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SYSTEMS STUDY OF PRECAST CONCRETE TUNNEL LINERS

Bechtel Incorporated

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Prepared for

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AND
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Washington, D.C.

SYSTEMS STUDY OF PRECAST CONCRETE TUNNEL LINERS

James Birkmyer

FINAL REPORT

April 1975

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16. Abstract

This study addresses precast concrete lining systems. Existing precast concrete systems designed or constructed in Europe, Japan, and the United States are evaluated. With these as a point of departure, designs for lining systems applicable to the specific conditions encountered in the United States are developed. A comparative cost analysis is made between the linings designed in the study, one existing precast concrete design and two in fabricated steel. Appreciably lower costs are found for all of the concrete liner designs when compared to those in fabricated steel. Water sealing systems are discussed and recommendations for the development and testing of sealing details are made. Guidelines for dissemination of information about, and for the implementation of the systems, are presented.

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PREFACE

In underground transit construction, few major cost elements involve such a degree of repetitive operations in manufacture and in installation as segmented tunnel linings.

It follows therefore that systemization of a lining design would provide substantial economic benefit. Complete standardization is neither possible nor desirable at present. National standards have not yet been established for transit cars and the related wayside equipment. Consequently, the adoption of a single tunnel diameter, which would be economical for use in all future transit systems, is not feasible. With respect to construction, tunneling machines and segment-erection systems are currently undergoing a certain amount of innovative development, providing the capability for rapid excavation and material handling, and of erecting wider and longer segments, all of which speed the total tunneling process. However, the cost of the new equipment is high. An 18-ft-diameter tunnel machine, with the attendant muck-handling and segment-erection equipment, costs upwards of $1.5 million (1975 prices), and to make its use economical and realize the saving of faster tunneling, the length of the tunnel contract must be adequate (see Reference 0.1). In addition, it is important that a lining design be such that it can be easily modified best to suit the maximum performance of the tunneling equipment a contractor may wish to select.

The lining systems concepts in the study were developed to permit, as far as possible, optimization of the above variables. Generally the base designs and details are not sensitive to small variations of diameter, or to modification of the segment width and length (i.e., width of ring and number of segments in ring). The uniform cross section and simple reinforcement patterns adopted would permit such changes to be made readily by a segment manufacturer.

The Through Bolt design is recommended as a standard design, and the proposed sealant system, would provide a tunnel lining, satisfactory in cost and performance, for the wet ground conditions assumed. However, it should be pointed out that the development of tunnel lining systems is never static. As tunneling equipment and construction techniques improve, and other lining materials become available, changes to the lining details, and perhaps in the system, will be needed. Also, in geographic areas where dry, homogenous, soft rock, and firm clays exist, the expandable non-bolted lining systems, used with considerable economic success in London and other European cities, must be considered.

The study work plan was as follows:

- Study the interrelationship of a tunnel lining system, and its design, in respect to varying ground conditions. For this objective assemble and analyze data on representative tunnels constructed in the United States and abroad. Define the rationale for different lining systems adopted in various ground groups.
- Develop tunnel linings suitable for the ground and the general construction conditions in the United States. This task required identification of the principal cost areas of manufacture, installation, and performance of a tunnel lining. The numerous controls, including the ground, were to be established and their interactions with the cost areas identified.
- Develop three lining systems for detailed study, make preliminary designs and derive component quantities for comparative cost studies. The base cost units were to be developed from in-house capability and

in discussion with precast concrete manufacturers, structural steel fabricators and contractors. The cost components of each of the three systems and two fabricated steel designs were to be assembled and the items of high cost identified.

- Provide an engineering design of the linings. To accomplish this, establish the design criteria. This required the classification of soils into the ground groups, to determine the lining design loads and the interactions between the ground and the lining.
- Undertake the analysis and design of the linings in conformity with accepted engineering practice and codes for reinforced precast and prestressed concrete.
- Concurrent with the development of the criteria and the design of the linings, undertake a detailed study of the properties and performance of three types of concrete relative to application in the linings. Make a similar study on water sealing systems for the concrete segment interfaces, with emphasis on the interrelationship of sealing systems and the lining systems. Make recommendations of a testing program for specific sealant details, if applicable.
- Hold discussions with, and solicit opinions from, Bechtel's consultants, tunneling contractors, steel fabricators, and tunnel machine manufacturers during the performance of the work in developing the new lining systems.
- Make recommendations for promoting the use of the lining systems by those concerned with rapid transit underground planning and construction.

The sponsor of the study was:

- The U.S. Department of Transportation, Office of the Secretary, Office of the Assistant Secretary for Systems Development and Technology, Washington, D.C.

The contract technical monitor was Mr. Glenn Larson of the U.S. Department of Transportation Systems Center, Cambridge, Massachusetts.

The authors wish to express their appreciation to the study sponsor and the technical monitor for the assistance and constructive advice given during all phases of the work.

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ILLUSTRATIONS

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1. SUMMARY AND CONCLUSIONS

This study develops tunnel lining systems in precast concrete for rapid transit construction. In the course of the study, existing precast concrete systems designed or constructed in Europe, Japan, and the United States are evaluated. Using these as a point of departure, designs for lining systems applicable for the specific conditions encountered to date in the United States are developed. An economic analysis is performed and recommendations for testing and implementations are made.

The work plan for the study was as follows:

- Define the basic performance requirements of a tunnel lining for rapid transit.
- Review existing tunnel lining systems; select those which are appropriate to the objectives of the study; and analyze their special or unique features.
- Formulate design criteria and develop designs and details of tunnel linings suitable for use in the United States, and perform an economic analysis.
- Recommend specific testing programs which should be undertaken to verify the developed systems and their components.
- Discuss and recommend methods of implementing the systems.

Summaries of the individual sections follow.

1.1 ## SECTION 2 – THE FUNDAMENTAL REQUIREMENTS OF A TUNNEL LINING

The two sets of service conditions required of a tunnel lining are: (1) the permanent service conditions which include structural integrity, watertightness, durability, and the inside surface of the tunnel; and (2) the temporary service conditions which include the segment size, segment fastenings, erection stresses, transportation, and erection.

The items in each set of conditions are discussed and related to precast concrete lining design.

1.2 ## SECTION 3 – EXISTING TUNNEL LINING SYSTEMS

Systems developed in the United States, Japan, Europe, and the Soviet Union are displayed and features described. In particular, the details of water sealant systems and fastening methods are discussed.

SECTION 4 – SYSTEMS DEVELOPED IN STUDY

Using a review of Section 3 as background material, the basic assumptions for development of the lining systems are outlined. The assumptions include both the type and condition of ground which may be encountered and the tunneling construction methods and equipment which may be used.

The three lining systems developed are: (1) Composite, which incorporates a steel perimeter angle; (2) Bolt Pocket, which uses steel face plates anchored in the concrete for transmitting the bolt forces; and (3) Through Bolt, where bolts passing through the segments tie the segments and the rings together continuously.

The proposed water seal system is described. All systems employ high-strength bolts and have identical water sealing systems.

Comparative cost estimates are made for the three systems developed, as well as for one concrete system, previously designed, and two of fabricated steel. Costs are itemized for the principal components of the linings and then summarized as lining costs per linear foot of tunnel, if manufactured in three geographic areas. A comparative evaluation of the component itemized costs is made.

SECTION 5 – ENGINEERING DESIGN OF THE LINING

The several aspects which determine the criteria for the design are discussed. These aspects include the interaction between the lining and the surrounding ground, both firm and soft. Two recommended ground groups for the design are described and the loading criteria for firm ground and soft ground established. The salient aspects of the analysis and design of the systems developed are discussed. Reference is made to the design drawings contained in Appendix A.

SECTION 6 – CONCRETE

Three types of concrete for tunnel linings are discussed with respect to two desirable quality categories. These are (1) structural, which includes high-strength, low-modulus of elasticity, and low shrinkage; and (2) durability, including resistance to chemical attack and fire.

The three concretes are normal aggregate, lightweight aggregate, and polymer-impregnated. A general description of their compositions is given and a comparison of their properties and qualities made. Lightweight aggregate concrete is recommended for the designs in firm ground.

SECTION 7 – WATER SEALING SYSTEMS AND TESTS

Water sealing systems used in segmented linings are described. The two systems in current use are: caulking of the lining segment perimeter from within the tunnel, and application of a gasket to the segment faces before its erection in the lining. The materials used in each system are evaluated. A sealant system for the linings developed in the study is proposed and procedures for testing it are suggested.

SECTION 8 – IMPLEMENTATION OF A STANDARD LINING SYSTEM

Three entities are interested in the functional and economic aspects provided by a standardized precast concrete tunnel lining design. The entities are: implementors and engineering consultants of rapid transit systems; precast concrete manufacturers; and tunneling contractors. Their specific interests are discussed and promotional approaches to each are outlined.

CONCLUSIONS

The study has determined the fundamental requirements for tunnel linings in rapid transit construction. After a review of precast concrete linings which have been developed or used in this country and abroad, it can be concluded that precast concrete is eminently suitable as a lining for transit tunnels in the United States.

Three applicable bolted lining systems were designed and the cost of their manufacture was estimated. The cost of each system was very sensitive to the amount of structural steel incorporated in the design.

A comparative cost analysis between the linings designed in the study and one existing concrete design, and two in fabricated steel, revealed appreciably lower costs for all the concrete linings against those in fabricated steel. Also, the most economical study design lining, Through Bolt, appeared considerably lower in cost than the existing Caracas design. The analysis indicates that the Through Bolt rings may be manufactured for about one-third of the cost of fabricated steel rings, e.g., for firm ground conditions, see Table 4-1. Providing that the cost of installing the linings in the two materials would be approximately the same (and this appears likely), the resulting lowered cost of concrete lined tunnels may, in a number of situations, demonstrate favorable tunnel construction versus that in cut-and-cover. The study recommends that consideration be given to adoption of the Through Bolt design as a standard.

The study disclosed that the joint sealing system is a most critical detail in precast concrete tunnel linings. A system was developed during the course of the study which showed considerable promise of performing successfully in bad water situations. It is recommended that the system be laboratory tested.

2. THE FUNDAMENTAL REQUIREMENTS OF A TUNNEL LINING

2.1 INTRODUCTION

A successful tunnel lining system, for use in soft ground construction, must satisfy the requirements of two principal sets of conditions.

The first condition relates to the permanent life of the tunnel and includes such factors as:

- Structural integrity
- Watertightness
- Durability
- Inside surface of the tunnel

The second set of conditions interrelates with the tunnel construction process and may be identified as the temporary service conditions. These conditions are important determinants both in the selection of the lining system and for the design details, and include:

- Speed and ease of lining erection
- Magnitude and position of shield shoving jacks
- Size and weight of segment in respect of transportation and handling

Equally important is the method of transporting the segments to the tunnel face and their placement in the ring.

A discussion of the most important aspects of the final and temporary service conditions follows. It also serves as an introduction and background to the succeeding sections in the report.

2.2 PERMANENT SERVICE CONDITIONS

2.2.1 Structural Integrity

The tunnel lining, and particularly the joints, must support the loads from the various types of ground encountered safely and without undue cracking and spalling of the concrete. Also in these respects, it must continue to perform satisfactorily if future adjacent construction, or other effects, causes ground disturbances and subsequent movements in the tunnels.

2.2.2 Structural Design

Although structural design is discussed in detail in Section 5, a brief review of the subject is beneficial at this juncture.

Tunnel linings are designed for two broadly classified ground groups. These are firm ground and soft or plastic ground. In both cases the tunneling operations cause movements in the soil and subsequently distortion of the lining after it is erected. These distortions produce bending stresses. However, in the case of firm ground, the movement is relatively small, and from purely structural considerations, the radial joints in the lining may be articulated without danger of collapse. On the other hand, the movements in soft or plastic ground tend to be large and the lining must be made sufficiently stiff with moment-carrying radial joints, to limit the ring distortions.

In both groups, the part of the segments most vulnerable to the effects of distortion are the radial, or cross joints. Here, when the joints are not articulated, the resulting bending moments may impose heavy stresses on the edges of the joints which, unless designed well, will crack and spall and expose the reinforcement to corrosion with subsequent deterioration of the segment.

Watertightness

In segmented lining systems, as in other materials, watertightness through the concrete segment itself is generally not of concern; it is through the segment joints where the problem lies. The traditional method for attaining a satisfactory degree of watertightness is by caulking the interfaces of metallic segments with lead, and concrete segments with asbestos cement yarn. Both these caulking materials rely mainly upon pressure, rather than adhesion and resilience, in resisting the inflows of water. As they are almost totally inelastic, small movements of the joint (due to ground movements), subsequent to the installation of caulking, will cause the joints to leak. The problem is greater in concrete segments owing to the fact that tightly bolted and rigid joints are more difficult to attain.

Durability

Generally, durability refers to the longevity of the lining and its degree of resistance to mechanical damage, chemical attack, and fire. Thus concrete members with sharp corners are more vulnerable to mechanical damage by chipping and cracking than thick ones. Smooth continuous surfaces are inherently less prone to damage than those with projections. In this latter respect, a lining with segments of constant thickness will perform better than one of channel section, insofar as susceptibility to damage is concerned.

Chemical attack, including electrochemical, usually starts at the tunnel lining interface with the ground. The parts of concrete lining vulnerable to attack generally are: the cement when sulphates or certain alkalis are present in the ground; the reinforcement and cement, as well as certain types of aggregates, when acids are present; and the reinforcement when electrolytic action is present. Resistance to chemical attack can be improved by several means including:

- Selection of the most suitable type of cement and aggregate for the chemical conditions expected.
- Design of the lining so as to be as crack-free as possible.
- Use of dense concrete and ensurance of the proper cover to the reinforcement.
- Where conditions so warrant, electrical bonding of the reinforcement within each segment, and the segments together, in conjunction with a cathodic protection system.
- Use of coated reinforcement, such as zinc or epoxy.

The fire resistance of a concrete lining is affected by the type of concrete and the configuration of the inside surface of the lining. In this latter respect, the ridges and recesses of a channel section segment would tend to create pockets of localized high temperature — a smooth inner surface would not be subject to this effect.

The Inside Surface

The inside surface of the tunnel affects both the installation of electrical and other service equipment and the tasks of operating and maintaining the trains.

Provisions must be made for the support of the track and walkway and the securing of electrical items such as high- and low-voltage power cables, communications cables and lights. Some tunnel engineers find economic advantages in casting the primary track support base with the lining invert segment. Inserts for the support of the electrical items or other utilities should be provided in the manufacture of the segments. With segments of uniform cross sections, drilling after erection for expansion-type anchor fixings is an easily accomplished alternative. The thinner components of the channel-type segments make such drilling impractical.

The surface of the lining can have some effect on the air pressure wave which develops as the train speeds through the tunnel. A smooth surface of a solid segment will produce less air turbulence,and therefore, less pressure resistance than a rib or channel section, but the magnitude is difficult to determine.

Similarly, in the event that it is necessary to use mechanical ventilation for emergency smoke evacuation, greater efficiency can be expected in a smooth as opposed to a ribbed surface.

A tunnel interior which is free from edges and pockets is advantageous with respect to reducing buildups of dust and accumulation of rubbish, thereby facilitating tidy housekeeping.

TEMPORARY SERVICE CONDITIONS

The tunnel construction process is rapidly becoming more mechanized, resulting in higher capitalization costs for the contractor. The importance of increasing the rate of tunneling will be readily apparent. As excavation rates increase, the speed of erecting the lining becomes more critical. One solution is to use segments of greater size; the labor and time of placing a segment in a ring being fairly constant irrespective of size. However, there are several factors which tend to restrict the dimensions of a segment.

Segment Size

The factors which determine the optimum width of a segment, and number of segments in a ring, relate primarily to several variables in the tunnel construction process. However, the principal determinant is the type and design of shield and support equipment, which includes muck-handling systems and vertical hoists within the tunnel and access shafts. A tunneling machine which can provide both full and constant support to the excavated face, coupled with continuous grouting techniques, even in ground which has no appreciable stand-up time, may permit the use of a wide segment. Less sophisticated equipment and grouting techniques in similar ground may dictate narrow segments. Wide segments require longer shields, owing to the increased length of the shove jacks and shield tail. A long shield makes alignment control — which is also affected by the type and condition of the ground encountered — somewhat more difficult to maintain than with a shorter shield. In addition, tunneling drives through low-radius curves, say below 1000 feet, with a long shield, may be impossible to negotiate with any degree of accuracy. There is also a tendency for a wide segmented ring to jam in the shield tail (in tunnel terminology, this condition is referred to as becoming "iron bound'). As the force required to move the shield through the soil is related to its surface area, a long shield mobilizes greater jack pressures than a short one, and the lining may need to be stronger.

The type and arrangement of muck handling and other tunneling equipment must be considered in making a decision on the number of segments in a ring. The space needed for this equipment in the tunnel behind the shield places constraints on the size, particularly the length of the segment which can be handled. The chord dimension of one segment of a six-segmented 18-ft-diameter tunnel ring is about 9 ft; that of a four-segmented ring is 13 ft (i.e., about 50 percent greater). The relative difficulties between the two segments of transporting and erecting them in the ring probably are proportional to their lengths.

Segment Fastenings

In general, segments require fastenings for three purposes:

- In the circle face during erection
- In the radial face for plastic ground conditions
- In both faces where groundwater is encountered

It may be advisable to provide locating devices in the radial faces to assist in segment alignment if bolted fastenings are not used.

The presence of groundwater in most areas of the United States where segment-lined rapid transit tunnels have been constructed has led to the common practice of providing bolts in each of the four faces of the segments — chiefly to maintain the integrity of the segment joint sealing system.

The use of bolts has a considerable influence on the cost of the installed lining for the following reasons:

- The bolt holes must be located within the segments to a fairly rigorous tolerance to ensure that adjacent segment bolt holes will match satisfactorily during erection and permit ready placement of the bolts. This increases the manufacturing cost of the segments.
- The placing and tightening of the bolts in a 16-ft-diameter tunnel involves significant labor, and tends to slow the tunneling advance.
- There is the cost of the bolts and washers themselves, together with grommets where groundwater is encountered. The necessity of installing grommets also slows the tightening of the bolts, resulting in less productivity.

An inherent disadvantage of bolting concrete segments directly through formed flanges is that the thickness of the flange needed to resist the bolt forces results in relatively long bolts. Owing to the creep properties of concrete under load, high-strength bolts do not remain satisfactorily tight. In addition, the long bolt holes tend to slow the matching of holes in the adjacent segments during the erection of the lining.

A typical channel section concrete segment, indicated in Figure 2-1, has flanges about 4-1/2 in. thick and requires mild-steel bolts that are 12 in. long and 1 in. in diameter. For comparison, an equivalent steel or cast iron segment with 1-in. -thick flanges is also shown. The high-strength bolts required for the metallic segments would be 4 in. long and 3/4-in. diameter. The different bolting methods results in a less rigid joint for the concrete system which, as mentioned previously, is more difficult to seal.

Erection Stresses

Generally, the amount of reinforcement provided in a precast concrete segment for the permanent forces is adequate for handling and placing stresses. An equally important influence is the load on the segments imparted by the shield-shoving jacks during the advance of the shield. The magnitude of the jacking reaction is governed principally by the friction of the ground on the external surface of the shield, together with the type and amount of ground which is displaced by the cutting edge. The weight of the shield and trailing support equipment increase the reactions. With 18-ft-diameter shields in granular soils, total jacking capacities of 2000 to 3000 tons are common, which is provided by 20 to 24 jacks disposed around the perimeter of the shield. The loads from the jacks are applied to the circle face of the segments through jack shoes, or sometimes by a jacking ring which distributes the loads over the segment faces. The segments must be designed to withstand these

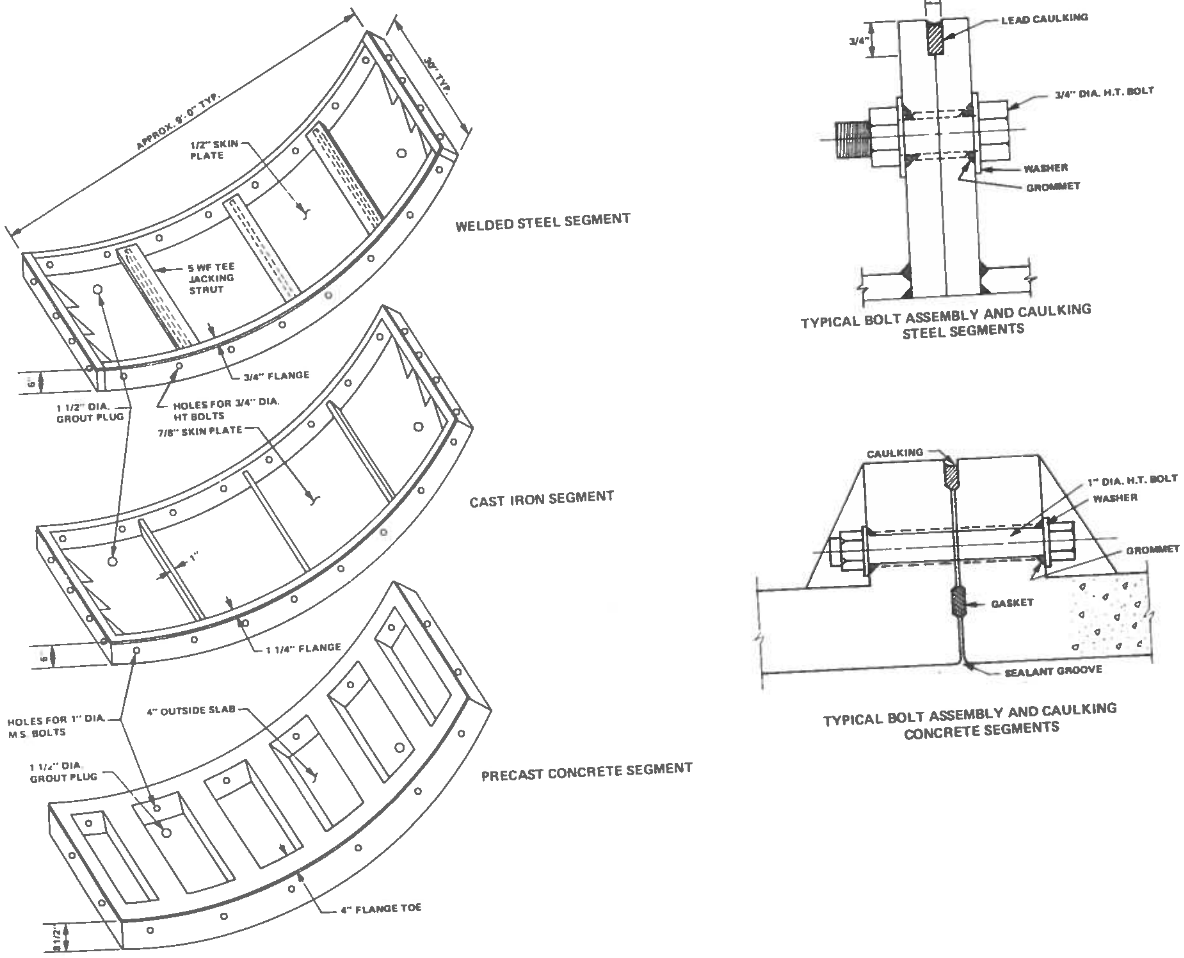


Figure 2-1. Typical Channel Section Segments

sizable jack loads applied in the longitudinal direction, and the face details must be such that cracking and spalling of exposed edges and corners are minimized. Careful consideration must also be given to manufacturing tolerances so that the high compressive forces are distributed uniformly over the circle faces.

