method.
03	Same as operation 02 for side 2 of the tunnel.
04	Excavate to the elevation of the gravel base and place temporary struts as required. Equipment anticipated includes one clamshell and several small dozers.
06	Place and grade 2'-0" (610 mm) gravel base.
08	Cast a 6 in. (152 mm) base slab over the gravel base to provide a surface for waterproofing.
10	Apply a 4-ply membrane waterproofing over the 6 in. (152 mm) base slab. Protect with 1/2 in. (13 mm) asphalt plank.
12	Form, reinforce and cast a 4'-0" (1.2 m) thick gravity slab and key into slurry wall.
14	Allow additional curing time for gravity slab before placing precast roof support columns.
16	Place precast roof support columns, secure in position and laterally brace to slurry wall as shown in Fig.43.

Table 16. Case Study 3: Construction sequence using prefabricated structural elements (continued)

Last 2 digits of Operation Number	Description of Operations
18	Form, reinforce and cast the supports for the precast roadway deck.
20	Allow additional curing time for roadway deck supports before placing precast roadway deck.
22	Place precast roof units and secure in position. Box beam sections are used from station 49 + 00 to station 53 + 50 and parabolic arch sections are used from station 40 + 80 to station 49 + 00.
24	Caulk all joints between adjacent precast roof units and grout between roof units and slurry wall. This grouting is to alleviate gap left for tolerances. Then cover entire roof with a 4-ply membrane waterproofing and protect with 1/2 in. (13 mm) asphalt plank.
26	Backfill enough to deliver a thrust equal to or greater than the reaction received as a strut during construction; approximately equal to two-thirds of total. Not applicable where box beams are used.
28	Remove bottom strut and place and secure precast roadway deck units.
30	Cast 4 in. (102 mm) composite topping over roadway deck, curbs, and mechanical enclosures. Operation includes rough-in for mechanical, electrical, etc.
32	Place and secure precast wall units.
34	Backfill to grade any remaining amount necessary.

Table 17. Case Study 3: Computer output of Critical Path Method (CPM) program for construction using prefabricated structural elements.

P R Ø J E C T   S C H E D U L E

FRØM MAR 1, 1978 TØ SEP 18, 1979 - SØRTED BY SEQ

VIRGINIA TUNNEL USING PRECAST CØMPØNENTS   FEB 7, 1977

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
* 100	CØN GDE TR-SD 1	4	1MAR78	6MAR78	1MAR78	6MAR78	0
* 101	CØN GDE TR-SD 2	4	1MAR78	6MAR78	1MAR78	6MAR78	0
* 102	CØN SLRY WALL-SD 1	10	7MAR78	20MAR78	7MAR78	20MAR78	0
* 103	CØN SLRY WALL-SD 2	10	7MAR78	20MAR78	7MAR78	20MAR78	0
* 104	EXC-PLACE TEMP STRTS	30	21MAR78	1MAY78	21MAR78	1MAY78	0
106	PLACE GRAVEL BASE	3	2MAY78	4MAY78	28MAR79	30MAR79	231
108	CAST 6 IN. BASE SLAB	2	5MAY78	8MAY78	2APR79	3APR79	231
110	APPLY WATERPRØØFING	2	9MAY78	10MAY78	4APR79	5APR79	231
112	CAST GRAVITY SLAB	6	11MAY78	18MAY78	6APR79	13APR79	231
114	CURE GRAVITY SLAB	5	19MAY78	25MAY78	16APR79	20APR79	231
116	PLACE RØØF SUP CØLS	4	26MAY78	1JUN78	23APR79	26APR79	231
118	CAST P/C DECK SUP	2	2JUN78	5JUN78	6JUL79	9JUL79	279
120	CURE P/C DECK SUP	5	6JUN78	12JUN78	10JUL79	16JUL79	279
122	PLACE P/C BØX GIRD	3	2JUN78	6JUN78	2MAY79	4MAY79	234
124	WATERPRØØF RØØF MEM	4	7JUN78	12JUN78	11JUL79	16JUL79	279
128	REM STRT-PL P/C DECK	1	13JUN78	13JUN78	17JUL79	17JUL79	279
130	CAST TØPPING + CURBS	9	14JUN78	26JUN78	18JUL79	30JUL79	279
132	PLACE P/C WALL UNITS	4	27JUN78	30JUN78	31JUL79	3AUG79	279
134	BACKFILL TØ GRADE	3	13JUN78	15JUN78	17JUL79	19JUL79	279
200	CØN GDE TR-SD 1	4	1MAR78	6MAR78	12APR78	17APR78	30
201	CØN GDE TR-SD 2	4	1MAR78	6MAR78	12APR78	17APR78	30
202	CØN SLRY WALL-SD 1	10	7MAR78	20MAR78	18APR78	1MAY78	30
203	CØN SLRY WALL-SD 2	10	7MAR78	20MAR78	18APR78	1MAY78	30
* 204	EXC-PLACE TEMP STRTS	32	2MAY78	15JUN78	2MAY78	15JUN78	0
206	PLACE GRAVEL BASE	3	16JUN78	20JUN78	3APR79	5APR79	203
208	CAST 6 IN. BASE SLAB	2	21JUN78	22JUN78	6APR79	9APR79	203
210	APPLY WATERPRØØFING	2	23JUN78	26JUN78	10APR79	11APR79	203
212	CAST GRAVITY SLAB	6	27JUN78	5JUL78	12APR79	19APR79	203
214	CURE GRAVITY SLAB	5	6JUL78	12JUL78	20APR79	26APR79	203
216	PLACE RØØF SUP CØLS	4	13JUL78	18JUL78	27APR79	2MAY79	203
218	CAST P/C DECK SUP	2	19JUL78	20JUL78	12JUL79	13JUL79	251
220	CURE P/C DECK SUP	5	21JUL78	27JUL78	16JUL79	20JUL79	251
222	PLACE P/C BØX GIRD	3	19JUL78	21JUL78	7MAY79	9MAY79	205
224	WATERPRØØF RØØF MEM	4	24JUL78	27JUL78	16JUL79	19JUL79	250
228	REM STRT-PL P/C DECK	1	28JUL78	28JUL78	23JUL79	23JUL79	251
230	CAST TØPPING + CURBS	9	31JUL78	10AUG78	24JUL79	3AUG79	251
232	PLACE P/C WALL UNITS	4	11AUG78	16AUG78	6AUG79	9AUG79	251
234	BACKFILL TØ GRADE	3	28JUL78	1AUG78	20JUL79	24JUL79	250
300	CØN GDE TR-SD 1	4	1MAR78	6MAR78	25MAY78	31MAY78	61
301	CØN GDE TR-SD 2	4	1MAR78	6MAR78	25MAY78	31MAY78	61
302	CØN SLRY WALL-SD 1	11	7MAR78	21MAR78	1JUN78	15JUN78	61
303	CØN SLRY WALL-SD 2	11	7MAR78	21MAR78	1JUN78	15JUN78	61
* 304	EXC-PLACE TEMP STRTS	35	16JUN78	4AUG78	16JUN78	4AUG78	0
306	PLACE GRAVEL BASE	3	7AUG78	9AUG78	9APR79	11APR79	172
308	CAST 6 IN. BASE SLAB	2	10AUG78	11AUG78	12APR79	13APR79	172
310	APPLY WATERPRØØFING	2	14AUG78	15AUG78	16APR79	17APR79	172
312	CAST GRAVITY SLAB	6	16AUG78	23AUG78	18APR79	25APR79	172
314	CURE GRAVITY SLAB	5	24AUG78	30AUG78	26APR79	2MAY79	172
316	PLACE RØØF SUP CØLS	4	31AUG78	6SEP78	3MAY79	8MAY79	172
318	CAST P/C DECK SUP	2	7SEP78	8SEP78	18JUL79	19JUL79	220

Table 17. Case Study 3: Computer output of Crital Path Method (CPM) program for construction using prefabricated structural elements (continued).

P R Ø J E C T   S C H E D U L E

FRØM MAR 1, 1978 TØ SEP 18, 1979 - SØRTED BY SEQ

VIRGINIA TUNNEL USING PRECAST CØMPØNENTS   FEB 7, 1977

	DEPT:			EARLIEST		LATEST		TØTAL
	NUMBER	DESCRIPTIØN	DUR	START	FINISH	START	FINISH	FLØAT
	320	CURE P/C DECK SUP	5	9SEP78	15SEP78	20JUL79	26JUL79	220
	322	PLACE P/C BØX GIRD	3	7SEP78	9SEP78	10MAY79	14MAY79	173
	324	WATERPRØØF RØØF MEM	4	12SEP78	15SEP78	19JUL79	24JUL79	218
	328	REM STRT-PL P/C DECK	1	16SEP78	16SEP78	27JUL79	27JUL79	220
	330	CAST TØPPING + CURBS	9	19SEP78	29SEP78	30JUL79	9AUG79	220
	332	PLACE P/C WALL UNITS	4	30SEP78	4OCT78	10AUG79	15AUG79	220
	334	BACKFILL TØ GRADE	4	16SEP78	21SEP78	25JUL79	30JUL79	218
	400	CØN GDE TR-SD 1	4	1MAR78	6MAR78	14JUL78	19JUL78	95
	401	CØN GDE TR-SD 2	4	1MAR78	6MAR78	14JUL78	19JUL78	95
	402	CØN SLRY WALL-SD 1	12	7MAR78	22MAR78	20JUL78	4AUG78	95
	403	CØN SLRY WALL-SD 2	12	7MAR78	22MAR78	20JUL78	4AUG78	95
*	404	EXC-PLACE TEMP STRTS	38	7AUG78	28SEP78	7AUG78	28SEP78	0
	406	PLACE GRAVEL BASE	3	29SEP78	2OCT78	13APR79	17APR79	138
	408	CAST 6 IN. BASE SLAB	2	3OCT78	4OCT78	18APR79	19APR79	138
	410	APPLY WATERPRØØFING	2	5OCT78	6OCT78	20APR79	23APR79	138
	412	CAST GRAVITY SLAB	6	9OCT78	16OCT78	24APR79	1MAY79	138
	414	CURE GRAVITY SLAB	5	17OCT78	23OCT78	2MAY79	8MAY79	138
	416	PLACE RØØF SUP CØLS	4	24OCT78	27OCT78	9MAY79	14MAY79	138
	418	CAST P/C DECK SUP	2	30OCT78	31OCT78	24JUL79	25JUL79	186
	420	CURE P/C DECK SUP	5	1NØV78	7NØV78	26JUL79	1AUG79	186
	422	PLACE P/C ARCHS	3	30OCT78	1NØV78	15MAY79	17MAY79	138
	424	WATERPRØØF RØØF MEM	4	2NØV78	7NØV78	18MAY79	23MAY79	138
	426	BACKFILL FØR THRUST	8	8NØV78	17NØV78	24MAY79	5JUN79	138
	428	REM STRT-PL P/C DECK	1	20NØV78	20NØV78	2AUG79	2AUG79	178
	430	CAST TØPPING + CURBS	9	21NØV78	4DEC78	3AUG79	15AUG79	178
	432	PLACE P/C WALL UNITS	4	5DEC78	8DEC78	16AUG79	21AUG79	178
	434	BACKFILL TØ GRADE	4	20NØV78	24NØV78	31JUL79	3AUG79	176
	500	CØN GDE TR-SD 1	4	1MAR78	6MAR78	6SEP78	9SEP78	132
	501	CØN GDE TR-SD 2	4	1MAR78	6MAR78	6SEP78	9SEP78	132
	502	CØN SLRY WALL-SD 1	13	7MAR78	23MAR78	12SEP78	28SEP78	132
	503	CØN SLRY WALL-SD 2	13	7MAR78	23MAR78	12SEP78	28SEP78	132
*	504	EXC-PLACE TEMP STRTS	41	29SEP78	24NØV78	29SEP78	24NØV78	0
	506	PLACE GRAVEL BASE	3	27NØV78	29NØV78	25APR79	27APR79	105
	508	CAST 6 IN. BASE SLAB	2	30NØV78	1DEC78	30APR79	1MAY79	105
	510	APPLY WATERPRØØFING	2	4DEC78	5DEC78	2MAY79	3MAY79	105
	512	CAST GRAVITY SLAB	6	6DEC78	13DEC78	4MAY79	11MAY79	105
	514	CURE GRAVITY SLAB	5	14DEC78	20DEC78	14MAY79	18MAY79	105
	516	PLACE RØØF SUP CØLS	4	21DEC78	27DEC78	21MAY79	24MAY79	105
	518	CAST P/C DECK SUP	2	28DEC78	29DEC78	30JUL79	31JUL79	149
	520	CURE P/C DECK SUP	5	2JAN79	8JAN79	1AUG79	7AUG79	149
	522	PLACE P/C ARCHS	3	28DEC78	2JAN79	25MAY79	30MAY79	105
	524	WATERPRØØF RØØF MEM	4	3JAN79	8JAN79	31MAY79	5JUN79	105
	526	BACKFILL FØR THRUST	10	9JAN79	22JAN79	6JUN79	19JUN79	105
	528	REM STRT-PL P/C DECK	1	23JAN79	23JAN79	8AUG79	8AUG79	139
	530	CAST TØPPING + CURBS	9	24JAN79	5FEB79	9AUG79	21AUG79	139
	532	PLACE P/C WALL UNITS	4	6FEB79	9FEB79	22AUG79	27AUG79	139
	534	BACKFILL TØ GRADE	5	23JAN79	29JAN79	6AUG79	10AUG79	137
	600	CØN GDE TR-SD 1	4	1MAR78	6MAR78	31ØCT78	3NØV78	172
	601	CØN GDE TR-SD 2	4	1MAR78	6MAR78	31ØCT78	3NØV78	172
	602	CØN SLRY WALL-SD 1	14	7MAR78	24MAR78	6NØV78	24NØV78	172

Table 17. Case Study 3: Computer output of Critical Path Method (CPM) program for construction using prefabricated structural elements (continued).

P R Ø J E C T   S C H E D U L E

FRØM MAR 1, 1978 TØ SEP 18, 1979 - SØRTED BY SEQ

VIRGINIA TUNNEL USING PRECAST CØMPØNENTS   FEB 7, 1977

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
603	CØN SLRY WALL-SD 2	14	7MAR78	24MAR78	6NØV78	24NØV78	172
* 604	EXC-PLACE TEMP STRTS	44	27NØV78	29JAN79	27NØV78	29JAN79	0
606	PLACE GRAVEL BASE	3	30JAN79	1FEB79	9MAY79	11MAY79	71
608	CAST 6 IN. BASE SLAB	2	2FEB79	5FEB79	14MAY79	15MAY79	71
610	APPLY WATERPRØØFING	2	6FEB79	7FEB79	16MAY79	17MAY79	71
612	CAST GRAVITY SLAB	6	8FEB79	15FEB79	18MAY79	25MAY79	71
614	CURE GRAVITY SLAB	5	16FEB79	22FEB79	29MAY79	4JUN79	71
616	PLACE RØØF SUP CØLS	4	23FEB79	28FEB79	5JUN79	8JUN79	71
618	CAST P/C DECK SUP	2	1MAR79	2MAR79	3AUG79	6AUG79	109
620	CURE P/C DECK SUP	5	5MAR79	9MAR79	7AUG79	13AUG79	109
622	PLACE P/C ARCHS	3	1MAR79	5MAR79	11JUN79	13JUN79	71
624	WATERPRØØF RØØF MEM	4	6MAR79	9MAR79	14JUN79	19JUN79	71
626	BACKFILL FØR THRUST	12	12MAR79	27MAR79	20JUN79	6JUL79	71
628	REM STRT-PL P/C DECK	1	28MAR79	28MAR79	14AUG79	14AUG79	97
630	CAST TØPPING + CURBS	9	29MAR79	10APR79	15AUG79	27AUG79	97
632	PLACE P/C WALL UNITS	4	11APR79	16APR79	28AUG79	31AUG79	97
634	BACKFILL TØ GRADE	6	28MAR79	4APR79	13AUG79	20AUG79	96
700	CØN GDE TR-SD 1	4	1MAR78	6MAR78	2JAN79	5JAN79	214
701	CØN GDE TR-SD 2	4	1MAR78	6MAR78	2JAN79	5JAN79	214
702	CØN SLRY WALL-SD 1	16	7MAR78	28MAR78	8JAN79	29JAN79	214
703	CØN SLRY WALL-SD 2	16	7MAR78	28MAR78	8JAN79	29JAN79	214
* 704	EXC-PLACE TEMP STRTS	47	30JAN79	4APR79	30JAN79	4APR79	0
706	PLACE GRAVEL BASE	3	5APR79	9APR79	25MAY79	30MAY79	36
708	CAST 6 IN. BASE SLAB	2	10APR79	11APR79	31MAY79	1JUN79	36
710	APPLY WATERPRØØFING	2	12APR79	13APR79	4JUN79	5JUN79	36
712	CAST GRAVITY SLAB	6	16APR79	23APR79	6JUN79	13JUN79	36
714	CURE GRAVITY SLAB	5	24APR79	30APR79	14JUN79	20JUN79	36
716	PLACE RØØF SUP CØLS	4	1MAY79	4MAY79	21JUN79	26JUN79	36
718	CAST P/C DECK SUP	2	7MAY79	8MAY79	9AUG79	10AUG79	66
720	CURE P/C DECK SUP	5	9MAY79	15MAY79	13AUG79	17AUG79	66
722	PLACE P/C ARCHS	3	7MAY79	9MAY79	27JUN79	29JUN79	36
724	WATERPRØØF RØØF MEM	4	10MAY79	15MAY79	2JUL79	6JUL79	36
726	BACKFILL FØR THRUST	14	16MAY79	5JUN79	9JUL79	26JUL79	36
728	REM STRT-PL P/C DECK	1	6JUN79	6JUN79	20AUG79	20AUG79	52
730	CAST TØPPING + CURBS	9	7JUN79	19JUN79	21AUG79	31AUG79	52
732	PLACE P/C WALL UNITS	4	20JUN79	25JUN79	4SEP79	7SEP79	52
734	BACKFILL TØ GRADE	7	6JUN79	14JUN79	21AUG79	29AUG79	53
800	CØN GDE TR-SD 1	4	1MAR78	6MAR78	6MAR79	9MAR79	259
801	CØN GDE TR-SD 2	4	1MAR78	6MAR78	6MAR79	9MAR79	259
802	CØN SLRY WALL-SD 1	18	7MAR78	30MAR78	12MAR79	4APR79	259
803	CØN SLRY WALL-SD 2	18	7MAR78	30MAR78	12MAR79	4APR79	259
* 804	EXC-PLACE TEMP STRTS	50	5APR79	14JUN79	5APR79	14JUN79	0
* 806	PLACE GRAVEL BASE	3	15JUN79	19JUN79	15JUN79	19JUN79	0
* 808	CAST 6 IN. BASE SLAB	2	20JUN79	21JUN79	20JUN79	21JUN79	0
* 810	APPLY WATERPRØØFING	2	22JUN79	25JUN79	22JUN79	25JUN79	0
* 812	CAST GRAVITY SLAB	6	26JUN79	3JUL79	26JUN79	3JUL79	0
* 814	CURE GRAVITY SLAB	5	5JUL79	11JUL79	5JUL79	11JUL79	0
* 816	PLACE RØØF SUP CØLS	4	12JUL79	17JUL79	12JUL79	17JUL79	0
818	CAST P/C DECK SUP	2	18JUL79	19JUL79	15AUG79	16AUG79	20
820	CURE P/C DECK SUP	5	20JUL79	26JUL79	17AUG79	23AUG79	20

Table 17. Case Study 3: Computer output of Critical Path Method (CPM) program for construction using prefabricated structural elements (continued).

P R Ø J E C T   S C H E D U L E
FRØM MAR 1, 1978 TØ SEP 18, 1979 - SØRTED BY SEQ
VIRGINIA TUNNEL USING PRECAST CØMPØNENTS   FEB 7, 1977

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
* 822	PLACE P/C ARCHS	3	18JUL79	20JUL79	18JUL79	20JUL79	0
* 824	WATERPRØØF RØØF MEM	4	23JUL79	26JUL79	23JUL79	26JUL79	0
* 826	BACKFILL FØR THRUST	16	27JUL79	17AUG79	27JUL79	17AUG79	0
828	REM STRT-PL P/C DECK	1	20AUG79	20AUG79	24AUG79	24AUG79	4
830	CAST TØPPING + CURBS	9	21AUG79	31AUG79	27AUG79	7SEP79	4
832	PLACE P/C WALL UNITS	4	4SEP79	7SEP79	10SEP79	13SEP79	4
834	BACKFILL TØ GRADE	8	20AUG79	29AUG79	30AUG79	11SEP79	8
900	CØN GDE TR-SD 1	2	1MAR78	2MAR78	7JUN79	8JUN79	325
901	CØN GDE TR-SD 2	2	1MAR78	2MAR78	7JUN79	8JUN79	325
902	CØN SLRY WALL-SD 1	10	3MAR78	16MAR78	11JUN79	22JUN79	325
903	CØN SLRY WALL-SD 2	10	3MAR78	16MAR78	11JUN79	22JUN79	325
904	EXC-PLACE TEMP STRTS	20	15JUN79	13JUL79	25JUN79	23JUL79	6
906	PLACE GRAVEL BASE	2	16JUL79	17JUL79	24JUL79	25JUL79	6
908	CAST 6 IN. BASE SLAB	1	18JUL79	18JUL79	26JUL79	26JUL79	6
910	APPLY WATERPRØØFING	1	19JUL79	19JUL79	27JUL79	27JUL79	6
912	CAST GRAVITY SLAB	4	20JUL79	25JUL79	30JUL79	2AUG79	6
914	CURE GRAVITY SLAB	5	26JUL79	1AUG79	3AUG79	9AUG79	6
916	PLACE RØØF SUP CØLS	2	2AUG79	3AUG79	10AUG79	13AUG79	6
918	CAST P/C DECK SUP	1	6AUG79	6AUG79	28AUG79	28AUG79	16
920	CURE P/C DECK SUP	5	7AUG79	13AUG79	29AUG79	5SEP79	16
922	PLACE P/C ARCHS	2	6AUG79	7AUG79	14AUG79	15AUG79	6
924	WATERPRØØF RØØF MEM	2	8AUG79	9AUG79	16AUG79	17AUG79	6
* 926	BACKFILL FØR THRUST	12	20AUG79	5SEP79	20AUG79	5SEP79	0
* 928	REM STRT-PL P/C DECK	1	6SEP79	6SEP79	6SEP79	6SEP79	0
* 930	CAST TØPPING + CURBS	5	7SEP79	13SEP79	7SEP79	13SEP79	0
* 932	PLACE P/C WALL UNITS	2	14SEP79	17SEP79	14SEP79	17SEP79	0
934	BACKFILL TØ GRADE	4	6SEP79	11SEP79	12SEP79	17SEP79	4
*1000	STRUC PHASE CØMPLETE	1	18SEP79	18SEP79	18SEP79	18SEP79	0

C. COMPARISON WITH CAST-IN-PLACE CONSTRUCTION

1. Description: The cast-in-place structure with which the comparison is made is taken from the preliminary plans prepared by Parson, Brinckerhoff, Quade and Douglas. Cross-sections of the tunnel designs are shown in Fig. 42. The ground support method assumed is shown in Fig. 41, i.e., open excavation for the first 450 ft (137 m) from the portal, soldier beam and lagging for the next 450 ft (137 m) and slurry wall for the last 370 ft (113 m).

2. Construction sequence: For the purpose of this study, the following assumptions have been made regarding the construction sequence:

   a. The open excavation portion is excavated on a 1-1/2 to 1 slope. For all sections, it was assumed that six ft (1.8 m) of clearance outside the tunnel structure is required for forming.

   b. Unlike Case Study 1, the steel soldier beams can be driven or jetted into place, rather than placed in drilled holes.

   c. Where slurry wall construction is used, it does not become a part of the permanent structure but is used only for excavation bracing and as a water barrier.

   d. As with the construction using prefabricated components, the cast-in-place construction will start at the east portal and proceed westerly toward the river. Succeeding operations are also kept approximately 150 ft (46 m) apart to avoid interference.

   e. A precedence diagram showing the relationships of the various construction operations is shown in Fig. 46. A detailed description of each operation is shown in Table 18. A CPM output is shown in Table 19.