Transportation and Erection

The chord length of about 9 ft for each of six segments of an 18-ft-diameter ring generally makes it necessary for the segments to be transported lengthwise through the tunnel to the heading. There they must be rotated 90 degrees to enable the shield erector arm to lift and place them in position in the ring.

Metallic segments for one ring are normally packaged together at the place of manufacture for transportation to the tunnel site, and thence through the tunnel to the heading. Concrete segments weigh about twice that of metallic. An 18-ft-diameter ring 3 ft wide of 7-in. solid concrete segments weighs about 7-1/2 tons which should not preclude the use of these same packaging and transportation procedures. The incidence of damage from chips and cracks at this stage thereby would be minimized.

3. EXISTING TUNNEL LINING SYSTEMS

INTRODUCTION

In order to ascertain the present state of development in precast concrete lining systems, a review of all available literature was undertaken. This was supplemented by a visit of the author to England, where a number of pertinent tunnel projects for the London Transport Executive (L. T. E.) were inspected. Discussions were held with the responsible engineers and contractors. A Bechtel representative on special assignment to investigate tunnel construction procedures and systems in Japan provided useful information concerning some of the precast concrete tunnel systems being used in that country.

In the United States there was no tunneling work using precast concrete linings under construction. However, a visit was made to a tunnel project using steel segments in Staten Island, New York, where a sealant system was inspected which would also be applicable to precast concrete segments.

As a result of these investigations, representative systems from several different countries have been displayed in Figures 3-1, 3-2, and 3-3, and their salient features are summarized in Tables 3-1, 3-2, and 3-3.

A data schedule listing the features of interest of additional tunnels lined in precast concrete which have been constructed in Japan and Europe is included in Appendix B.

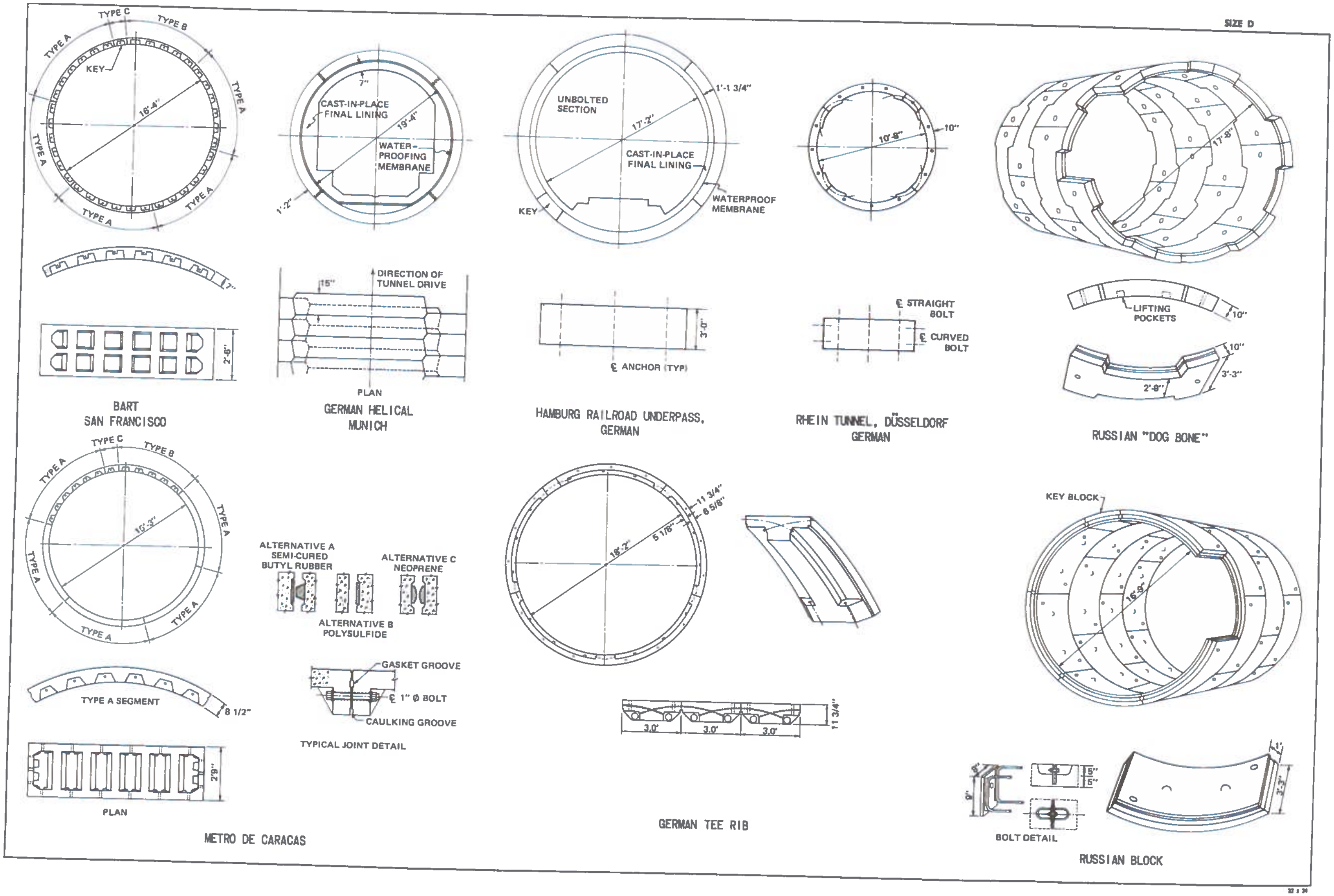


Figure 3-1. Existing Tunnel Lining Systems – Sheet 1

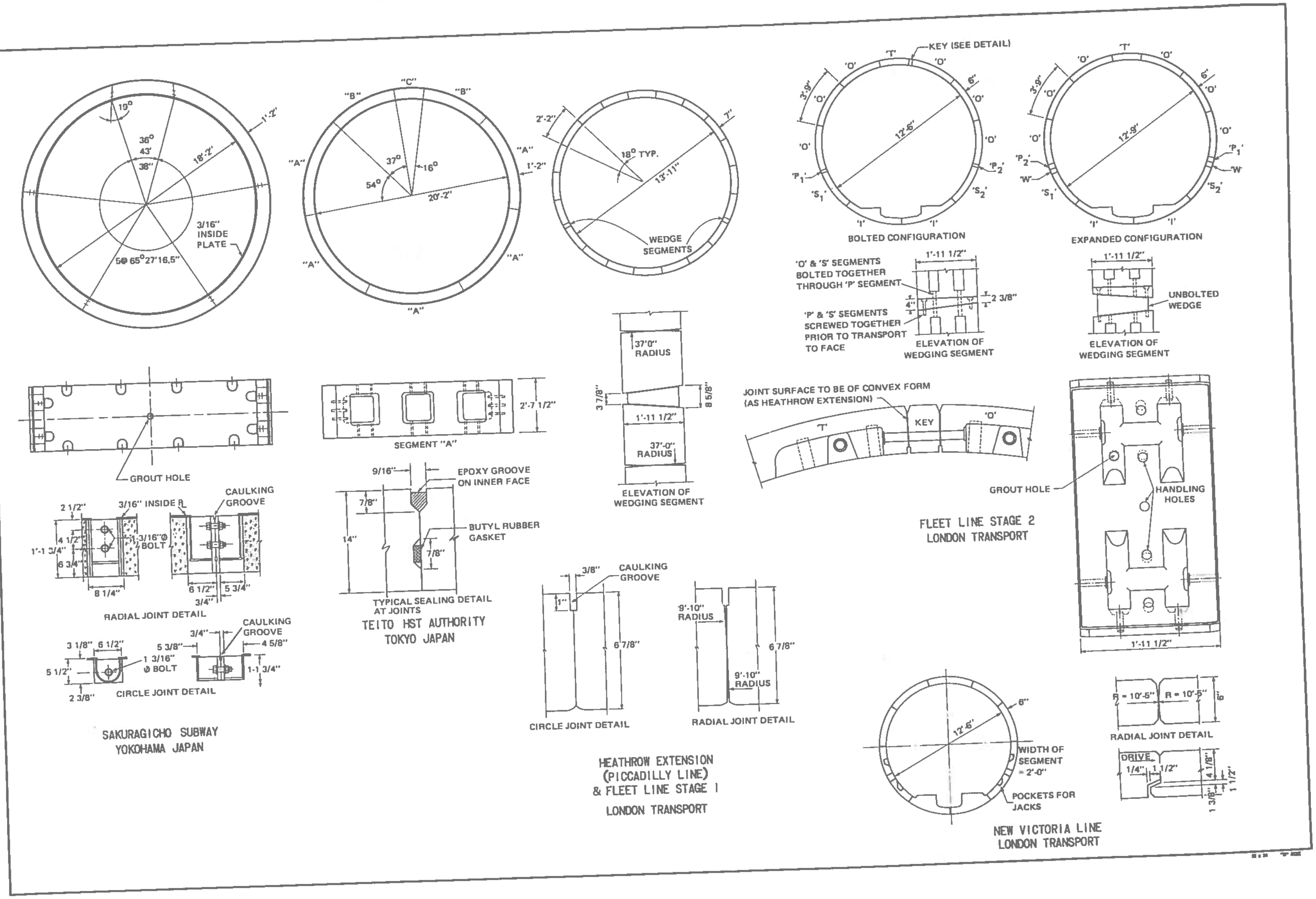
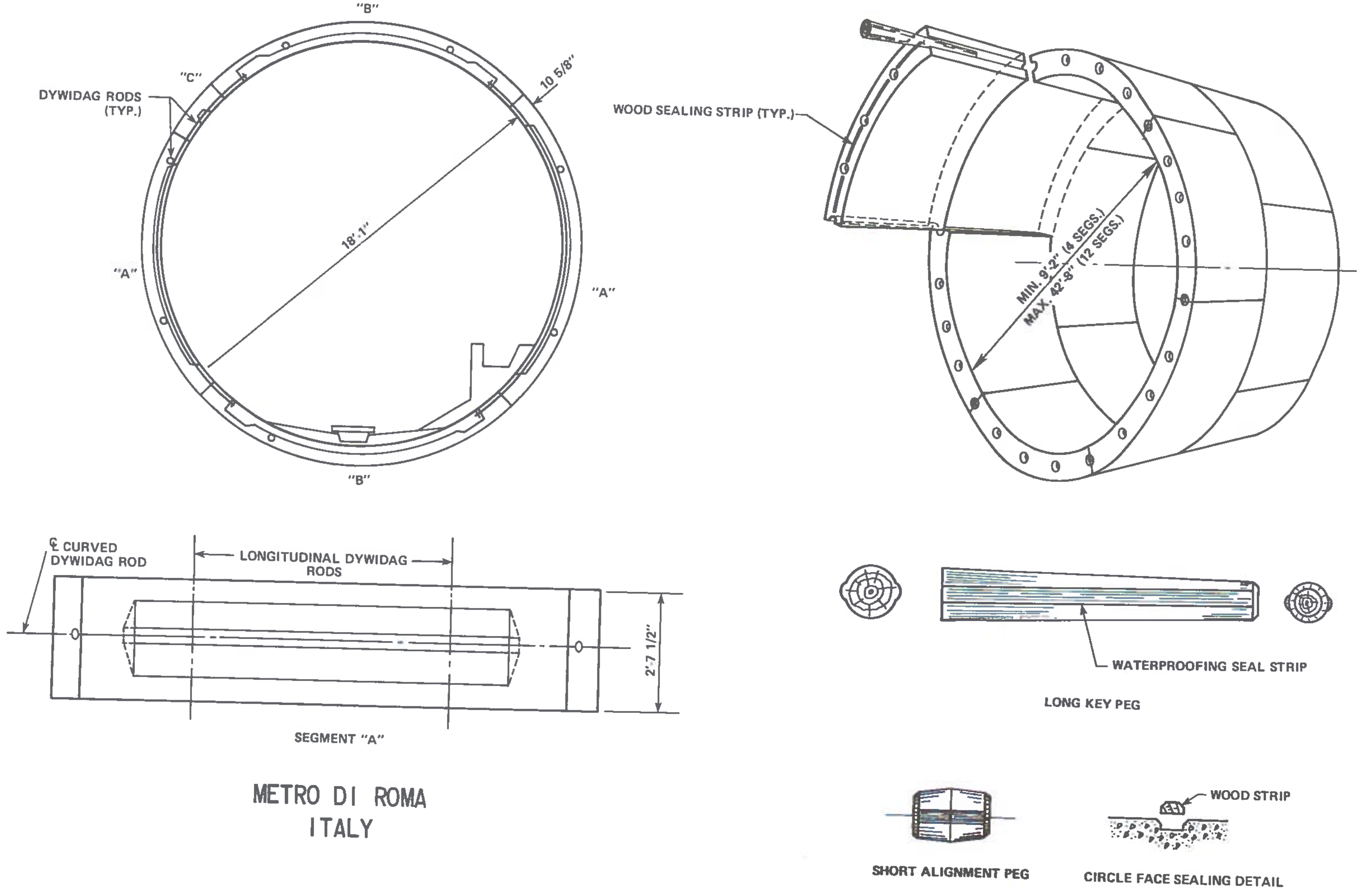


Figure 3-2. Existing Tunnel Lining Systems – Sheet 2



METRO DI ROMA
ITALY

TABOR PEG BLOCK TUNNEL LINER

Figure 3-3. Existing Tunnel Lining Systems – Sheet 3

Table 3-1

REPRESENTATIVE TUNNEL LINING SYSTEMS – SHEET 1

System	Soil	Maximum Ground Cover	Water-Table From Ground	Sealing	Fastenings
BART Fef. 3.1	Mixture of sand, clay, and silt	50 ft	10 ft	Asbestos-cement caulking	See Figure 3-1
Caracas Ref. 3.2	Mixture of sand, clay, and silt	60 ft	Top of ground	Gaskets (neoprene with alternative polysulohide buyl), asbestos - cement caulking	See Figure 3-1
Munich Helical System, Germany Ref. 3.3	Cohensionless silts sensitive to settlement	20 ft ±	15 ft ±	Waterproof membrane provided behind the final cast-in-place lining	Four radial joints located at the zero-moment points. Light bolting was used only for segment or normal force in the longitudinal direction.
Hamburg Railroad Underpass, Germany Ref. 3.4	Sand and marl	10 ft ±	Water table above tunnel	Sealing strips for holding the grout. Water-tightness was provided by the inner-lining and a 3/4" thick plastic layer and three bitumen layers.	12 longitudinal rods per ring for circle joints, connecting groups of seven rings. Steel dowels in radial joints.
Rhein Tunnel Dusseldorf, Germany Ref. 3.5, 3.7, 3.8	Cohesionless soils sensitive to settlement	50 ft ±	50 ft ±	Bituminized asbestos packings between segment faces. Fibre tow, or rapid-setting cement applied in caulking grooves. Special rubber stoppers at the points of intersection of joints.	Prestressed curved bars with rolled-on thread and nuts were used in the radial joints. Similar bars, but straight, were used in the circle joints. (Dywidag System)

Table 3-2

REPRESENTATIVE TUNNEL LINING SYSTEMS – SHEET 2

System	Soil	Maximum Ground Cover	Water-Table From Ground	Sealing	Fastenings
Tee Rib, Germany	For most types of soils	All normal depths	No limit	Adhesive plastic coating, elastic synthetic filler and neoprene strips were recommended for combined application	Curved bolts at all joints (see Figure 3-1). Temporary bolts used at the radial joints for erection only.
"Dog Bone" System Soviet Union	Medium clays elastoplastic design	Uncertain	Moderate water bearing	Grouting Groove	Key-type joints without fasteners, with pocket-bolt fastening of circle joints as an alternate.
Block Segments Soviet Union	Medium clays elastoplastic design	Uncertain	Moderate water bearing	Caulking groove plus semicircular rabbets (1-3/8" radius) pressure grouted with cement mortar after erection	Key only, for radial joints. Dowels at the circle joints. See Figure 3-1.
Sakuragicho Subway, Composite Lining Yokohama, Japan	Mostly silts deposits remains and a peat with sand layers or silt with sandy layers	26 ft	1 ft	One butyl rubber gasket plus a caulking groove per joint. Groove filled with epoxy resin after erection	See Figure 3-2.
Tokyo Teito HST Authority Japan	Permeable sands and silts	71 ft	6 ft	Butyl rubber gasket or elastomeric-bitumastic coating between segments. Epoxy or elastomeric-asbestos compound filled caulking grooves. Optional inside membrane with cast-in-place inner lining.	See Figure 3-2.

Table 3-3

REPRESENTATIVE TUNNEL LINING SYSTEMS – SHEET 3

System	Soil	Maximum Ground Cover	Water-Table From Ground	Sealing	Fastenings
Piccadily Line & Fleet Line Stage 1 London Transport, England Ref. 3.10	Firm clay with pockets of sandy silt	110 ft±	Generally below crown of tunnel	Caulking grooves along joints on inner face caulked with asbestos-cement after ground was stabilized. Expanding cement mortar as keeper	See Figure 3-2.
Fleet Line Stage 2 London Transport, England Ref. 3.10	Clay and other soft materials. Firm clay with pockets of sandy silt	110 ft±	Generally below crown of tunnel	Caulking grooves along joints on inner face caulked with asbestos-cement after ground was stabilized. Expanding cement mortar as keeper	See Figure 3-2.
New Victoria Line London Transport, England Ref. 3.10	Firm clay with pockets of sandy filt	70 ft ±	Below crown of tunnel	Not needed	No fastenings used. Rounded convex or key only. (See Figure 3-2)
Tabor Peg Block System Mining Equipment M.F.G. Corporation Ref. 3.11				Peg (Treated wood) with waterproofing seal strip	Peg (See Figure 3-3)
Portion of Metro Di Roma, Italy Ref. 3.12	Sand and silt. Pozzolane			Bituminous sand and asbestos sheets on segment faces	Curved and straight Dywidag rods for radial and longitudinal fastenings respectively. (See Figure 3-3)

Although the information obtained was not complete, it was sufficient to enable the general principles of the designs to be described below. Refer to the figures and tables noted above

UNITED STATES

San Francisco Bay Area Rapid Transit System (BART)

A precast tunnel lining was designed and tested for possible use in the BART system in the early 1960's. It was typical of most channel section concrete segmented bolted rings. The design was based upon the methods outlined in Section 5, and some rings were manufactured and tested in San Francisco in 1965. The report of the tests (see Reference 5. 1) indicated satisfactory structural performance in all respects. One of the several water sealing systems tested performed reasonably well under 5 to 10 psi water pressure, but failed under the application of higher pressures. Other systems failed under pressures of less than 5 psi.

It was decided that the linings would be satisfactory for tunnels in locations where the groundwater tables were relatively low. Consequently, bids were solicited for about 25, 000 ft of lining in precast concrete segments, concurrently with bids for the alternate fabricated steel design, which called for the supply of approximately 62, 000 ft of lining.

Only two viable bids were received for the concrete linings. The low bid was somewhat higher than for an equivalent length of steel liners, and therefore, was rejected.

The successful steel lining bidder had facilities which were particularly well suited for the economic production of the linings. This bid was 20 percent below that of the nearest metallic lining competition. The concrete manufacturers were disadvantaged by having small existing plant capacities, relative to the large number of rings required for a fast delivery schedule. This resulted in sizable concrete segment mobilization costs as compared to those for the steel linings.

Metro de Caracas

The Caracas segmented lining was designed in the late 1960's for higher ground loads and water table conditions than those used for the BART segments, but design methods were similar. The segments were heavier, i.e., the flanges were 8-1/2 in. deep versus 7 in. in BART, and a gasket was provided on the earth side of the bolt circles as well as caulking grooves at the toes of the segments. The specifications listed three acceptable alternate gasket types and required that the contractor demonstrate the integrity of the type he selected. The alternative gaskets are indicated in Figure 3-1.

Although design work was completed some years ago for the first phase of the system, construction was postponed and no linings have been manufactured at this writing.

GERMANY

Munich Helical System

This system represents a basic departure from the usual parallel ring concept in that the rings are built in helixes. The four segments which comprise a ring are so shaped that, as each is erected, the tunnel is advanced by one-fourth of the segment width. From the brief information available about the system, it appears that no fastenings or dowels were provided in the radial faces but longitudinal bolting of several segments was undertaken some distance behind the heading. The segments were kept in position as they were erected by the shield shove jacks. The ground along the tunnel route was dense, fine, and in some sections, water bearing sand. Dewatering was accomplished by pumping in deep wells during construction. A membrane behind a final cast-in-place lining provided permanent watertightness.

Hamburg Railroad Underpass

This railway tunnel was constructed in granular soil with a high water table. It consists of a primary concrete segmented lining followed by a cast-in-place reinforced concrete lining 8 in. thick. The primary lining comprises four 14-in.-thick constant cross section precast concrete segments plus a key. As the joints are located in the ring at the theoretical points of contraflexure, no fastenings are provided in the radial joints. However, twelve 3/4-in.-diameter longitudinal anchor bolts tie the rings together.

Some type of soft, mastic-type gaskets were applied to the concrete segments as an initial water barrier. After the erection of the primary lining, a waterproof membrane was applied to the inner surface to provide final water sealing before placing the secondary lining.

Rhine Tunnel at Dusseldorf

Although this is a sewer tunnel and is of smaller diameter than would be used for rapid transit, it is included because it represents an interesting principle of joint post-tensioning. In the tunnel, the four segments plus key are tied together across the radial joints with curved high-strength bolts (as is noted in Table 3-2). Longitudinal high-strength rods fasten the rings together. No details have been obtained of the anchorages or the sequence of these installations.

Watertightness was apparently obtained with bitumized packings between the segment faces supplemented with rubber pieces at the corners. In addition, caulking consisting of asbestos fibers and rapid-setting cement was placed in caulking grooves.

Tee Rib

This design was inspired by the Dusseldorf tunnel system. It was presented as a concept during the precast concrete tunnel lining symposium held in Czechoslovakia in 1970, and the system appears to be patented in both Germany and Austria. There is no evidence of its actual use. A ring consists of five 3-ft-wide segments plus a key; the tee section and other details of the ring are indicated in Figure 3-1. The segments and rings are tied together by about 1-1/4-in.-diameter curved high-strength (post-tension) bolts.

For erection purposes, the radial faces are provided with clips for temporary bolts which are removed after the ring is in place. Caulking grooves are provided around the inside perimeter edges of the segments.

UNION OF SOVIET SOCIALIST REPUBLICS

Dog Bone System

The "Dog Bone" segment system with several variants was developed for the Moscow Rapid Transit System in the 1930's. The principal features appear to be a solid cross section segment and an interlocking configuration which in concept could permit the rings to be erected without fastenings. It was reported that difficulties were experienced both in the manufacture and the erection of the rings, and consequently the system never found favor. The more orthodox block design indicated was successfully used in a number of the Moscow transit tunnels.

Block System

The solid blocks are 12 in. thick, 3 ft 3 in. wide and number six per ring. They are not bolted but have two dowels in the radial face for positioning in the segments during erection. The water sealing system consists of 2-in. semicircular grooves in the center of the segment faces which are pressure-grouted with cement grout after ring erection. Cement mortar is used to fill the caulking grooves in the inside face joints.

No information is available on the water and soil conditions in which the tunnels were installed or on the performance of the system.

JAPAN

Sakuragicho Subway, Yokohama

This provides an interesting example of a composite lining design. The segment flange faces are of 3/4-in. steel plate.

The bolt pockets in the radial faces contain pairs of bolts; those in the circle faces have single bolts. The bolts are 1-3/16-in.-diameter high-strength, and it would seem that the resulting ring would be quite stiff. To waterproof the segment itself, a 3/16-in.-thick steel plate on the inside face was welded to the flange plates. Both gasket and caulking grooves in the flange faces were provided with butyl rubber gaskets placed in the former and epoxy resin in the latter. The seals appear to have been effective, where they were not damaged during erection.

Tokyo Teito HST Authority

This transit authority, as well as others in Tokyo, has constructed several precast concrete lined tunnels. The channel section bolted segmented rings are typical of most of the systems employed. Generally, the grounds encountered have been permeable sands and silts with high water tables. Of interest is the gasket detail using butyl rubber and the epoxy-filled caulking grooves. Variations of this double form of water barrier includes coating the segment faces with various elastomeric/bitumastic materials and filling the caulking grooves with elastomeric/asbestos compounds. In addition, many tunnels have inside membranes with a cast-in-place concrete inner lining.

UNITED KINGDOM

London Transport Executive (L. T. E.)

The first use of concrete segments by London Transport was about 1939 when several miles of tunnel were constructed as a part of the Ilford tube in northeast London. The tunnel lining rings were comprised of bolted segments of channel cross section similar in detail to those developed for BART. Bitumen sheet packs were used between the faces to even out the high shield jacking pressures and to provide some measure of waterproofing. The segment toes were caulked with asbestos cement. The installation was in ground with low water tables, but a certain amount of leakage into the tunnels was experienced after completion. In the extensions to the L. T. E. system after World War II, the use of bolted concrete segments was limited mainly to temporary construction shafts and access tunnels. However, a large number of tunnels for water and sewer agencies were, and still are being, constructed of bolted segmented linings. For their new train tunnels, L. T. E. has used almost exclusively expanded concrete linings when the ground is "good," generally firm, dry clay. In wet or poor ground, bolted cast iron segments have been used.

The lining systems which are discussed directly hereafter are those used in three transit lines constructed since 1950. The Fleet Line is still under construction.

Victoria Line

Two variations of the articulated lining segment joints were installed for an initial evaluation. In the first, all faces were slightly rounded convex across the thickness of the segment; in the second one, the matching segment face was convex and the other was concave to provide a knuckle joint. An evaluation indicated little advantage in the latter joint and consequently the all-rounded joint was adopted for the remainder of the construction. A ring was composed of eleven segments which were placed directly against the ground. The ring was then expanded by placing jacks in slots provided in two pairs of segments located below the spring line and inserting concrete packing pieces in the arising spaces. As the system was used in dry ground, no provision was made for water sealing.

Heathrow Extension (Piccadilly Line) and Fleet Line Stage 1

In both of these lines lining ring consisted of twenty segments plus two tapered wedge segments which are driven into place longitudinally by special shield jacks and thus expanding the ring. The radial faces are rounded both across the thickness and the width of the segment. In erection, the segments below the wedge positions are placed directly on the ground. Those above are winched onto semicircular erection frames. They are then lifted into position in the ring and the wedges are placed and jacked into position. The segments are without reinforcement, except for those adjacent to the wedges, and are therefore relatively inexpensive to manufacture.

Fleet Line Stage 2

This lining has been developed, but not yet manufactured, to permit it to be erected either as an expanded lining in similar fashion to the lining described for Fleet Line Stage 1, or as a bolted lining when bad ground is encountered within a tail of a shield. The basic system for the latter use consists of eleven segments, including two with horizontal wedges which are bolted to two of them, plus one key, as indicated in Figure 3-2. When used as an expanded lining, it is erected directly against the ground and the diameter will be about 5-in. greater than when erected within the shield. In order to achieve this, the wedges are reversed and additional wedge segments, as indicated in Figure 3-2, are provided to obtain the desired diameter increase. The key piece is deleted.

It is interesting to note that tapered rings were not provided in any of the linings described for the above three extensions. Alignment changes and corrections were made by inserting timber or wood composition packings of various thickness up to about 5/8 in. between the circle joints.

As the segments have to be reinforced, they are somewhat more expensive than those in the lining system in Fleet Line 1. Therefore, their use may be restricted to tunnel contracts where the ground is known to be variable.

Provision for caulking the segments used in both the Heathrow Extension and Fleet Line tunnels was made by providing grooves in the inside segment perimeter edges. When some water was encountered, and water tables were generally below the crown of the tunnels, the lining was caulked with asbestos-cement rope several months after erection when major ground movements had ceased. This was sometimes followed by an expanding cement-mortar filler. In the case of more severe water pressure, where the flow could not be stopped, the L. T. E. philosophy was to channelize the water above the tunnel spring line and lead it into the tunnel drainage system.

OTHER PLACES

Tabor Peg Block

This lining system has been designed for a range of tunnel diameters between 9 and 42 ft. Corresponding to these diameters, the segment widths are 3 ft-3 in. and 5 ft, and their thickness 10 in. and 20 in. Tapered-around oak pegs driven into the half rounds in the opposite sides of the radial faces of the segments act as shear keys (and perhaps hinges). The driven ends of the peg, supplemented with short intermediate pegs, key adjacent rings together.

The waterproofing system in the segment circle faces comprises wood sealing strips seated into rebates. To seal the radial joint strips, sealing materials are applied to the long wooden peg dowels. The short alignment pegs are sealed in a similar fashion.

Information indicates that one 30-ft-diameter tunnel has been completed in Osaka, Japan, and three others of greater and lesser diameters, which employ this concept, are under construction in Czechoslovakia and also in Switzerland.

Metro Di Roma

A portion of the Rome subway includes tunnels which are lined with a post-tensioned concrete segmented lining. The lining consists of four segments and one small key segment 2 ft-7-1/2 in. wide and 10-5/8 in. thick. The segments of a ring are conneced by means of two rods of the Dywidag type, shaped to cover half the circumference. Each rod connects three segments. The connection between the rings is effected by means of eight longitudinal Dywidag rods (two for each segment) in sleeves through the segments. The rods are tensioned every ten rings and cement grouted. The post-tensioning of the lining in two directions would appear to provide a competent jointing system and reports indicate that the performance has been satisfactory. However, information regarding soil conditions, and waterproofing details are not available.

CONCLUSIONS

In reviewing the aforegoing, it can be seen that contemporary tunnel lining systems fall into two general categories. Those that are bolted and those that are non-bolted. The adoption of one or the other appears to be determined by the type of ground encountered and the position of the groundwater table in relation to the tunnel.

Many of the cities with rapid transit systems are shipping ports with their downtown areas adjacent to the waterways. Consequently, in these cities it is not surprising to find grounds which frequently consist of sandy, silty, clayey deposits, often with large areas of man-made fills, and which also exhibit high groundwater tables.

In these conditions, where concrete segmented tunnels have been used, the joints have been bolted or post-tensioned. In particular, the Japanese have constructed considerable lengths of tunnel using bolted concrete lining in difficult ground conditions. However, bolted linings are expensive both in manufacturing and erection costs and where ground conditions permit, engineers generally prefer non-bolted segmented systems. The L. T. E., for example, have wholeheartedly adopted a variety of non-bolted concrete tunnel linings for the competent almost dry stiff London blue clay encountered.

4. SYSTEMS DEVELOPED IN STUDY

INTRODUCTION

The economic optimization of the design of a segmented concrete tunnel lining system requires the resolution of the interactions of a number of controls upon three major cost areas.

Figure 4-1 is a pictorial representation of the major elements of the controls or design variables and the cost areas.

The costs areas are:

A. Manufacture of the segments
B. Construction, or installation of the lining
C. Performance of the lining during its service life

The costs of the elements in each area are affected directly or indirectly by the controls.

I. The ground
1. The lining system
2. The sealant system
3. Type of concrete
4. Configuration (or cross section) of the segment controls.

The ground (I) — its type and condition is the prime control in the selection and design of a tunnel lining. It represents a fixed control at any particular site location for a tunnel.

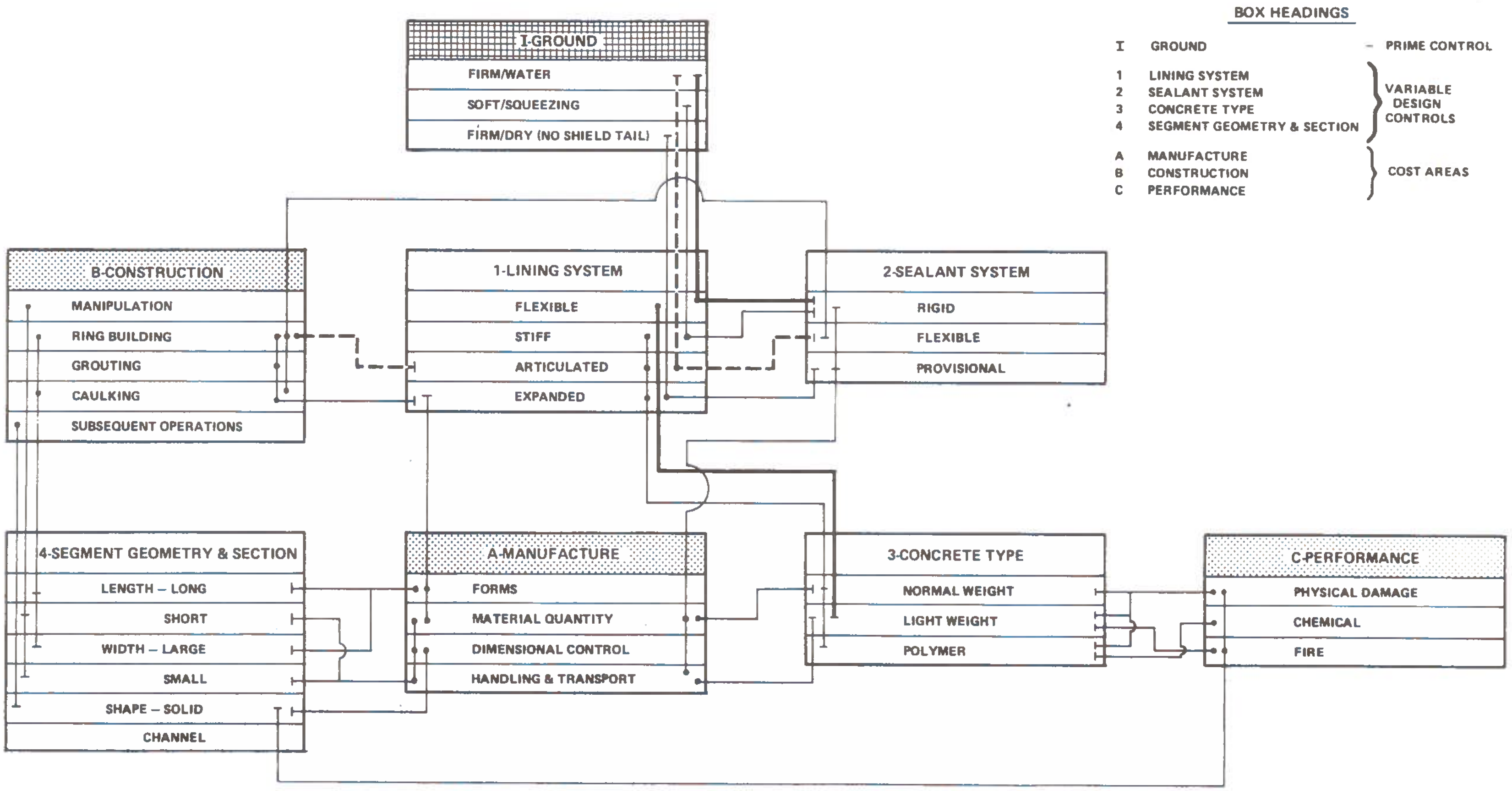


Figure 4-1. Interaction of Major Controls on Cost Areas

The controls 1 through 4 may be termed elective variables. The ground (Control I) usually imposes the overall boundaries, or restrictions, which reduce the choice of lining system and its details. However, within such boundaries the designer will still have a number of options for the elements available within each control. This is illustrated hereafter.

The links between the elements in the controls and in the cost areas indicated in Figure 4-1 may be termed optimizing links. These are shown to indicate the desirable economic element selection for the application of a particular control. For example, referring to Figure 4-1, where a tunnel is located in firm water-bearing ground there are two possible tunnel linings, "flexible" (the link is heavied in) or "articulated" (the link dashed). However, as shown, an articulated or non-bolted lining would require a sealant system which was sufficiently flexible to accommodate joint movements; whereas a flexible lining, with rigidly bolted joints, would be satisfactory with a rigid sealant.

If the choice of lining was "flexible," then the most economic concrete to use in the segment would be lightweight, owing to its "flexibility properties" and the consequent beneficial effect on the ring bending moments arising from ground distortions. This is indicated in the figure by solid lines.

Turning to the impact of lining systems upon construction costs, it will be noted that an expanded lining has advantages over the other types because the cost of grouting the tailspace is eliminated, as is the caulking, and the ring building is fast (and economic) since there are no bolts to install.

A similar logic exists for the other optimizing links indicated, however, the control variables, and the interaction between them, as well as unknowns inherent in some of the elements within the cost areas, make a mathematical integration of the links in order to determine the details of a particular lining system unrealistic. Not withstanding, Figure 4-1 does serve a purpose in identifying the desirable engineering detail for a particular control or ground situation and, as such, it is presented as a guide framework for the material discussed in this and the succeeding sections.

In the selection and development of the study lining systems, consideration was given to the parallel importance of construction techniques, sequences, and economics, in addition to the constraints imposed by the ground conditions. The construction process includes the basic tasks of excavation, its removal, the support excavation, and installation of the lining. The worldwide general trend has been in the direction of greater mechanization to speed up the tunnel construction. The degree of mechanization (i.e., the proportion or mix of equipment and labor) to produce the most economic end-product varies considerably among European countries, Japan, and the United States, being largely influenced by relative labor-productivity costs. The United States, with its more costly labor structure, has been moving toward mechanizing construction operations to the maximum extent possible in order to attain high economic productivity.

BASIC ASSUMPTIONS

The basic assumptions upon which the lining systems in this study were based are as follows:

- In the United States, most cities with fairly immediate plans for rapid transit tunneling in soft ground (e.g., Baltimore; Washington, D.C.; and Chicago) have a mix of ground conditions. Accordingly, for the purpose of developing design criteria, two ground groups, or types, were assumed. The first, which would probably represent the majority of the ground encountered, comprises firm soils with a water table 10 ft below the ground surface. The second group comprises soft plastic, or squeezing soils.

- It was assumed that the tunnels in both groups of ground would be constructed using shields, either mechanized or manual. As the width of a ring and the number of segments are subject to a number of variables, including a contractor's preference, it was decided not to recommend a standard segment size. Instead, a lining system would be developed in which the segment size could be varied without appreciably modifying the design or details.

SYSTEMS DEVELOPED

Predicated upon the above two assumptions, three systems were developed for two ground groups. The systems developed were: (1) Composite, incorporating a steel perimeter angle. Pockets are provided in the concrete for the installation of high-strength bolts which connect the segment through the steel angles. (2) Bolt Pocket, which uses steel face plates anchored in the concrete for transmitting the bolt forces. (3) Through Bolt, where bolts passing through the segments tie the segments and the rings together in a continuous fashion. The two design ground groups were (1) firm soils with high groundwater tables, and (2) soft or plastic soils. In all the designs, a six-segmented ring 3 ft wide was adopted for the design base. Comparative cost estimates for these designs, as well as for a ring width of 4 ft, have been provided.

As discussed in Section 2, the inherent drawbacks of bolting through the flanges of a channel cross section led to the development of segments of constant cross section.

All the systems in firm ground and in plastic ground are similar in concept; the segments are essentially solid in cross section; are bolted together along their four faces; and have identical waterproofing details.

FEATURES OF THE SYSTEMS

A discussion of the principal features of the three systems is included below.

Composite System (See Figure 4-2)

This system comprises a steel angle frame with a reinforced concrete in-filling and shear connections to provide composite action. The 7 x 4 x 5/8-in. angle which frames the four faces of the segment is provided with 1/2-in.-diameter welded studs which serve both as shear connectors and tension anchors. Three-quarter-inch diameter high-strength bolts are used to connect the segments. The bolt pockets are sized to permit the use of a standard direct drive impact wrench.

A 1/4- x 2-in. steel plate welded to the circle faces is machined to 1/8-in. thickness to a specified tolerance (0-1/32-in. is suggested). The purpose of this plate is to locate the high-jacking forces on the transverse center of the segment, thus avoiding the possibility of spalling the edges of the concrete behind the facing angles.

Essentially, the system provides the advantages of a metallic segmented system, in that steel to steel is bolted tightly together. If adopted as a standard, the system would greatly simplify the concreting aspects of the segment manufacture, both in the speed of final production and in maintaining the required tolerances.

Steel Pocket System (See Figure 4-3)

As is the case of the composite system, the steel bolting faces permit the use of short high-strength bolts to ensure tight concrete interfaces and competent structural joints. The bolt pockets indicated are shorter than those provided in the composite system and would require the use of right angle drive torque wrenches, of which there are several suitable types, either presently on the market or under development.

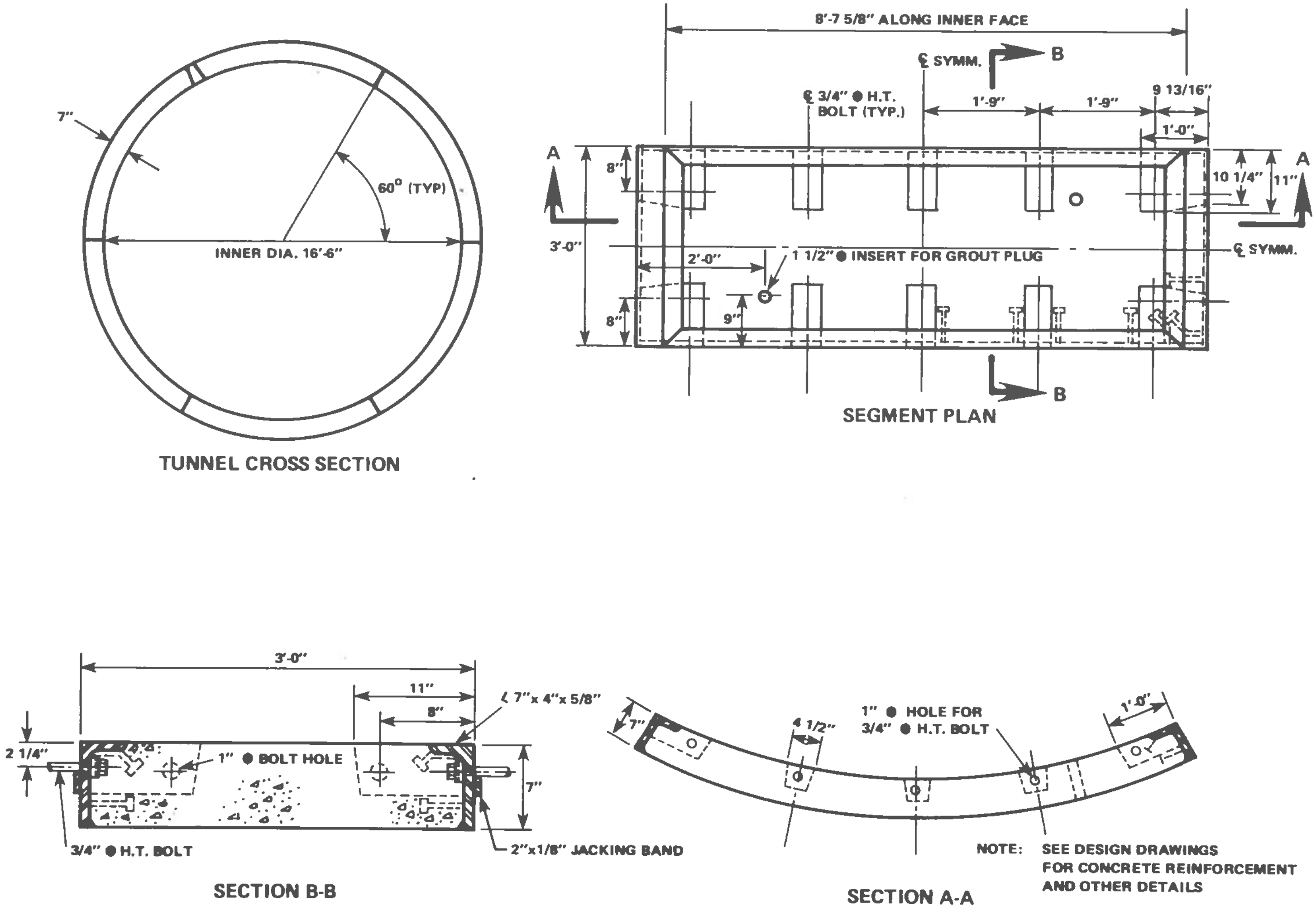
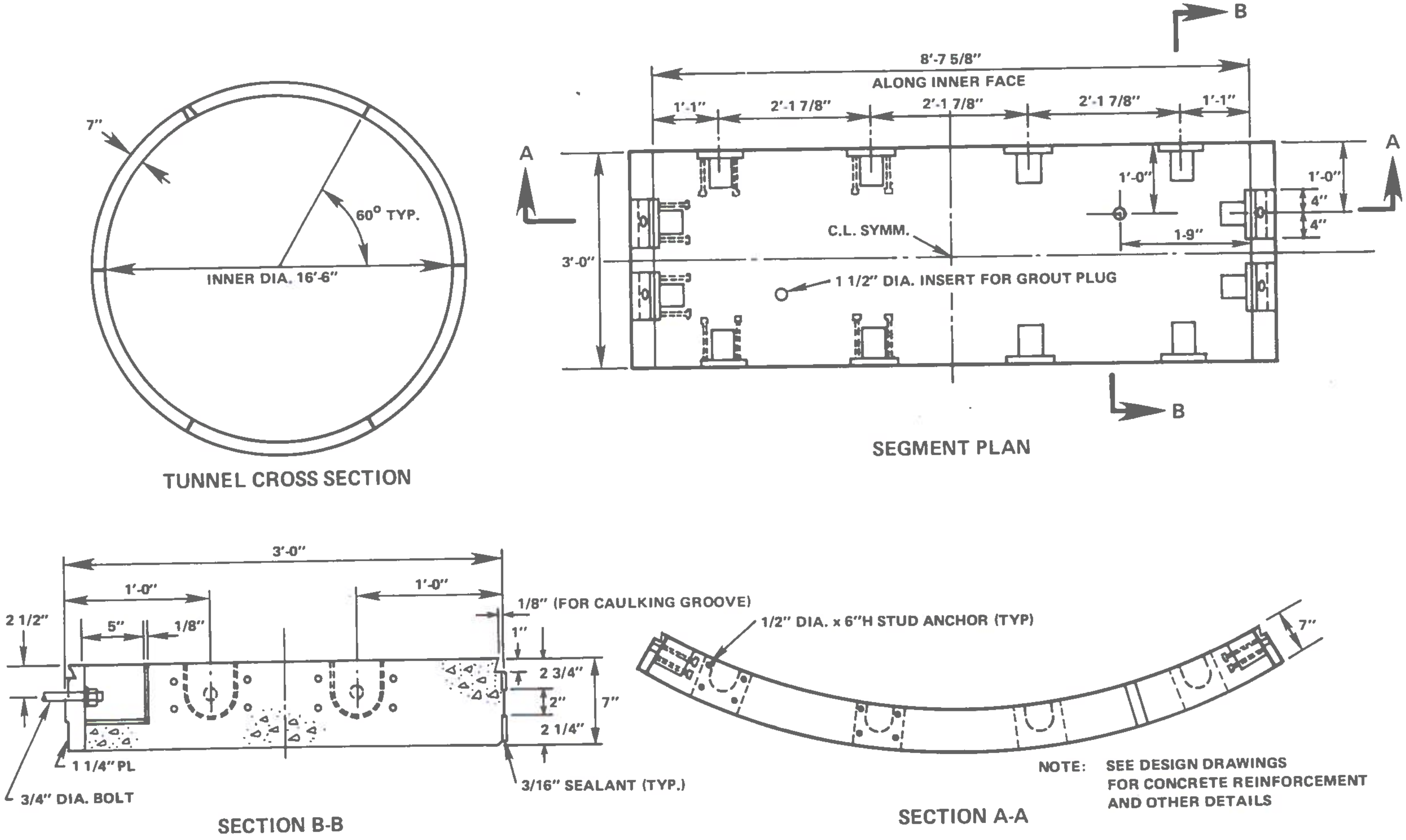


Figure 4-2. Composite System



NOTE: SEE DESIGN DRAWINGS FOR CONCRETE REINFORCEMENT AND OTHER DETAILS

Figure 4-3. Steel Pocket System

The 1/8-in. x 2-in. raised band on the circle face aids in attaining specified tolerances of the circle faces as well as centering the jacking forces on the segment cross section.