Table 18. Case Study 3: Construction sequence using cast-in-place construction

(See Fig. 46 for Precedence Diagram)

Last 2 digits of Operation Number	Description of Operations
00	Drive or jet in soldier piles at required spacing. Used between stations 44 + 50 and 49 + 00.
01	Same as operation 00 for side 2 of the tunnel.
02	Construct a guide trench to be used to align the slurry trench. Operation includes concreting of trench sides. Used between stations 40 + 80 and 44 + 50.
03	Same as operation 02 for side 2 of the tunnel.
04	Construct a slurry trench and cast-in-place a wall using the tremie method. Used between stations 40 + 80 and 44 + 50.
05	Same as operation 04 for side 2 of the tunnel.
10	Excavate to the elevation of the gravel base. Sta. 49 + 00 - 53 + 50 -- Open excavation with an approximate 1-1/2 to 1, horizontal to vertical slope. Sta. 44 + 50 - 49 + 00 -- Excavate between soldier piles and place struts and lagging. Sta. 40 + 80 - 49 + 00 -- Excavate between slurry walls and place struts.
12	Place and grade 2'-0" (610 mm) gravel base.
14	Cast a 6 in. (152 mm) base slab over the gravel base to provide a surface for waterproofing.

Table 18. Case Study 3: Construction sequence using cast-in-place construction (continued)

Last 2 digits of Operation Number	Description of Operations
16	Apply a 4-ply membrane waterproofing over the 6 in. (152 mm) base slab. Protect with 1/2 in. (13 mm) asphalt plank.
18	Form, reinforce and cast the base of the tunnel.
20	Form, reinforce and cast the remainder of the tunnel.
22	Apply a 4-ply membrane waterproofing to the entire exterior of the tunnel excluding the bottom surface where it has already been done.
24	Backfill to grade.
26	Form, reinforce and cast all roadway deck supports, curbs and mechanical enclosures. Operation includes rough-in for mechanical, electrical, etc.
28	Place and secure precast roadway deck units or form, reinforce and cast-in-place the roadway deck.
30	Cast 4 in. (102 mm) wearing surface over roadway deck.
32	Construct finished walls within the tunnel.

Table 19. Case Study 3: Computer output of Critical Path Method (CPM) program for construction using cast-in-place method.

P R Ø J E C T   S C H E D U L E

FRØM MAR 1, 1978 TØ MAY 6, 1980 - SØRTED BY SEQ

VIRGINIA TUNNEL USING CAST-IN-PLACE CØNS FEB 8, 1977

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
* 110	EXCAVATE	18	1MAR78	24MAR78	1MAR78	24MAR78	0
112	PLACE GRAVEL BASE	3	27MAR78	29MAR78	17AUG78	21AUG78	101
114	CAST 6 IN. BASE SLAB	2	30MAR78	31MAR78	22AUG78	23AUG78	101
116	APPLY WATERPRØØFING	2	3APR78	4APR78	24AUG78	25AUG78	101
118	CAST GRAVITY SLAB	40	5APR78	31MAY78	28AUG78	20ØCT78	101
120	CAST WALLS + RØØF	40	1JUN78	27JUL78	23ØCT78	18DEC78	101
122	WTRPRF WALLS + RØØF	20	28JUL78	24AUG78	3APR79	30APR79	174
124	BACKFILL TØ GRADE	32	25AUG78	9ØCT78	1MAY79	14JUN79	174
126	CAST DECK SUP/CURBS	14	28JUL78	16AUG78	13DEC79	3JAN80	352
128	PLACE DECK MEM	1	17AUG78	17AUG78	4JAN80	4JAN80	352
130	CAST WEARING SURFACE	1	18AUG78	18AUG78	7JAN80	7JAN80	352
132	CØNST FINISHED WALL	10	21AUG78	1SEP78	8JAN80	21JAN80	352
* 210	EXCAVATE	20	27MAR78	21APR78	27MAR78	21APR78	0
212	PLACE GRAVEL BASE	3	24APR78	26APR78	12ØCT78	16ØCT78	121
214	CAST 6 IN. BASE SLAB	2	27APR78	28APR78	17ØCT78	18ØCT78	121
216	APPLY WATERPRØØFING	2	1MAY78	2MAY78	19ØCT78	20ØCT78	121
218	CAST GRAVITY SLAB	40	1JUN78	27JUL78	23ØCT78	18DEC78	101
220	CAST WALLS + RØØF	40	28JUL78	22SEP78	19DEC78	14FEB79	101
222	WTRPRF WALLS + RØØF	20	23SEP78	19ØCT78	17MAY79	14JUN79	166
224	BACKFILL TØ GRADE	36	20ØCT78	11DEC78	15JUN79	6AUG79	166
226	CAST DECK SUP/CURBS	14	23SEP78	11ØCT78	28DEC79	17JAN80	322
228	PLACE DECK MEM	1	12ØCT78	12ØCT78	18JAN80	18JAN80	322
230	CAST WEARING SURFACE	1	13ØCT78	13ØCT78	21JAN80	21JAN80	322
232	CØNST FINISHED WALL	10	16ØCT78	27ØCT78	22JAN80	4FEB80	322
* 310	EXCAVATE	24	24APR78	25MAY78	24APR78	25MAY78	0
312	PLACE GRAVEL BASE	3	26MAY78	31MAY78	8DEC78	12DEC78	137
314	CAST 6 IN. BASE SLAB	2	1JUN78	2JUN78	13DEC78	14DEC78	137
316	APPLY WATERPRØØFING	2	5JUN78	6JUN78	15DEC78	18DEC78	137
318	CAST GRAVITY SLAB	40	28JUL78	22SEP78	19DEC78	14FEB79	101
320	CAST WALLS + RØØF	40	23SEP78	16NØV78	15FEB79	11APR79	101
322	WTRPRF WALLS + RØØF	20	17NØV78	15DEC78	10JUL79	6AUG79	162
324	BACKFILL TØ GRADE	50	18DEC78	27FEB79	7AUG79	16ØCT79	162
326	CAST DECK SUP/CURBS	14	17NØV78	7DEC78	14JAN80	31JAN80	292
328	PLACE DECK MEM	1	8DEC78	8DEC78	1FEB80	1FEB80	292
330	CAST WEARING SURFACE	1	11DEC78	11DEC78	4FEB80	4FEB80	292
332	CØNST FINISHED WALL	10	12DEC78	26DEC78	5FEB80	18FEB80	292
400	SØLDIER PILES-SD 1	10	1MAR78	14MAR78	12MAY78	25MAY78	52
401	SØLDIER PILES-SD 2	10	1MAR78	14MAR78	12MAY78	25MAY78	52
* 410	EXC-PL TEMP STRT/LAG	50	26MAY78	7AUG78	26MAY78	7AUG78	0
412	PLACE GRAVEL BASE	3	8AUG78	10AUG78	6FEB79	8FEB79	127
414	CAST 6 IN. BASE SLAB	2	11AUG78	14AUG78	9FEB79	12FEB79	127
416	APPLY WATERPRØØFING	2	15AUG78	16AUG78	13FEB79	14FEB79	127
418	CAST GRAVITY SLAB	40	23SEP78	16NØV78	15FEB79	11APR79	101
420	CAST WALLS + RØØF	40	17NØV78	16JAN79	12APR79	7JUN79	101
422	WTRPRF WALLS + RØØF	20	17JAN79	13FEB79	19SEP79	16ØCT79	172
424	BACKFILL TØ GRADE	16	28FEB79	21MAR79	17ØCT79	7NØV79	162
426	CAST DECK SUP/CURBS	14	17JAN79	5FEB79	28JAN80	14FEB80	262
428	PLACE DECK MEM	1	6FEB79	6FEB79	15FEB80	15FEB80	262
430	CAST WEARING SURFACE	1	7FEB79	7FEB79	18FEB80	18FEB80	262
432	CØNST FINISHED WALL	10	8FEB79	21FEB79	19FEB80	3MAR80	262

Table 19. Case Study 3: Computer output of Critical Path Method (CPM) program for construction using cast-in-place method (continued).

P R Ø J E C T   S C H E D U L E
FRØM MAR 1, 1978 TØ MAY 6, 1980 - SØRTED BY SEQ
VIRGINIA TUNNEL USING CAST-IN-PLACE CØNS   FEB 8, 1977

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
500	SØLDIER PILES-SD 1	10	1MAR78	14MAR78	25JUL78	7AUG78	102
501	SØLDIER PILES-SD 2	10	1MAR78	14MAR78	25JUL78	7AUG78	102
* 510	EXC-PL TEMP STRT/LAG	65	8AUG78	6NØV78	8AUG78	6NØV78	0
512	PLACE GRAVEL BASE	3	7NØV78	9NØV78	3APR79	5APR79	102
514	CAST 6 IN. BASE SLAB	2	10NØV78	13NØV78	6APR79	9APR79	102
516	APPLY WATERPRØØFING	2	14NØV78	15NØV78	10APR79	11APR79	102
518	CAST GRAVITY SLAB	40	17NØV78	16JAN79	12APR79	7JUN79	101
520	CAST WALLS + RØØF	40	17JAN79	13MAR79	8JUN79	3AUG79	101
522	WTRPRF WALLS + RØØF	20	14MAR79	10APR79	11ØCT79	7NØV79	148
524	BACKFILL TØ GRADE	20	11APR79	8MAY79	8NØV79	6DEC79	148
526	CAST DECK SUP/CURBS	14	14MAR79	2APR79	11FEB80	28FEB80	232
528	PLACE DECK MEM	1	3APR79	3APR79	29FEB80	29FEB80	232
530	CAST WEARING SURFACE	1	4APR79	4APR79	3MAR80	3MAR80	232
532	CØNST FINISHED WALL	10	5APR79	18APR79	4MAR80	17MAR80	232
600	SØLDIER PILES-SD 1	11	1MAR78	15MAR78	23ØCT78	6NØV78	166
601	SØLDIER PILES-SD 2	11	1MAR78	15MAR78	23ØCT78	6NØV78	166
* 610	EXC-PL TEMP STRT/LAG	70	7NØV78	15FEB79	7NØV78	15FEB79	0
612	PLACE GRAVEL BASE	3	16FEB79	20FEB79	30MAY79	1JUN79	72
614	CAST 6 IN. BASE SLAB	2	21FEB79	22FEB79	4JUN79	5JUN79	72
616	APPLY WATERPRØØFING	2	23FEB79	26FEB79	6JUN79	7JUN79	72
618	CAST GRAVITY SLAB	40	27FEB79	23APR79	8JUN79	3AUG79	72
620	CAST WALLS + RØØF	40	24APR79	19JUN79	6AUG79	1ØCT79	72
622	WTRPRF WALLS + RØØF	20	20JUN79	18JUL79	8NØV79	6DEC79	99
624	BACKFILL TØ GRADE	24	19JUL79	21AUG79	7DEC79	11JAN80	99
626	CAST DECK SUP/CURBS	14	20JUN79	10JUL79	25FEB80	13MAR80	173
628	PLACE DECK MEM	1	11JUL79	11JUL79	14MAR80	14MAR80	173
630	CAST WEARING SURFACE	1	12JUL79	12JUL79	17MAR80	17MAR80	173
632	CØNST FINISHED WALL	10	13JUL79	26JUL79	18MAR80	31MAR80	173
702	CØN GDE TR-SD 1	4	1MAR78	6MAR78	19JAN79	24JAN79	227
703	CØN GDE TR-SD 2	4	1MAR78	6MAR78	19JAN79	24JAN79	227
704	CØN SLRY WALL-SD 1	16	7MAR78	28MAR78	25JAN79	15FEB79	227
705	CØN SLRY WALL-SD 2	16	7MAR78	28MAR78	25JAN79	15FEB79	227
* 710	EXC-PLACE TEMP STRTS	72	16FEB79	29MAY79	16FEB79	29MAY79	0
712	PLACE GRAVEL BASE	3	30MAY79	1JUN79	26JUL79	30JUL79	40
714	CAST 6 IN. BASE SLAB	2	4JUN79	5JUN79	31JUL79	1AUG79	40
716	APPLY WATERPRØØFING	2	6JUN79	7JUN79	2AUG79	3AUG79	40
718	CAST GRAVITY SLAB	40	8JUN79	3AUG79	6AUG79	1ØCT79	40
720	CAST WALLS + RØØF	40	6AUG79	1ØCT79	2ØCT79	27NØV79	40
722	WTRPRF WALLS + RØØF	20	2ØCT79	29ØCT79	13DEC79	11JAN80	51
724	BACKFILL TØ GRADE	29	30ØCT79	10DEC79	14JAN80	21FEB80	51
726	CAST DECK SUP/CURBS	14	2ØCT79	19ØCT79	10MAR80	27MAR80	111
728	PLACE DECK MEM	1	22ØCT79	22ØCT79	28MAR80	28MAR80	111
730	CAST WEARING SURFACE	1	23ØCT79	23ØCT79	31MAR80	31MAR80	111
732	CØNST FINISHED WALL	10	24ØCT79	6NØV79	1APR80	14APR80	111
802	CØN GDE TR-SD 1	4	1MAR78	6MAR78	27APR79	2MAY79	297
803	CØN GDE TR-SD 2	4	1MAR78	6MAR78	27APR79	2MAY79	297
804	CØN SLRY WALL-SD 1	18	7MAR78	30MAR78	3MAY79	29MAY79	297
805	CØN SLRY WALL-SD 2	18	7MAR78	30MAR78	3MAY79	29MAY79	297
* 810	EXC-PLACE TEMP STRTS	80	30MAY79	20SEP79	30MAY79	20SEP79	0
* 812	PLACE GRAVEL BASE	3	21SEP79	25SEP79	21SEP79	25SEP79	0

Table 19. Case Study 3: Computer output of Critical Path Method (CPM) program for construction using cast-in-place method (continued).

P R Ø J E C T S C H E D U L E

FRØM MAR 1, 1978 TØ MAY 6, 1980 - SØRTED BY SEQ

VIRGINIA TUNNEL USING CAST-IN-PLACE CØNS FEB 8, 1977

DEPT: NUMBER	DESCRIPTIØN	DUR	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH	TØTAL FLØAT
* 814	CAST 6 IN. BASE SLAB	2	26SEP79	27SEP79	26SEP79	27SEP79	0
* 816	APPLY WATERPRØØFING	2	28SEP79	1ØCT79	28SEP79	1ØCT79	0
* 818	CAST GRAVITY SLAB	40	2ØCT79	27NØV79	2ØCT79	27NØV79	0
* 820	CAST WALLS + RØØF	40	28NØV79	24JAN80	28NØV79	24JAN80	0
* 822	WTRPRF WALLS + RØØF	20	25JAN80	21FEB80	25JAN80	21FEB80	0
* 824	BACKFILL TØ GRADE	34	22FEB80	9APR80	22FEB80	9APR80	0
826	CAST DECK SUP/CURBS	14	25JAN80	13FEB80	24MAR80	10APR80	41
828	PLACE DECK MEM	1	14FEB80	14FEB80	11APR80	11APR80	41
830	CAST WEARING SURFACE	1	15FEB80	15FEB80	14APR80	14APR80	41
832	CØNST FINISHED WALL	10	18FEB80	29FEB80	15APR80	28APR80	41
902	CØN GDE TR-SD 1	2	1MAR78	2MAR78	9NØV79	12NØV79	434
903	CØN GDE TR-SD 2	2	1MAR78	2MAR78	9NØV79	12NØV79	434
904	CØN SLRY WALL-SD 1	10	3MAR78	16MAR78	13NØV79	27NØV79	434
905	CØN SLRY WALL-SD 2	10	3MAR78	16MAR78	13NØV79	27NØV79	434
910	EXC-PLACE TEMP STRTS	40	21SEP79	15NØV79	28NØV79	24JAN80	47
912	PLACE GRAVEL BASE	2	16NØV79	19NØV79	25JAN80	28JAN80	47
914	CAST 6 IN. BASE SLAB	1	20NØV79	20NØV79	29JAN80	29JAN80	47
916	APPLY WATERPRØØFING	1	21NØV79	21NØV79	30JAN80	30JAN80	47
918	CAST GRAVITY SLAB	20	28NØV79	26DEC79	31JAN80	27FEB80	44
920	CAST WALLS + RØØF	20	25JAN80	21FEB80	28FEB80	26MAR80	24
922	WTRPRF WALLS + RØØF	10	22FEB80	6MAR80	27MAR80	9APR80	24
* 924	BACKFILL TØ GRADE	18	10APR80	5MAY80	10APR80	5MAY80	0
926	CAST DECK SUP/CURBS	8	22FEB80	4MAR80	15APR80	24APR80	37
928	PLACE DECK MEM	1	5MAR80	5MAR80	25APR80	25APR80	37
930	CAST WEARING SURFACE	1	6MAR80	6MAR80	28APR80	28APR80	37
932	CØNST FINISHED WALL	5	7MAR80	13MAR80	29APR80	5MAY80	37
*1000	STRUC PHASE CØMPLETE	1	6MAY80	6MAY80	6MAY80	6MAY80	0

D. COST ESTIMATES

An estimated cost comparison of the "cast-in-place" construction with the "system using prefabricated components" is shown in Tables 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, and 30. Since the "cast-in-place" system in this study actually employs three different construction methods (open excavation, soldier piles and lagging, and slurry wall) a separate cost comparison was made for each of the three segments of the total project. A "total project" cost comparison is also included.

Table 20. Case Study 3: Construction cost estimate of system using prefabricated components
Total Cost - Sta. 49 + 00 - 53 + 50

Item	Performed by	Cost to Gen Contr.	G. C. O.H. & P (%)	Cost to Owner
1. Guide Trench	Sub	$ 22,500	10	$ 24,750
2. Slurry Wall	Sub	1,215,120	10	1,336,632
3. Excavation	G. C.	74,217	25	92,771
4. Gravel Base	G. C.	9,065	25	11,331
5. 6 inch Base Slab	G. C.	18,998	25	23,748
6. Waterproofing	Sub	85,680	10	94,248
7. Gravity Slab	G. C.	193,799	25	242,249
8. Roof Support Columns	Sub	121,163	10	133,279
9. Roof Members	Sub	199,696	10	219,666
10. Roadway Deck Supports	G. C.	11,241	25	14,051
11. Roadway Deck	Sub	54,576	10	60,034
12. Topping, Curbs & Enclosures	G. C.	47,539	25	59,423
13. Precast Wall Units	Sub	40,500	10	44,550
14. Grouting & Caulking	Sub	9,312	10	10,243
15. Backfill	G. C.	16,527	25	20,659
16. Steel Struts	G. C.	56,485	25	70,606
17. Concrete Struts	G. C.	44,880	25	56,100
				$2,514,340

Table 21. Case Study 3: Construction cost estimate of system using prefabricated components.
Total Cost - Sta. 44 + 50 - 49 + 00

Item	Performed by	Cost to Gen Contr.	G. C. O.H. & P (%)	Cost to Owner
1. Guide Trench	Sub	$ 22,500	10	$ 24,750
2. Slurry Wall	Sub	1,716,120	10	1,887,732
3. Excavation	G. C.	110,027	25	137,534
4. Gravel Base	G. C.	9,065	25	11,331
5. 6 inch Base Slab	G. C.	18,998	25	23,748
6. Waterproofing	Sub	106,020	10	116,622
7. Gravity Slab	G. C.	193,799	25	242,249
8. Roof Support Columns	Sub	121,163	10	133,279
9. Roof Members	Sub	215,550	10	237,105
10. Roadway Deck Supports	G. C.	11,241	25	14,051
11. Roadway Deck	Sub	54,576	10	60,034
12. Topping, Curbs & Enclosures	G. C.	47,539	25	59,423
13. Precast Wall Units	Sub	40,500	10	44,550
14. Grouting & Caulking	Sub	10,213	10	11,234
15. Backfill	G. C.	68,072	25	85,090
16. Steel Struts	G. C.	139,590	25	174,488
17. Concrete Struts	G. C.	53,040	25	66,300
				$3,329,520

Table 22. Case Study 3: Construction cost estimate system using prefabricated components
Total Cost - Sta. 40 + 80 - 44 + 50

Item	Performed by	Cost to Gen Contr.	G. C. O.H. & P (%)	Cost to Owner
1. Guide Trench	Sub	$ 18,500	10	$ 20,350
2. Slurry Wall	Sub	1,843,920	10	2,028,312
3. Excavation	G. C.	104,916	25	131,145
4. Gravel Base	G. C.	7,454	25	9,318
5. 6 inch Base Slab	G. C.	15,621	25	19,526
6. Waterproofing	Sub	87,172	10	95,889
7. Gravity Slab	G. C.	159,347	25	199,183
8. Roof Support Columns	Sub	99,622	10	109,585
9. Roof Members	Sub	177,230	10	194,953
10. Roadway Deck Supports	G. C.	9,243	25	11,554
11. Roadway Deck	Sub	44,874	10	49,361
12. Topping, Curbs & Enclosures	G. C.	39,087	25	48,860
13. Precast Wall Units	Sub	33,300	10	36,630
14. Grouting & Caulking	Sub	8,398	10	9,238
15. Backfill	G. C.	85,873	25	107,341
16. Steel Struts	G. C.	277,200	25	346,500
17. Concrete Struts	G. C.	58,480	25	73,100
				$3,490,845

Table 23. Case Study 3: Construction cost estimate system using prefabricated components
Total Cost for Project

Item	Performed by	Cost to Gen Contr.	G. C. O.H. & P (%)	Cost to Owner
1. Guide Trench	Sub	$ 63,500	10	$ 69,850
2. Slurry Wall	Sub	4,775,160	10	5,252,676
3. Excavation	G. C.	289,160	25	361,450
4. Gravel Base	G. C.	25,584	25	31,980
5. 6 inch Base Slab	G. C.	53,618	25	67,022
6. Waterproofing	Sub	278,872	10	306,759
7. Gravity Slab	G. C.	546,945	25	683,681
8. Roof Support Columns	Sub	341,948	10	376,143
9. Roof Members	Sub	592,476	10	651,724
10. Roadway Deck Supports	G. C.	31,725	25	39,656
11. Roadway Deck	Sub	154,026	10	169,429
12. Topping, Curbs, & Enclosures	G. C.	134,165	25	167,706
13. Precast Wall Units	Sub	114,300	10	125,730
14. Grouting & Caulking	Sub	27,923	10	30,715
15. Backfill	G. C.	170,472	25	213,090
16. Steel Struts	G. C.	473,275	25	591,594
17. Concrete Struts	G. C.	156,400	25	195,500
				$9,334,705

Table 24. Case Study 3: Construction cost estimate system using prefabricated components Cost to General Contractor

Item No.	Item			Cost to G. C. (Dollars)
1	Guide Trench - $50 per foot of tunnel (from CSI - includes Sub O.H. & Profit) $50 x 1270 =			63,500
2	Slurry Wall - Soil information indicates easy digging. Cost information from ICOS. (Includes Sub O.H. & Profit) $30/S.F. x 159,172 S.F. =			4,775,160
3	Excavation - side enclosed 96,386.7 c.y. @ $3.00/c.y. =			289,160
4	Gravel Base 3,198 c.y. @ $8.00/c.y. =			25,584
5	6 inch Base Slab			
	Concrete - 800 c.y. @ $45/c.y.	=	36,000	
	Reinforcing - (Assuming #4 @ 12 each way) 1.36 psf x 1,270 x 34 x $.30/16	=	17,618	53,618
6	4-Ply Membrane Waterproofing			
	Sta. 49 + 00 - 53 + 50 2 x 43 x 450 @ $2.80	=	85,680	
	Sta. 40 + 80 - 49 + 00 1 x 34 x 820 @ $2.80	=	78,064	
	1 x 39 x 820 @ $3.60	=	115,128	278,872
7	4'-0 Gravity Slab			
	Concrete - 6,397 c.y. @ $45/c.y.	=	287,865	
	Reinforcing - 20 lb/S.F. x 34 x 1,270 x $.30	=	259,080	546,945
8	Roof Support Columns (See Detailed Breakdown) $538.50/unit x 635	=		341,948
9	Roof Members (See Detailed Breakdown)			
	Box Beams - $1,783/unit x 112	=	199,696	
	Arches - $1,916/unit x 205	=	392,780	592,476
10	Roadway Deck Supports			
	Concrete - 470 c.y. @ $45/c.y.	=	21,150	
	Reinforcing - 75lb/c.y. x 470 @ $0.30	=	10,575	31,725