Through Bolt System (See Figure 4-4)

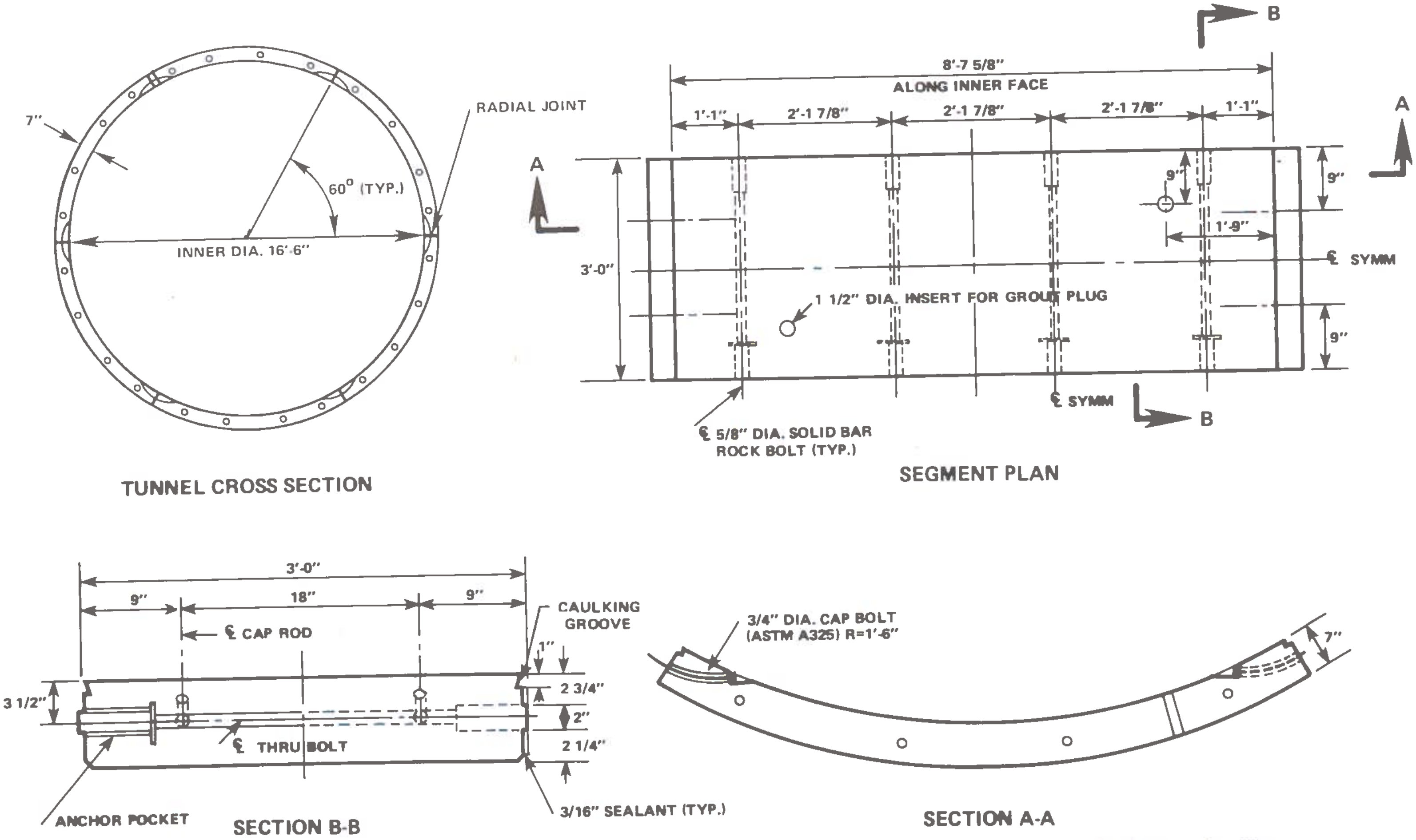
This concept differs from that of the steel pocket in the fastening details. The segment rings are fastened together by post-tensioned bolts, located centrally in the thickness of the segment and anchored in the segments of the adjacent rings. The radial joints are provided with 3/4-in.-diameter high-strength (H. S.) capping bolts.

The through bolts are indicated in Figure 4-5 as typical solid rock bolts, but the alternative hammer head bolt would provide a more economical and direct anchorage. For convenience, the bolts would be placed in the segment — not projecting from either face — before transportation to the tunnel heading. The erection procedure would consist of placing the segment in position in the ring, pushing the bolt and anchorage back in the bolt pocket of the previously erected ring, torquing either the bolt or the nut according to the system used, to obtain the specified bolt tension. This sequence is established rock bolting procedure and can be performed with one wrench socket actuated by a direct drive impact wrench. About 9 in. would be required between the segment and the jack shoe for the operation. Tightening of the circle bolts and the radial joint cap bolts may be undertaken concurrently.

All of the Through Bolts would be grouted for corrosion protection; the 3/4-in.-cap bolts could also be grouted at the engineer's option.

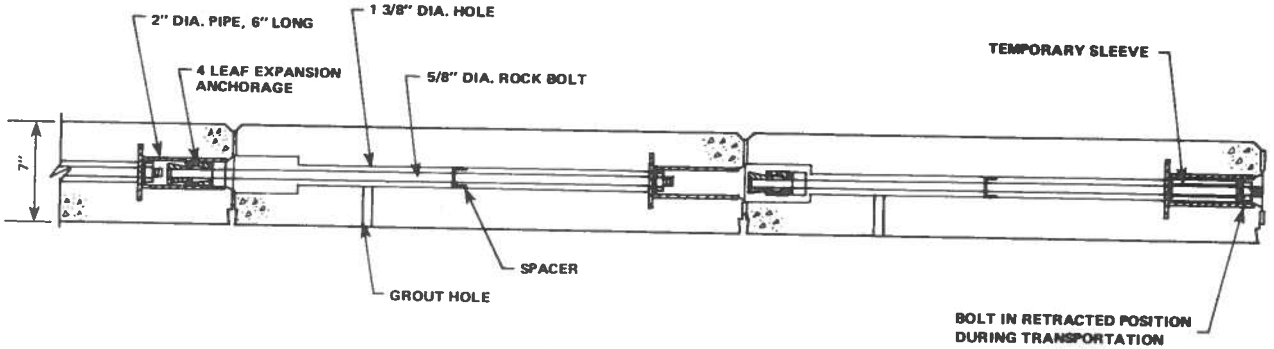
Water Seal System (See Figure 4-6)

The three lining systems are provided with identical primary gasket seals and secondary caulking seals.

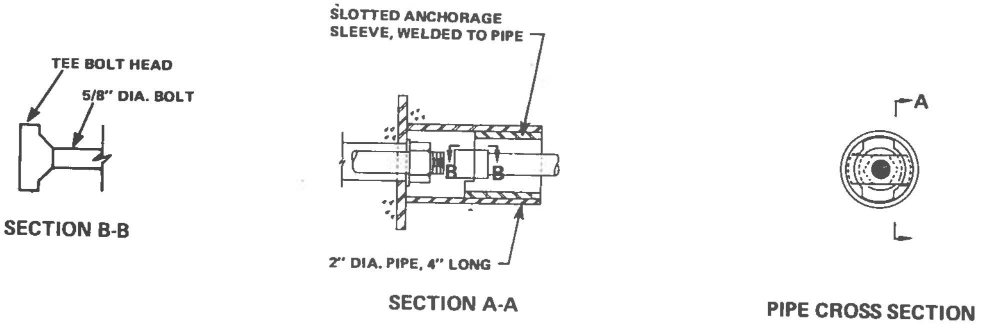


NOTE: SEE DESIGN DRAWINGS
FOR CONCRETE REINFORCEMENT
AND OTHER DETAILS

Figure 4-4. Through Bolt System

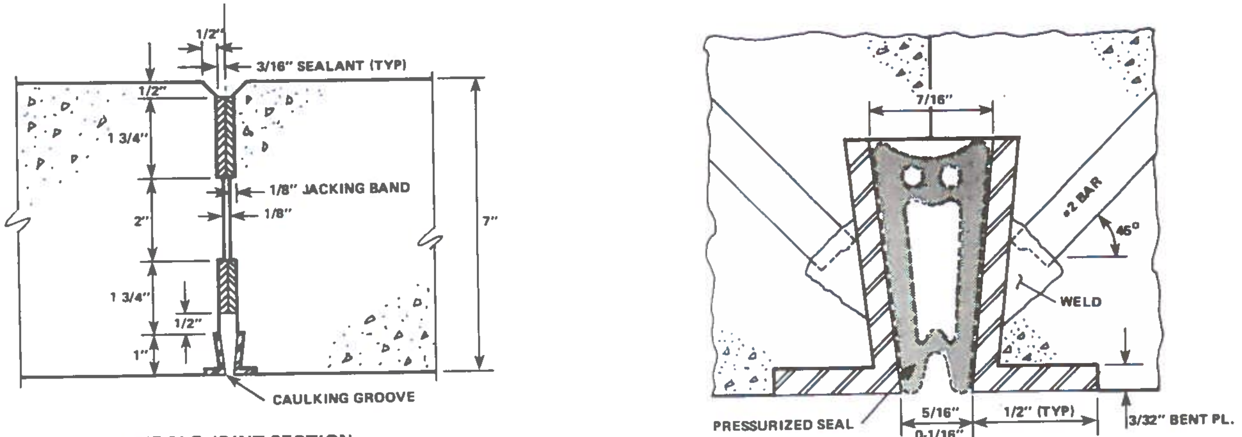


ROCK ANCHOR FASTENING



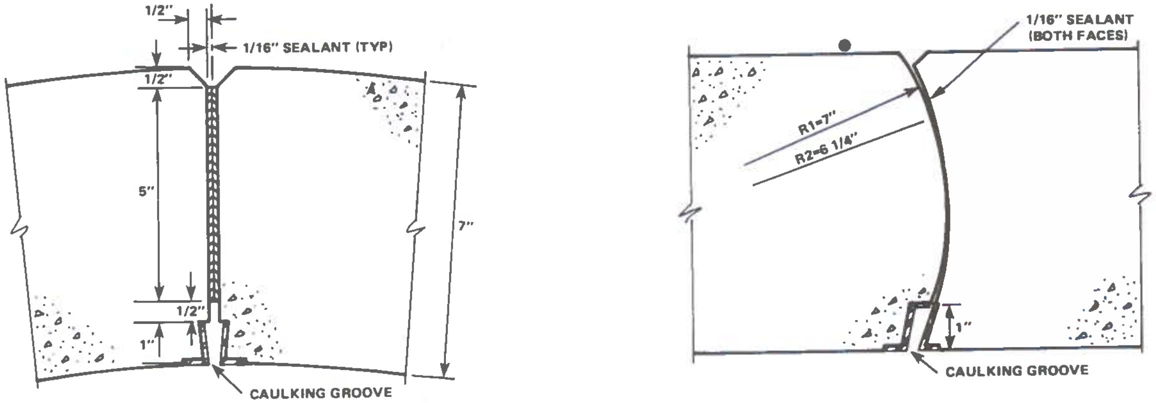
ALTERNATE TEE HEAD ANCHOR FASTENING

Figure 4-5. Typical Anchor Bolts



CIRCLE JOINT SECTION
(Prior to Bolting)

CAULKING GROOVE DETAIL



RADIAL JOINT SECTION
(Prior to Bolting)

KNUCKLE JOINT DETAIL

NOTE: DETAILS SHOWN APPLY TO THE THROUGH BOLT AND STEEL POCKET SYSTEMS. DETAILS FOR THE COMPOSITE SYSTEM ARE SIMILAR

Figure 4-6. Sealant System and Knuckle Joint Detail

The primary gasket in the circle faces consists of two 3/16-in.-thick bands of butyl rubber applied to the faces on either side of the raised central jacking band. As the segments are placed, the circle bolts and shield shove jacks bring the faces together, concrete-to-concrete, at the jacking bands, compressing sealants to 60 percent of their original thickness, and thereby, effecting a positive water seal.

On the radial faces, the primary gasket material would be applied 1/16-in. thickness across the full face of each segment. It is anticipated that the tightening of the radial bolts and the ground loading will compress these sealants about 50 percent of their combined original thickness. That is, the final sealant thickness of the two bands at the interface would average 1/16 in.

Due to the distortion of the lining, the circumferential bending moments will cause a varying compression across the joint, and a corresponding variation in the thickness of the gasket. It is also anticipated that due to the flow of the sealant under compression, the inherent voids which are present at the intersection of the segment corners and which always are a source of leakage, will be filled satisfactorily.

The secondary caulking seal is provided as a backup system in the event of failure of the primary seals. This seal is in the nature of a caulking groove provided along the four inside edges of the segments.

The caulking seal presently proposed would be in the form of an inflatable tube of "O" ring which, after being inserted in the grooves, would be pressurized by injecting a liquid filler. This would solidify after placement, thereby maintaining permanent expansion of the seals. While both the proposed primary and secondary sealant systems are simple in concept — and a certain amount of experience already has been gained with the primary one — it is deemed advisable to verify by testing the properties of the materials and the principles of their intended application. Such a test program, together with a more detailed discussion on sealant systems, is presented in Section 7.

Alternate Radial Joints

Given a sealant system which would provide satisfactory watertightness when movement occurs in the segment joints, the fastenings between the segments could be reduced, certainly for the firm ground condition, to the minimum required for that of the erection of the lining. This would permit the elimination of the radial joint bolts altogether and allow articulation of the radial joint, thereby reducing the cost of both segment manufacture and ring erection. A detail for a proposed articulated "knuckle" joint and the related water barrier system is shown in Figure 4-6.

COMPARATIVE COST ESTIMATES

Cost estimates were prepared for the study lining designs, and for comparative purposes, linings for the designs of Caracas and Washington Metropolitan Area Transit Authority (WMATA) were also estimated. The manufacture of 10,000 ft. of lining at the rate of fifty rings a week was used as a basis for the estimates.

The costs for the main components of the concrete linings are summarized for firm ground conditions in Table 4-1 and for soft ground conditions in Table 4-2.

The total cost in dollars per linear foot of tunnel was first compiled on a San Francisco base and then modified to reflect the differences of labor, materials, and productivity in three other geographic areas. The study lining types were estimated both for 3- and 4-ft-wide rings.

Table 4-1

ESTIMATED MANUFACTURE COSTS, $/FOOT RUN TUNNEL – FIRM GROUND CONDITIONS

PRICE ITEM	LINING TYPE										
	PRECAST CONCRETE								FABRICATED STEEL		METALIC
	CARACAS		COMPOSITE		BOLT POCKET & CAP RODS		THROUGH BOLT & CAP RODS		KAISER STEEL	COMMERCIAL SHEARING INC.	M.T.A. BALTIMORE
	3'		3'	4'	3'	4'	3'	4'	2'-6	4'	4'
CONCRETE	43		42	42	42	42	42	42			
REINFORCEMENT	135		58	58	68	68	52	52			
MISC. STEEL & BOLTS	26		568	486	313	273	146	121			
LABOR	187		102	92	104	94	100	90			
OVERHEADS PLANT MARK-UP	70		48	45	48	45	48	45			
SUBTOTAL	461		818	723	575	522	388	350			
CONTINGENCIES	89		42	37	55	48	42	40			
GRAND TOTAL SAN FRANCISCO BASE	550		860	760	630	570	430	390			
LOS ANGELES CA.	476		823	724	590	531	395	356			
CHICAGO IL.	569		872	772	643	582	442	402			
BALTIMORE MD.	568		872	772	643	503	443	403	1100	950	1250*

COSTS 1ST QUARTER 1975

*BID RECIEVED MAY, 1975

Table 4-2

ESTIMATED MANUFACTURE COSTS, $/FOOT RUN TUNNEL – SOFT GROUND CONDITIONS

PRICE ITEM	LINING TYPE									
	PRECAST CONCRETE								FABRICATED STEEL	
	CARACAS		COMPOSITE		BOLT POCKET & CAP RODS		THROUGH BOLT & CAP RODS		KAISER STEEL	COMMERCIAL SHEARING INC.
	3'		3'	4'	3'	4'	3'	4'	2'-6	4'
CONCRETE					49	49	49	49		
REINFORCEMENT					114	114	114	114		
MISC. STEEL & BOLTS					229	190	152	126		
LABOR					115	105	115	105		
OVERHEADS PLANT MARK-UP					48	45	48	45		
SUBTOTAL	NOT ESTIMATED				555	503	478	439		
CONTINGENCIES					55	47	52	41		
GRAND TOTAL SAN FRANCISCO BASE					610	550	530	480		
LOS ANGELES CA.					554	495	474	425		
CHICAGO IL.					626	565	546	495		
BALTIMORE MD.					625	563	545	493	1600*	1400*

COSTS 1ST QUARTER 1975

* PRORATED FROM BART LINING COSTS FOR FIRM GROUND AND SOFT GROUND.

The costs indicated for the fabricated steel linings were based on the costs applying to linings bid for delivery to the WMATA Project, 1st Quarter 1975. That for the metallic (cast iron) was the low bid price received by MTA Baltimore in May 1975. The cast iron low bid was slightly lower than the next lowest for fabricated steel. The price for the metallic linings would (probably) be based on costs escalated to the mid-point of the delivery schedule which would be about the third quarter in 1976. Table 4-4, Inflation Analysis Cost Trends, illustrates these cost differences.

EVALUATION OF THE COSTS

The benefit of such a cost study is the ability it provides to focus on the high-cost items in a design which, in turn, will hopefully result in the engineer doubling his efforts to devise more economic solutions. With this in mind, the component costs of the various lining types for firm ground conditions were analyzed, as discussed hereafter. As the relationship of the component costs for each lining type is similar for the soft ground condition, the analysis was not duplicated for these designs.

Concrete

The Caracas channel section lining requires more complex inside forming than do the uniform sections of the study linings. However, the cost of the concrete (quantitatively equal in all designs) and the forms are about the same for all the linings. Also, for all the design types, the concrete appears to be a small cost item. In the Through Bolt design, the least costly design, the concrete contributes only 10 percent of the total cost, and in the composite, the most costly design, it contributes 5 percent.

Reinforcement

For all of the study linings, the reinforcing steel represents about 10 percent of the total cost. This small percentage is partly due to a very simple arrangement of the reinforcing cages, with few bent bars. In contrast is the Caracas lining which requires about twice the quantity of more complex reinforcement. The cost of the latter represents about 30 percent of the total.

Miscellaneous Steel and Bolts

The impact of today's high price of fabricated steel components is seen in its effect upon the cost of the composite design and to a lesser degree, but still major in effect, in the bolt pocket design. The Composite design requires about half a ton of steel angle per foot of ring and it is not surprising that, at today's prices of $900 per ton, this is a costly element in the design. In addition, the welded anchorages, whose major function is to transmit the bolt forces to the concrete, accounts for an appreciable part of the total cost of the item in both the Composite and the Bolt Pocket designs.

Labor and Overhead Plant Markup

These items do not appear to vary appreciably between the different study lining types. However, the effects upon the labor and other costs of the more complex forming and reinforcing in the Caracas lining are noticeable. In this design the additional costs involved (above those for the study linings) are 80 percent for labor, and 50 percent for overheads, plant, and markup.

Basis of Pricing

In deriving the prices for the manufacture of the segments, the principals of the firm of precasters responsible for the production of the trial concrete segments for BART in 1965 were among those who were consulted. Others included steel fabricators for the composite design, and precast concrete product manufacturers in various geographic areas. As noted in the tables, the prices were estimated on a 1975 base.

Escalation

To provide an indication of future cost trends, an inflation analysis, based on the likely year by year cost increases up until 1980, for two tunnel linings was undertaken. The two lining systems analyzed were the Through Bolt design and one in fabricated steel, both 4 ft wide. The latter was assumed to be similar to the Kaiser Steel design, and with the same price.

The first task in the analysis was to establish the component percentage costs (to the total ring cost) and to estimate the likely inflation percentage to be applied to each, over the time period 1975 to 1980. The products of the component percentages and the inflation percentages were summed to give yearly composite values, which were then divided by 100 to provide the yearly inflation values. These results for both the concrete and steel linings are displayed in Table 4-3.

Table 4-3

INFLATION ANALYSIS COMPONENT PERCENTAGES
AND YEARLY INFLATION RATES

Through Bolt Design	Comp. %	Yearly Inflation Percentage				
Component:		1976	1977	1978	1979	1980
Concrete	12	8	7	6	6	5
Steel Products	49	9	9	8	7	7
Labor	26	9	9	8	8	7
O.H, Plant, and Profit	13	8	8	7	7	6
	100					
Yearly Composite Values		875	863	763	714	663
Yearly Inflation Percentages		8.8	8.6	7.6	7.1	6.6
Fabricated Steel — Kaiser Steel						
Component:	%					
Steel	42	9	9	8	7	7
Labor	39	9	9	8	8	7
O.H. Plant/Profit	19	8	8	7	7	6
	100					
Yearly Composite Values		881	881	781	739	681
Yearly Inflation Percentages		8.9	8.9	7.9	7.4	6.8

Historical estimating records, with input from manufacturers and consultants, assisted the cost engineers in determining the component cost percentages in the two lining systems. Bechtel's Escalation Group was the principal source of input for the determination of the component yearly inflation percentages.

The second task in the analysis was to apply the yearly inflation percentages for each year being compounded. Refer to Table 4-4. It will be noted that the rate of increase in cost for both liner designs is about equal. Between 1975 and 1980 the cost in both cases will increase by about 46 percent or about 9 percent average per year.

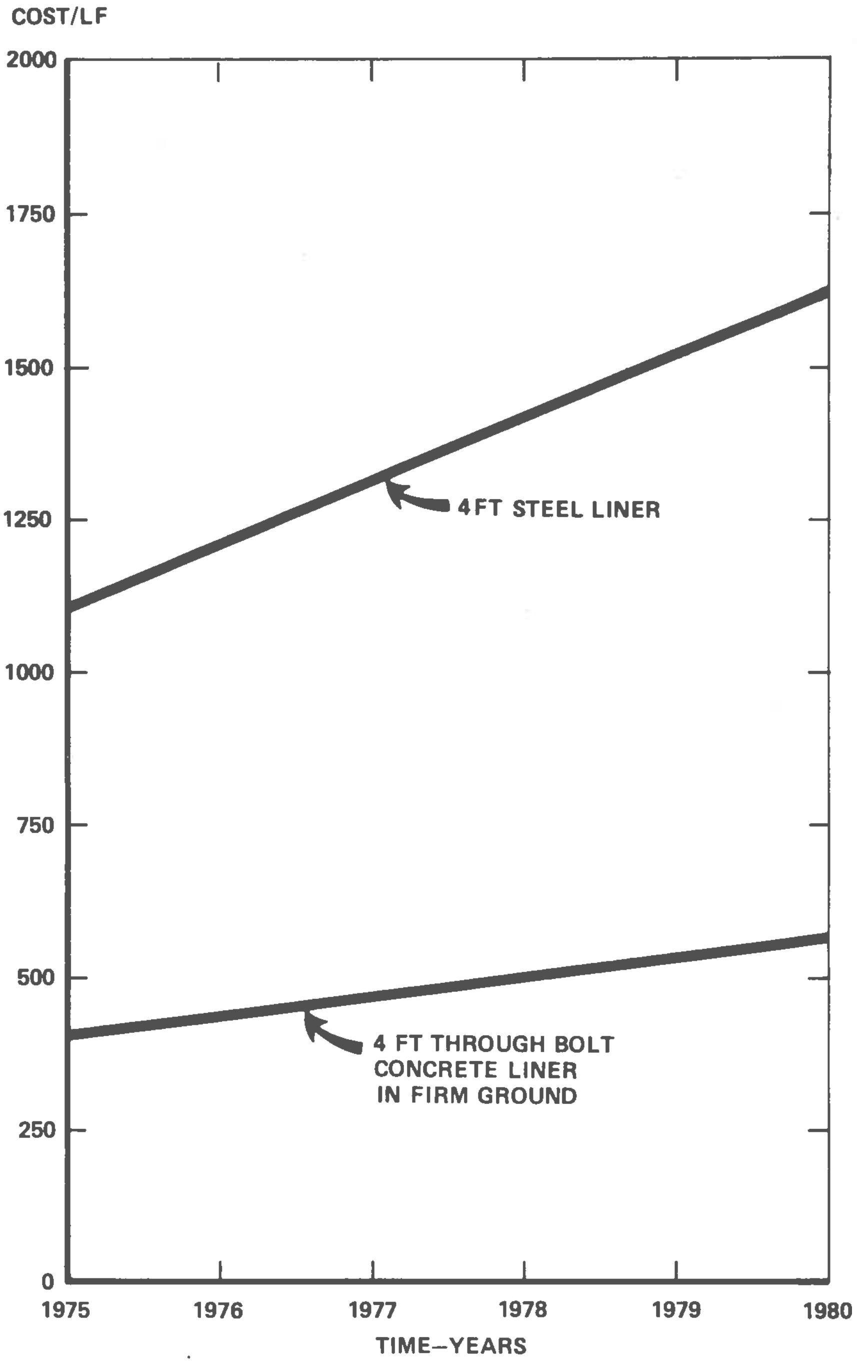
Table 4-4

INFLATION ANALYSIS COST TRENDS
THROUGH BOLT AND FABRICATED STEEL (4-FT WIDE BASIS)

	Base Cost	Annual Inflated Costs				
	1975	1976	1977	1978	1979	1980
P.C. Through Bolt (Cost per foot)	403	439	476	512	548	584
Fabricated Steel (Cost per foot	1100	1198	1304	1408	1510	1615

1980 Increase Over Base Year		Annual Average (÷5)
P.C. Through Bolt	45.4%	9.08%
Fabricated Steel	46.8%	9.38%

Figure 4-7 was prepared to indicate in graphic form the likely cost trends of concrete lining and fabricated steel.



NOTE: Prices based on
Baltimore Area.

Figure 4-7. Predicted Escalation Costs

COMPARISON OF THE STUDY LINING COSTS

An inspection of the cost tables reveals the following:

- The cost of the Through Bolt design indicates the desirability of both simplifying the concrete outline and reducing the dependency upon fabricated steel.
- The increase of ring width from 3 to 4 ft reduces the costs of manufacture of all the systems by about 10 percent. A large proportion of these savings can be attributed to the fact that, irrespective of the width of a segment, the number of fastenings remain constant and the cost of provision for and the supply of the fastenings is relatively substantial. In addition, as discussed in Section 2, further economies in the cost of installation might be expected with the wider ring.
- The substantial cost differences between the Through Bolt design and the other types estimated, particularly those fabricated in steel, could lead to important cost savings in underground transit projects. This might possibly affect decisions on cut-and-cover versus bored tunnel alternatives.

5. ENGINEERING DESIGN OF THE LINING

INTRODUCTION

The determination of satisfactory design criteria and analytic methods for the design of a segmented tunnel lining requires a balancing of engineering theory and structural insight into the dictates of tunnel functions, ground behavior, and economic construction procedures.

At its best, the design of a tunnel lining is a rough art. Although the analysis methods and the ensuing design of the structural details appear to be precise by engineering standards, the major load generants such as the actual ground to be tunneled, the tunneling equipment to be used, together with the detailed lining erection procedures to be employed on any one contract, are known only in general terms at the time of the lining design.

These are all important variables that must be considered in the development of a standardized lining system for use in the ground and under construction conditions assumed in this study. However, it is believed that the rationale for determining the loading values and their application in the lining design calculations will provide tunnel linings which are both economical and satisfactory in service.

INTERACTION BETWEEN THE GROUND AND THE TUNNEL LINING

Any discussion on the criteria selected for the lining design must be predicated on a review of fundamental concepts of the interaction of the ground and the lining.

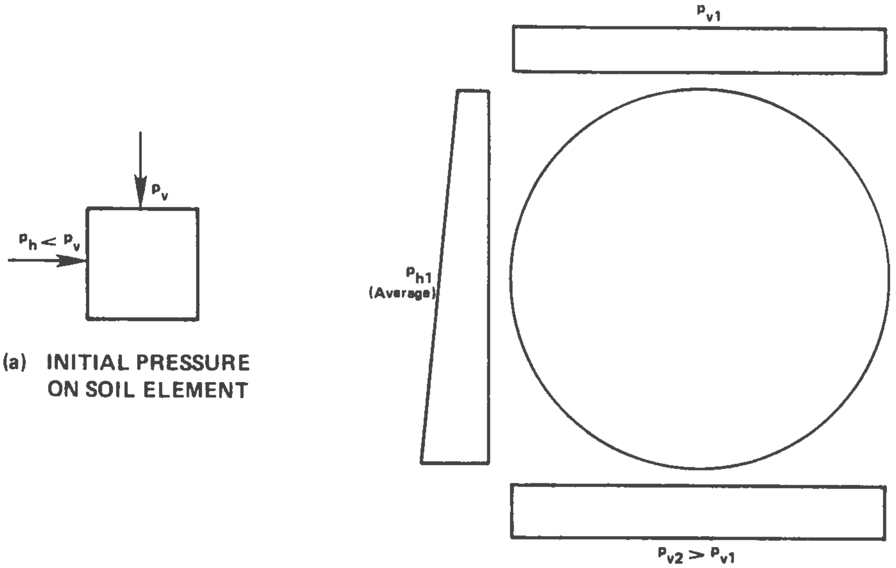
To do this, let us consider a hypothetical situation of a tube which is pushed horizontally, and without disturbance, into a soil.

Firm Grounds

First, consider the situation in reasonably firm soils, such as sands, silts, and non-plastic clays, having properties such that the "at rest" horizontal pressure (p_h) on an elemental cube of soil is sensibly less than the vertical "at rest" pressure (p_v). This is indicated in Figure 5-1a. The ground pressures on the horizontal and vertical projected plane of the tube are depicted in Figure 5-1b. It should be noted that although the actual values of the pressures will increase with depth, the proportion between the p_v and p_h will remain constant.

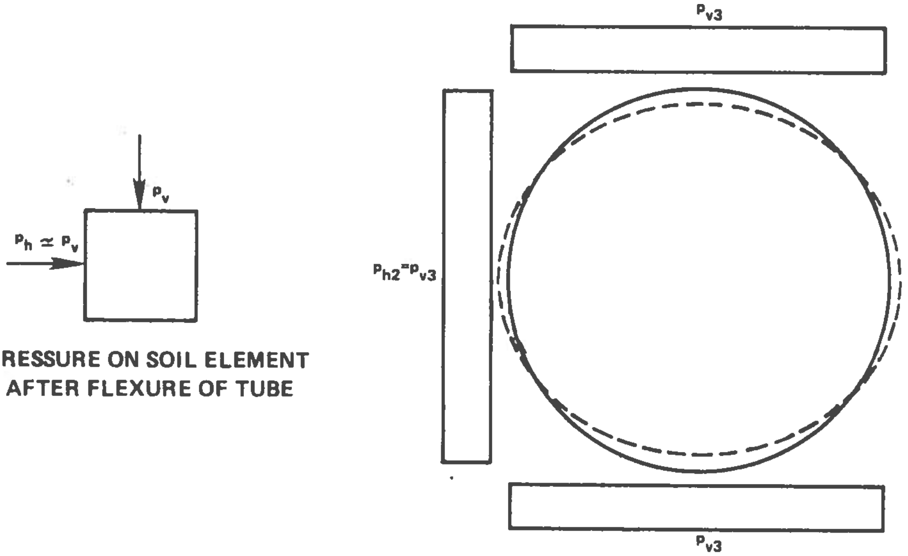
If the soil within the tube is removed and if the tube is circumferentially stiff, it will not change shape appreciably. However, due to the differential pressures on the projected horizontal and vertical planes of the tube, circumferential bending stresses will be introduced, in addition to those of direct compression, which are generated by the soil mass around the tube.

Now consider a tube which is circumferentially flexible and able to distort freely with the ground movements. The higher vertical pressures on the horizontal plane would cause the vertical diameter to shorten and the horizontal plane to lengthen. The value of the soil pressures around the tube would change as follows: the vertical pressure would reduce and the horizontal pressure would increase as it mobilized resistance to the action of



(a) INITIAL PRESSURE ON SOIL ELEMENT

(b) PRESSURES ON HORIZONTAL AND VERTICAL PLANES OF A STIFF TUBE



(c) PRESSURE ON SOIL ELEMENT AFTER FLEXURE OF TUBE

(d) ADJUSTED PRESSURES ON A FLEXIBLE TUBE AFTER INSIDE EXCAVATION IS REMOVED

Figure 5-1. Soil Pressure Diagram

the tube expanding against it. The adjusted pressures on the elemental cube are shown in Figure 5-1c and the adjusted pressures on the projected horizontal and vertical planes are indicated on Figure 5-1d.

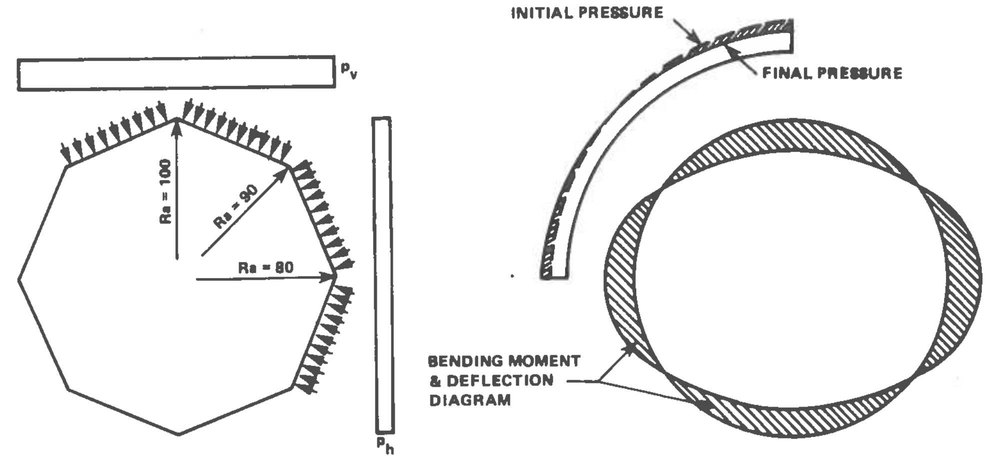
Translating this hypothetical situation into a tunneling concept where firm ground interacts with a supporting structure is referred to in Figure 5-2a, in which a tunneled opening is supported by straight members, articulated at the node points. Consider a structure installed in the ground with the nodes held rigidly so that no movement can take place. The relative values of the reactions at the nodes might be indicated by $R_a = 100$ at the crown, diminishing to $R_a = 80$ at the springline.

If the restraint is removed (Figure 5-2b), the structure will deform in the manner indicated until a balance of the node reactions, which is necessary for structural equilibrium, is attained. In so doing, the crown node will drop and the reaction may diminish by 10 to $R_b = 90$. By an equal and opposite movement, the springline node may increase by 10 to $R_b = 90$. The intermediate node may not change its position and consequently the original value of $R_a = 90$ will remain unchanged.

Of course, this example is highly idealized and neglects factors such as tangential friction between the structure and soil during the movements, but it does bring out the essential concept of a flexible tunnel structure/soil interaction.

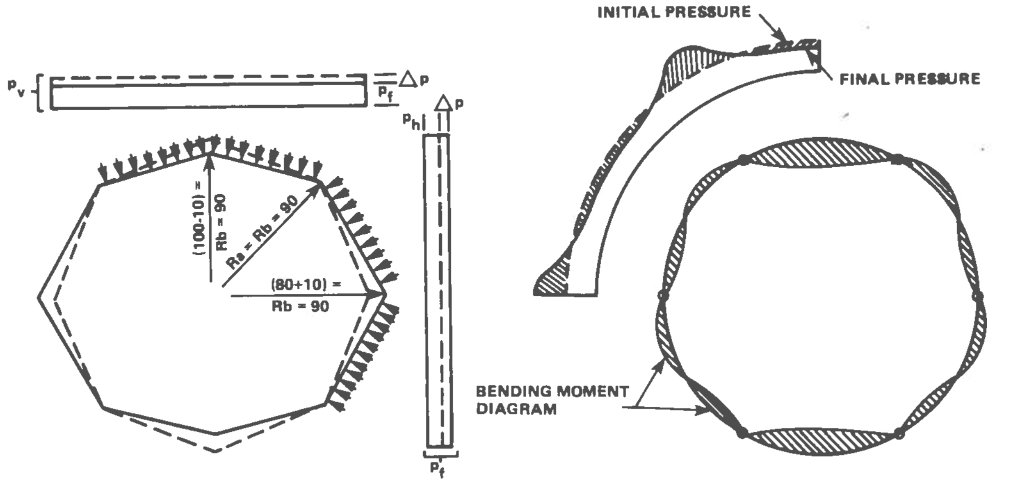
Figure 5-2c applies the concept to a flexible segmented lining with bolted joints, which provide continuity in the ring. The resulting "before" and "after" moment-deflection-pressure distributions are indicated.

Figure 5-2d shows a like situation for a similar lining and loading with articulated segment joints. Such a lining system might have application in



(a) JOINTS RESTRAINED IN LOCATION

(c) SEGMENTED RING WITH BOLTED JOINTS



(b) JOINT LOCATION RESTRAINTS REMOVED

(d) SEGMENTED RING WITH ARTICULATED JOINTS

(R = RESTRAINING FORCE)

Figure 5-2. Soils Pressure Distribution Around Segmented Lining Structures homogeneous firm dry grounds. Here it is assumed that high-ground pressure areas would develop at the segment joints (in a similar fashion to those in Figure 5-2b) to satisfy the necessary equilibrium requirements.

Soft Grounds

Soft grounds may be typically classified as low-strength, highly plastic sensitive clays and silts. The pressures of these soils acting on a tube or tunnel will be similar to those of a hydraulic fluid.

Vertical and horizontal pressures on a point would be approximately equal and pressures around a tube, restrained against buoyancy, would vary according to depth (i.e., it would be greater at the bottom than at the top).

However, if restraint against buoyancy is removed, the tube would tend to move upwards and the pressure on the top would tend to equal that on the bottom. Flotation would be prevented by the cohesion or friction in the soil mass above the tube.

In this situation, the horizontal pressure on the tube would tend to remain constant. At the horizontal half-diameter of the tube, the pressure would be equal to the weight of the soil above the plane and this would be less than the adjusted vertical pressure.

Application to Tunnel Design

Observations in segmented lined tunnels, constructed in a variety of grounds for rapid transit properties in San Francisco, Chicago, Toronto, and London, indicate that distortion patterns closely parallel those outlined in the aforegoing discussion of ground/tunnel lining interaction. To extend these concepts to the design of tunnel liners, the following is propounded:

- The distribution of ground pressures on a tunnel lining is dependent upon whether the lining is circumferentially stiff or flexible.
- If a lining is stiff, it will be subject to bending by the forces arising from the difference in the ground pressures on the vertical and horizontal projected planes, both in firm and in soft grounds.
- If a lining is flexible and in firm ground, it will deform with the strains that occur in the ground as it reaches stress equilibrium.
- A stiff lining is required in soft ground in order to limit the lining deformations.

Conclusions

For practical design purposes, the ground pressure around a flexible tunnel lining can be considered uniform. The bending stresses in the lining will depend upon its circumferential flexibility and the extent of the deformation. In firm grounds, the deformations resulting from the installation of the lining and the ground adjusting to the uniform pressure condition are relatively small. However, they are sufficiently finite to produce bending moments which increase rapidly (with a consequent increase in the lining cost) for every inch added to the lining thickness. For example, for a given distortion in a lining, the bending moments in a 7 in. thick lining would be greater by about 50 percent for a 8-in. thickness; 100 percent for 9 in.; 200 percent for 10 in.; etc. Therefore, in the interest of economy, it is desirable to provide as much flexibility in a lining as possible.

In soft plastic grounds (or firm for that matter), providing the ground properties do not change, the bending moments in a stiff lining will remain constant irrespective of the depth of the tunnel. In these ground types, a thicker circumferentially stiff lining must be used to keep distortions and bending moments within acceptable limits.

GROUND GROUPS

For tunneling work, soils may be classified in several different ways. For instance, Dr. Ralph Peck suggested a classification based essentially upon the soils behavioral properties in respect to tunnel excavation and support requirements. (Reference 5.2.)

For the purpose of transit tunnel lining design, the soil properties of interest are those which determine the final loads and stresses in the lining, and those which govern the selection of the principal tunneling equipment.

On this basis, three prime groups of soil can be established for tunnel lining design.

- Firm or strong grounds, with or without water, requiring the use of a protective shield for the support of the excavation and an integral tail section for the erection of the lining
- Firm homogenous grounds generally without water or, if present, readily removable. Here, a shield may be required during excavation but the ground is sufficiently strong and homogenous to allow the lining to be erected directly against the ground, without the need of a shield tail
- Soft or weak grounds requiring the use of the same type of shield and tail as in the case of firm or strong grounds

Bearing in mind the soils in those cities in the United States which may install rapid transit tunnels in the near or immediate future, only the first and third groups are considered in the following discussion.

The principal constituents of the two ground groups are listed below. It should be noted that in each group the ground may consist of mixtures in various proportions of the soils listed. Group 1 — firm or strong grounds — consists of the following:

- Gravels
- Sands
- Clays and silts, not sensitive
- Conglomerates

Group 2 — soft or weak grounds — consists of the following:

- Soft, plastic, sensitive clays and silt
- Muds

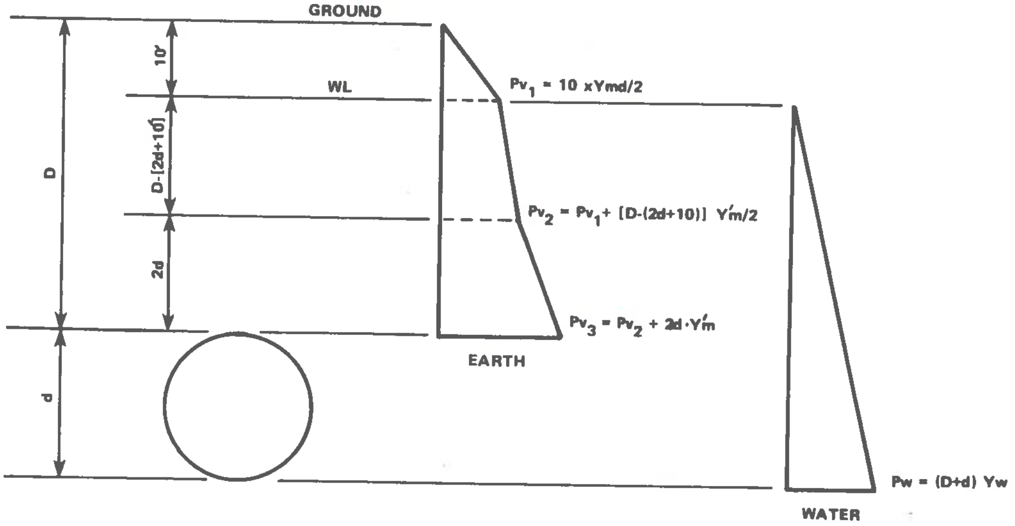
LOADING CRITERIA

The fundamental bases for the loading criteria were outlined in the discussion of interaction between ground and lining. The actual loading values for the two ground groups are defined in the design calculations. They were developed with due consideration of desirable values for the actual load versus ultimate load factors, (i.e., safety factors).

Firm Ground (See Figure 5-3a.)

The loading criteria used for the study design is predicated on the use of flexible linings and consists of two parts; the first consists of the weight of the ground (or some part of it) above the crown of the tunnel plus the groundwater pressure at the bottom of the tunnel — the combination of these loadings is assumed to act in a uniform radial direction around the linings; the second part consists of the effects that the ground distortion has on producing diameter changes in the lining.