Conversion to SI units shown on pg xi

Table 24. Case Study 3: Construction cost estimate system using prefabricated components (continued)
Cost to General Contractor

Item No.	Item		Cost To G. C. (Dollars)
11	Roadway Deck (See Detailed Breakdown)		
	$3.79/S.F. x 32 x 1,270		154,026
12	Composite Topping, Curbs & Enclosures (Does not include cost of rough-in)		
	Concrete - 1,374 c.y. @ $45	= 61,830	
	Reinforcing - 100 lb/c.y. (avg.) x 1,374 x $.30/lb	= 41,220	
	Formwork - 7 S.F./ft x 1,270 @ $3.50	= 31,115	134,165
13	Precast Wall Units (See Detailed Breakdown)		
	$180/unit x 635	=	114,300
14	Grouting & Caulking		
	Caulking - $1.50/l.f. x (34 x 112 + 39 x 206)	= 17,763	
	Grouting - $4.00/l.f. x 1,270 x 2	= 10,160	27,923
15	Backfill - Sta. 40 + 80 - 53 + 50		
	Hand backfill and compaction 4,337 c.y. @ $8.00/c.y.	= 34,696	
	Machine backfill and compaction 38,793 c.y. @ $3.50/c.y.	= 135,776	170,472
16	Temp. Steel Struts - Sta. 51 + 50 - 53 + 50 (Assume 40% reuse factor)		
	Labor - 425 lb/ft x 200 x $.16/!b	= 13,600	
	Mat - .60 x (.20/.16) x $13600	= 10,200	
	Net Salvage - .5 x $10200	= - 5,100	
	Sta. 49 + 00 - 51 + 50		
	Labor - 687 lb/ft x 250 ft x $.16/lb	= 27,480	
	Mat - .60 x (.20/.16) x $27480	= 20,610	
	Net Salvage - .5 x $20610	= -10,305	
	Sta. 44 + 50 - 49 + 00		
	Labor - 1410 lb/ft x 450 ft x $.16/lb	= 101,520	
	Mat - .60 x (.20/.16) x $101520	= 76,140	
	Net Salvage - .5 x $76140	= -38,070	
	Sta. 40 + 80 - 44 + 50		
	Labor - 2800 lb/ft x 450 ft x $.16/lb	= 201,600	
	Mat. - .60 x (.20/.16) x $201600	= 151,200	
	Net Salvage - .5 x $151200	= -75,600	473,275
17	Concrete Struts (Not removed)		
	115 x 34 ft x $40/l.f.	=	156,400

Table 25. Case Study 3: Precast concrete estimate

1. ROOF ARCHES
   7.17 cu. yd. per arch

		Cost/cu. yd.	
Concrete (6000 psi)		33.00	
Reinforcing Steel 1065 lb x $0.20/lb ÷ 7.17	=	29.71	
Embedded Steel Items $80/panel ÷ 7.17	=	11.16	
Misc. Handling Devices, etc.	=	2.00	
TOTAL MATERIAL		75.87	
On line labor - 4 men x 4 hrs x $8 (Ave) ÷ 7.17	=	17.85	
Off-line labor	=	10.00	
Labor overhead @ 250%	=	69.63	
TOTAL LABOR		97.48	
Forms - 2 sets @ $6000 each = $12,000 ÷ (7.17 x 205)	=	8.16	
Curing and handling equipment	=	6.00	
		14.16	
SUB TOTAL			187.51
+35% O.H. & Profit			65.63
FOB PLANT			253.14
Haul - Truck & Driver @ $20/hr - 4 units per day = 20 x 8 ÷ (4 x 7.17)			5.58
Crane - $500/day 5 man crew @ $18/hr x 8 x 5 = $720 Set 20 per day = 1220 ÷ (20 x 7.17)			8.51
267.23 x 7.17 = 1916 per unit or $14.09/S.F.			$267.23/cu. yd.

Cost per cu metre ≈ 1.31 x cost per cu yd.

Table 25. Case Study 3: Precast concrete estimate (continued)

2. BOX BEAMS

6.58 cu. yd./unit

8 units per bed

		Cost/cu. yd.	
Concrete (6000 psi)		33.00	
Strands - 21 (avg) x 38' long x $0.21/ft ÷ 6.58	=	25.47	
Reinforcing steel - 700 lb x $0.20/lb ÷ 6.58	=	21.28	
Embedded Steel Items - $40/beam ÷ 6.58	=	6.08	
Cardboard form - $100/unit ÷ 6.58	=	15.20	
Misc.	=	2.00	
		103.03	
On line labor - 10 men x 8 hrs x $8 (avg) ÷ (8 x 6.58)	=	12.16	
Off line labor (est)	=	5.00	
Labor Overhead @ 250%	=	42.90	
		60.06	
Equipment write-off			
Forms - 300 l.f. @ $125 x 10% = $3750 ÷ (112 x 6.58)		5.09	
Curing and handling equipment		6.00	
		11.09	
Diaphragms - $50/beam ÷ 6.58		7.60	
SUB TOTAL			189.38
+ 35% O.H. & Profit			66.28
			$255.66
Haul - truck & driver @ $20/hr - 4 units/day = 20 x 8 ÷ (4 x 6.58)			6.08
Set 20 per day = 1220 ÷ (20 x 6.58)	=		9.27
			$271.01/cu. yd.

271.01 x 6.58 = $1783.25 per unit or $13.11/S.F.

Table 25. Case Study 3: Precast concrete estimate (continued)

3. ROADWAY DECK (DOUBLE TEES)

3.93 cu. yd. per tee
8 units per bed

	Cost/cu. yd.	
Concrete (6000 psi)	33.00	
Strands 12 x 38' x $0.21/ft ÷ 3.93 =	24.37	
Reinforcing Steel 200 lb x $0.20/lb ÷ 3.93 =	10.18	
Embedded Steel Items $40/Tee ÷ 3.93 =	10.18	
Misc. =	2.00	
TOTAL MATERIAL	79.73	
On line labor - 8 men x 8 hrs x $8/hr ÷ (8 x 3.93) =	16.28	
Off line labor (est) =	5.00	
Labor Overhead @ 250%	53.20	
TOTAL LABOR	74.48	
Equipment write-off		
Forms - 300 l.f. @ $125 x 10% = $3750 ÷ (159 x 3.93)	6.00	
Curing & handling equipment	6.00	
TOTAL EQUIPMENT	12.00	
SUB TOTAL		166.21
+ 35% O.H. & Profit		58.17
		$224.38
Haul - truck & driver @ $20/hr - 6 units/day = 20 x 8 ÷ (6 x 3.93)		6.79
Crane - $500/day; 5 man crew @ $18/hr x 8 x 5 = $720; Set 20 per day = $1220 ÷ (20 x 3.93)		15.52
TOTAL		$246.69/cu. yd.

246.69 x 3.93 = $969.50 per unit or
$ 3.79/S.F.

Table 25. Case Study 3: Precast concrete estimate (continued)

4. ROOF SUPPORT COLUMNS

1.92 cu. yd. per unit
12 units per bed

	Cost/c. y.	
Concrete (6000 psi)	33.00	
Strands 4 x 25.33' x $0.21/ft ÷ 1.92	5.41	
Reinforcing Steel 10016 x $0.20/lb ÷ 1.92	10.42	
Embedded Steel Items $40/Col. ÷ 1.92	20.83	
Misc.	2.00	
TOTAL MATERIAL	71.66	
On line labor - 8 men x 8 hrs x $8/hr ÷ (12 x 1.92)	22.22	
Off line labor (est)	5.00	
Labor Overhead @ 250%	68.05	
TOTAL LABOR	95.27	
Equipment write-off		
Forms - 300 l.f. @ $125 x 20% - $7500 ÷ (635 x 1.92)	6.15	
Curing & handling equipment	6.00	
TOTAL EQUIPMENT	12.15	
SUBTOTAL		$179.08
+ 35% O.H. & Profit		62.68
		$241.76
Haul - truck & driver @ $20/hr - 12 units/day = 20 x 8 ÷ (12 x 1.92)	=	6.94
Crane - $500/day		
5 man crew @ $18/hr x 8 x 5 = $720/day		
set 20 per day - 1220 ÷ (20 x 1.92)		31.77
TOTAL		$280.47/cu. yd.

280.47 x 1.92 = $538.50 per unit or
$ 8.41/S.F.

Table 25. Case Study 3: Precast concrete estimate (continued)

5. INFILL WALL PANELS

13'-0 (avg)
40 cu. yd. per unit

		Cost/cu. yd.	
Concrete (5000 psi)		30.00	
Reinforcing Steel 15lb x $0.20/lb ÷ .4		7.50	
Embedded Steel $20 ÷ .4		50.00	
		6.00	
	TOTAL MATERIAL	93.50	
On line labor - 4 men x 4 hrs @ $8/hr ÷ (15 x .4)	=	21.33	
Off line labor (est)		10.00	
Labor Overhead @ 250%		78.33	
	TOTAL LABOR	109.66	
Equipment write-off Forms, curing & handling equipment, etc.		12.00	
	SUBTOTAL		$215.16
	+ 35% O. H. & Profit		75.31
			$290.47
Haul - truck & driver @ $20/hr - 60 units/day 20 x 8 ÷ (60 x .4)	=		6.67
Crane & 5 man crew = $500 + $18/hr x 8 hrs x 5 = $1220 Set 20 per day = 1220 ÷ (20 x .4)			152.50
	TOTAL		$449.64/cu. yd.

$449.64 x .4 = $179.86 per unit or
$ 6.92/S.F.

Table 26. Case Study 3: Construction cost estimate system using cast-in-place construction
Total Cost - Sta. 49 + 00 - 53 + 50

Item	Performed by	Cost to Gen Contr.	G. C. O.H. & P (%)	Cost to Owner
1. Open Excavation	G. C.	$ 124,293	25	$ 155,366
2. Gravel Base	G. C.	11,733	25	14,666
3. 6 inch Base Slab	G. C.	22,344	25	27,930
4. Waterproofing	Sub	198,720	10	218,592
5. Structure	G. C.	1,217,925	25	1,522,406
6. Roadway Deck Supports	G. C.	92,250	25	115,313
7. Roadway Deck	Sub	44,343	10	48,777
8. Wearing Surface	G. C.	11,710	25	14,638
9. Backfill	G. C.	88,293	25	110,366
10. Finished Wall	Sub	63,000	10	69,300
				$2,297,354

Table 27. Case Study 3: Construction cost estimate system using cast-in-place construction
Total Cost - Sta. 44 + 50 - 49 + 00

Item	Performed by	Cost to Gen Contr.	G. C. O.H. & P (%)	Cost to Owner
1. Side-Enclosed Excavation	G. C.	$ 162,657	25	$ 203,321
2. Steel Sold Piles - Material	Sub	287,980	10	316,778
3. Steel Sold Piles - Placing	Sub	30,800	10	33,880
4. Timber Lagging	G. C.	125,000	25	156,250
5. Steel Struts	G. C.	228,047	25	285,059
6. Steel Wales	G. C.	95,175	25	118,969
7. Concrete Struts	G. C.	81,120	25	101,400
8. Gravel Base	G. C.	11,733	25	14,666
9. 6 inch Base Slab	G. C.	22,344	25	27,930
10. Waterproofing	Sub	210,060	10	231,066
11. Structure	G. C.	1,116,225	25	1,395,281
12. Roadway Deck Supports	G. C.	92,250	25	115,313
13. Roadway Deck	Sub	44,343	10	48,777
14. Wearing Surface	G. C.	11,710	25	14,638
15. Backfill	G. C.	142,108	25	177,635
16. Finished Wall	Sub	63,000	10	69,300
				$3,310,263

Table 28. Case Study 3: Construction cost estimate system using cast-in-place construction
Total Cost - Sta. 40 + 80 - 44 + 50

Item	Performed by	Cost to Gen. Contr.	G. C. O.H. & P (%)	Cost to Owner
1. Side-Enclosed Excavation	G. C.	$ 163,482	25	$ 204,353
2. Steel Struts	G. C.	372,350	25	465,438
3. Concrete Struts	G. C.	89,440	25	111,800
4. Guide Trench	Sub	18,500	10	20,350
5. Slurry Wall	Sub	1,843,920	10	2,028,312
6. Gravel Base	G. C.	9,646	25	12,058
7. 6 inch Base Slab	G. C.	18,372	25	22,965
8. Waterproofing	Sub	172,716	10	189,988
9. Structure	G. C.	917,785	25	1,147,231
10. Roadway Deck Supports	G. C.	75,850	25	94,813
11. Roadway Deck	Sub	36,460	10	40,106
12. Wearing Surface	G. C.	9,628	25	12,035
13. Backfill	G. C.	171,354	25	214,193
14. Finished Wall	Sub	51,800	10	56,980
				$4,620,622

Table 29. Case Study 3: Construction cost estimate system using cast-in-place construction Total Cost for Project

Item	Performed by	Cost to Gen Contr.	G. C. O.H. & P (%)	Cost to Owner
1. Open Excavation	G. C.	$ 124,293	25	$ 155,366
2. Side-Enclosed Excavation	G. C.	326,139	25	407,674
3. Steel Sold. Piles-Material	Sub	287,980	10	316,778
4. Steel Sold. Piles-Placing	Sub	30,800	10	33,880
5. Timber Lagging	G. C.	125,000	25	156,250
6. Steel Struts 44+50-49+00	G. C.	228,047	25	285,059
7. Steel Struts 40+80-44+50	G. C.	372,350	25	465,438
8. Steel Wales	G. C.	95,175	25	118,969
9. Concrete Struts	G. C.	170,560	25	213,200
10. Guide Trench	Sub	18,500	10	20,350
11. Slurry Wall	Sub	1,843,920	10	2,028,312
12. Gravel Base	G. C.	33,112	25	41,390
13. 6 inch Base Slab	G. C.	63,060	25	78,825
14. Waterproofing 49+00-53+50	Sub	198,720	10	218,592
15. Waterproofing 40+80-49+00	Sub	382,776	10	421,054
16. Structure 49+00-53+50	G. C.	1,217,925	25	1,522,406
17. Structure 40+80-49+00	G. C.	2,034,010	25	2,542,512
18. Roadway Deck Supports	G. C.	260,350	25	325,439
19. Roadway Deck	Sub	125,146	10	137,660
20. Wearing Surface	G. C.	33,048	25	41,311
21. Backfill 49+00-53+50	G. C.	88,293	25	110,366
22. Backfill 40+80-49+00	G. C.	313,462	25	391,828
23. Finished Wall	Sub	177,800	10	195,580
				$10,228,239

Table 30. Case Study 3: Construction Cost estimate system using cast-in-place construction Costs to General Contractor

Item No.	Item		Cost to G. C. (Dollars)
1	Open Excavation - Sta. 49 + 00 - 53 + 50 82862 c. y. @ $1.50/c. y.		$124,293
2	Side-Enclosed Excavation - Sta. 40 + 80 - 49 + 00 108713 c. y. @ $3.00/c. y.		326,139
3	Steel Soldier Piles - Sta. 44 + 50 - 49 + 00 (Material only) Cost + $0.22/lb - $0.05/lb Net Salvage Profit after removal + $0.17/lb 7700 l.f. x 220 plf @		287,980
4	Steel Soldier Piles - Sta. 44 + 50 - 49 + 00 (Placing - Driving or Jetting) 7700 l. f. @ $4.00 plf (Includes Sub O. H. & Profit)		30,800
5	Timber Lagging - Sta. 44 + 50 - 49 + 00 250 MFBM @ $600/MFBM - $100/MFBM Salvage =		125,000
6	Temp. Steel Struts - Sta. 44 + 50 - 49 + 00 (Assume 25% Reuse Factor) Labor (52/34) x 1410 lb/ft x 450 ft x $0.16/lb Mat. - .75 x (.20/.16) x $155266 Net Salvage - .5 x $145562	= 155,266 = 145,562 = -72,781	228,047
7	Temp. Steel Struts - Sta. 40 + 80 - 44 + 50 Labor (52/34) x 2800 lb/ft x 370 ft x $0.16/lb Mat. - .75 x (.20/.16) $253515 Net Salvage - .5 x $237670	= 253,515 = 237,670 =-118,835	372,350
8	Steel Wales - Sta. 44 + 50 - 49 + 00 (Assume 150 lb/ft Material & 25% Reuse) Total - 2700 l. f. Labor - 2700 l.f. x 150 lb/l.f. x $0.16/lb Mat. - .75 x (.20/.16) x $64800 Net Salvage - .5 x $60750	= 64,800 = 60,750 = -30,375	95,175
9	Concrete Struts - Sta. 40 + 80 - 49 + 00 (Not Removed) - 82 required 82 x 52 ft. x $40/l.f.	=	170,560
10	Guide Trench - Sta. 40 + 80 - 44 + 50 $50 per ft of Tunnel (from CS-1 and Includes Sub Contractor O. H. & Profit) $50 x 370 ft	=	18,500

Conversion to SI units shown on pg xi

Table 30. Case Study 3: Construction Cost estimate system using cast-in-place construction (continued)
Costs to General Contractor

Item No.	Item		Cost to G. C. (Dollars)
11	Slurry Wall - Sta. 40 + 80 - 44 + 50		
	Soil information indicates easy digging.		
	Cost information from ICOS.		
	$30/S.F. x 61464 S.F. (Includes Sub O.H. & Profit)		$1,843,920
12	Gravel Base - Sta. 40 + 80 - 53 + 50		
	$8/c.y. x 4139 c.y.		33,112
13	6 inch Base Slab - Sta. 40 + 80 - 53 + 50		
	Concrete - 1270 x 40 x .5 ÷ 27 = 941 c.y. @ $45/c.y.	= 42,334	
	Reinforcing (Assuming #4 @ 12 each way) 1.36 psf x 1270 x 40 x $0.30/lb	= 20,726	63,060
14	4-Ply Membrane Waterproofing - Sta. 49 + 00 - 53 + 50		
	2 x 40 ft x 450 ft @ $2.80	= 100,800	
	2 x 34 ft x 450 ft @ $3.20	= 97,920	
	(Includes Sub O.H. & Profit)		198,720
15	4-Ply Membrane Waterproofing - Sta. 40 + 80 - 49 + 00		
	1 x 40 x 820 @ $2.80	= 91,840	
	2 x 20 x 820 @ $3.20	= 104,960	
	1 x 63 x 820 @ $3.60	= 185,976	
	(Includes Sub O.H. & Profit)		382,776
16	Structure - Sta. 49 + 00 - 53 + 50		
	Concrete - 26.5 c.y./ft x 450 ft x $45/c.y.	= 536,625	
	Reinforcing - 3250 lb/ft x 450 x $0.30/lb	= 438,750	
	Formwork - 2 x (34 + 11 + 6 + 12) + 1 x (28) = 154 S.F./ft x 450 = 69300 S.F.		
	69300 S.F. @ $3.50/S.F.	= 242,550	1,217,925
17	Structure - Sta. 40 + 80 - 49 + 00		
	Concrete - 24.5 c.y./ft x 820 ft @ $45 c.y.	= 904,050	
	Reinforcing - 1920 lb/ft x 820 ft x $0.30/lb	= 472,320	
	Formwork - 52 S.F./ft x 820 @ $3.50/S.F.	= 149,240	
	- 124 S.F./ft x 820 @ $5.00/S.F.	= 508,400	2,034,010
18	Roadway Deck Supports - Sta. 40 + 80 - 53 + 50 (Does not include cost of rough-in)		
	Concrete - 2 c.y./ft x 1270 ft @ $45	= 114,300	
	Reinforcing - 75 lb/c.y. x 2 x 1270 @ $0.30	= 57,150	
	Formwork - 20 S.F./ft x 1270 ft @ $3.50	= 88,900	260,350

Table 30. Case Study 3: Construction Cost estimate system using cast-in-place construction (continued)
Costs to General Contractor

Item No.	Item		Cost to G. C. (Dollars)
19	Roadway Deck - Sta. 40 + 80 - 53 + 50 (Assume precast) See detailed breakdown $3.79/S.F. x 26 x 1270 (Includes Sub O.H. & Profit)		125,146
20	4 inch Wearing Surface Concrete - 408 c.y. @ $45/c.y. Reinforcing - 120 lb/c.y. x 408 @ $0.30	 = 18,360 = 14,688	33,048
21	Backfill - Sta. 49 + 00 - 53 + 50 48862 c.y. @ 1.50		88,293
22	Backfill - Sta. 40 + 80 - 49 + 00 Hand backfill & compaction 24.4 c.y./ft x 820 ft @ $8.00/c.y. Machine backfill & compaction 43828 c.y. @ $3.50/c.y.	 = 160,064 = 153,398	313,462
23	Finished Wall - Sta. 40 + 80 - 53 + 50 (Includes Sub Contractor O.H. & Profit) Assume 4 inch glazed tile 28 S.F./ft x 1270 ft @ 5.00		177,800

See Summary Sheet for Overhead and Profit

E. SUMMARY COMPARISON

1. Construction Time: From the CPM outputs and the summary tables below, it can be seen that the total project time for the precast method is about 18-1/2 months versus about 26 months for the cast-in-place system. Also, that this time savings appears to be independent of the construction method used by the cast-in-place system. In each of the three segments and in the total project time, the precast method shows roughly a 30% - 40% time savings.

Table 31. Comparison of construction time for Case Study 3

a. System using cast-in-place construction

Segment of Total Project	Earliest Start of Excavation	Earliest Finish of Segment	Add. Time Prior to Exc. (Months)	Duration (Months)
Sta. 49 + 00 - 53 + 50	1 Mar 78	27 Feb 79	---	12
Sta. 44 + 50 - 49 + 00	26 May 78	21 Aug 79	1	16
Sta. 40 + 80 - 44 + 50	16 Feb 79	6 May 80	2	16.7
Total Project	1 Mar 78	6 May 80	---	26

b. System using prefabricated components

Segment of Total Project	Earliest Start of Excavation	Earliest Finish of Segment	Add. Time Prior to Exc. (Months)	Duration (Months)
Sta. 49 + 00 - 53 + 50	21 Mar 78	4 Oct 78	2/3	7.5
Sta. 44 + 50 - 49 + 00	7 Aug 78	16 Apr 79	1-1/2	9.5
Sta. 40 + 80 - 44 + 50	27 Nov 78	18 Sep 79	2	11.7
Total Project	21 Mar 78	18 Sep 79	2/3	18.5

As in the other case studies, it should be noted that only optimum conditions have been assumed, that no allowances have been made for severe weather or learning time in the early stages, and that only the "structural phase" has been considered.

2. Costs: The cost estimates in Tables 20-30 are summarized below. Notice, that while the precast method shows a savings over the whole project, it is not the most economical in certain segments.

Table 32. Cost comparisons for Case Study 3

Segment of Total Project	Cast-in-Place System	Precast System	Savings in Costs
Sta. 49 + 00 - 53 + 50	$ 2,297,354	$2,514,340	$ 216,986 (C)
Sta. 44 + 50 - 49 + 00	3,310,263	3,329,520	19,257 (C)
Sta. 40 + 80 - 44 + 50	4,620,622	3,490,845	1,129,777 (P)
Total Project	10,228,239	9,334,705	893,534 (P)

In the segment where soldier piles and lagging are used by the cast-in-place system (Sta. 44 + 50 - 49 + 00), the cost difference is only about one-half of one percent; not within the accuracy of this estimate. Therefore, while the cost advantage could slightly favor either method, the two must be considered roughly equal.

In the other two segments, however, the two systems are not equal. Clearly, when open excavation is possible, the cast-in-place system is more cost efficient; roughly 9%. However, when slurry walls are required because of the depth of the excavation or as a water constraint, they should be incorporated into the final design. If they are not, and conventional cast-in-place methods are used, the cost can be substantially higher; 32% in this case.