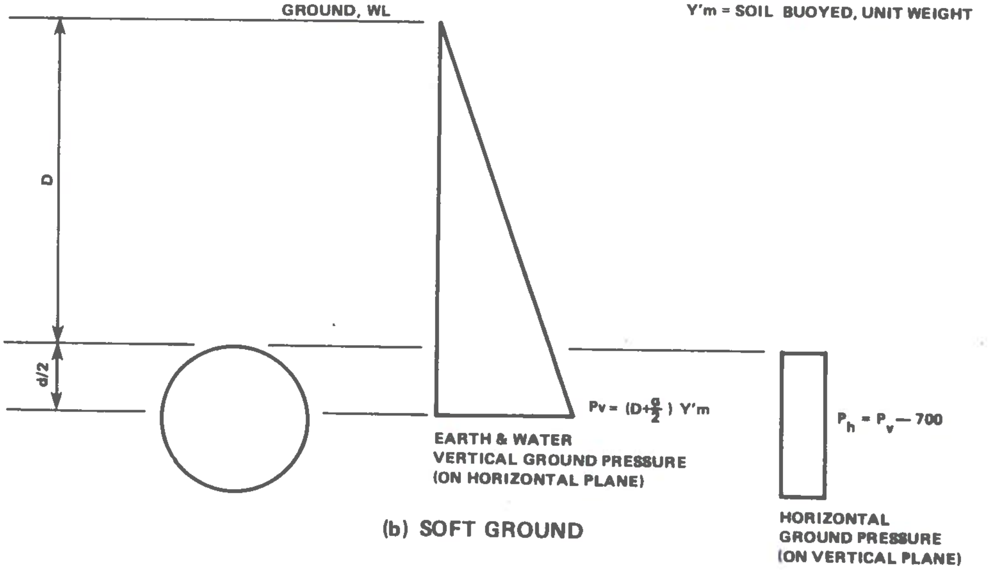
Figure 5-3a indicates the ground loading formula used for the designs. It will be noted that for depths greater than twice the diameter of the



(a) FIRM GROUND (VERTICAL PRESSURES ASSUMED TO ACT UNIFORMLY AROUND TUNNEL)

SYMBOLS

Pv = VERTICAL PRESSURE
Ph = HORIZONTAL PRESSURE
Ymd = SOIL DRY, UNIT WEIGHT
Y'm = SOIL BUOYED, UNIT WEIGHT



(b) SOFT GROUND

Figure 5-3. Design Loadings

tunnel, some arching of the ground above the plane at 2 diameters above the crown is assumed. The mechanics of such arching is discussed by Karl Terzaghi (Reference 5.3) and accordingly the weight of the soil above the "2d" plane is reduced by one-half.

A diameter, or axis, distortion of 1/2 in. was assumed for the "working" design condition, with a load factor of 4 for the ultimate design requirements of the governing minimum ground cover.

It may appear that the 1/2-in. figure is rather arbitrary. However, measurements on segmented lined tunnels constructed under similar conditions to those contemplated in the study justify its use. The bulk of the 1/2-in. deflection may be attributed to the local disturbance of the ground during the excavation and the lining erection procedures. A relatively small share, probably about 1/16, is required for the ground strain adjustment during the pressure equalization process.

<u>Soft Ground (See Figure 5-3b.)</u>

The loading is based upon the assumption that the ground can develop no passive pressures within the limits of acceptable distortion of the lining, and that the final vertical and horizontal ground pressures will both approach a value of unity. Under such conditions, due to the inherent buoyancy of the tunnel, the vertical pressure on the crown will increase to approach that of the bottom — less the weight of the tunnel. The tunnel is restrained from floating by the cohesion of the ground above it.

In actuality, the pressure on the horizontal projected plane will not necessarily achieve this value. A reasonable assumption for this value appears to be the pressure at the bottom of the tunnel, less the unit weight of the ground multiplied by the half-diameter of the tunnel. In the calculations, the out-of-balance between horizontal and vertical pressures was estimated as 700 psf. The basic vertical load was assumed as saturated unit weight of the ground multiplied by the height from the ground surface to tunnel mid-diameter.

ANALYSIS AND DESIGN

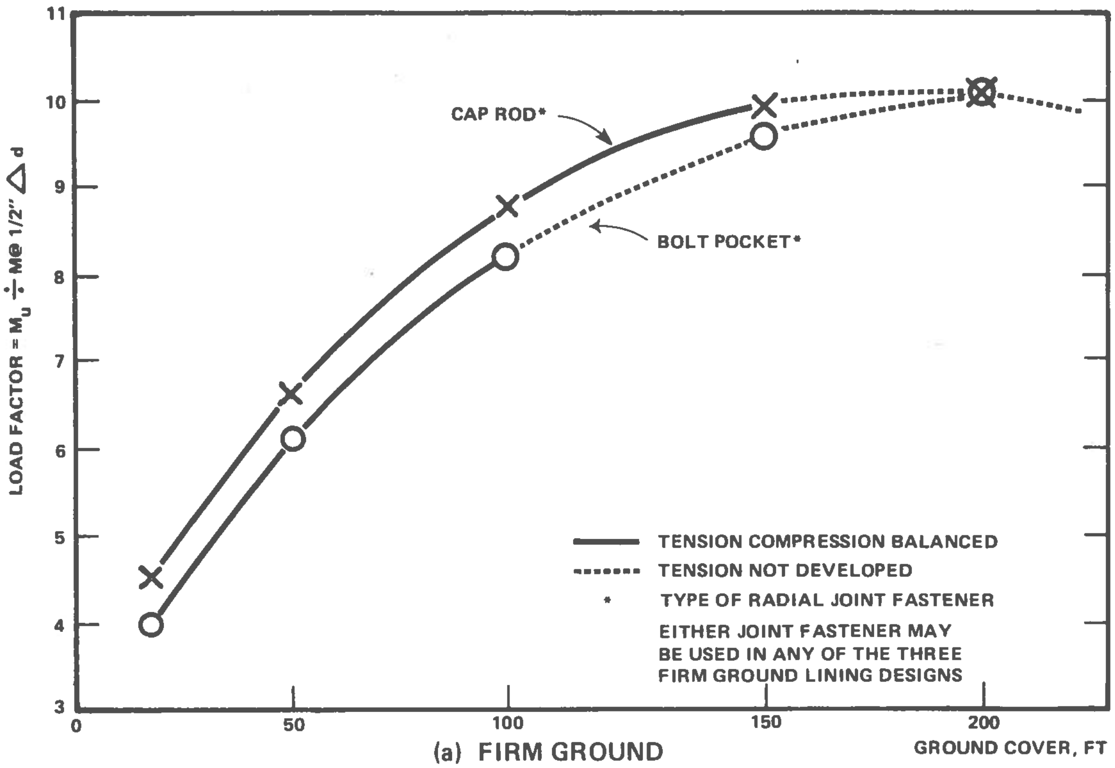
The three systems selected were analyzed by the methods indicated in the calculations. The circumferential compression and bending moments from the two ground loadings determined the design of the segment connections and the radial joints. The ACI ultimate design method was used for the design of the sections.

Firm Ground Linings

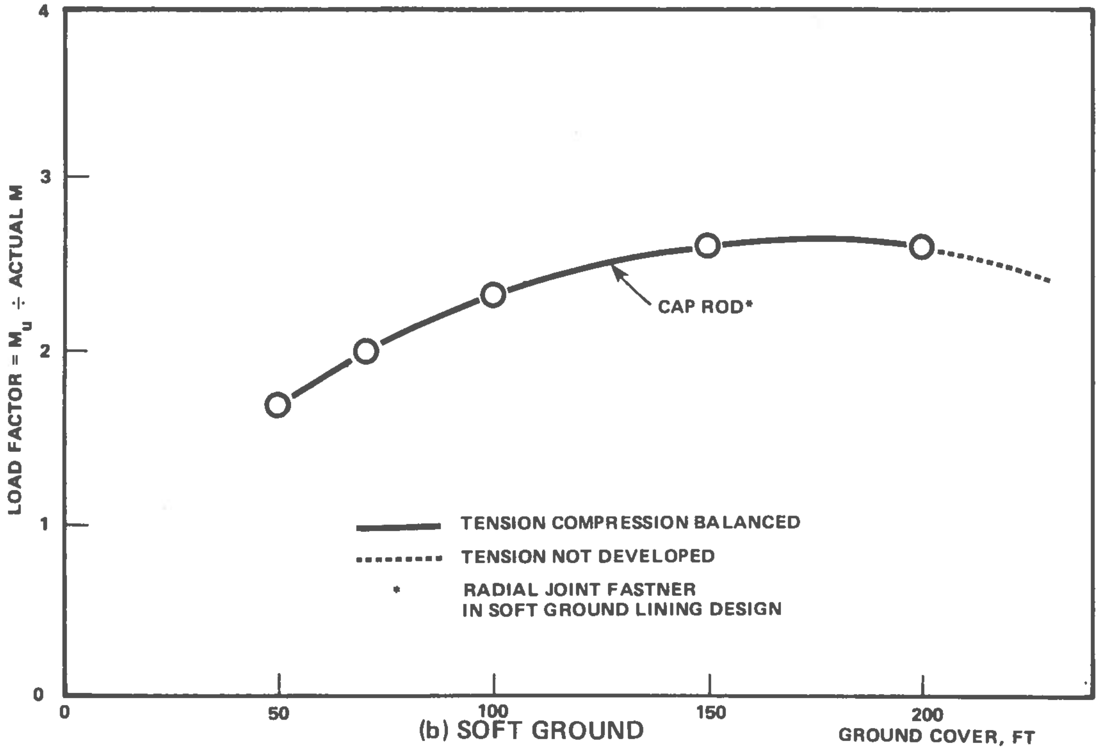
For the analysis in the firm ground base case in order to provide an adequate ultimate/service load factor, the 1/2-in. axis displacement was multiplied by 4 (i.e., 2-in. displacement was assumed) and a minimum ground cover of 18 ft was used.

The interaction diagram in Figure 5-4a was then produced to indicate values of the load factor for ground covers between the limits of 18 ft (i.e., one tunnel diameter) and 200 ft and for two alternative types of radial joint fastenings. The fasteners are interchangeable in all of the three study designs. It will be seen that for ground covers above 18 ft, the load factors increase with the ground cover up to 200 ft.

As the degree of distortion in a tunnel is often a matter of construction procedures, for tunnels in indifferent ground or those of lower densities, particularly for the shallower depths, the lining designs should not be used unless strict control of workmanship can be exercised.



(a) FIRM GROUND



(b) SOFT GROUND

Figure 5-4. Interaction Diagram, Load Factor vs. Ground Cover
(In reference to radial joint at spring line)

Soft Ground Linings

For the analysis, the base design assumed a load factor of 2 on the bending moment and the minimum ground cover that could be applied was determined. An interaction diagram, Figure 5-4b, was produced to show the variation of the load factor with increase of ground cover.

Variations in the condition of this ground class, as if affects the tunnel lining design, can be far greater than for the firm grounds. Before the lining systems are considered, a thorough soils investigation and testing program should be undertaken and the results reviewed against the design bases. For the 8-in.-thick lining design presented,the tunnels should have a ground cover of 70 ft to provide a load factor of 2. For lesser depths, depending upon the actual soil conditions, the lining thickness may have to be increased and the radial joints made stronger.

Temporary Loads

For the six-segmented ring, the reinforcement required for the final service loads is adequate to accommodate the stresses arising from normal handling and erection methods. The raised "jacking bands" provided in the circle faces should prevent local damage to the faces from the high jack pressures. Some restriction in the magnitude of single jacking loads at certain positions in the segment are indicated in the calculations but these should not be restrictive in most tunneling projects.

LINING DESIGN CALCULATIONS AND DRAWINGS

Design calculations and drawings for the three systems were prepared. See Appendix A. The drawings are for the following four lining types with a standard detail and notes sheets.

- Composite — firm ground
- Bolt pocket — firm ground
- Bolt pocket — soft ground
- Through Bolt — firm ground
- Standard Details and Notes

Specific designs have not been prepared for the Composite and Through Bolt types in soft ground. However, these may be readily produced by slightly modifying the design data for the designs noted above.

The designs developed for this study were made for comparative purposes only. Additional final design work and detailing will be required for the preparation of contract drawings. In this respect details would be required for tapered rings, tolerances, welding requirements, protection coating to concrete if any, inserts, etc. Design analysis should consider the actual nature of the subsurface materials, and evaluate the loading conditions to be used.

TESTING THE LINING

As discussed in Section 3, there has been considerable international experience demonstrating satisfactory structural behavior of precast concrete lining in transit tunnels. The study linings have been designed with conservative load (safety) factors. A full-scale laboratory structural test on the lining(s) would not appear as meaningful as installing a length of lining under actual tunneling conditions.

Laboratory structural tests could be undertaken to test the fastenings and joint behavior under ultimate loading conditions. Such testing should preferably be performed after a system is selected for consideration in a specific situation.

The installation of lining rings within a construction context,as well as providing economic and other information of value, should produce confidence in the liner systems. Such an installation would demonstrate, or provide information on the following:

- Attainable tolerances of segment manufacture
- Production techniques for the application of the sealants
- Techniques of handling and erecting the segments
- Installation of the fastenings
- Behavior of segments under the applied jacking loads
- Short-term structural and water sealant performance
- Economics of segment manufacture and lining erection

It is therefore recommended that efforts be directed toward the actual installation of precast concrete liners within a transit system. Preferably, this should be decided at the outset of the construction of a new transit system, and the tunnel section chosen should not be on the critical path of the construction. This is suggested in light of the unfamiliarity of U.S. Contractors with the type of lining and to provide time to "tune" and details of the segments, including the sealant system, before full-scale manufacturing committment. Alternatively, the rings might satisfactorily be incorporated within ongoing rapid transit system construction.

In order for the evaluation of the manufacture and installation of the liners to be realistic, a length of at least one-half mile of tunnel should be constructed. Some of the requirements for the design, drawings, and specifications for the production and installation of the liners in a tunnel are noted in Appendix A.

6. CONCRETE

INTRODUCTION

The desirable qualities for concrete in tunnel linings may be listed in two categories.

- Structural
  - high strength
  - low modulus of elasticity (for linings in firm ground)
  - low shrinkage
- Durability
  - resistance to chemical attack
  - resistance to fire

There are three possible types of concrete that can be used. These are normal aggregate, lightweight aggregate, and polymer-impregnated. Each one has better properties than the others in some respects for certain conditions of performance.

A general description of differences between the composition and production of the concretes will be given and their relative qualities evaluated.

CONCRETE TYPES

The basic materials for all the concretes are coarse aggregate, fine aggregate, and portland cement. During the production process, the materials are mixed with water which hydrates the cement, causes it to harden, and sets the aggregates in a matrix of cement mortar. Admixtures in the nature of air entraining agents are included at the time of mixing to improve workability and other properties of the concrete. After its initial hardening, concrete requires careful curing for a week or so to control its shrinkage and to increase the rate of strength gain, particularly in the manufacture of precast concrete products. Typically for precast work, the process consists of a few hours of initial curing under steam, followed by several days in a moist temperature controlled atmosphere.

The basic difference between the composition of normal weight aggregate concrete and lightweight is in the composition of the aggregates. Polymer-impregnated concrete may start its life as either normal weight aggregate or lightweight and only differs from them by the change in properties brought about by the subsequent polymer treatment.

The essential differences between the aggregates (or production) of the concretes is examined below.

Normal Weight Aggregate Concrete

In general, the aggregates are naturally occurring rocks which are crushed from quarries or obtained from natural deposits of sand and gravel. Inorganic silicous rocks and metamorphic rocks are base material for normal weight concrete aggregates.

Lightweight Aggregate Concrete

For structural concrete, several lightweight aggregates are in use in this country including the expanded clays, shales, and slates. The expanded clay aggregate is readily available in all the major industrial areas in the United States and is assumed for the purpose of this discussion.

As lightweight aggregate is more difficult to work with than normal-weight aggregate, it is important in production to include the correct proportion of an air entraining agent to provide workability of the concrete.

Polymer-impregnated Concrete

After curing, precast concrete sections must be thoroughly dried. They are then immersed in a tank of methyl methacrylate (MMA) or other qualified monomers for one or two days to enable impregnation of this chemical to take place by capillary flow. The MMA is then replaced with warm water which is maintained at 80°C for another several hours to polymerize MMA into polymetheyl-methacrylate (PMMA). This completes the process.

COMPARISON OF STRUCTURAL PROPERTIES

A comparison of the pertinent structural related properties of the three concretes is tabulated in Table 6-1. For this purpose, 5000-psi strength has been adopted for the normal and lightweight aggregate concretes.

Table 6-1

STRUCTURAL PROPERTIES

Property	Normal	Lightweight*	Polymer
Unit Weight (lb/ft^3)	145	105	145
Nominal 28-day compression strength (psi)	5,000	5,000	18,000
Modulus of elasticity (psi)	4.0×10^6	2.4×10^6	6.2×10^6

* Both coarse and fine aggregates are lightweight

In respect of normal weight aggregate concrete, it is of interest to note that 6,000 psi strength is the standard adopted by the Precast Concrete Manufacturer's Association of California. With a careful selection of aggregates, 8,000 psi concrete can be obtained on a production basis and 10,000 psi is attainable through use of new water reducing admixtures. There are strong trends in the precasting industry towards making available these higher-strength concretes. At this stage in the development of concrete tunnel linings, it is not appropriate to consider the use of these concretes owing to the presently unknown economics and controls for their production. However, future lining designs should access these factors.

DURABILITY

The durability properties of the concretes will be discussed in relation to their predicted performance under chemical attack and exposure to fire.

Chemical

Some normal weight aggregates of a silica base are subject to alkali attack. This causes the aggregates to expand, with resulting disintegration of the concrete. Obviously, care must be exercised in the specifications to avoid the use of such aggregates. Lightweight aggregates of expanded clays do not exhibit this characteristic.

Acids, alkalis, and sulfates may be present in the ground, or groundwater, and over a period of time can attack and destroy portland cement concretes. The existence of stray electrical currents, which are always present in an electrically powered transit system, can increase the rate of attack.

However, in tunnel linings there are some lines of defense which mitigate attack from these sources. These are: 1) the 3-in. or so thick cement grout placed in the annular space between the lining and ground may act as sacrificial protection for a period of time. However, its continuity cannot be relied upon; 2) a protective coating such as epoxy coal tar can be applied to the earth face of the lining segments; 3) in the case of grounds containing sulfates, special resistant cement can be used; and 4) for corrosive ground conditions and stray electrical currents, cathodic protection can be provided. Reinforcement in the segments must then be electrically bonded, and also the segments must be bonded one to another.

Under corrosive conditions, there appears to be little to choose between the performance of normal and lightweight aggregate concrete, providing that in the former the aggregates are appropriately selected for the conditions. However, tests by the U.S. Bureau of Reclamation (see Reference 6.1) indicate that polymer-impregnated concrete is superior to the other two in resistance to acid and sulfate attack. The reason for this appears partly attributable to the increased density and the greatly reduced permeability of the polymer-impregnated concrete.

In general, it may be stated that precast segments in any of the concretes, by virtue of superior quality of the product and control during manufacture, will exhibit better resistance against electrochemical attack than their counterparts in fabricated steel or cast iron.

RESISTANCE TO FIRE

In general, the fire-resistance ratings of concrete depend on the type of aggregate used, the thickness of the material, and the particular application. Silicous gravels containing a large percentage of chert or flint are badly disrupted by exposure to fire, whereas limestone and traprock show only minor cracking and spalling after similar exposure.

Tests have shown that 1000°F is the highest temperature that normal weight reinforced concrete can reach without a significant reduction of load carrying capacity. Furthermore, the fire endurance period is approximately proportional to the square of the thickness.

Due to its lower thermal conductivity, the lightweight concrete possesses 20 to 50 percent greater fire resistance than does the normal weight concrete. Structural lightweight aggregate concretes made with different aggregates performed remarkably alike under identical fire test conditions. Owing to its greater fire resistance, lightweight aggregate concrete appears to have the following advantages:

- The thickness of lightweight concrete required for a given fire endurance period is about 20 percent less that required for normal weight concrete. This is graphically illustrated in Figure 6-1.
- The reinforcement cover requirements for lightweight concrete are slightly lower than those for normal weight concrete.
- Lightweight concretes lose little strength at high temperatures. For example, at 1200°F, lightweight concrete specimens have about 85 percent of their normal strength while normal weight concretes retain 35 to 75 percent, depending on the type of aggregate.

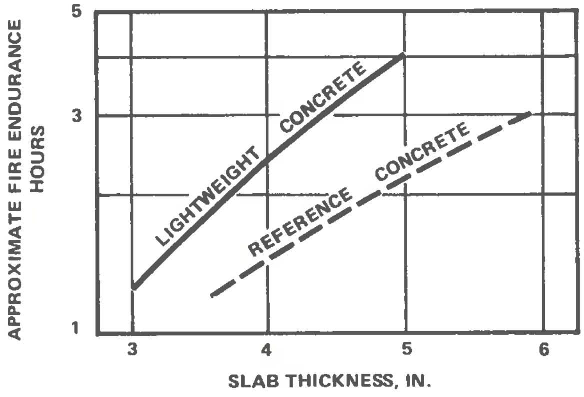


Figure 6-1. Relation of Slab Thickness to Approximate Fire Endurance

Comparable information on fire endurance of polymer-impregnated concrete was not available. However, according to tests carried out by Brookhaven National Laboratory and the U.S. Bureau of Reclamation (see Reference 6.2), the polymer-impregnated concretes seem to contribute fuel to the combustion process and continue to burn for varying periods of time after removal of the flame. Most samples smoked badly and several emitted an odor.

SUMMARY

A review of the foregoing material indicates that lightweight aggregate concrete has some particular properties which make it well suited for use in precast concrete tunnel linings.

A most important property is its low modulus of elasticity which is 60 percent of normal aggregate concrete of equal strength. As the bending stresses in the firm ground lining design are directly proportional to the stiffness of the lining — which in turn is proportional to the modulus of elasticity — the use of lightweight aggregate concrete in these designs results in lower stresses and consequent economies in material.

The lightweight aggregate concrete exhibits superior fire resistant properties and, under some conditions, better resistance to chemical attack than normal weight concrete. Its 25 percent less weight may effect some cost savings in transportation and erection. The advantages of low modulus of elasticity in the firm ground lining, as well as the good durability characteristics, led to the adoption of the lightweight aggregate concrete for all the study designs. Its initial cost is greater by about $10 per cubic yard of concrete than that of normal weight, however, this represents a small percentage increase in the cost of the final tunnel ring, and is considerably outweighed by other factors discussed above.

Polymer-impregnated concrete's principal advantage is its high structural strength and its resistance to chemical attack. The former property should make a 4-in.-thick segment of the "Through Bolt" design possible, and several attractive economic savings would result. However, its resistance to heat and behavior under direct flame must be investigated further before a final recommendation of this concrete can be made.

7. WATER SEALING SYSTEMS AND TESTS

INTRODUCTION

Where high ground water tables exist in otherwise reasonably competent soils, the joint sealing and fastening systems of the segments are generally the determining factor in the selection of the liner material. For some time, engineers have viewed the fact that precast concrete is a perfectly satisfactory structural material for segmented tunnel linings installed in all but the softest grounds. However, the difficulties of sealing the joints of precast concrete segments have been such that their use, without a secondary lining for waterproofing, has generally been restricted to "good" ground and water conditions. A major exception is in Japan where a number of transit tunnels lined with precast concrete segments have been constructed under fairly high groundwater heads.

SEALANT SYSTEMS

Segmented tunnel liners may be made watertight either by caulking, or by gasketing, the segment interfaces. When gaskets are used, provision for caulking is generally made. Also, in most cases, water sealing grommets are installed between the bolt washers and the segment faces.

CAULKING SYSTEMS

Until recently, the joint sealing system for segmented linings, in metal or concrete, has nearly always consisted of caulking the inside perimeter edges of the segments. Grooves, typically 1-in. deep and 1/4-in. wide, are provided in the inside faces of the segments, and following erection, these are packed with a caulking material. Such materials include lead, asbestos cement rope, and epoxy-elastomerics.

Lead is a satisfactory but costly sealing material when it is installed properly and exerts sufficient pressure in the caulking groove to resist the water pressure behind it. Metallic flanges can resist the high pressures exerted by the installation of the caulking, but concrete generally cannot. Furthermore, the free calcium in the concrete chemically interacts with the lead, causing both materials to breakdown physically. As lead is inelastic, caulking joints will leak if joint movements occur. However, where the joint in the tunnel is accessible, the lead can be recaulked to attain watertightness again.