APPENDIX

DETAILED DESIGN DRAWINGS

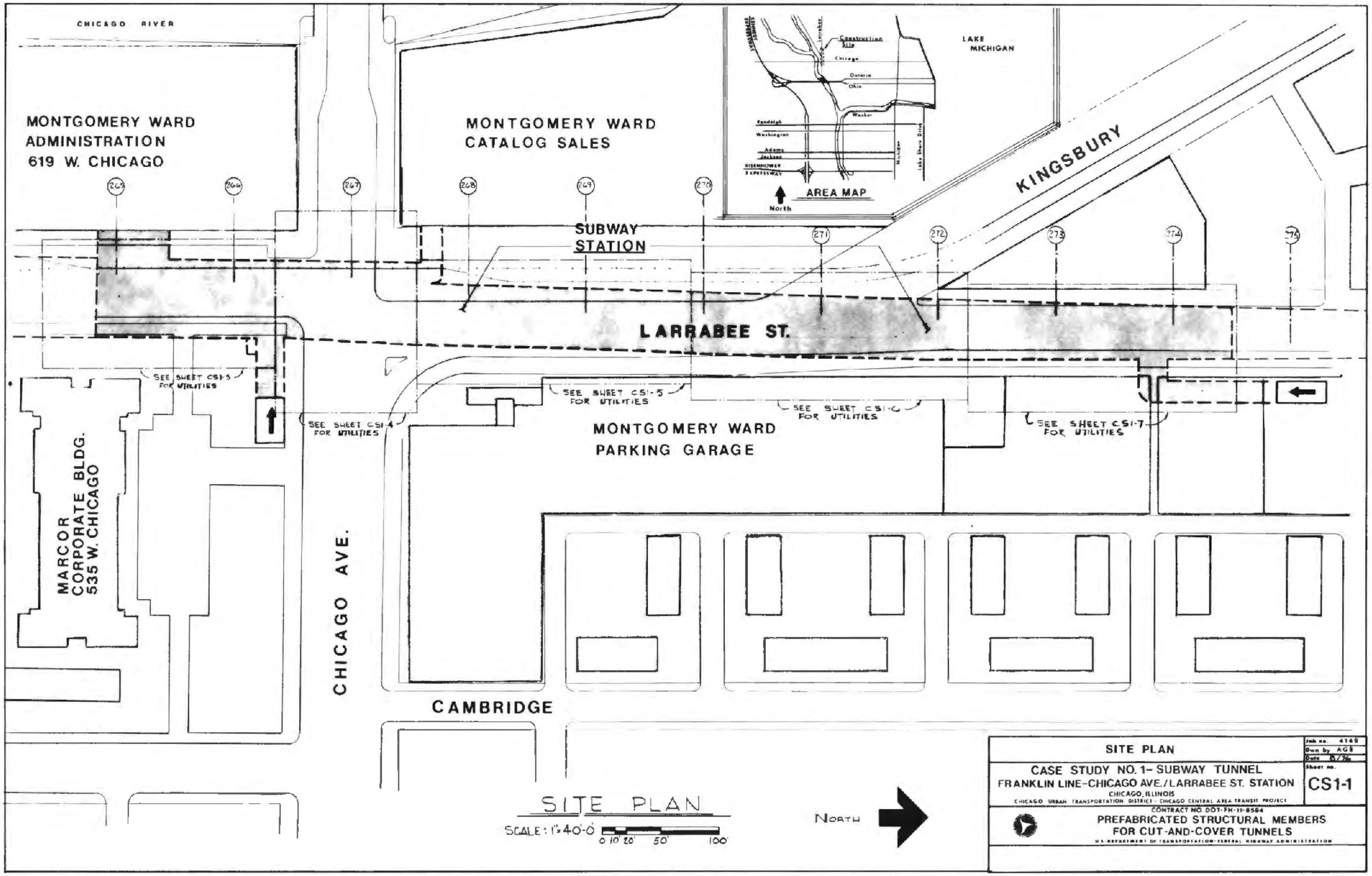


Fig. 16. Case Study 1: Site plan

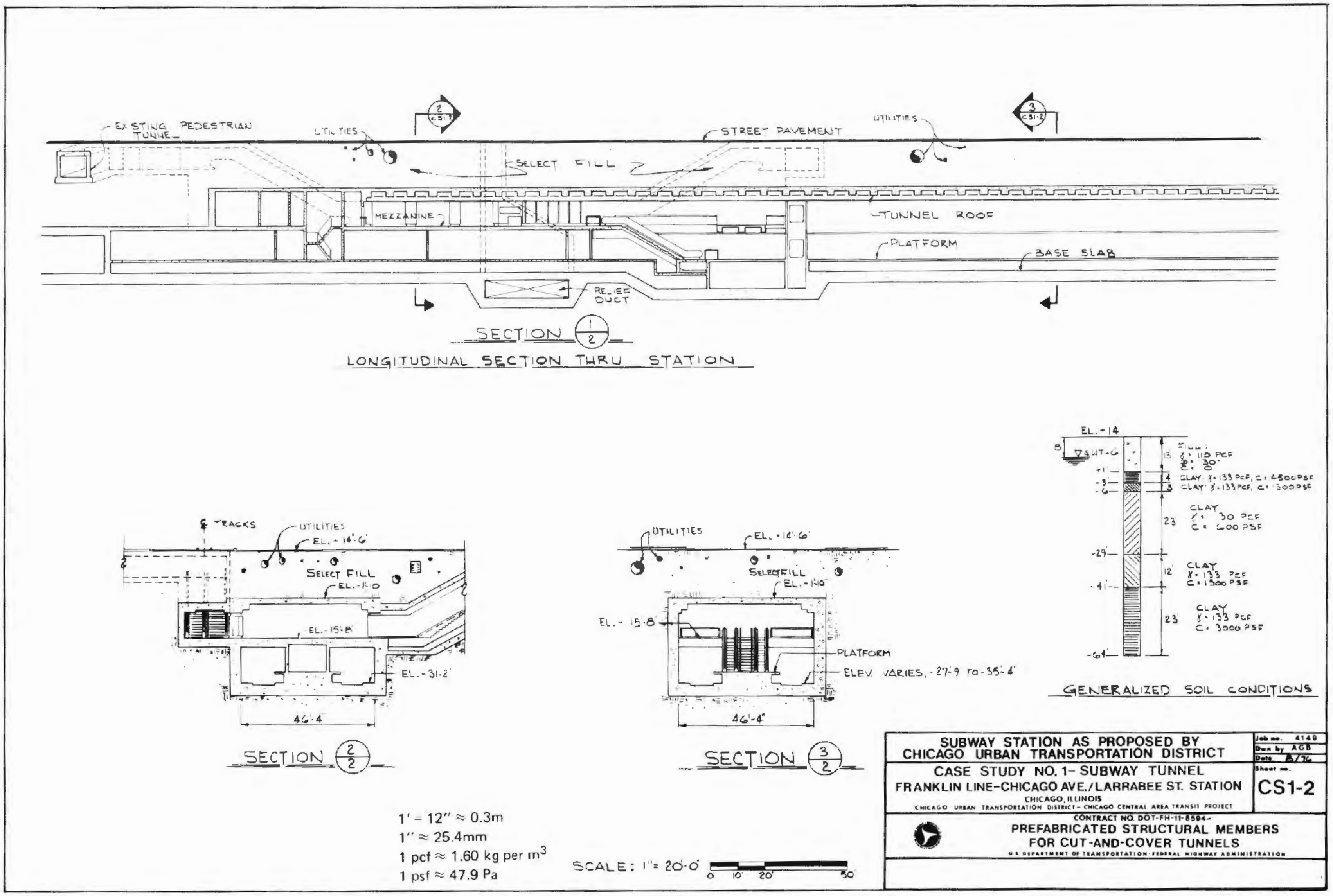


Fig. 17. Case Study 1: Subway station as proposed by Chicago Urban Transportation District

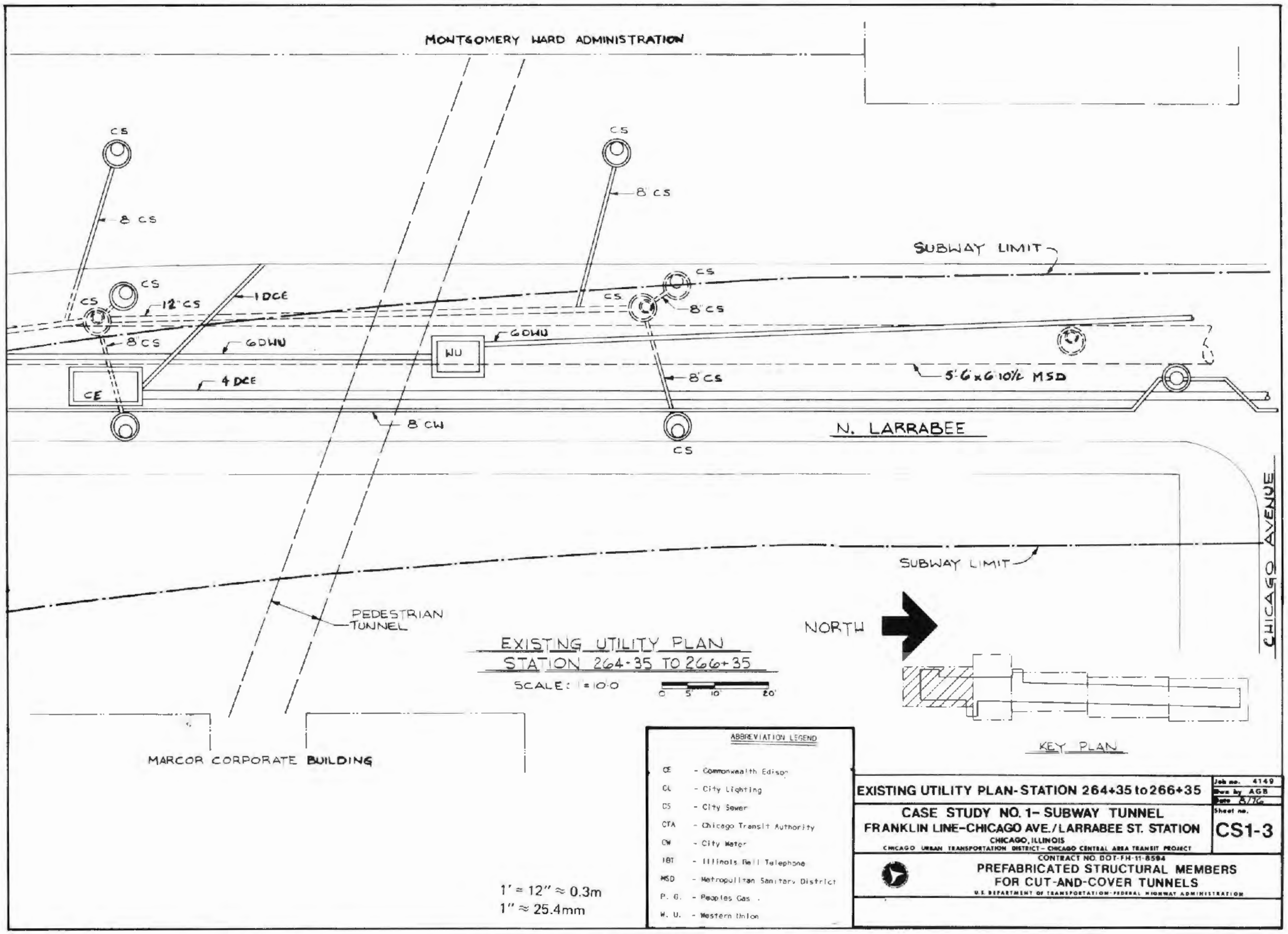


Fig. 18. Case Study 1: Existing utility plan - Station 264 + 35 to 266 + 35

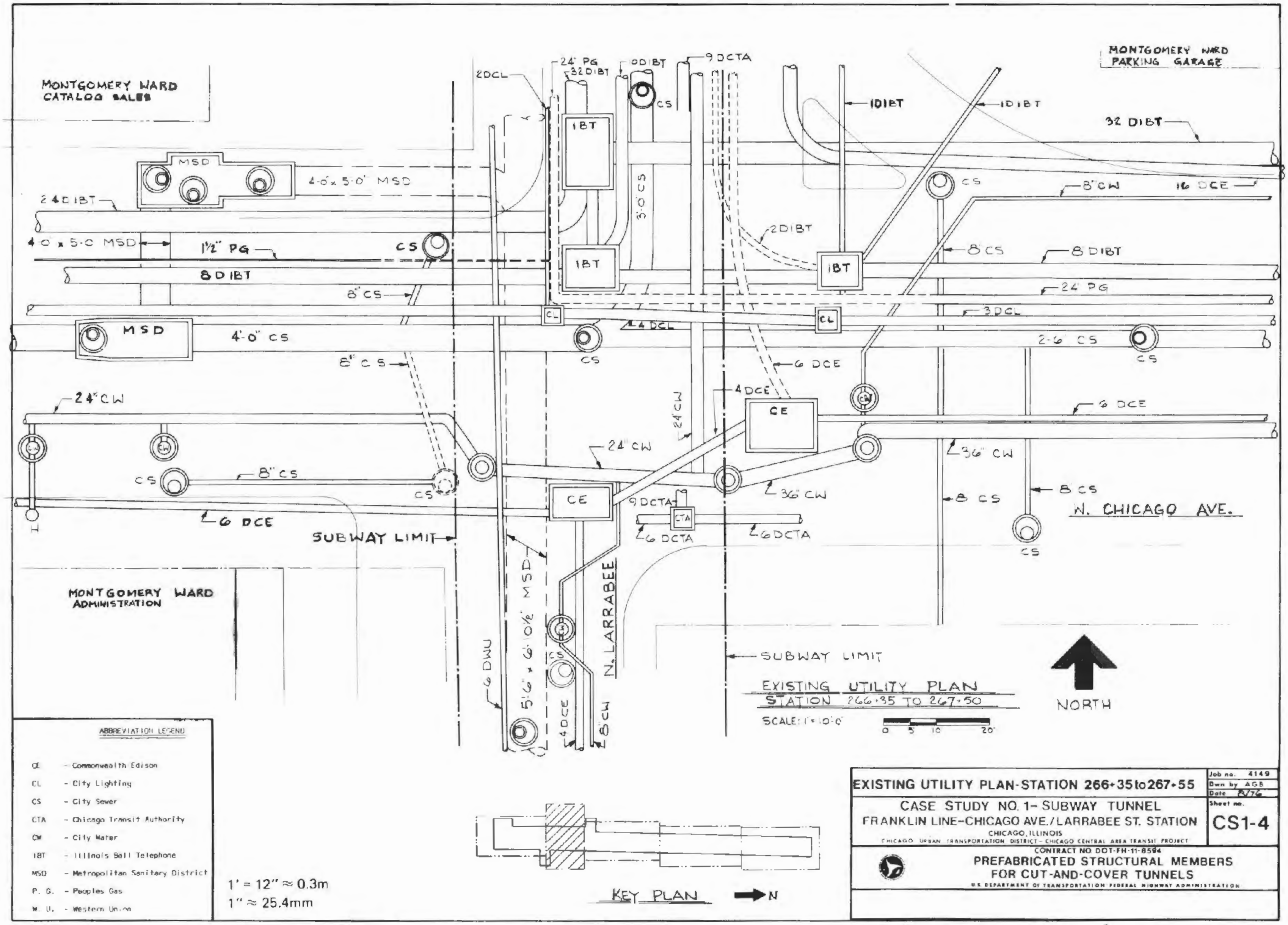


Fig. 19. Case Study 1: Existing utility plan - Station 266 + 35 to 267 + 55

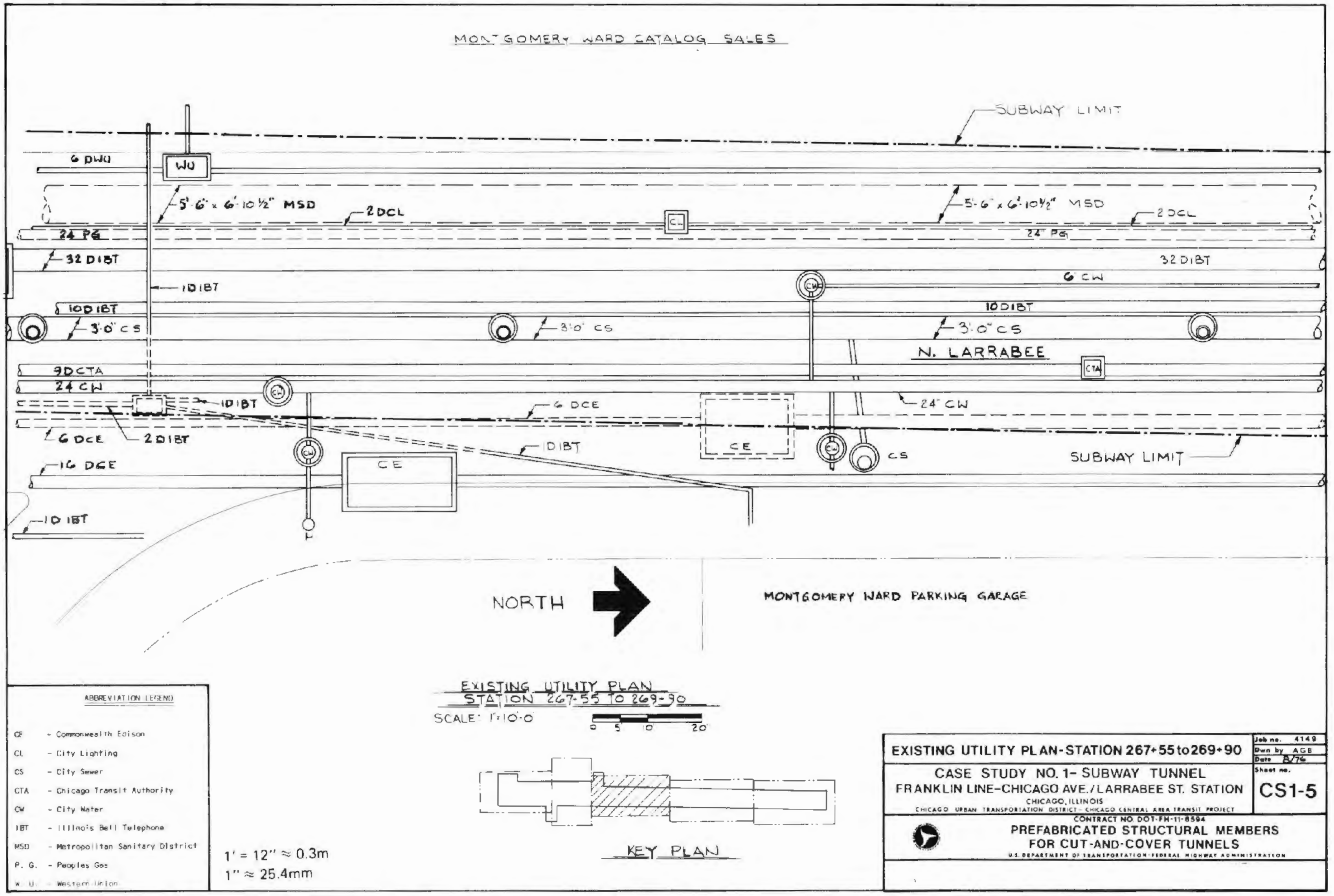


Fig. 20. Case Study 1: Existing utility plan - Station 267 + 55 to 269 + 90

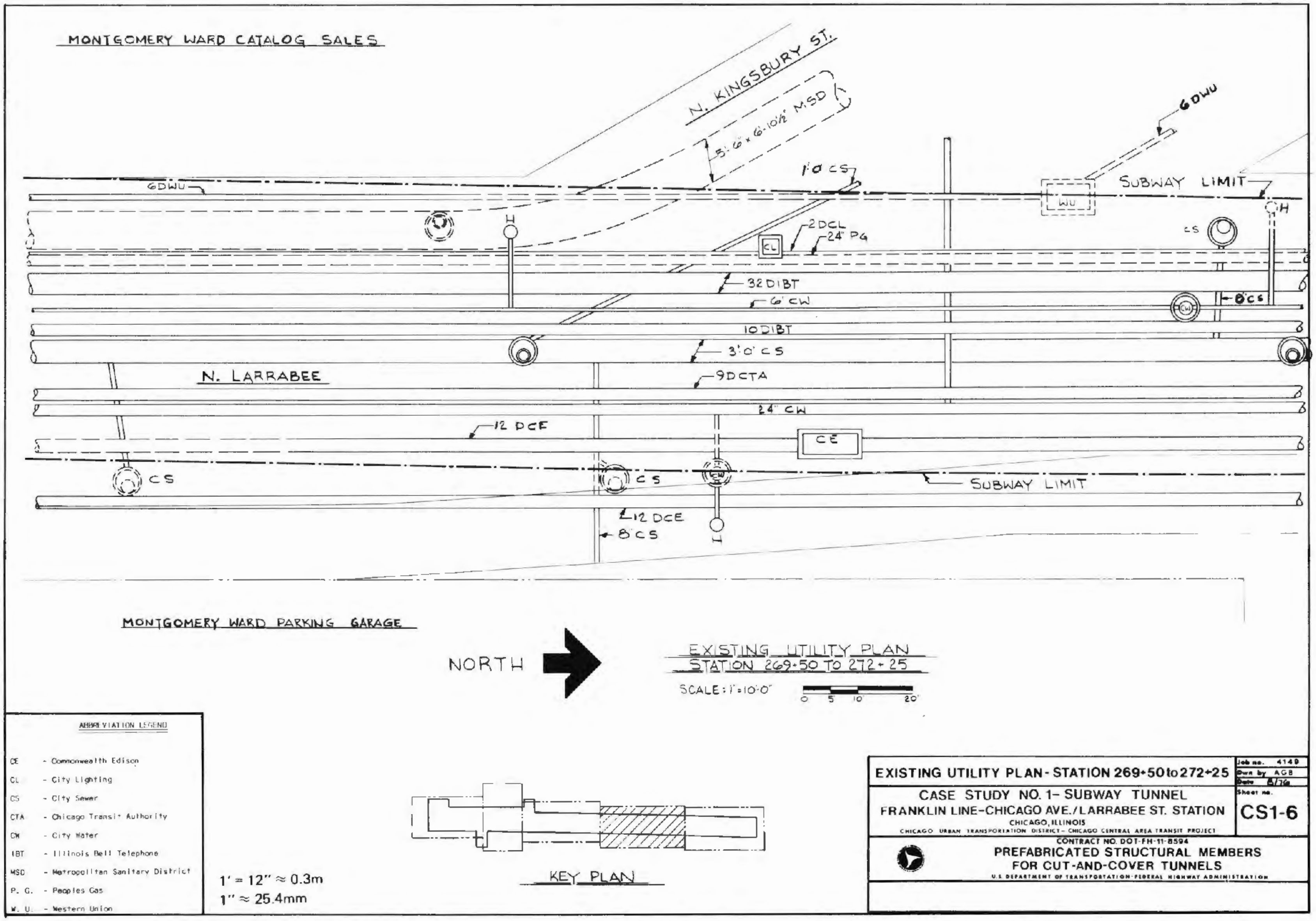


Fig. 21. Case Study 1: Existing utility plan - Station 269 + 50 to 272 + 25

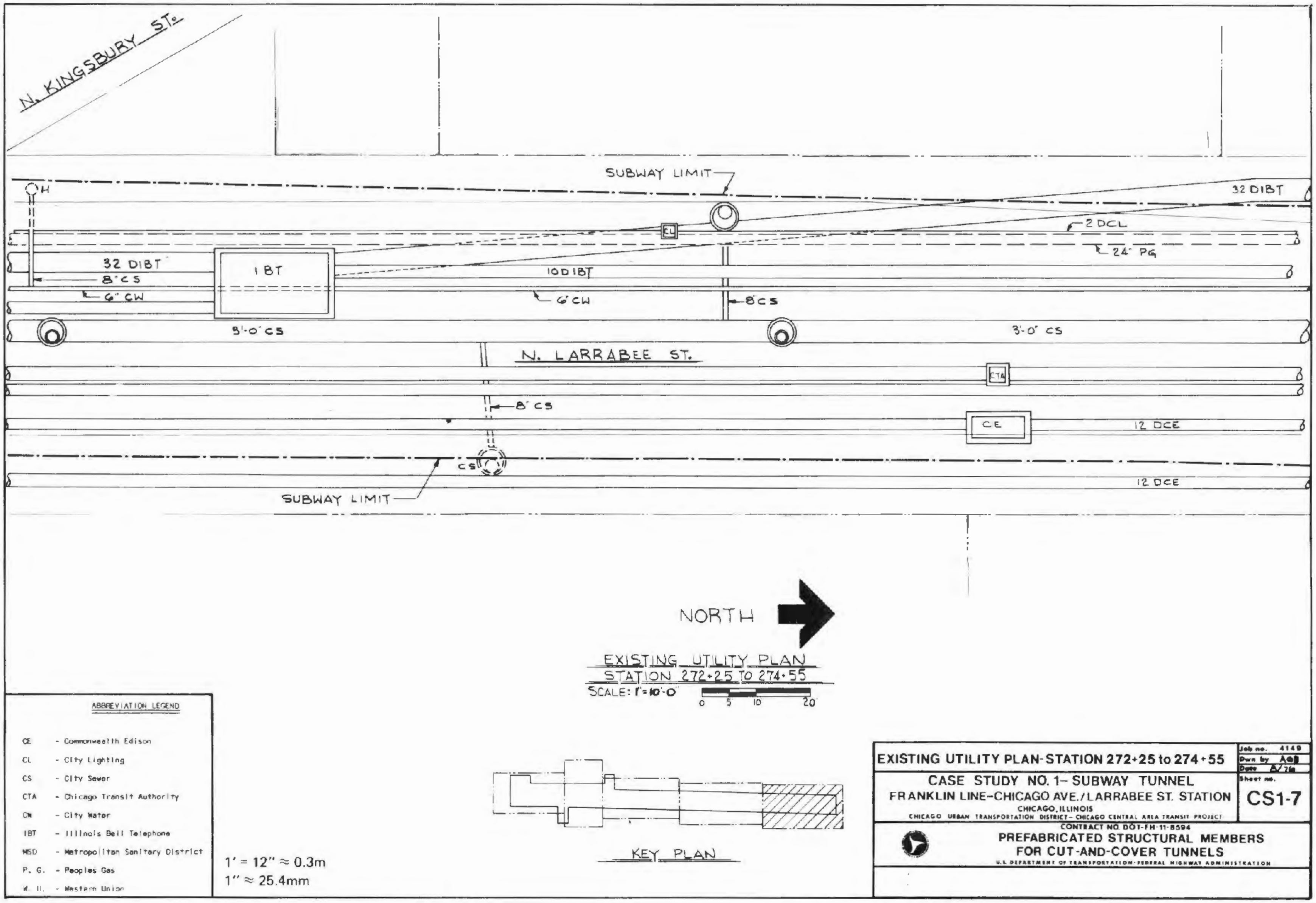


Fig. 22. Case Study 1: Existing utility plan - Station 272 + 25 to 274 + 55

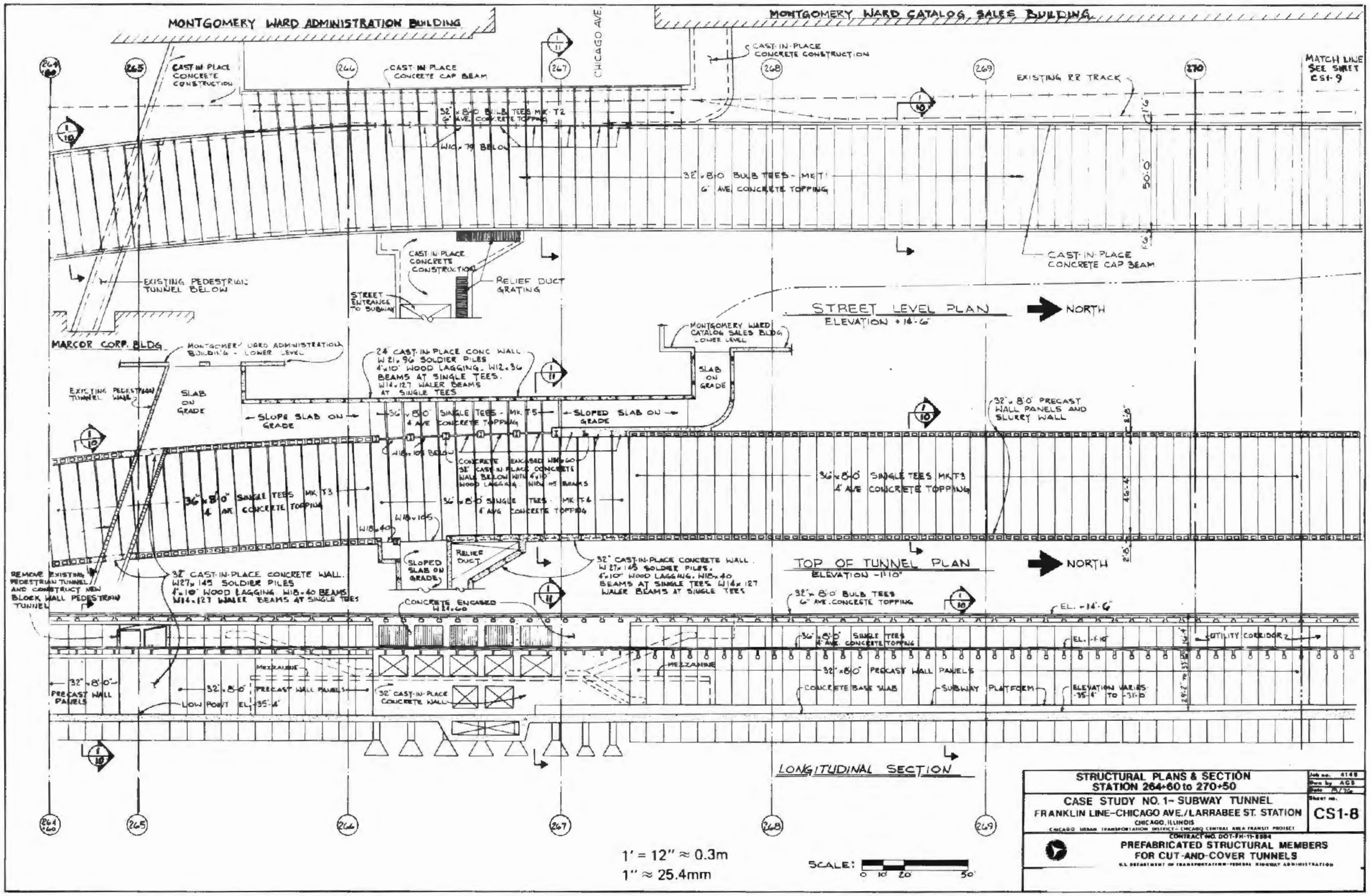


Fig. 23. Case Study 1: Structural plans & section - Station 264 + 60 to 270 + 50

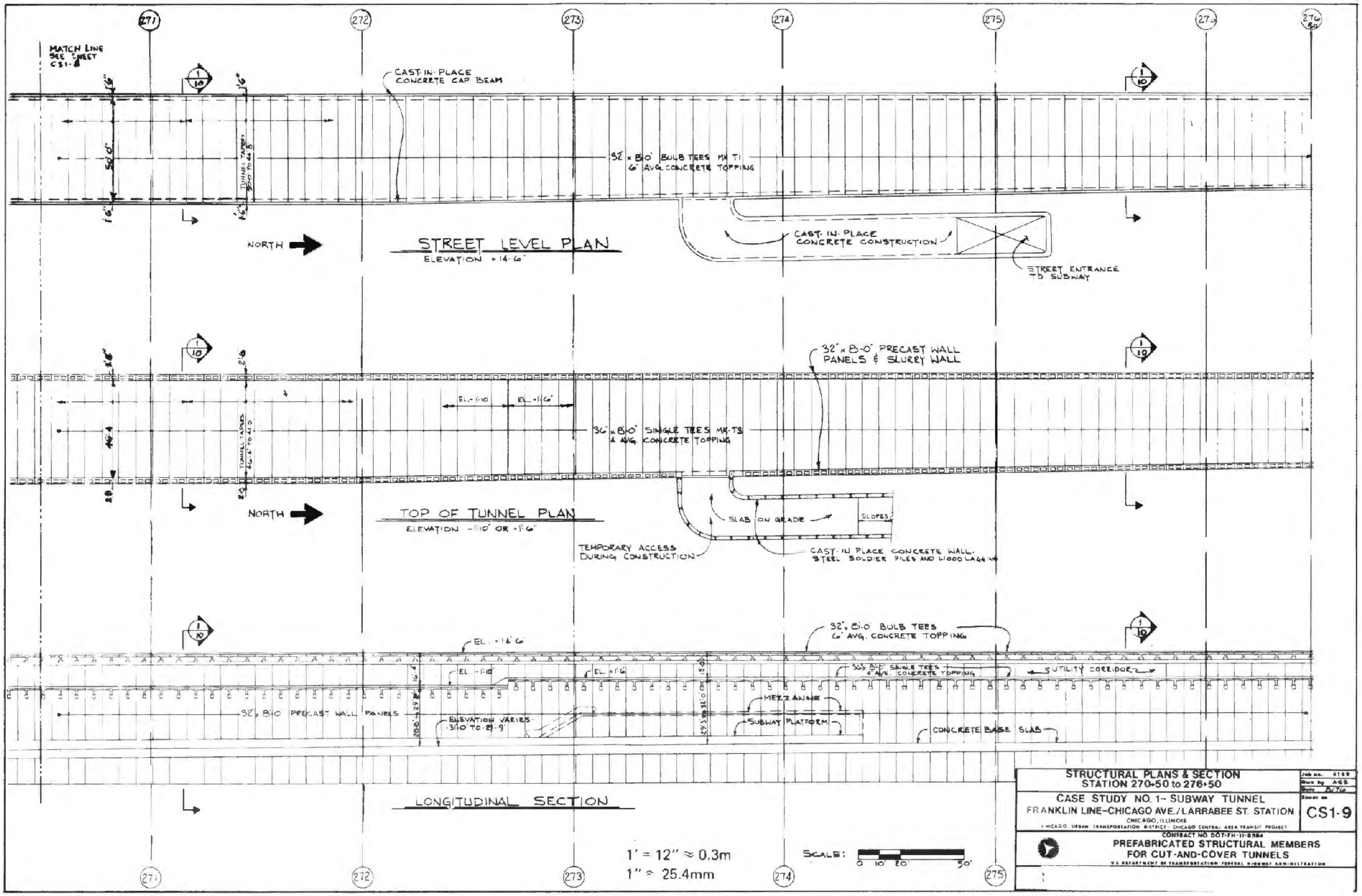


Fig. 24. Case Study 1: Structural plans & section - Station 270 + 50 to 276 + 50