The use of high-tensile bolts in fastening the segment flanges reduces the possibilities of movement across the joint and greatly assists in maintaining the integrity of the lead caulking system.

Asbestos Cement Rope

Asbestos-cement rope has enjoyed some success as a caulking material for concrete, as well as metallic segments in ground where movements in the lining are very small and the water pressures are low. Asbestos-cement rope caulking, once installed, is relatively inelastic and when leaks occur it has to be cut out and the groove recaulked. As most concrete segment lining systems cannot employ high-strength bolts to limit the joint movements, this material should be installed after most of the ground movements have ceased.

Epoxy-elastomerics

These have been used in several of the Tokyo transit tunnels. The materials are troweled or extruded into the caulking grooves and this appears to require a high degree of labor, both in the preparation of the joint and in application. These are discussed further in Appendix B.

GASKET SYSTEMS

Gaskets consist of elastic or plastic adhesive materials applied either to four or two adjacent faces of a segment before erection in the tunnel.

Elastic Materials

Suitable material is neoprene or butyl rubber. The gaskets may be in relatively narrow bands, typically 1-in. wide and 1/4-in. thick, bonded to the segment faces in grooves provided for this purpose. Such a gasket was used in the tunnel lining design for Metro de Caracas (see Figure 3-1, Alternative C.) The Japanese have used similar gaskets in tunnels, both for the Teito HST Authority and for other subway systems in Tokyo (see Figure 3-2 and Appendix B).

Recently, cellular neoprene gaskets have been used on the steel segment faces in some of the WMATA transit tunnels. The gaskets were 4-in. wide and 1/4 in. thick and attached with an adhesive to two adjacent segment faces.

Both the Japanese and the WMATA gaskets appear to have produced reasonably dry tunnels, although full details relating to the performance had not been made available at the time of this report.

Sealing by this gasket principle is accomplished by compressing the gasket between the faces of the segments upon erection. The success of the system requires adequate elasticity in the gasket to maintain watertightness when movements occur across the segment joints.

Plastic Adhesive Materials

Materials which have been used include polysulfide semi-cured butyl rubber and tar epoxy. Gaskets are either preformed in strips and bonded into grooves provided in the segment faces, or sprayed or troweled over the segment face. An example of performed gaskets is indicated in the Metro de Caracas designs (see Figure 3-1, Alternatives A and B).

Many of the Tokyo bolted, precast, concrete lining systems have employed similar details, often using two gaskets, one each side of the bolt circle. Alternatively, the material has been applied over the full segment face. Caulking has been used in addition. The philosophy seems to have been that the gaskets will provide a temporary water barrier until the caulking can be installed.

History of all the details of the water performance is not yet available. The disadvantages of the plastic materials for long-term performance appears to be a tendency to flow under long-term pressure, unless the gaps being sealed are very small. In addition, as the materials are soft and somewhat sticky, they are prone to damage and gather dirt during erection.

OTHER SYSTEMS

There are several examples, both in Germany and Japan, of waterproofing segmented tunnels with a continuous bitumistic or plastic sheet membrane followed by a secondary cast-in-place concrete lining.

In England, in precast concrete traffic tunnels, essentially complete watertightness has been achieved by incorporating 1/4-in.-thick steel plates on the inside segment faces. After erection of the lining cover, plates are welded continuously across the segment joints.

Both of the above systems add considerably to the cost of the tunnels.

Proposed Sealant System.

This system would consist of a primary gasket seal applied to the segment faces before erection, and provision for a secondary caulked seal installed in the edges of the segments after erection.

Gasket Seal

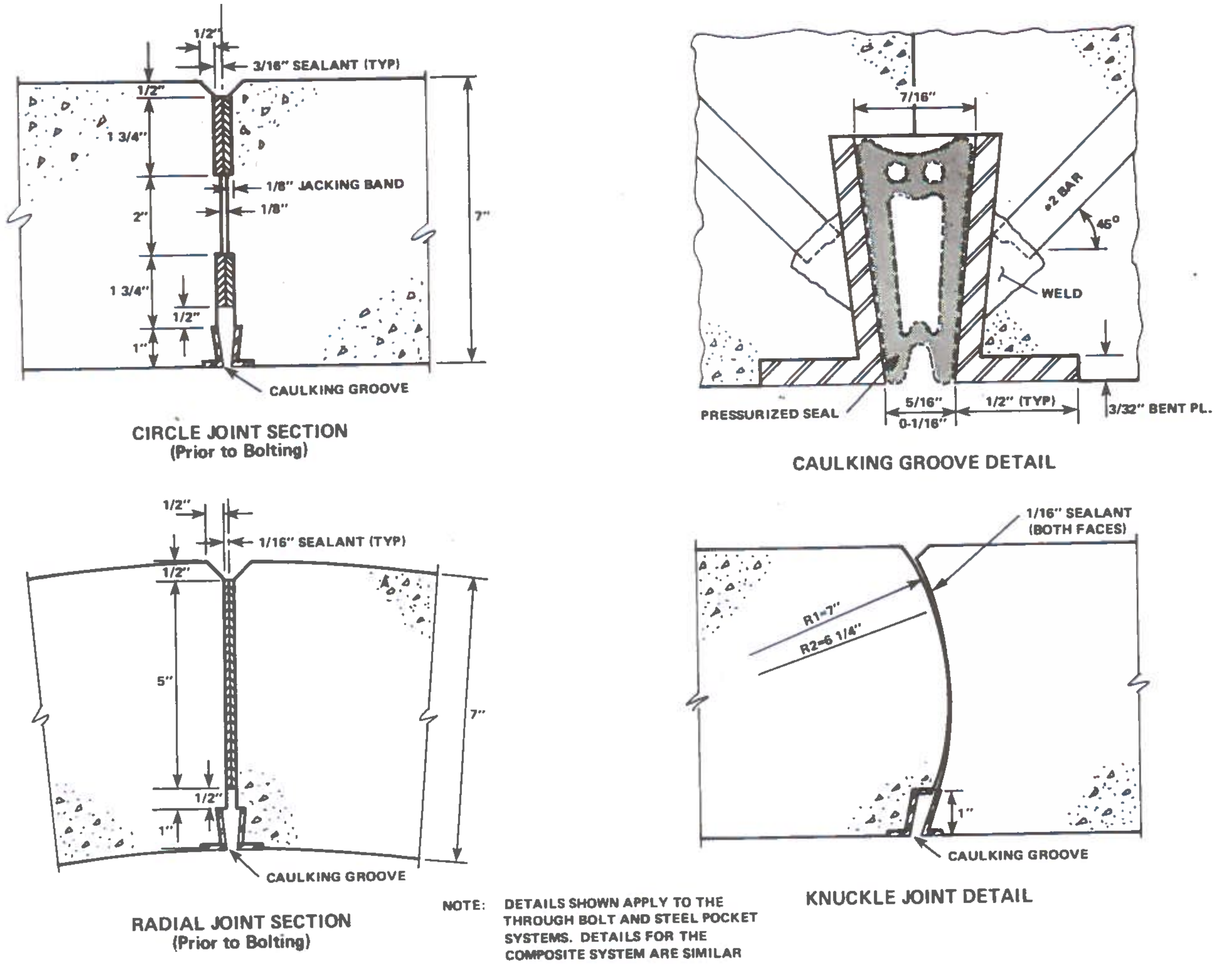
Of interest is a recently developed gasket material, called TSE sealant, from Commercial Shearing Inc. (CSI). It is a two-component butyl/polymer material. It can be formulated to give various degrees of durometer (hardness) and can be applied by spraying or formed by extrusion.

Tests undertaken by CSI appear to indicate satisfactory physical properties, including longevity. The compound seems to have the qualities required to provide a primary water barrier in the segment joints. Using this or similar material, the primary system would be applied to the segment faces in the manufacturer's yard, to the details indicated in Figure 7-1.

Caulking Seal

The concept for this system is also indicated in Figure 7-1. It will be noted that the details comprise a segment inner edge caulking groove into which an "O" ring is placed. An expanding material is then introduced under pressure to set and provide solid elastic core. Installation would involve cutting the "O" ring into the required lengths for the circle joints and the cross joints, plugging the ends, placing the "O" rings in the grooves, and injecting the material.

Advantages of the concept include: sealing of the groove by pressure rather than by bond (which requires fairly clean and dry joints); and the degree of elasticity provided by the system, permitting appreciable



CIRCLE JOINT SECTION
(Prior to Bolting)

CAULKING GROOVE DETAIL

RADIAL JOINT SECTION
(Prior to Bolting)

NOTE: DETAILS SHOWN APPLY TO THE THROUGH BOLT AND STEEL POCKET SYSTEMS. DETAILS FOR THE COMPOSITE SYSTEM ARE SIMILAR

KNUCKLE JOINT DETAIL

Figure 7-1. Sealant System and Knuckle Joint Detail (Same as Figure 4-6).

movements in the segment joints without loss of watertightness. The secondary sealant system would be installed only in those places where the primary system fails to prevent inflow.

LABORATORY TESTING OF THE PROPOSED JOINT SEALING SYSTEMS

The previously described primary system and secondary systems may be tested independently of each other. The following is a discussion of general recommendations for testing the systems. The specifics would be worked out in detail after further disucssions with all concerned.

Primary System

The system to be tested would use the TSE sealant. A certain amount of the testing has already been carried out by the manufacturer, including independent testing by the Polymer Institute in Detroit. Additional testing using the concrete lining joints system proposed in this study is suggested. Initially, the testing would be of a physical nature. The Polymer Institute performed a number of tests on the chemical properties of the material which generally demonstrated satisfactory behavior. After the physical tests have been undertaken, the conclusions of the Polymer Institute should be reviewed to determine whether further information on the chemical properties would be desirable.

It will be noted from Figure 7-1 that the gasket for the segment radial face differs from that of the circle face in the following manner:

- The radial face is entirely covered with a relatively thin gasket, whereas
- The circle face has a thicker gasket on either side of the 1/8-in.-thick jacking pad.

Physical testing to determine the compression and tension properties of the material on the face joints may be undertaken on the following basis:

- Radial Face Gasket

  Uniform compression tests for stresses of 300 psi, 600 psi, and 1200 psi

  - Triangular compression tests for stresses of zero on one edge to 600 psi and 1200 psi
  - Tensions tests after compression tests of stresses of 300 psi, 600 psi, and 1200 psi

- Circle Face Gasket

  Compression tests to stress required for bringing the bearing faces together

  - Tensions tests

After each of the compression test stages, a determination of the elastic recovery, or rebound, properties of the sealants should be established.

Caulking Seal

To evaluate this system, the configuration and material of the "O" ring first must be established. This would be followed by the determination and testing of the in-filling compound.

8. IMPLEMENTATION OF A STANDARD LINING SYSTEM

INTRODUCTION

To gain acceptance of a tunnel lining system, informational efforts should be directed toward three principal entities. These are: the implementors of rapid transit systems and their engineering consultants, precast concrete manufacturers, and tunneling contractors. Each entity is interested in somewhat different aspects of tunnel linings, and therefore, the informational effort to each should be geared accordingly.

INFORMATIONAL EFFORTS

Three principal informational efforts are suggested.

Implementors and Engineering Consultants

The advantages of a designed and systemized tunnel lining design would be readily appreciated by this group. Design time would be limited to that required to correlate specific ground conditions with those assumed in the designs, and to make whatever modifications are necessary to suit special situations. The problems of scheduling to allow for the design and manufacturing of the linings would also be simplified. The economics of manufacturing costs of the linings, as well as the costs of installation would be of major interest and a prime incentive.

Specific approaches could include the following:

- Disseminate the study report and other information describing the lining system, the advantages relative to economics and durability, design information, and test results.
- Establish a design authority whose services would be available to the entities for information and to advise on special situation problems which are always prevalent in a tunnel project.

Precast Concrete Manufacturers

The appeal of a product standardized in principal detail, which could be produced in volume, and possibily stockpiled in order to equalize production fluctuations, should be self-evident to this group. The amount of tunneling predicted for the future represents a large market previously denied to precast concrete manufacturers.

The information sent to manufacturers in areas where rapid transit tunneling is projected should include literature describing the tunnel segment lining manufacture potential, the techniques of production, and quality control requirements.

Tunneling Contractors

This group should be especially interested in readily available standardized tunnel lining providing a choice in segment size.

Information issued to potential contractors should emphasize the following:

- The flexibility of the lining systems with respect to segment size.
- The ready availability of the lining, through establishment of interest by the precast concrete industry in this production.
- Techniques and potential economics of installing the lining.

9. REFERENCES

0.1 A.J. Birkmyer and D.L. Richardson, Systems Analysis of Rapid Transit Underground Construction, prepared for U.S. Department of Transportation, DOT-TST 75-72.1, UMTA-MA-06-0025 74-11-1, December 1974.

5.1 Bechtel Corporation, Report on Testing Precast Concrete Tunnel Linings, prepared for San Francisco Bay Area Rapid Transit District, February 1966.

5.2 R.B. Peck, Deep Excavation and Tunneling in Soft Ground, Proceedings of 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico City, 1969.

5.3 K. Terzaghi, "Introduction to Tunnel Geology," Rock Tunnelling with Steel Supports by Proctor and White, Commercial Shearing and Stamping Company, 1946.

6.1 M. Steinberg et al., "Concrete-Polymer Materials," 2nd Topical Report, BNL 50218 (T-560) and REC OCE 70-1, December 1969.

6.2 J.T. Dikeou et al., "Concrete-Polymer Materials," 4th Topical Report, REC - ERC 72-10, BNL 50328, and TID-4500, January 1972.

A-1 Manual for Quality Control for Plants and Production of Precast Prestressed Concrete Products.

APPENDICES

CONTENTS

Appendix A

STUDY DESIGN DRAWINGS – PRECAST CONCRETE SEGMENTED TUNNEL LINING

DISCUSSION

The tunnel lining drawings displayed hereafter indicate the general arrangement of the reinforcement and fastening details for the lining systems developed in the study. The analysis and design of the systems was based upon the ground groups and loading criteria discussed in Section 5.

The additional investigations or tasks needed to translate the conceptual tunnel lining designs of the Study Report into engineering designs for lining manufacture and installation, within an actual transit system, will include the following:

- Geological Conditions. The geological conditions along the tunnel alignment of the intended construction must be fully investigated to determine the design class of the lining, i.e., "firm ground" or "soft ground." In addition, particularly in the case of soft grounds, a detailed study and assessment of the likely behavior of the ground during the tunnel construction process should be undertaken. It must be verified that the ground cover above the crown of the tunnel will be adequate to provide the desired design safety factors. The minimum spacing between adjacent tunnels may also be a consideration. This is dependent both on the ground encountered and the construction techniques to be used. However, with the normal center platform cut-and-cover station design used for tunneled line structures this is usually not a critical factor.

- Engineering Design. For the segment manufacture, supplementary engineering detail required will include: secondary reinforcement behind bolts and bolting pockets; welding details; bonding of the reinforcement and the segments (if provision for cathodic protection is required); inserts for support of electrical and mechanical services, walkways, etc., provisions for sealant systems. Dimensional tolerances must be indicated; requirements for tapered rings and special segments at openings must be defined.

  The specifications must include coverage of: quality control of concrete production and products (an excellent guide for this subject is Reference A. 1); dimensional tolerances, template and measurement requirements; schedules of delivery and coordination with the tunnel contractor marking segments; packaging and transportation. . .

For the tunnel construction (relative to the tunnel lining), the drawings must indicate:

- The assembly of segments in rings and at openings; framing requirements at openings; interface details at the start and end of tunnel drives and all appurtenant structures; water seal details; walkway and track support details. . .

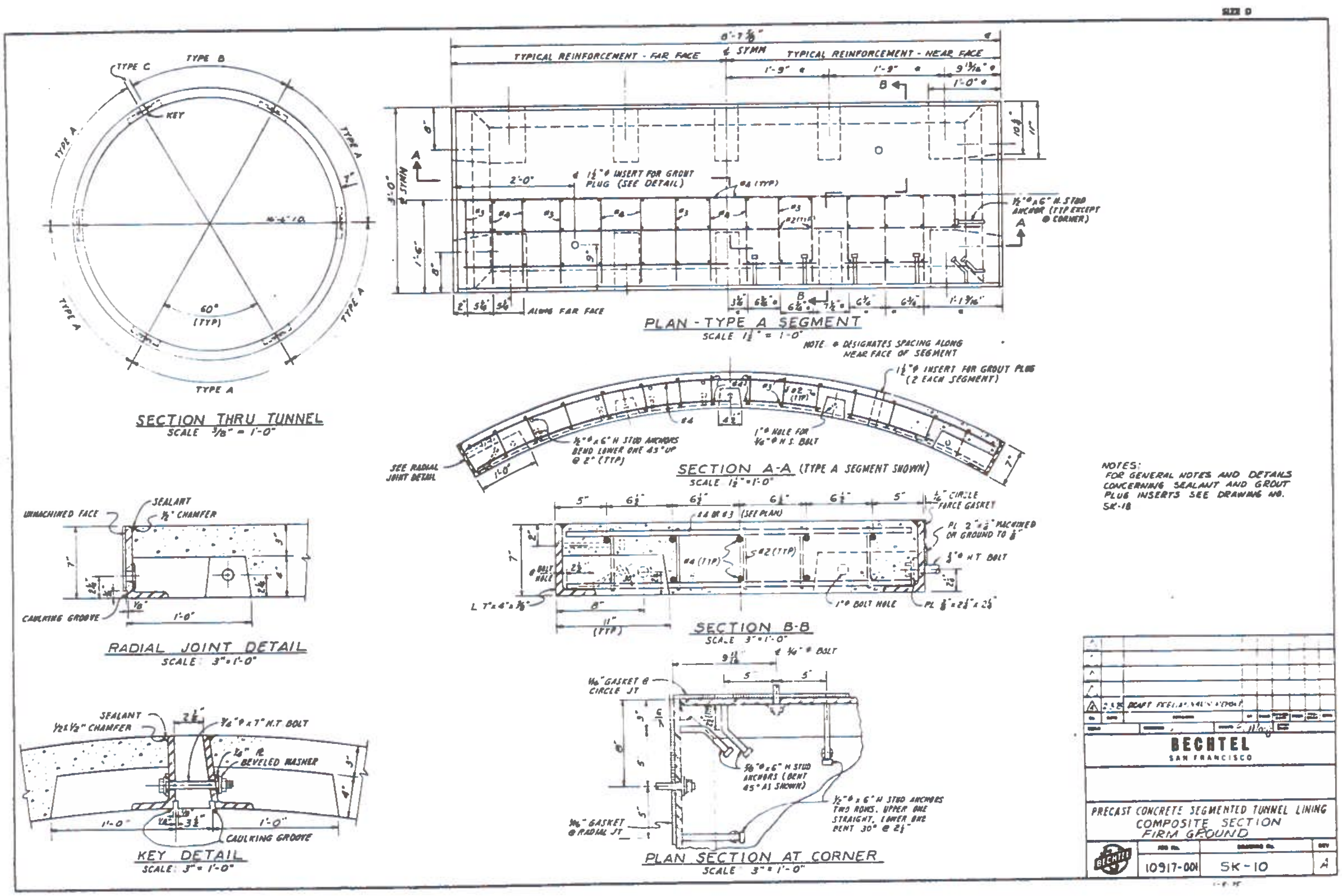
The specifications must include:

- Coverage of the above drawing items as well as the requirements for coordination with the segment manufacturer in respect of schedule and delivery; handling and erection of the segments; segment fastening procedures and sequences; shield jacking force transference requirements; responsibility for segment damage...

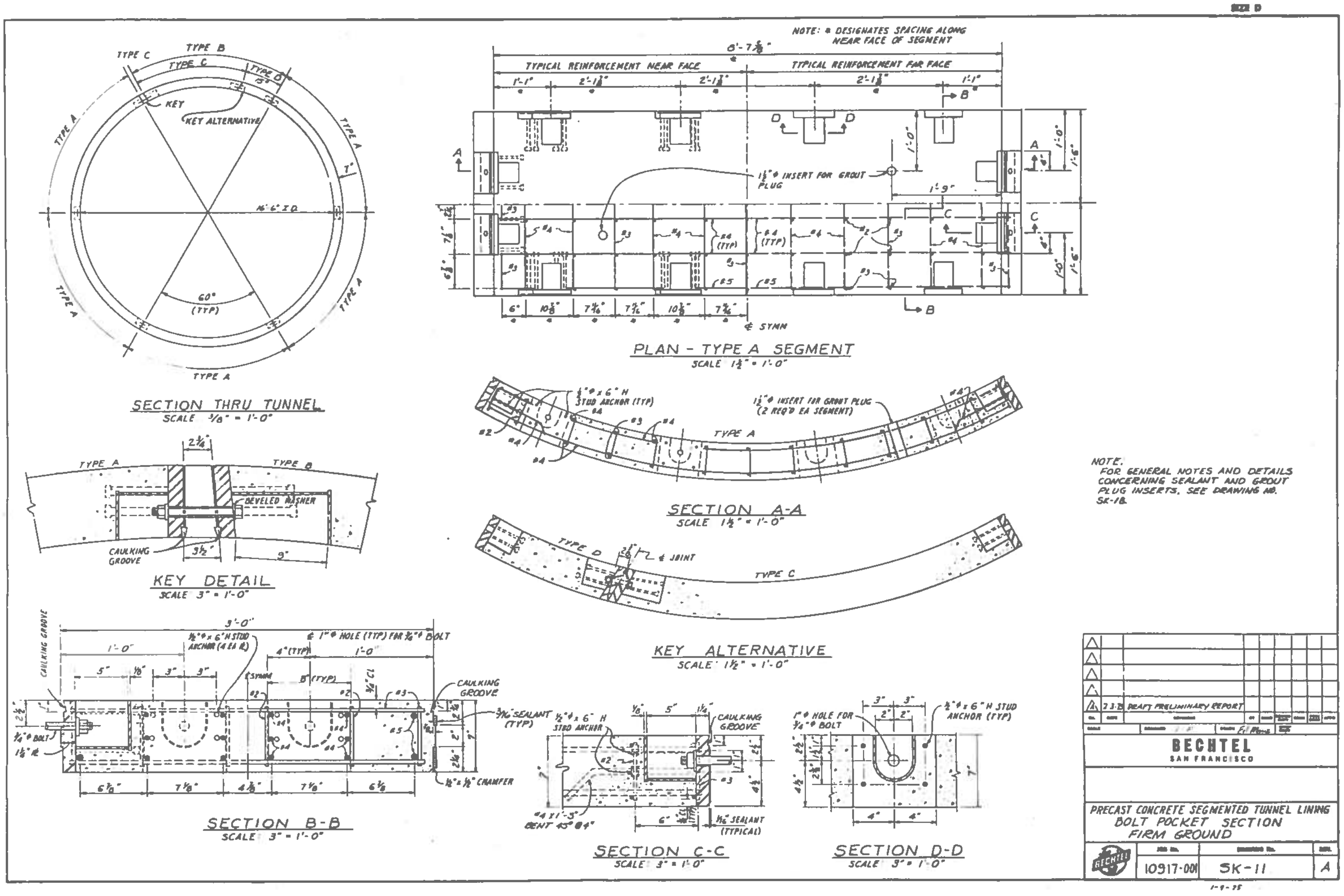
Drawing sheet A-9 indicates a second alternative through bolt system developed around a standard reinforcing bar spacing coupling (patented) manufactured by Fox Industries, Berkeley, California. A feature of the system is the tapered thread on the rebar (corresponding to that of the coupling) which permits full development of the strength of the rebar.