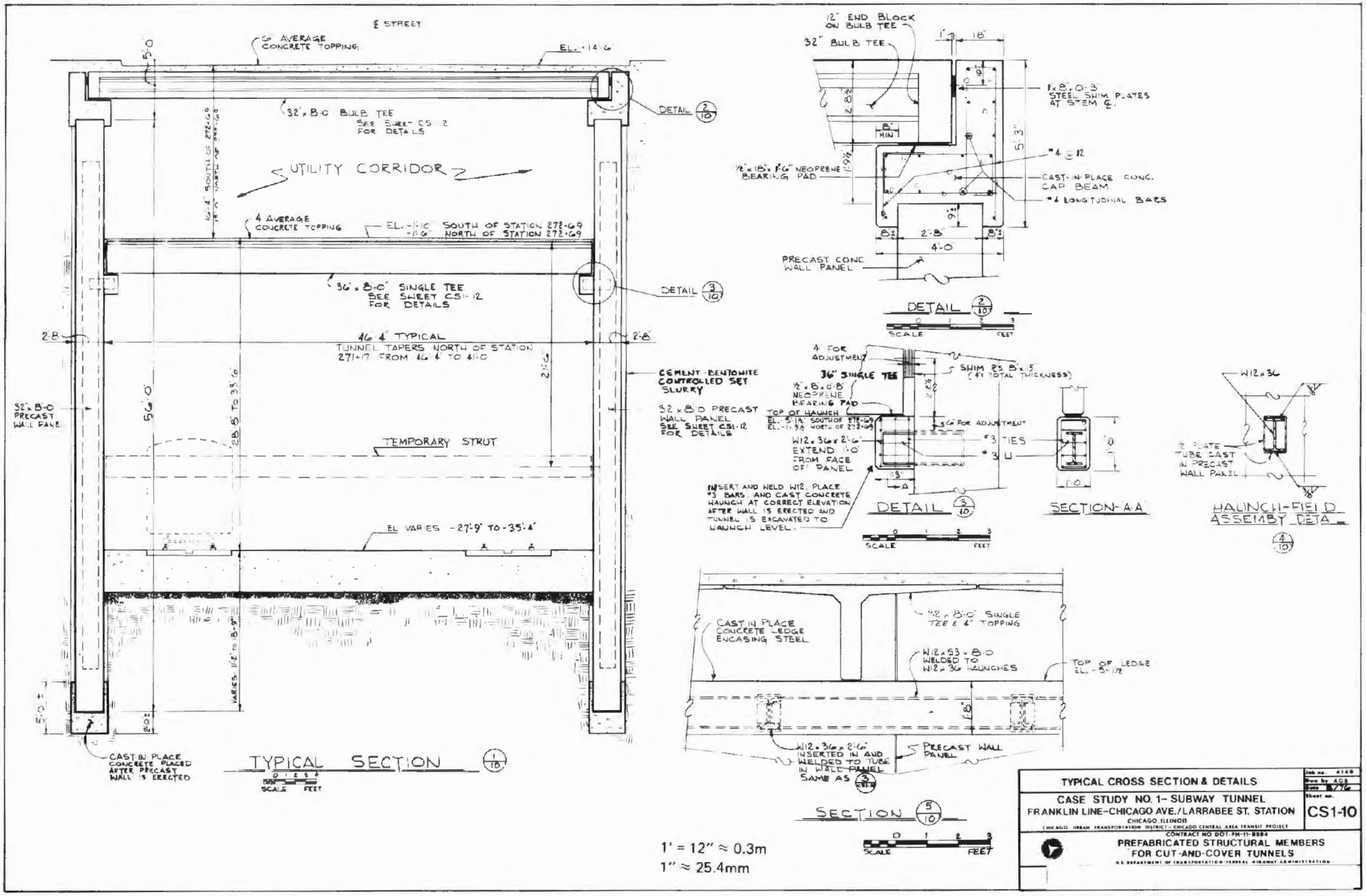


Fig. 25. Case Study 1: Typical cross section & details

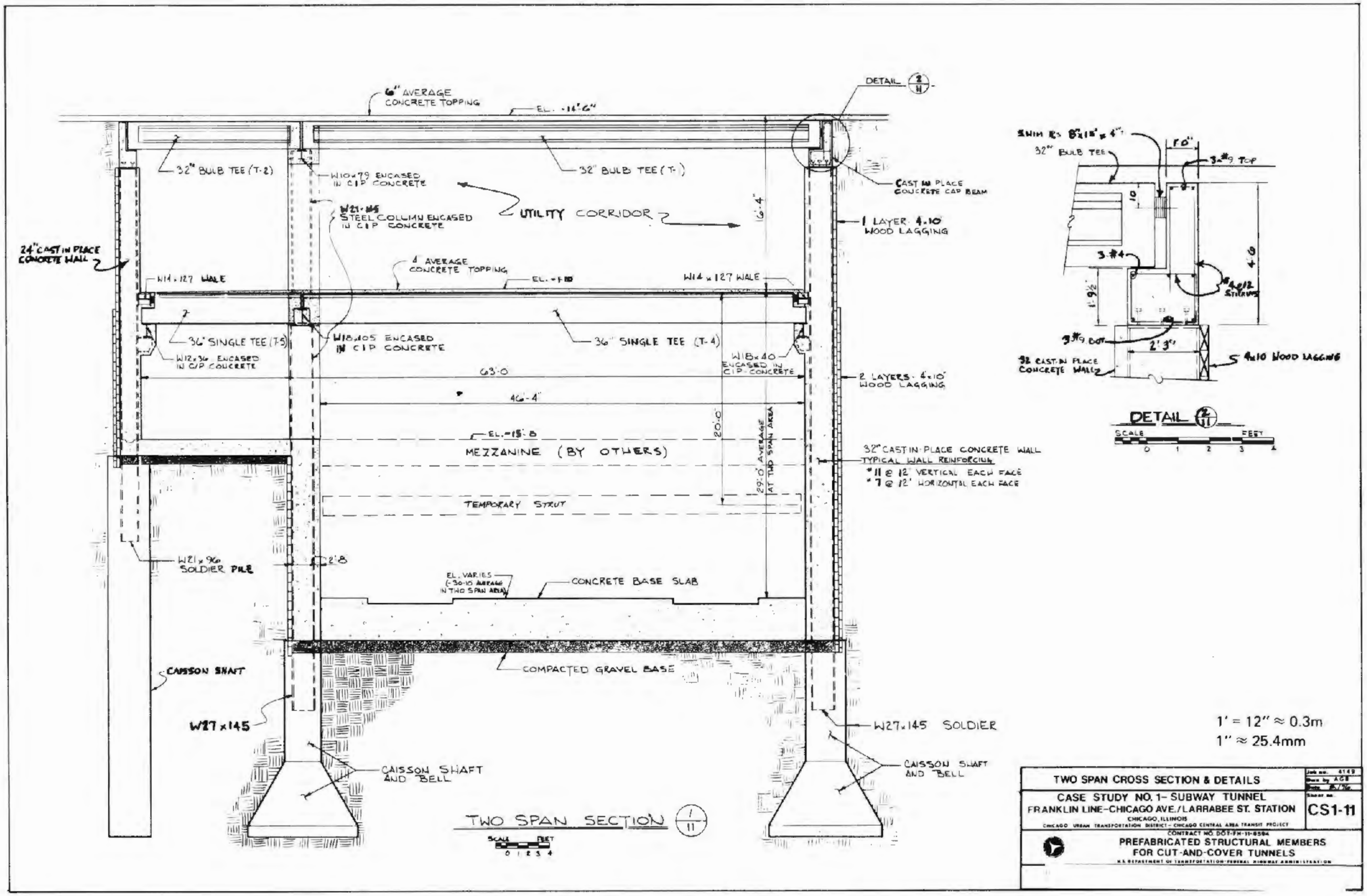


Fig. 26. Case Study 1: Two span cross section & details

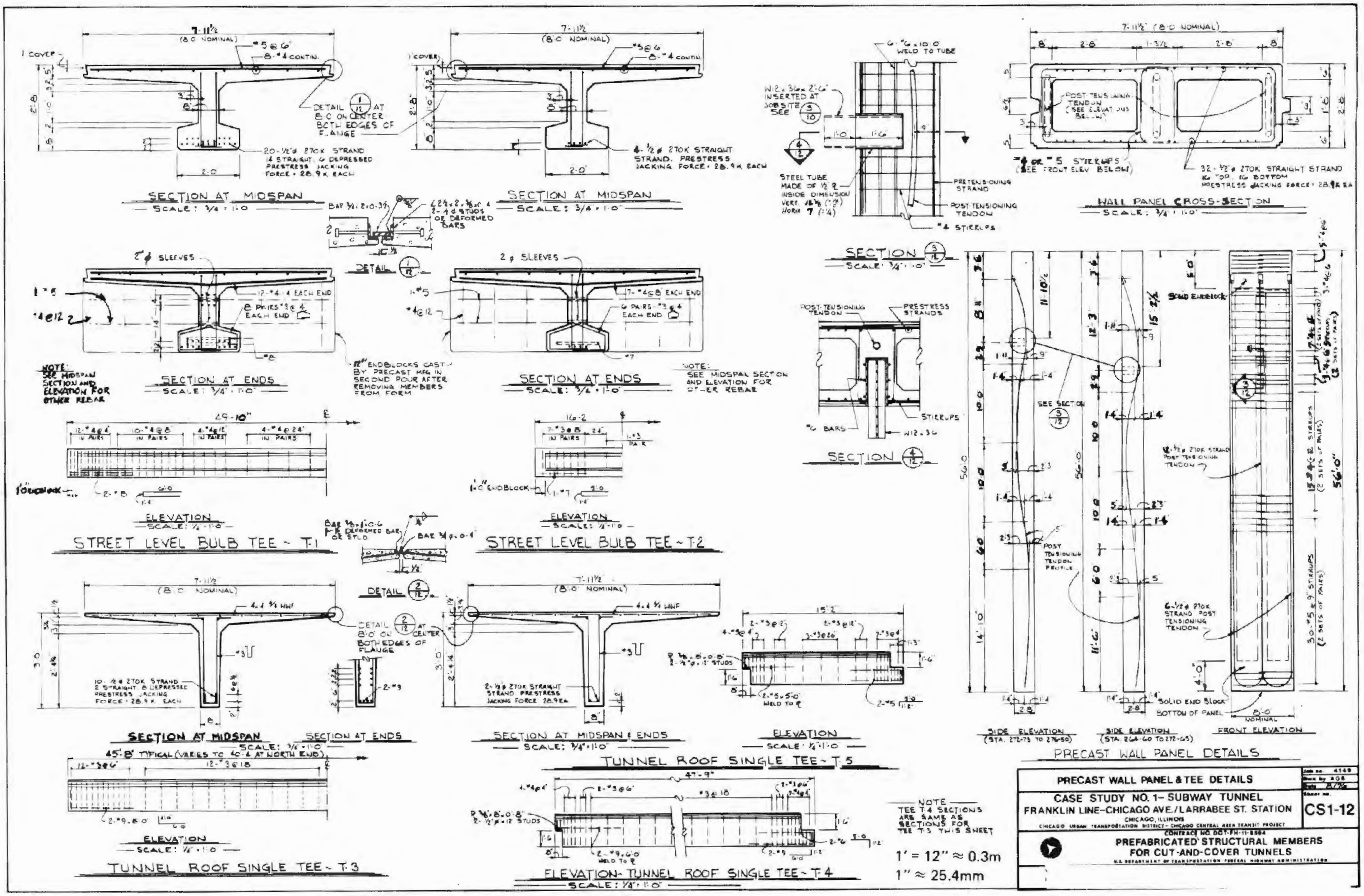


Fig. 27. Case Study 1: Precast wall panel & tee details

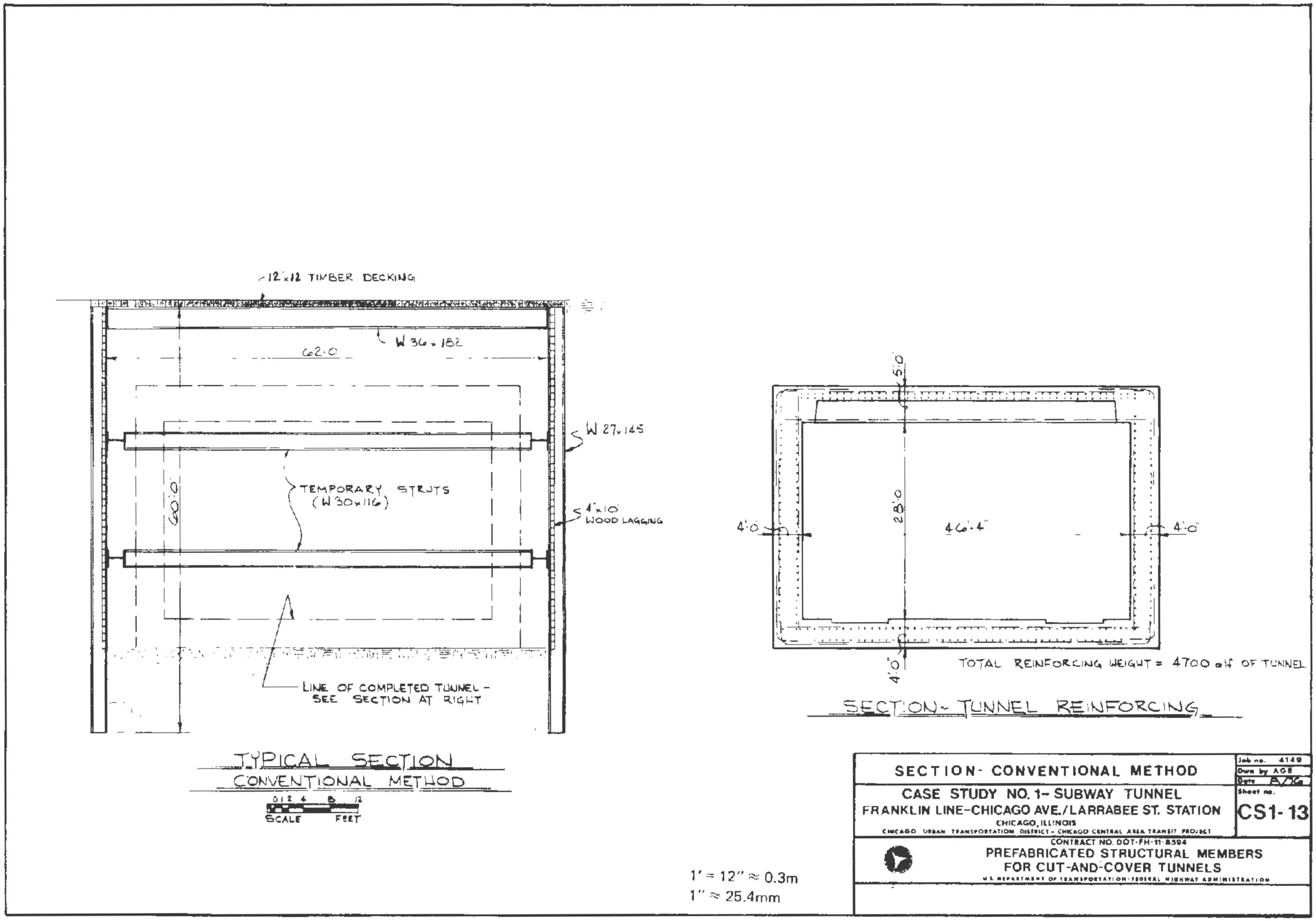


Fig. 28. Case Study 1: Section - Conventional method

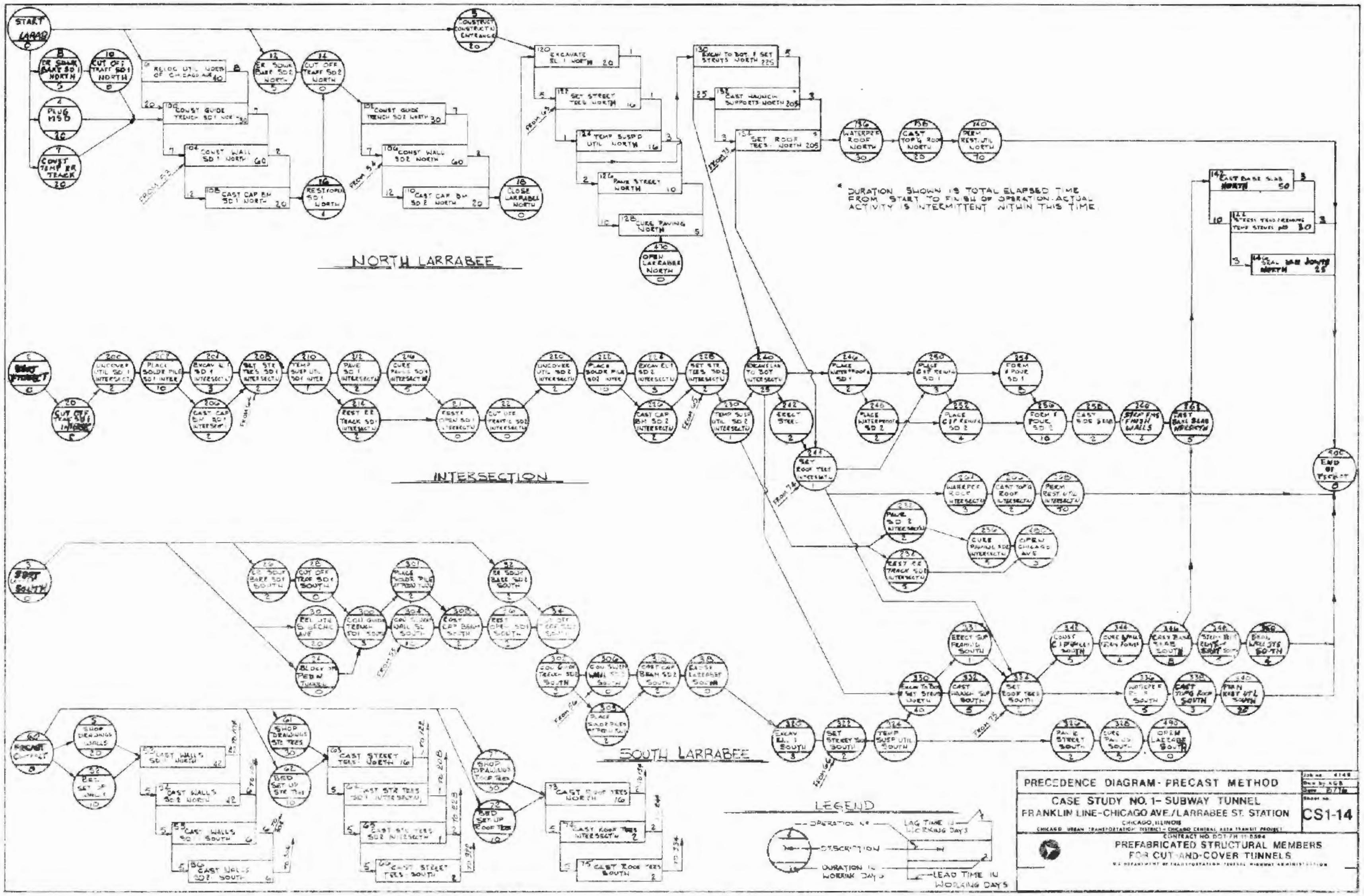


Fig. 29. Case Study 1: Precedence diagram - Precast method

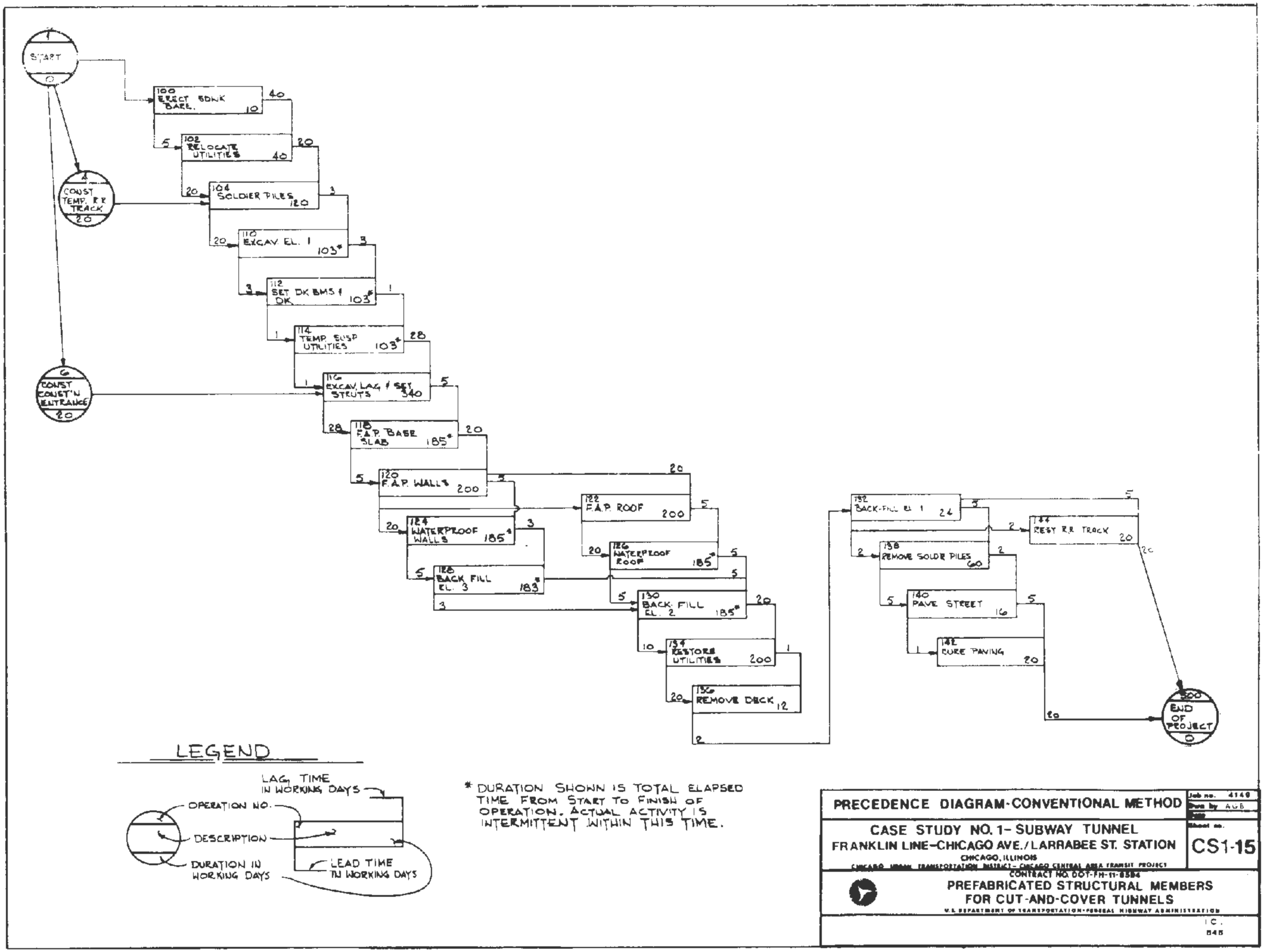


Fig. 30. Case Study 1: Precedence diagram - Conventional method

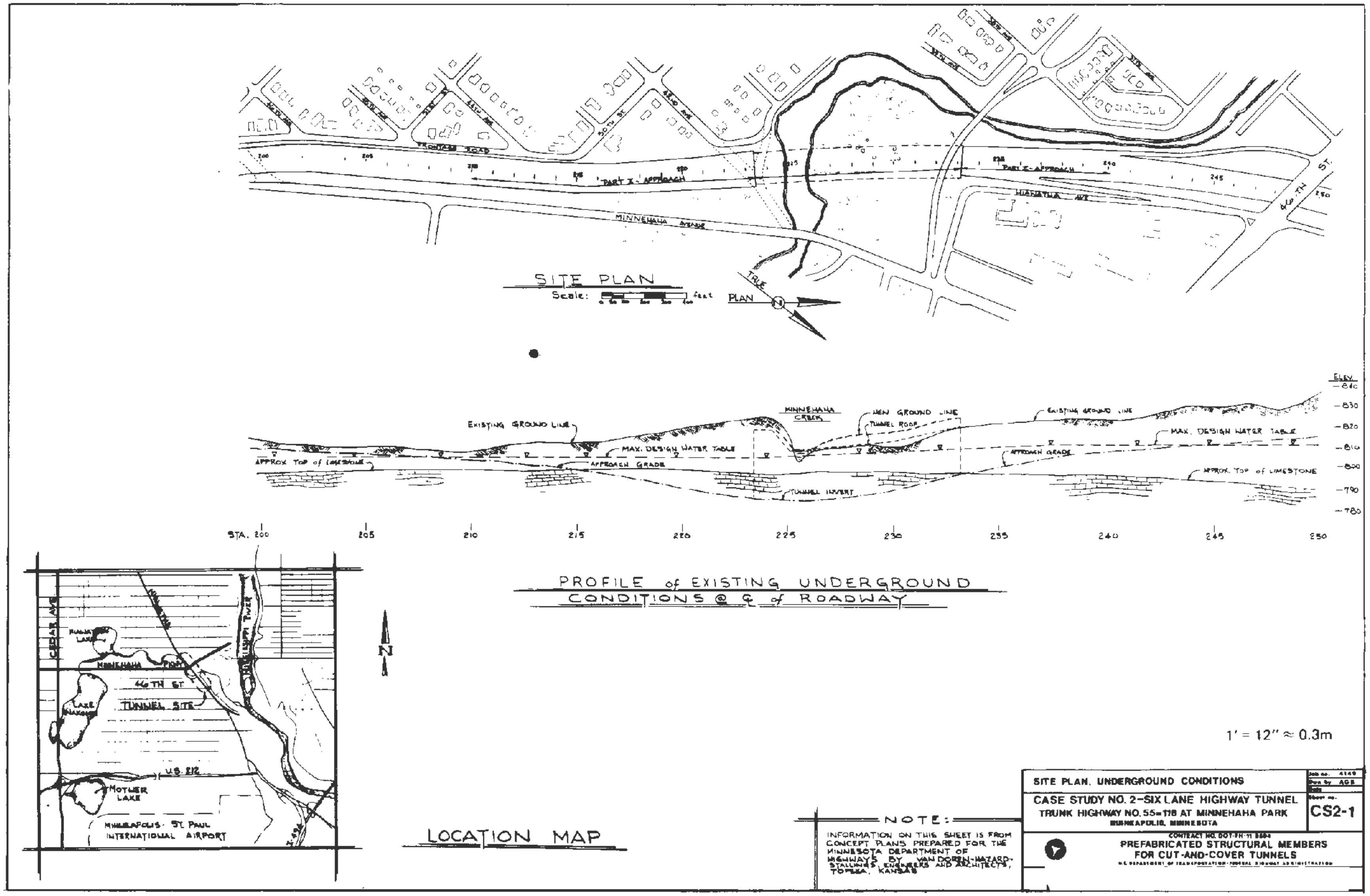


Fig. 31. Case Study 2: Site plan. Underground conditions

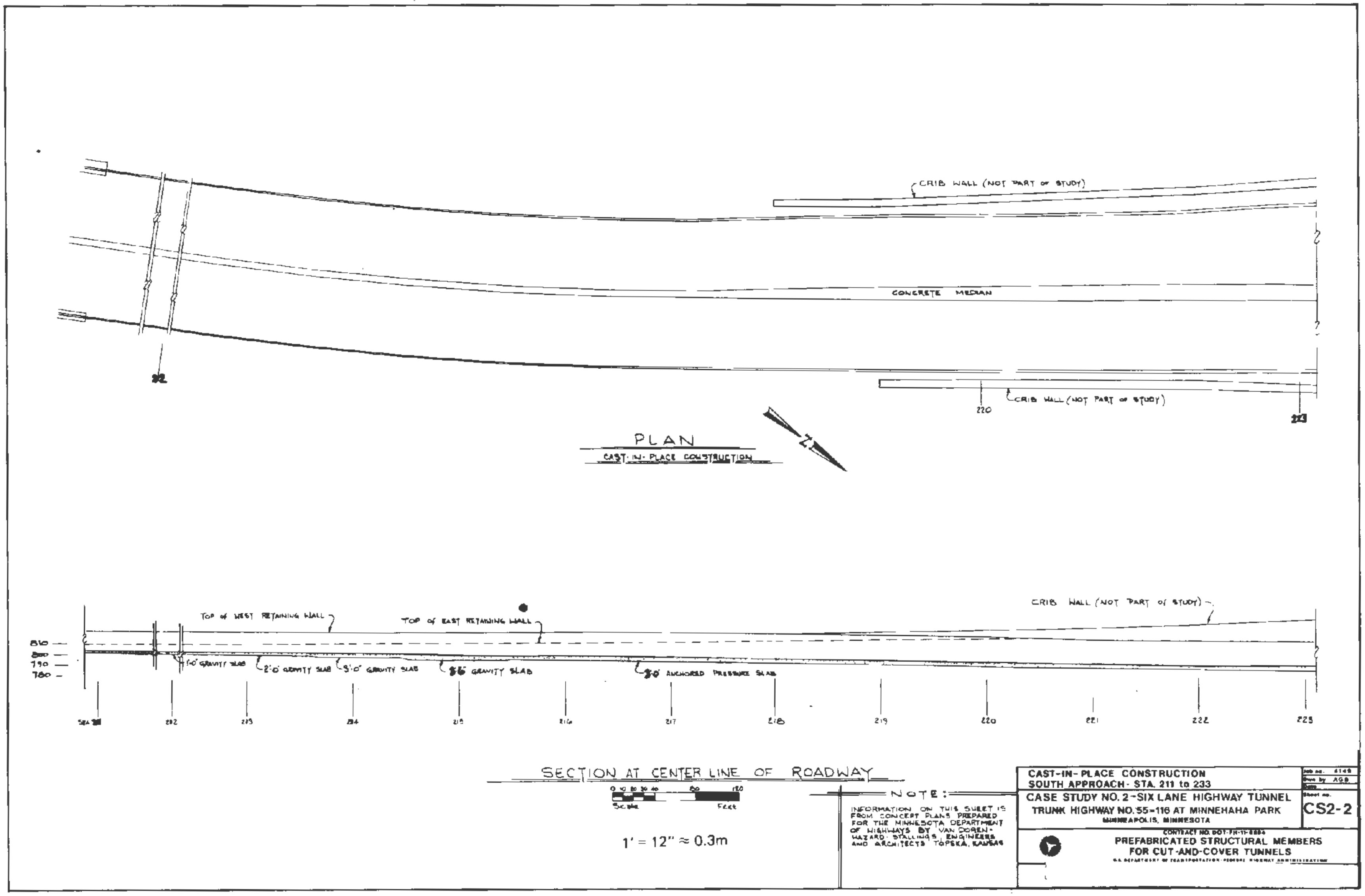


Fig. 32. Case Study 2: Cast-in-place construction. South approach - Sta. 211 to 233

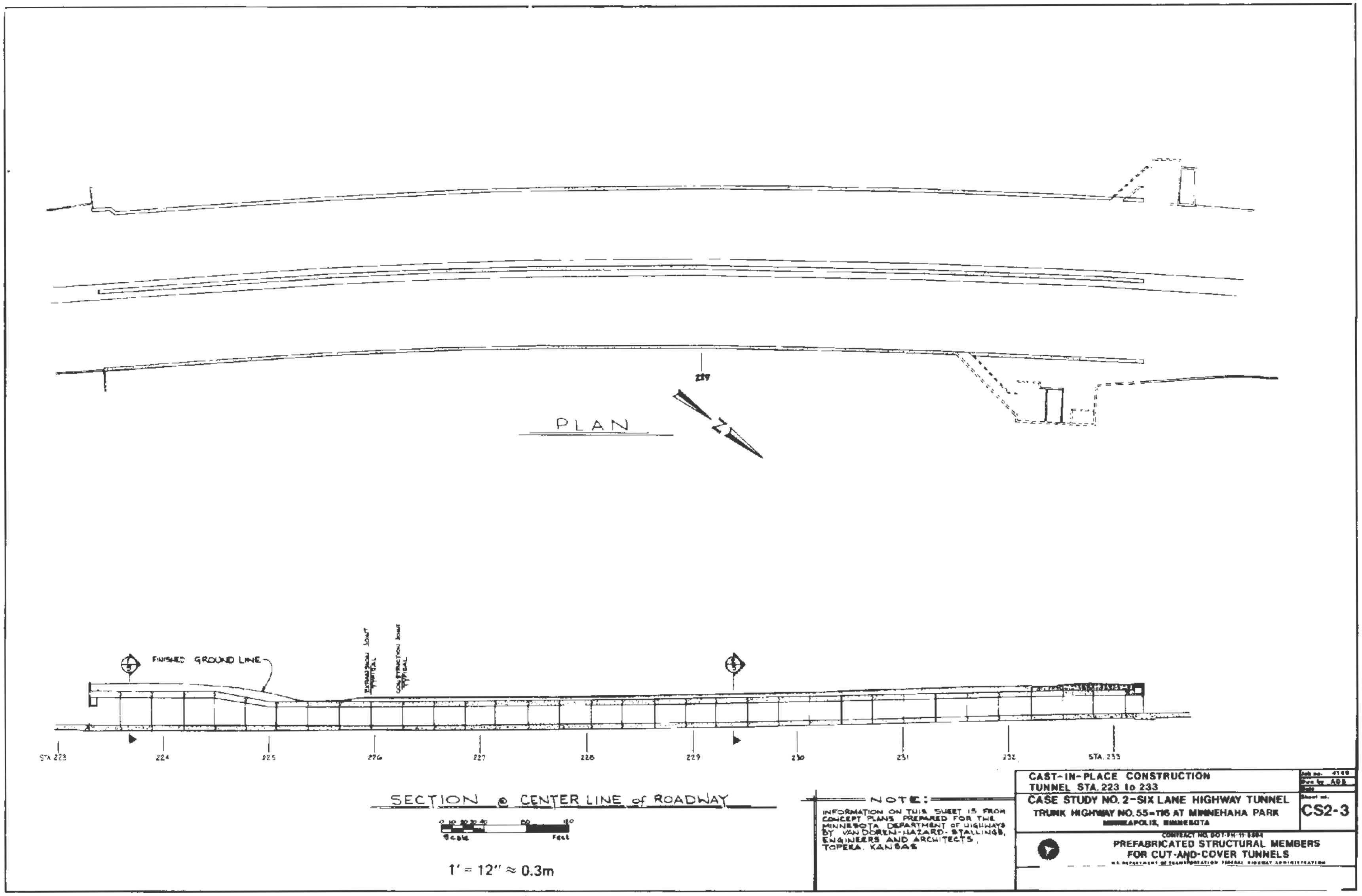


Fig. 33. Case Study 2: Cast-in-place construction. Tunnel Sta. 223 to 233

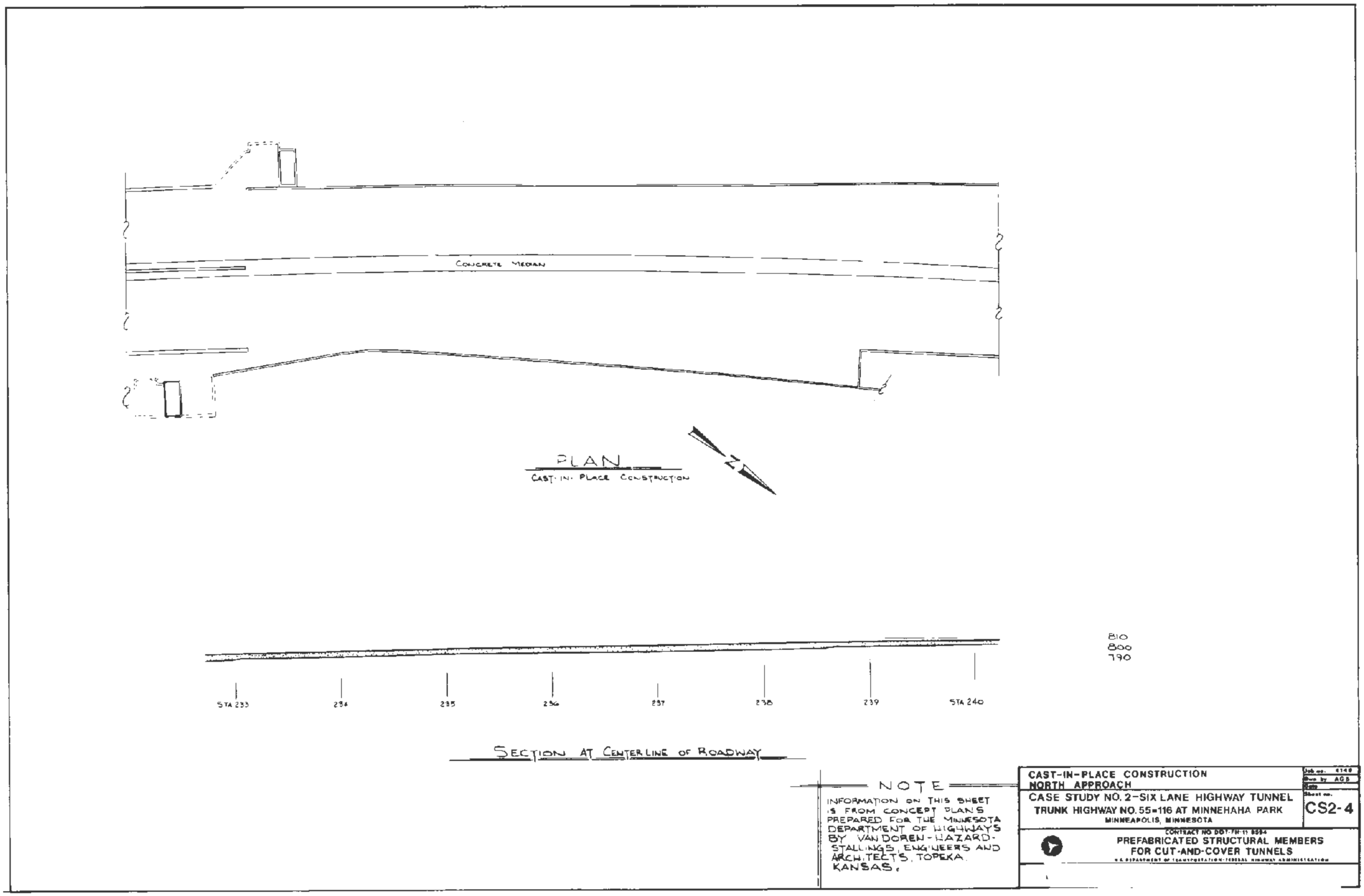


Fig. 34. Case Study 2: Cast-in-place construction. North approach

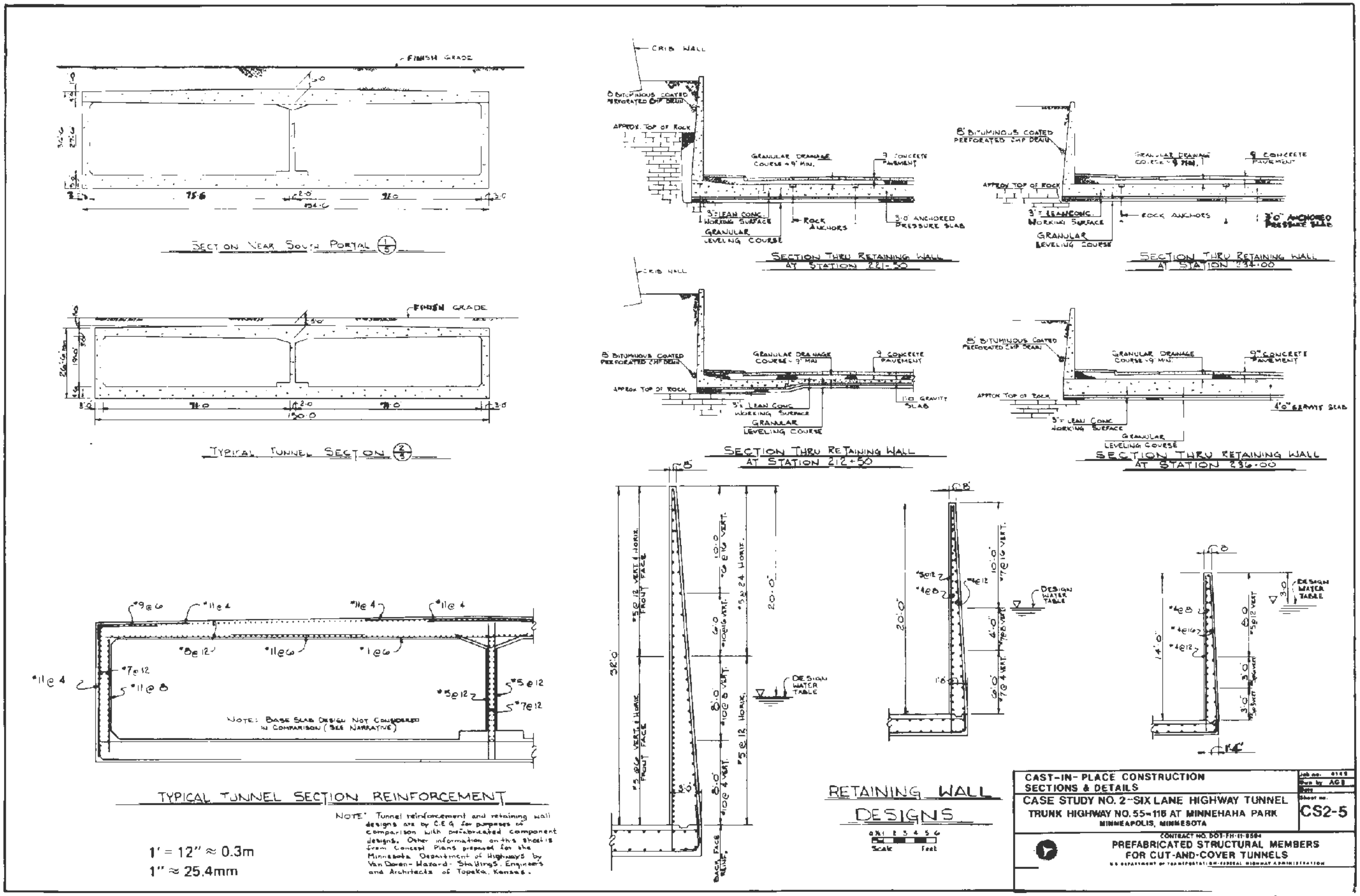


Fig. 35. Case Study 2: Cast-in-place construction - Sections & details

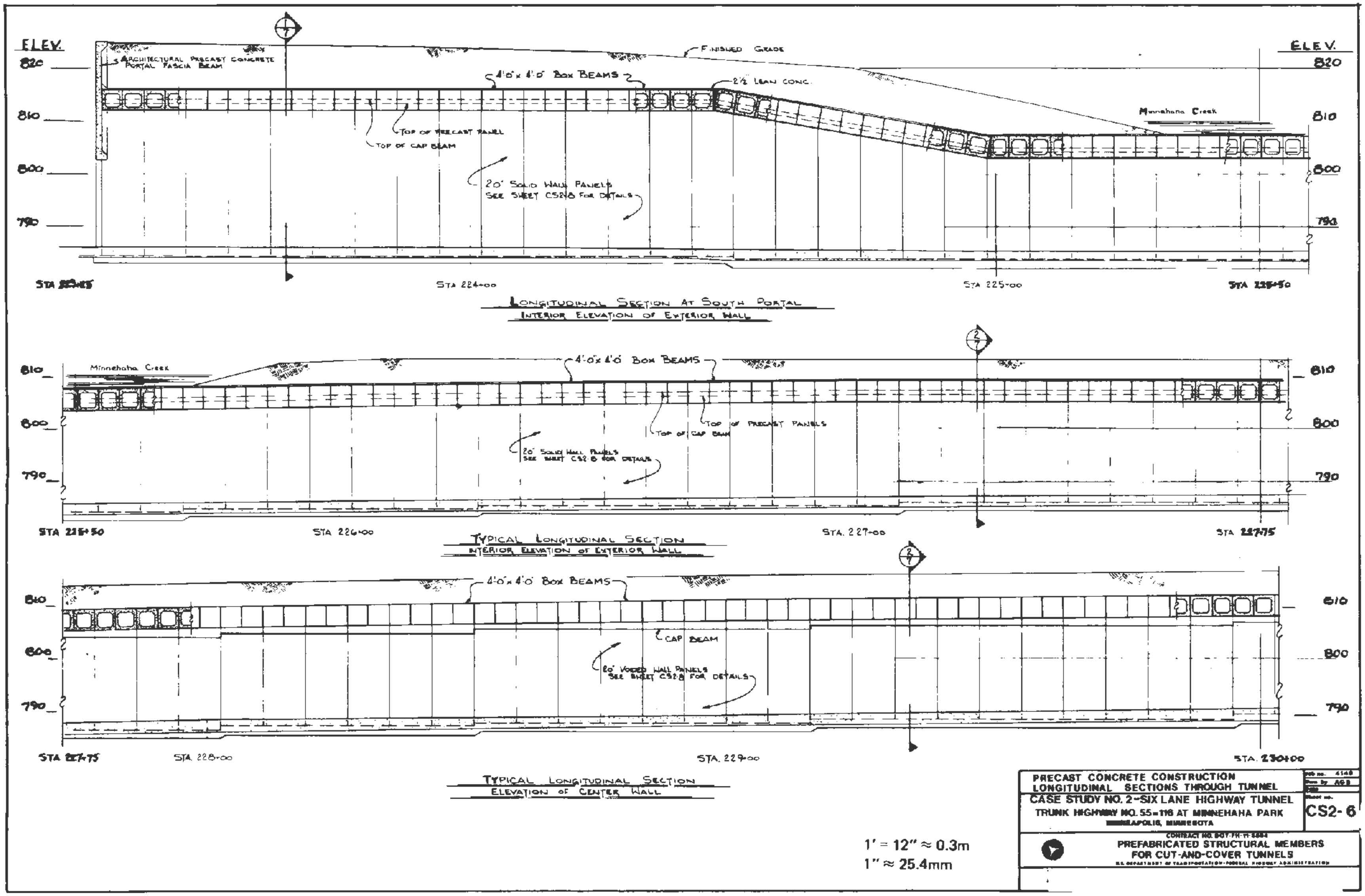


Fig. 36. Case Study 2: Precast concrete construction. Longitudinal sections through tunnel

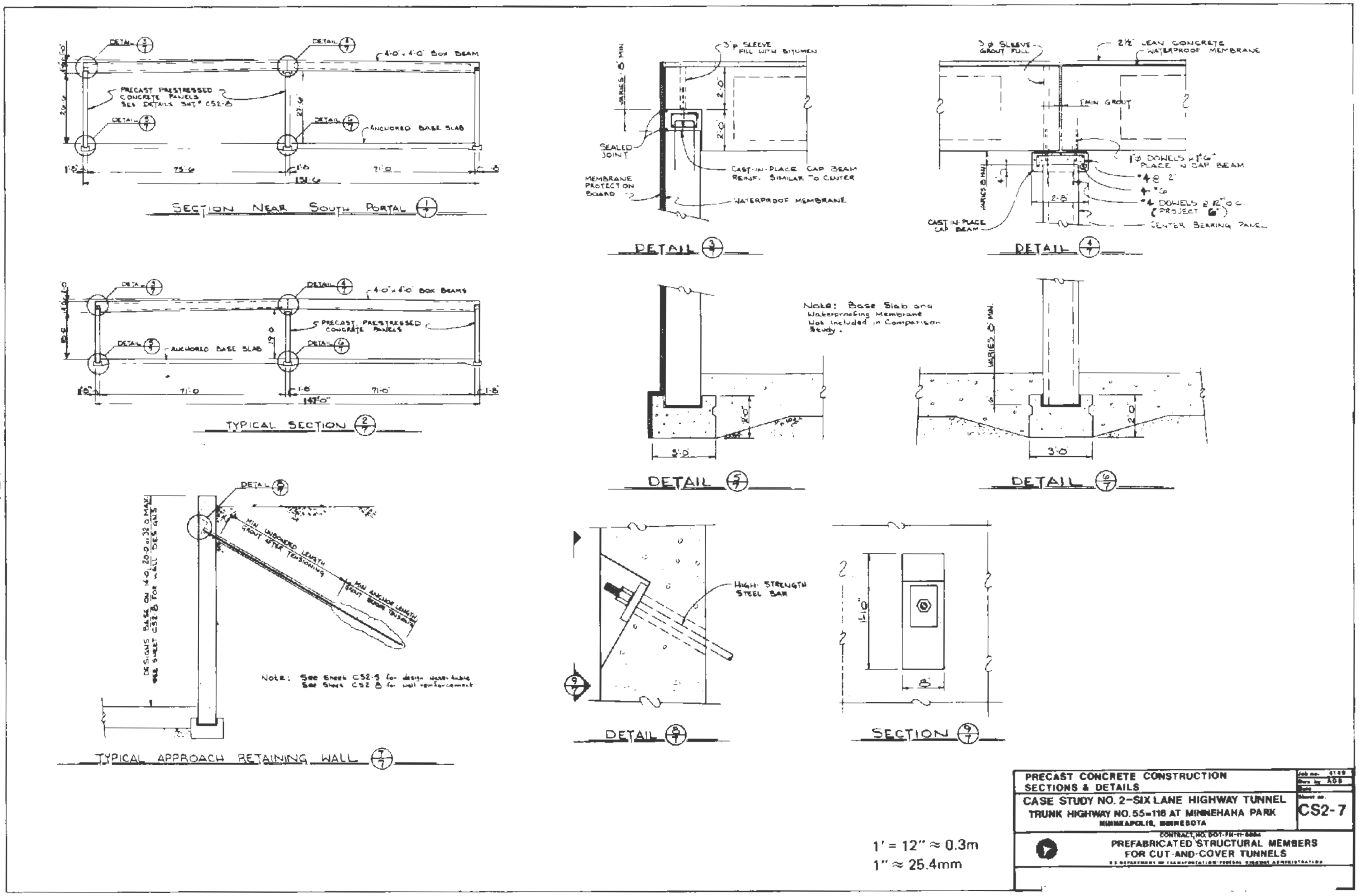


Fig. 37. Case Study 2: Precast concrete construction. Sections & details

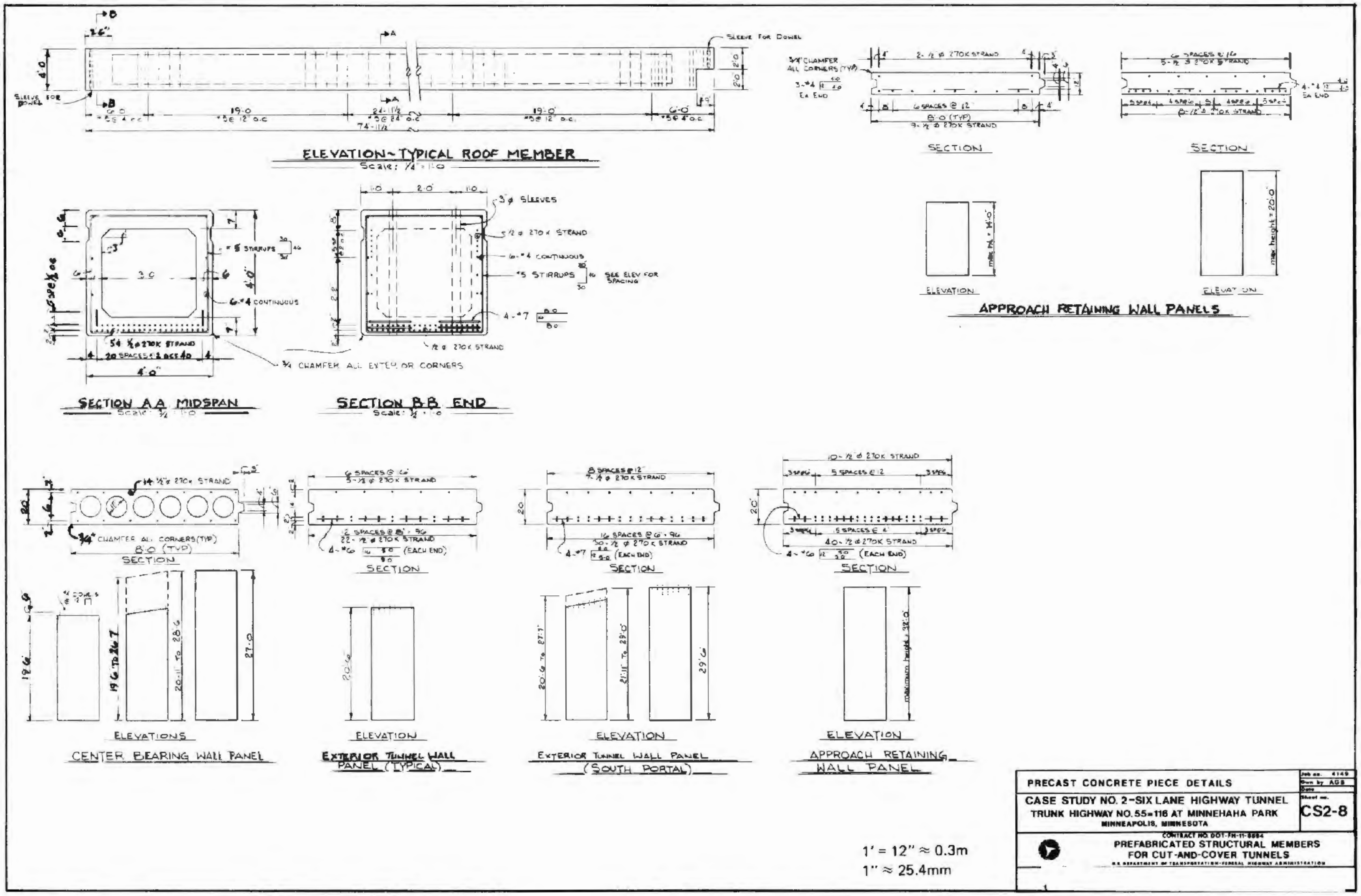


Fig. 38. Case Study 2: Precast concrete piece details

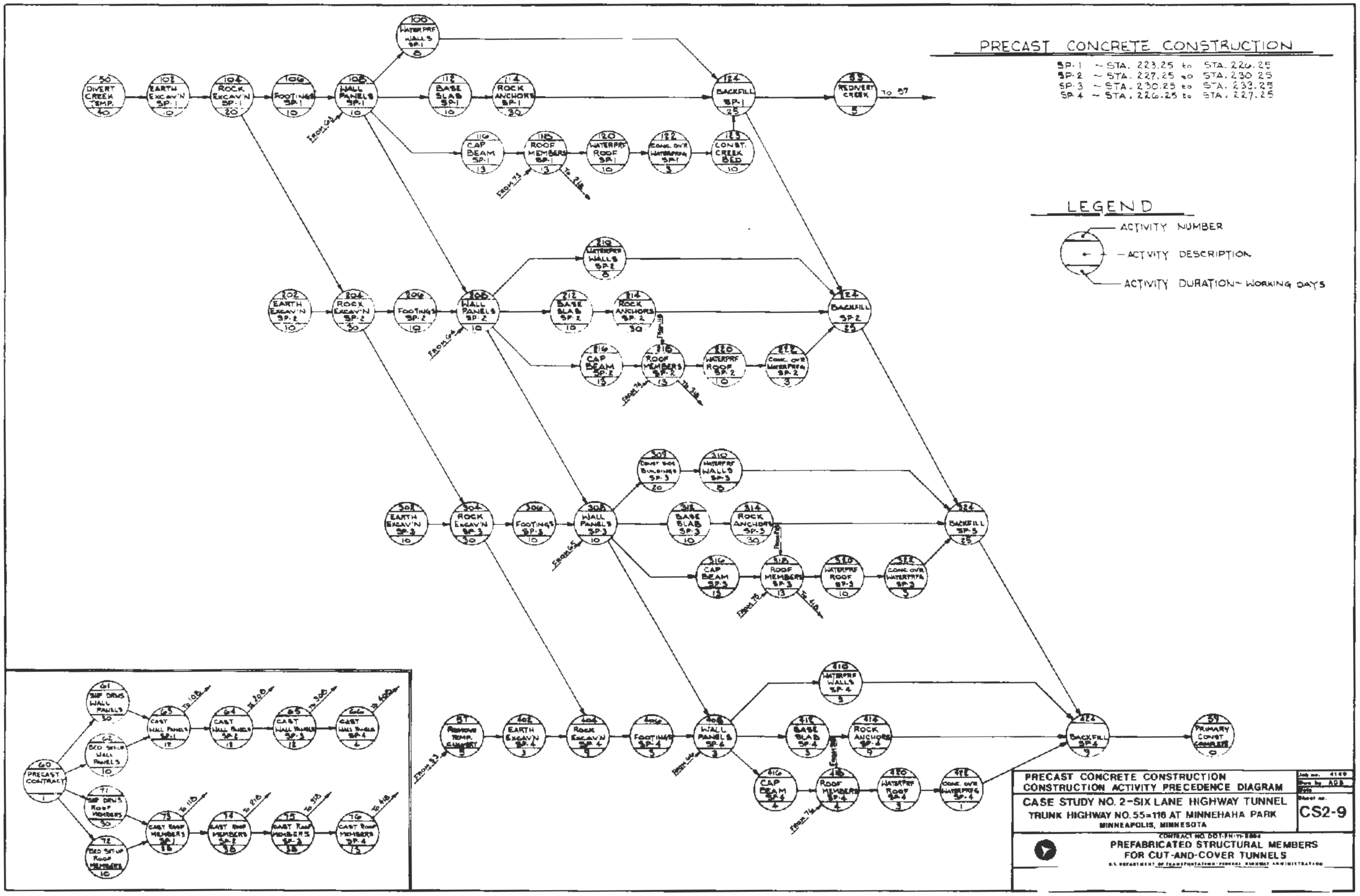


Fig. 39. Case Study 2: Precast concrete construction. Construction activity precedence diagram

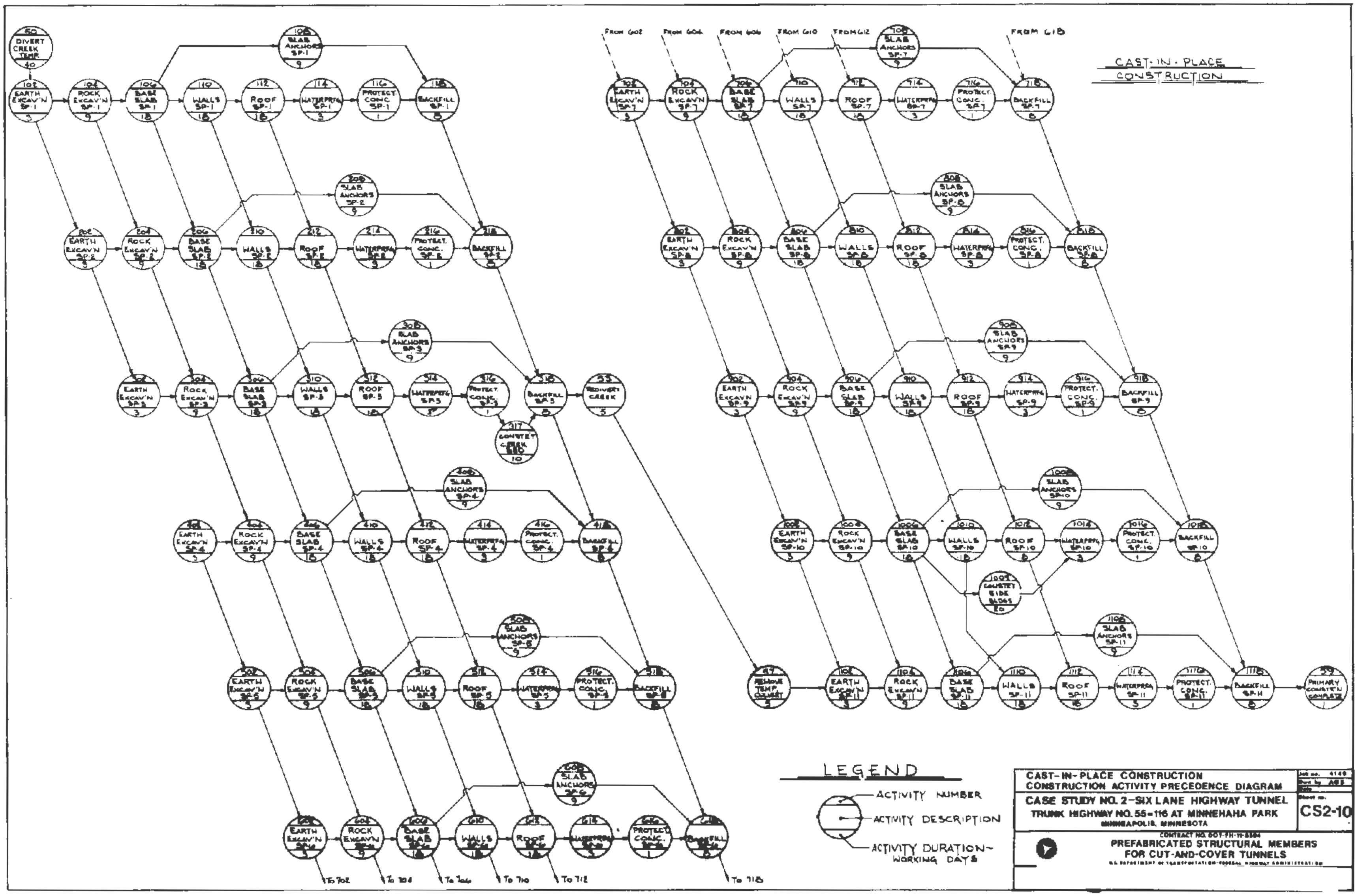


Fig. 40. Case Study 2: Cast-in-place construction. Construction activity precedence diagram

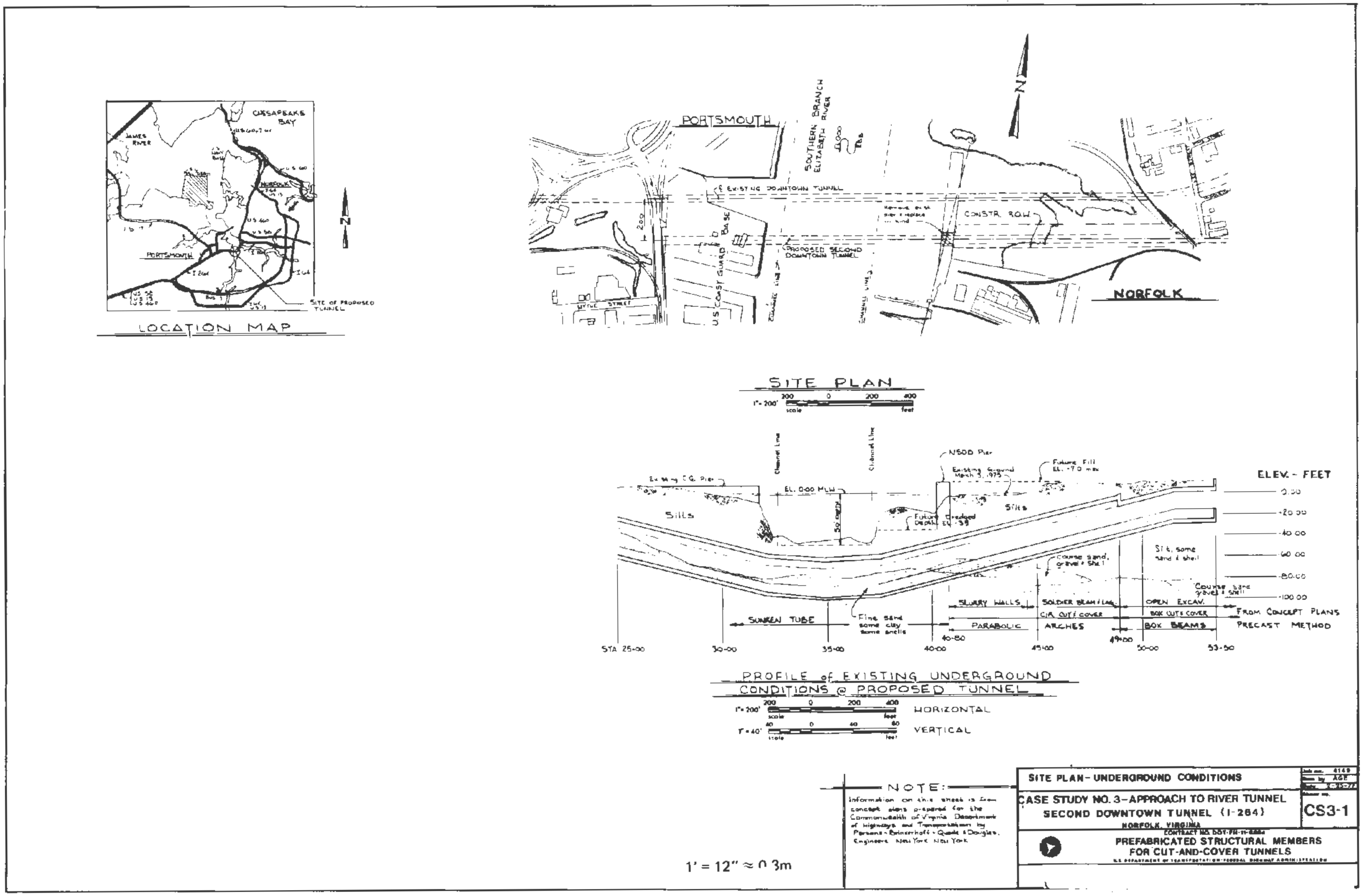
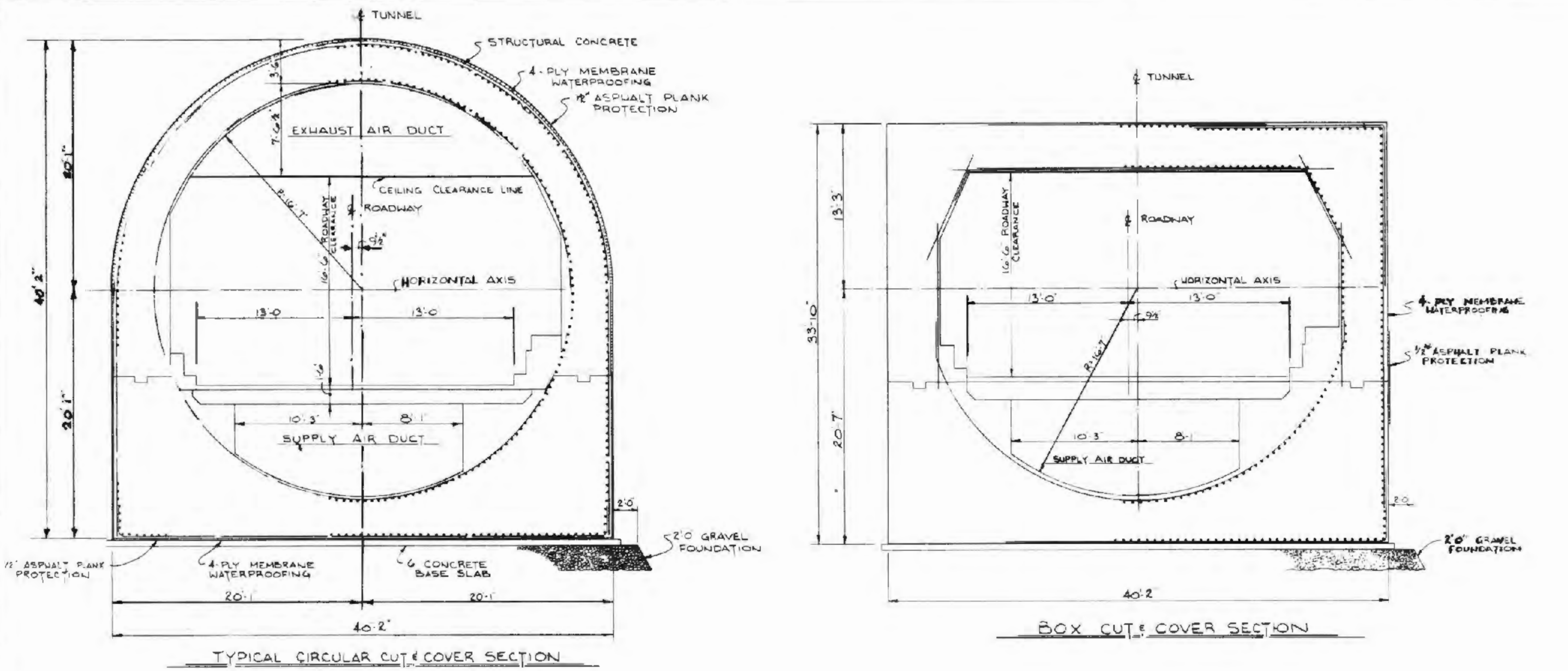


Fig. 41. Case Study 3: Site plan - Underground conditions



ESTIMATED QUANTITIES FOR CUT & COVER STRUCTURE		
Item	Unit	Quantity per L.F.
Structural Concrete	C.Y.	24.5
Reinforcing Steel	LB.	1920.0
4-ply Membrane Waterproofing	S.Y.	16.0
½" Asphalt Plank Protection	S.F.	144.0
6" Concrete Base Slab	C.Y.	0.78
2'-0" Foundation	C.Y.	3.4

ESTIMATED QUANTITIES FOR BOX CUT & COVER STRUCTURE		
Item	Unit	Quantity per L.F.
Structural Concrete	C.Y.	26.5
Reinforcing Steel	LB.	3230.0
4-ply Membrane Waterproofing	S.Y.	16.4
½" Asphalt Plank Protection	S.F.	148.0
6" Concrete Base Slab	C.Y.	0.78
2'-0" Foundation	C.Y.	3.4

1' = 12" ≈ 0.3m
1" ≈ 25.4mm

NOTE

Information on this sheet is from concept plans prepared for the Commonwealth of Virginia Department of Highways and Transportation by Parsons-Brinkerhoff-Quade & Douglas, Engineers New York, New York

CAST-IN-PLACE CONSTRUCTION SECTIONS

Job no. 4149
Drn by AGB
Date 2-25-77

CASE STUDY NO. 3–APPROACH TO RIVER TUNNEL
SECOND DOWNTOWN TUNNEL (I-264)
NORFOLK, VIRGINIA

Sheet no. CS3-2

CONTRACT NO. DOT-FH-11-8594
PREFABRICATED STRUCTURAL MEMBERS FOR CUT-AND-COVER TUNNELS
U.S. DEPARTMENT OF TRANSPORTATION-FEDERAL HIGHWAY ADMINISTRATION

Fig. 42. Case Study 3: Cast-in-place construction sections

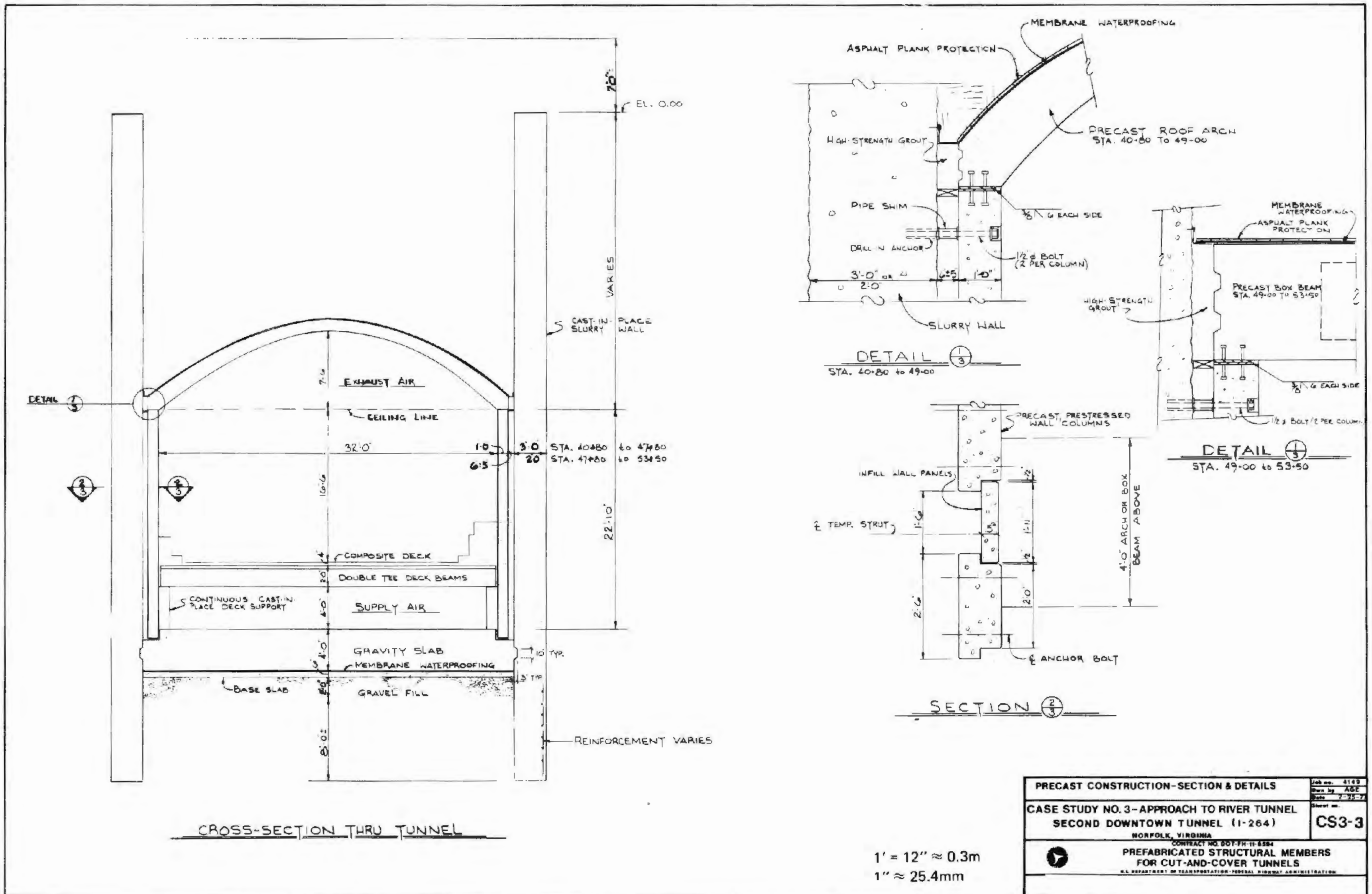


Fig. 43. Case Study 3: Precast construction - Section & details

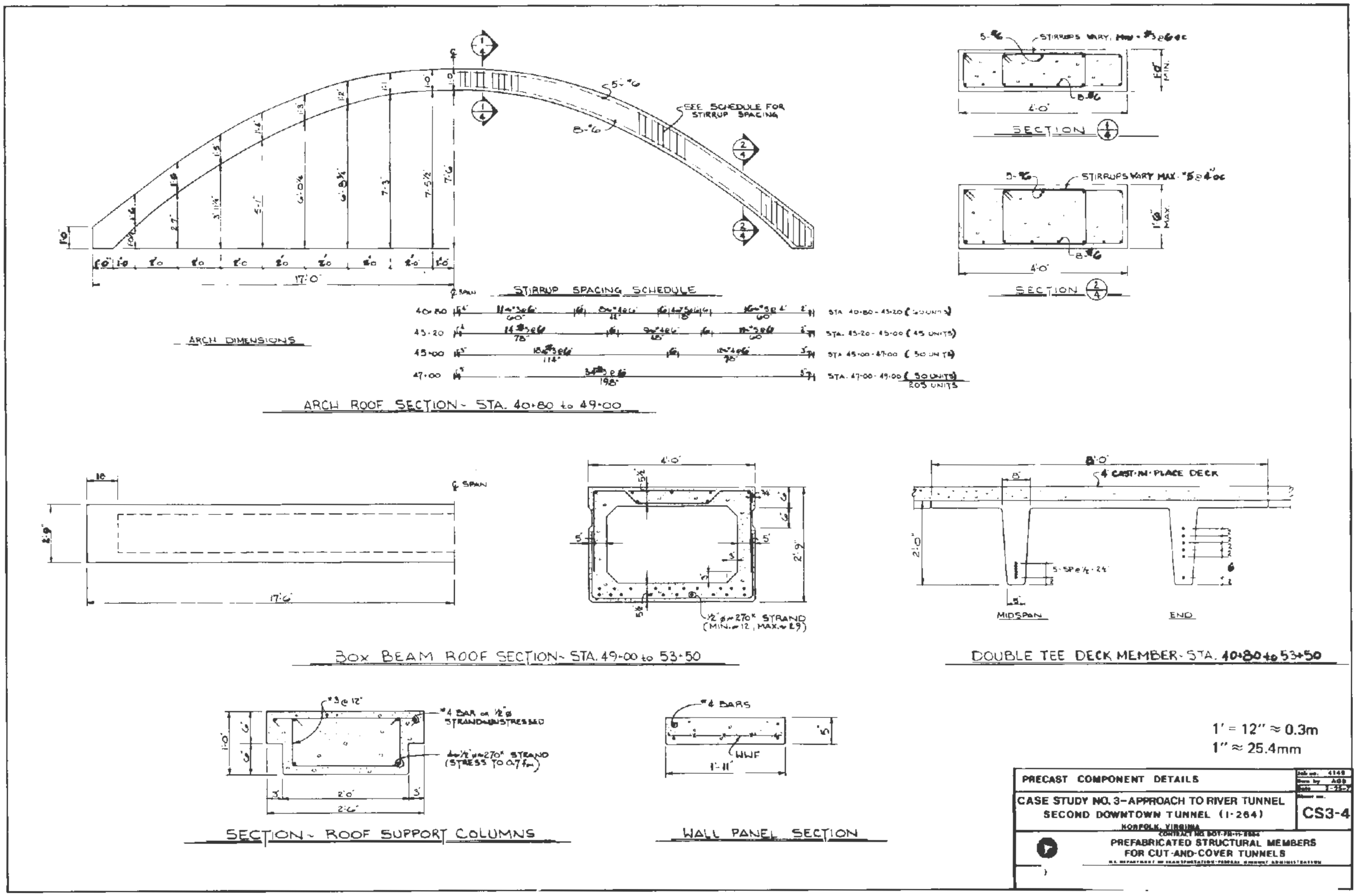


Fig. 44. Case Study 3: Precast component details

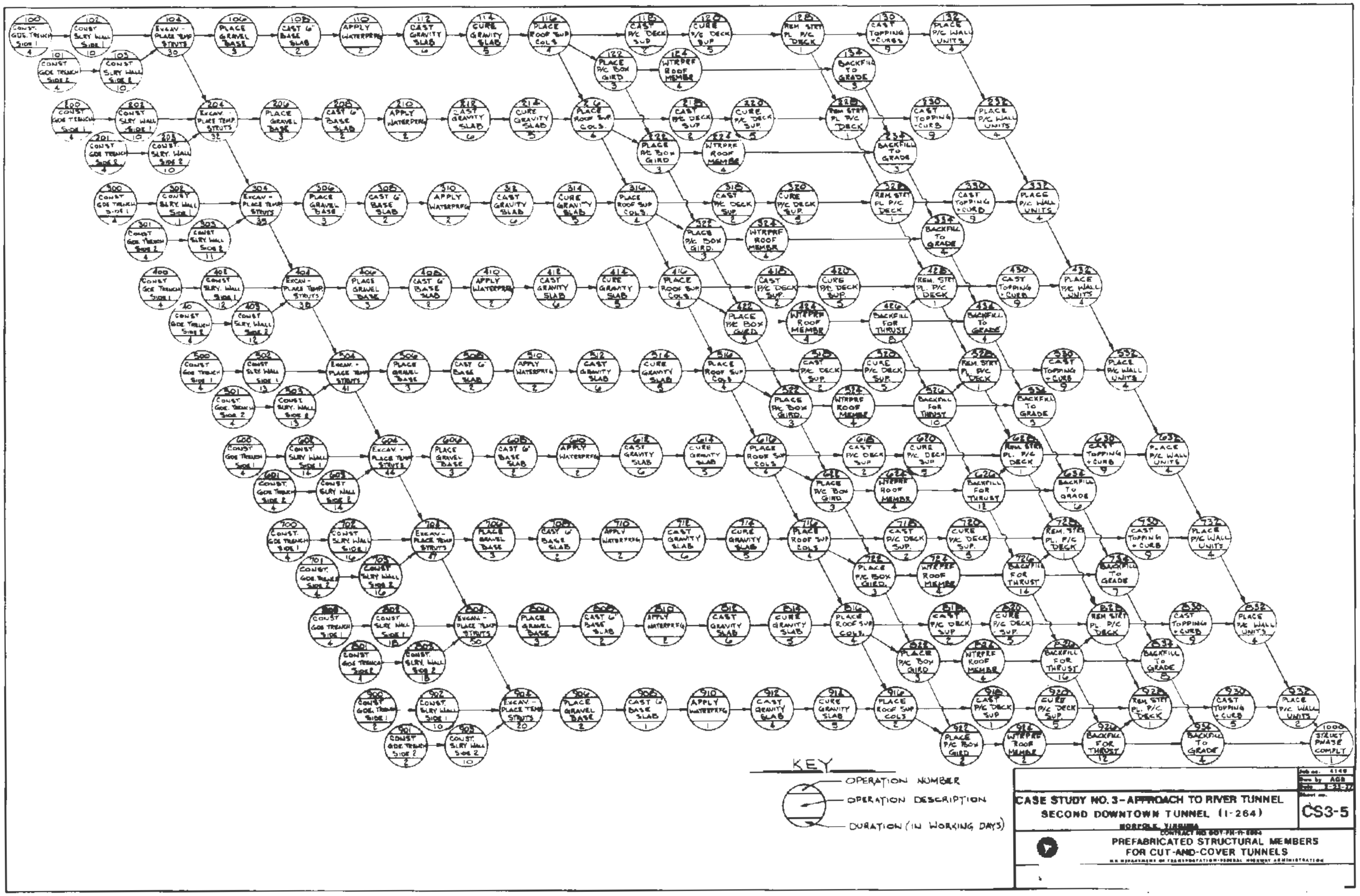


Fig. 45. Case Study 3: Precast concrete construction. Construction activity precedence diagram

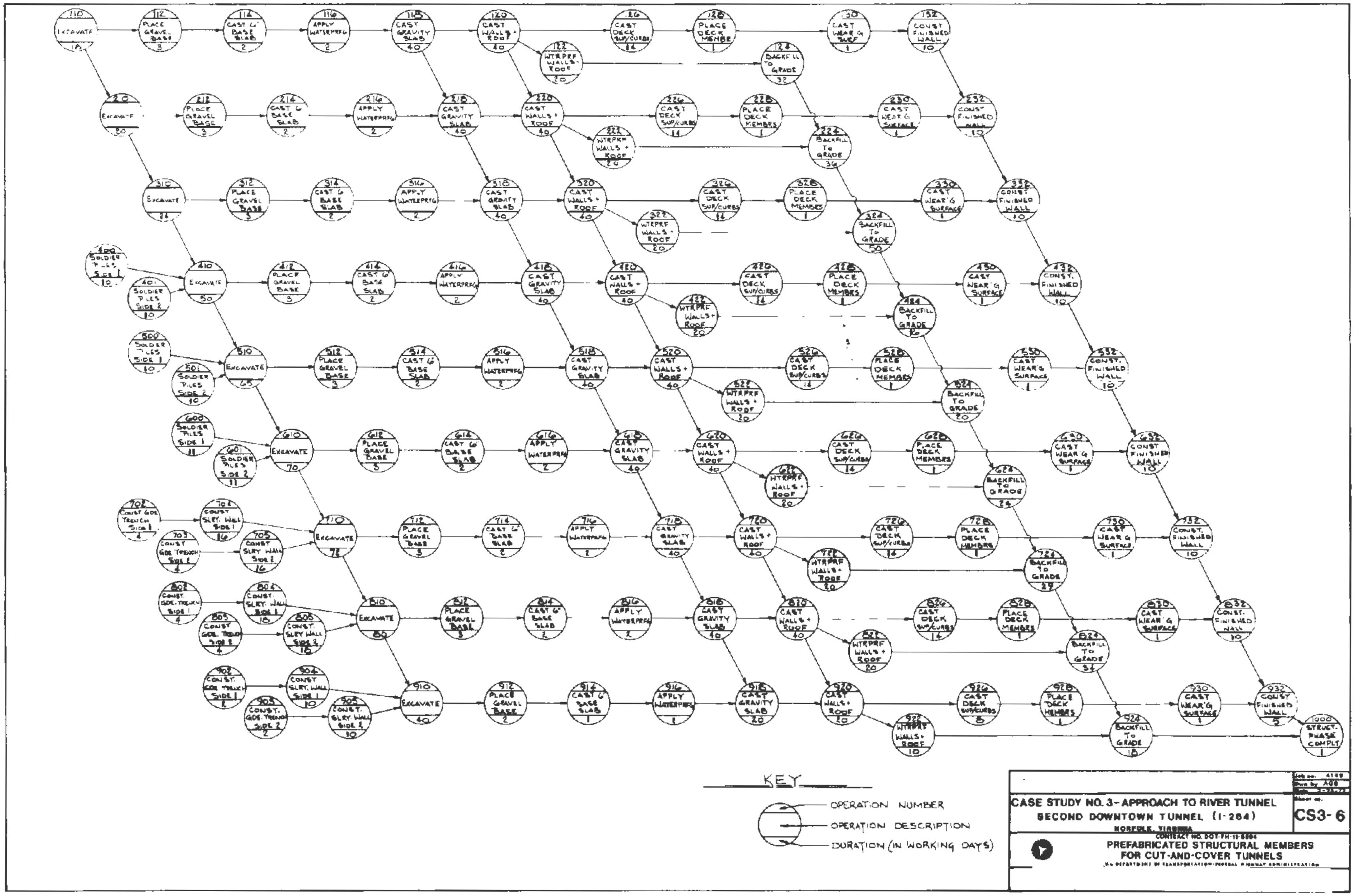


Fig. 46. Case Study 3: Cast-in-place concrete construction. Construction activity precedence diagram

* U.S. GOVERNMENT PRINTING OFFICE : 1977 0-729-526/1419