For the use in the segmented linings, one of two details may be used. As indicated in Detail 1, a 5/8 in. high-strength (H. S.) reinforcing bar is used and the outside of the coupling is threaded to receive a 7/8 in. H. T. nut. Detail 2 uses a 3/4 in. H. T. reinforcing bar in which a straight thread follows the tapered thread of one end to receive a 3/4 in. H. T. nut. The full bar section of the 5/8 in. bar is about equal in area to the net area at the root of the straight thread of the 3/4 in. bar. Therefore, the strengths of the two details are about equal.

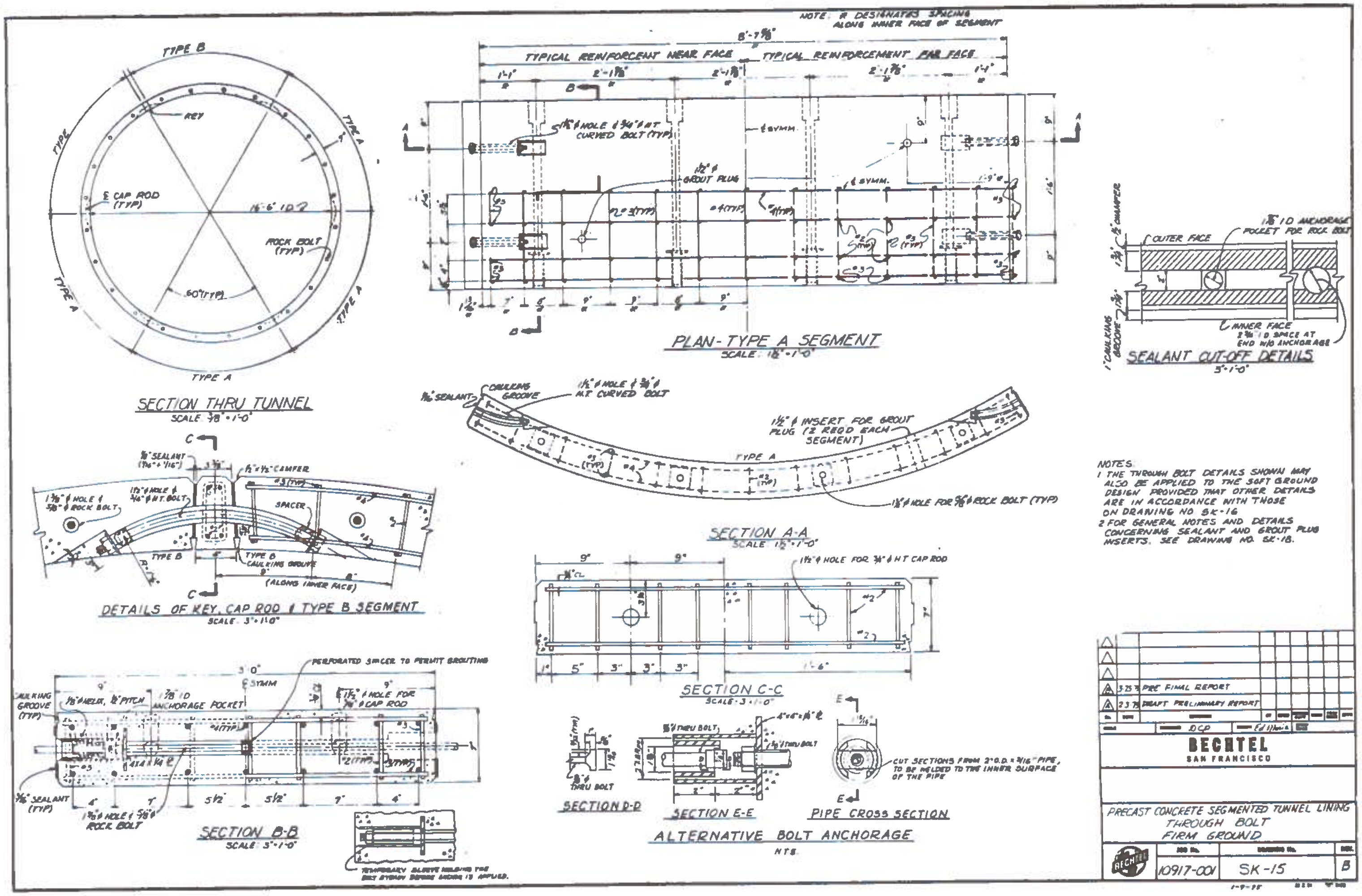
During the assembly of the rings, the stressing procedures for both details are the same. After a segment is placed in position in the ring, the bars are pushed into the couplings on the anchored ends in the preceding ring. A double-action socket head, actuated by an impact wrench, worked from the face of the segment being erected, first tightens the rods into the anchor couplings and then torques the 7/8 in. or 3/4 in. nuts to the specified bar tension.



Precast Concrete Segmented Tunnel Lining: Composite System – Firm Ground



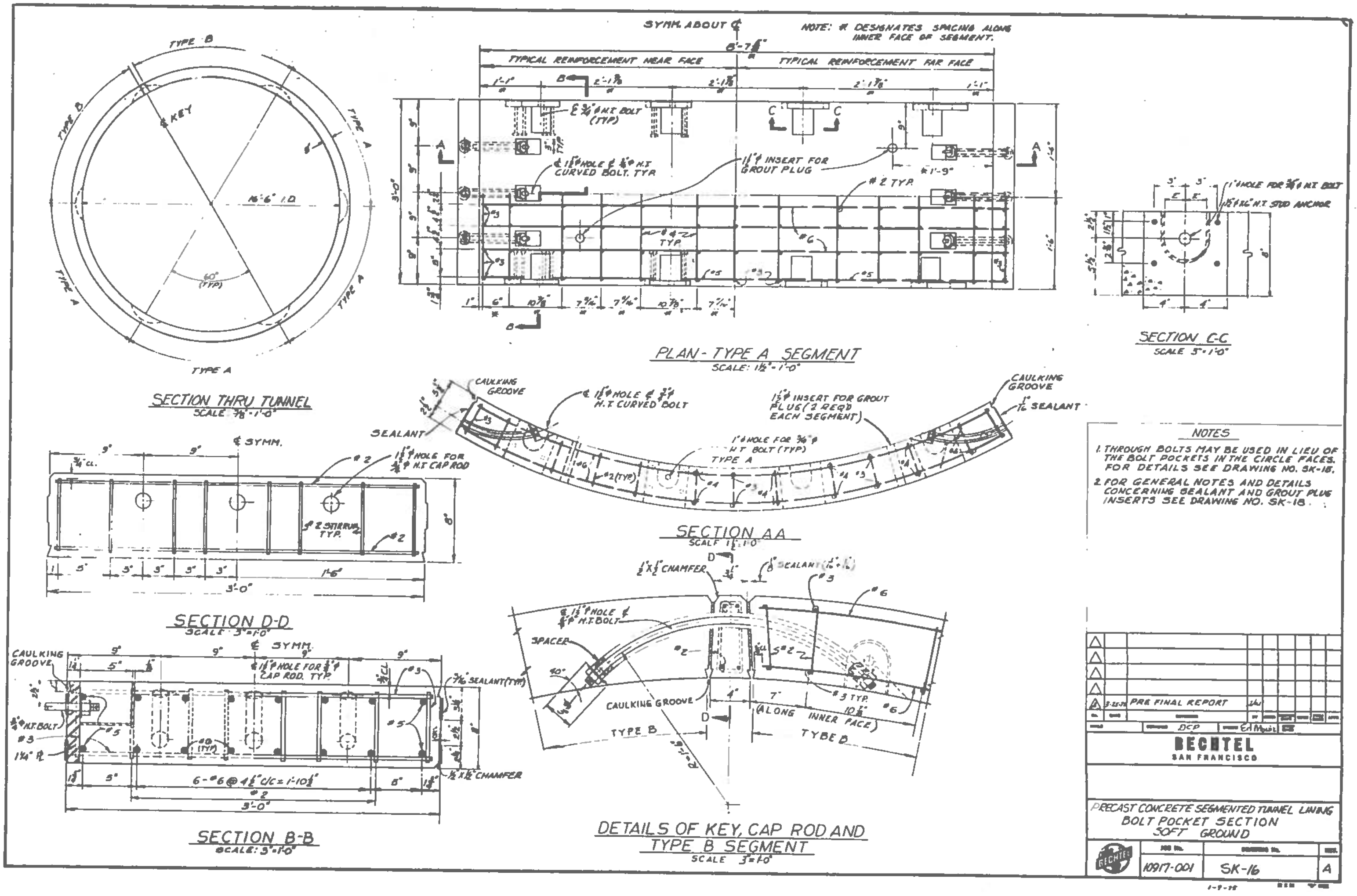
Precast Concrete Segmented Tunnel Lining: Bolt Pocket System — Firm Ground



NOTES.
1 THE THROUGH BOLT DETAILS SHOWN MAY ALSO BE APPLIED TO THE SOFT GROUND DESIGN PROVIDED THAT OTHER DETAILS ARE IN ACCORDANCE WITH THOSE ON DRAWING NO SK-16
2 FOR GENERAL NOTES AND DETAILS CONCERNING SEALANT AND GROUT PLUG INSERTS. SEE DRAWING NO. SK-18.

3-25-75 PRE FINAL REPORT
2-3-75 DRAFT PRELIMINARY REPORT
DCP
BECHTEL
SAN FRANCISCO
PRECAST CONCRETE SEGMENTED TUNNEL LINING
THROUGH BOLT
FIRM GROUND
10917-001
SK-15
B

Precast Concrete Segmented Tunnel Lining: Through Bolt System – Firm Ground



NOTES

1. THROUGH BOLTS MAY BE USED IN LIEU OF THE BOLT POCKETS IN THE CIRCLE FACES. FOR DETAILS SEE DRAWING NO. SK-18.
2. FOR GENERAL NOTES AND DETAILS CONCERNING SEALANT AND GROUT PLUG INSERTS SEE DRAWING NO. SK-18.

3-25-76 PRE FINAL REPORT

DCP

BECHTEL
SAN FRANCISCO

PRECAST CONCRETE SEGMENTED TUNNEL LINING
BOLT POCKET SECTION
SOFT GROUND

10917-001 SK-16 A

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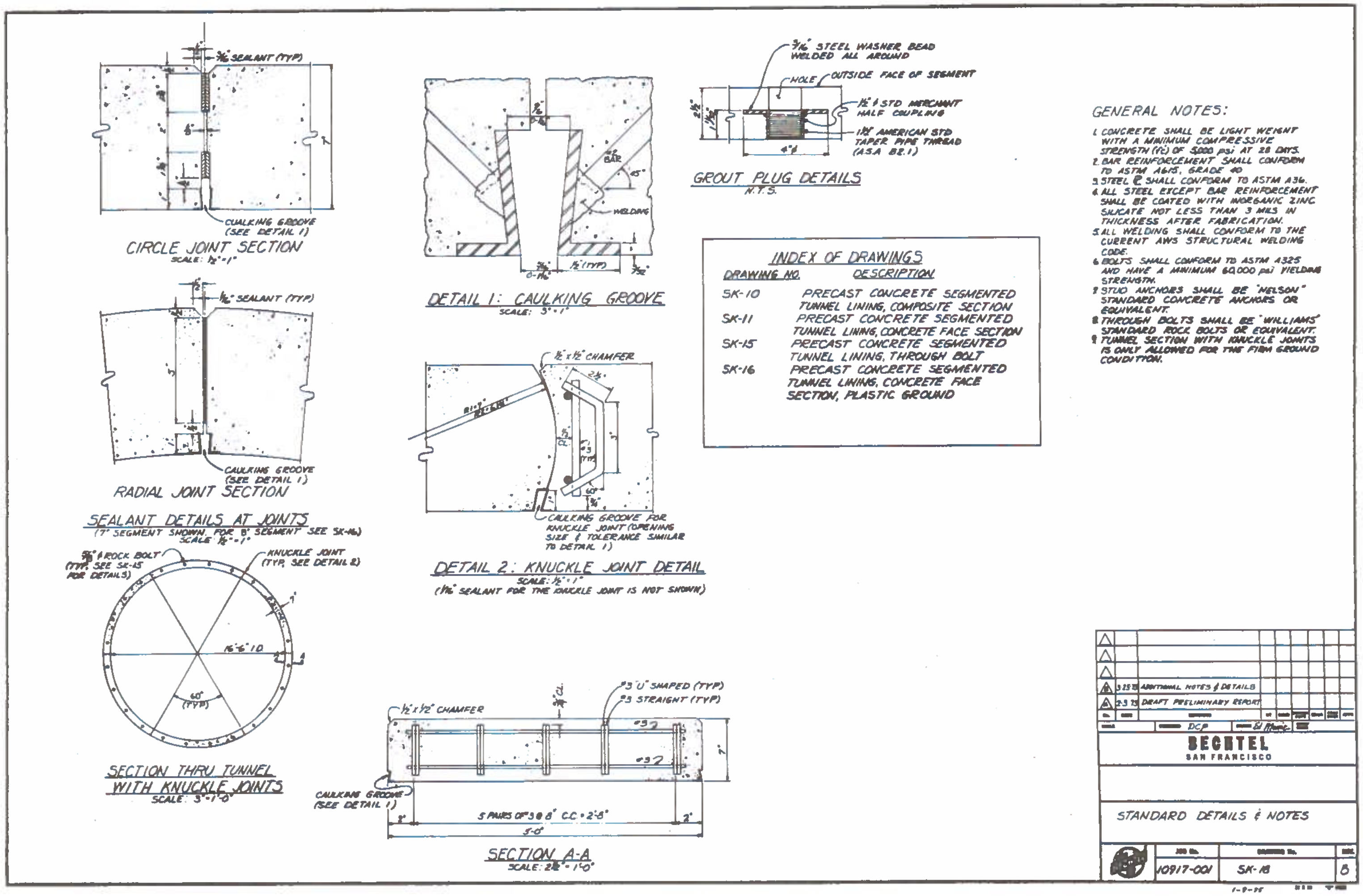
Precast Concrete Segmented Tunnel Lining: Bolt Pocket System – Soft Ground



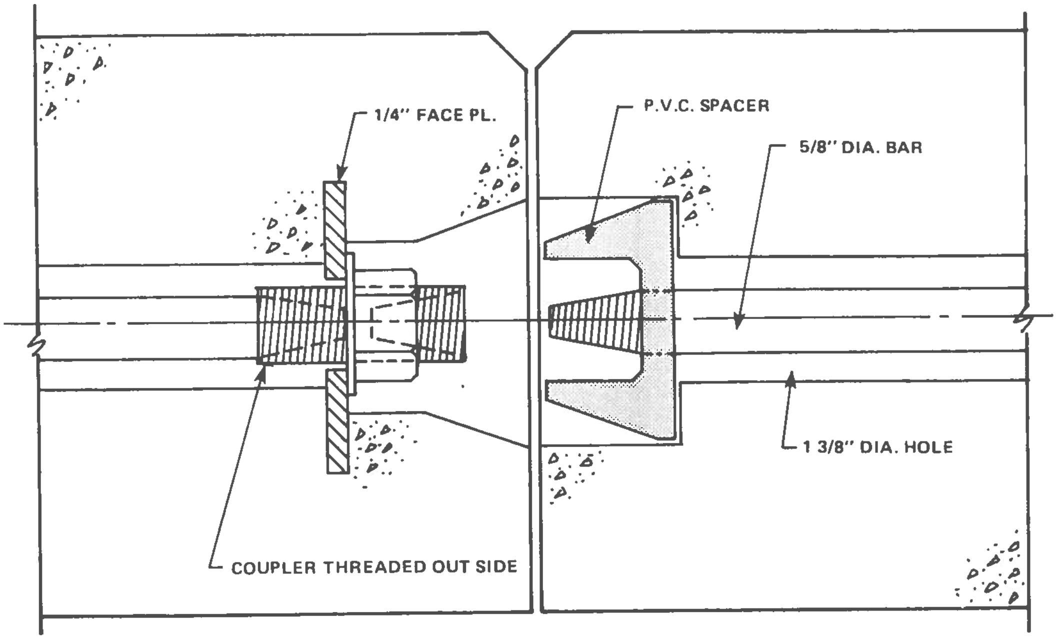
GENERAL NOTES:

1. CONCRETE SHALL BE LIGHT WEIGHT WITH A MINIMUM COMPRESSIVE STRENGTH (f'c) OF 5000 psi AT 28 DAYS.
2. BAR REINFORCEMENT SHALL CONFORM TO ASTM A615, GRADE 40
3. STEEL ℄ SHALL CONFORM TO ASTM A36.
4. ALL STEEL EXCEPT BAR REINFORCEMENT SHALL BE COATED WITH INORGANIC ZINC SILICATE NOT LESS THAN 3 MILS IN THICKNESS AFTER FABRICATION.
5. ALL WELDING SHALL CONFORM TO THE CURRENT AWS STRUCTURAL WELDING CODE.
6. BOLTS SHALL CONFORM TO ASTM A325 AND HAVE A MINIMUM 60,000 psi YIELDING STRENGTH.
7. STUD ANCHORS SHALL BE "NELSON" STANDARD CONCRETE ANCHORS OR EQUIVALENT.
8. THROUGH BOLTS SHALL BE "WILLIAMS" STANDARD ROCK BOLTS OR EQUIVALENT.
9. TUNNEL SECTION WITH KNUCKLE JOINTS IS ONLY ALLOWED FOR THE FIRM GROUND CONDITION.

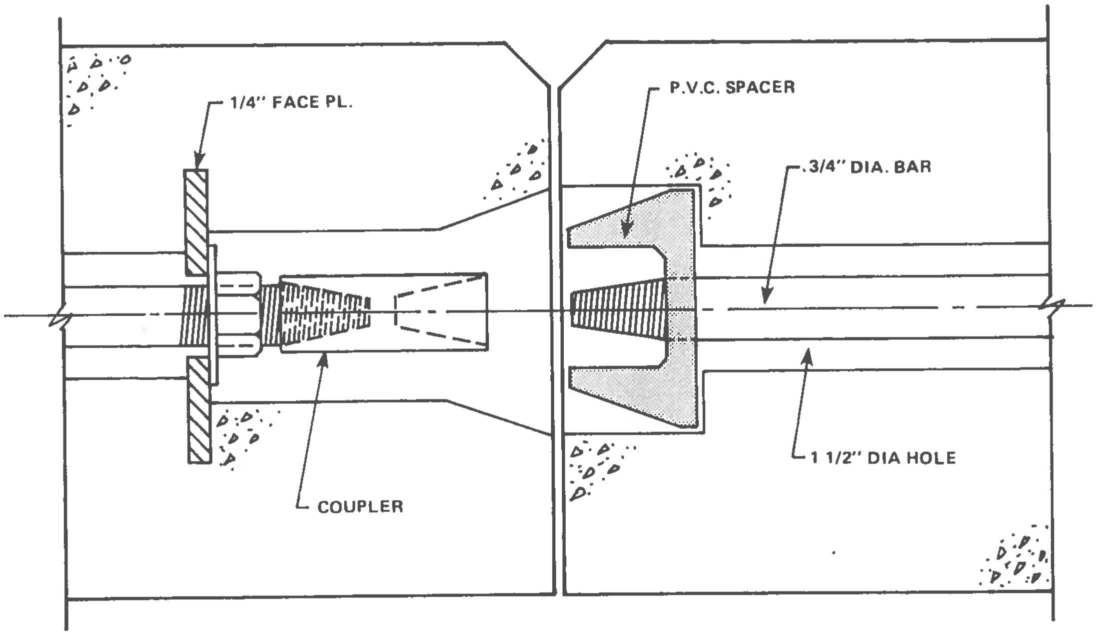
INDEX OF DRAWINGS

DRAWING NO.	DESCRIPTION
SK-10	PRECAST CONCRETE SEGMENTED TUNNEL LINING, COMPOSITE SECTION
SK-11	PRECAST CONCRETE SEGMENTED TUNNEL LINING, CONCRETE FACE SECTION
SK-15	PRECAST CONCRETE SEGMENTED TUNNEL LINING, THROUGH BOLT
SK-16	PRECAST CONCRETE SEGMENTED TUNNEL LINING, CONCRETE FACE SECTION, PLASTIC GROUND

Standard Details and Notes



DETAIL 1
(5/8" bar with stressing nut on coupling)



DETAIL 2
(3/4" bar with stressing nut on bar)

ALTERNATE THROUGH BOLT SYSTEMS

Appendix B

ADDITIONAL EXISTING TUNNEL LINING SYSTEMS

TUNNEL CONSTRUCTION IN MUNICH (See pages B-4 through B-17)

Discussion

The two projects exhibited comprise:

- Four tunnels, each about 1,600 ft in length, within the first section of the Munich transit system. The work started in 1966. (Pages B-4 through B-14)
- Two tunnels, 4,400 ft and 3,300 ft in length, for which construction was started in 1973 and was completed recently. (Pages B-15 through B-17)

Each project encountered similar wet ground conditions which required the use of shields for the excavation process, and from within which the precast concrete linings could be erected.

In project 1, the final waterproofing was accomplished by placing a continuous membrane against the segmented lining prior to installing a 6 in. (minimum thickness) cast-in-place concrete secondary lining. In project 2, a well-engineered sealing system of gasket seals on the segment faces, supplemented by caulking the segment edges, provided an adequate water barrier and for the first time a precast concrete lining was used in Munich without a membrane and a secondary backup lining.

A summary of the principal features of interest in the lining system is:
Project 1: The 19 ft-6 in. I.D. lining ring comprises 4 segments

plus a key segment, 34 in. wide of constant 12 in. thick cross section. A shallow tongue and groove is provided in the radial joint which is not bolted. The rings are tied one to another with through bolts, approximately 1 in. diameter and four to a segment. Couplings connect each bolt and tightening is effected by impact wrenches worked from the leading face of the segment.

The cross joint tongue and groove is faced with steel plates which sit upon neoprene strips (presumably to provide uniform load bearing). Water sealing is accomplished by two strips of a tar compound, applied along the edges of the segment faces.

One circle joint in each segment has a 3/8 in. plywood facing glued to it to distribute the shield jacking loads. Water sealing strips on one face are similar to those in the cross joint.

Ground cover over the tunnel was 40 to 60 ft and the water high table in the sands, and sandy silts, was lowered with some difficulty from closely spaced deep wells, to permit tunneling in free air. The initial water sealing system was only partially effective and water running through the joints had to be diverted through plastic tubes during the membrane and secondary lining.

Project 2, pages B-11 and B-12, the 20 ft-6 in. I. D. ring comprises 8 segments plus a key segment, 34 in. wide and thick, with recessed bolt pockets. The segments are bolted in both the radial and the circle faces. Three-quarter in. deep 4-1/2 in. wide tongue and grooves are cast into the circle faces.

The water sealing system consists of 3 components: a continuous neoprene compression seal, near the earth face, along the four faces of the segment; bands of plastic packings on one circle face and one radial face of each segment; caulking in grooves provided along the inside edges of the segments. Information on the plastic packing and the caulking material is not available at the time of this writing.

Ground cover over the tunnels was about 40 ft. Tunneling was generally within a strata of marl which was overlain with water-bearing gravel. Numerous water-bearing pockets of sandy material were encountered during tunneling. The control of these water conditions required the use of compressed air.

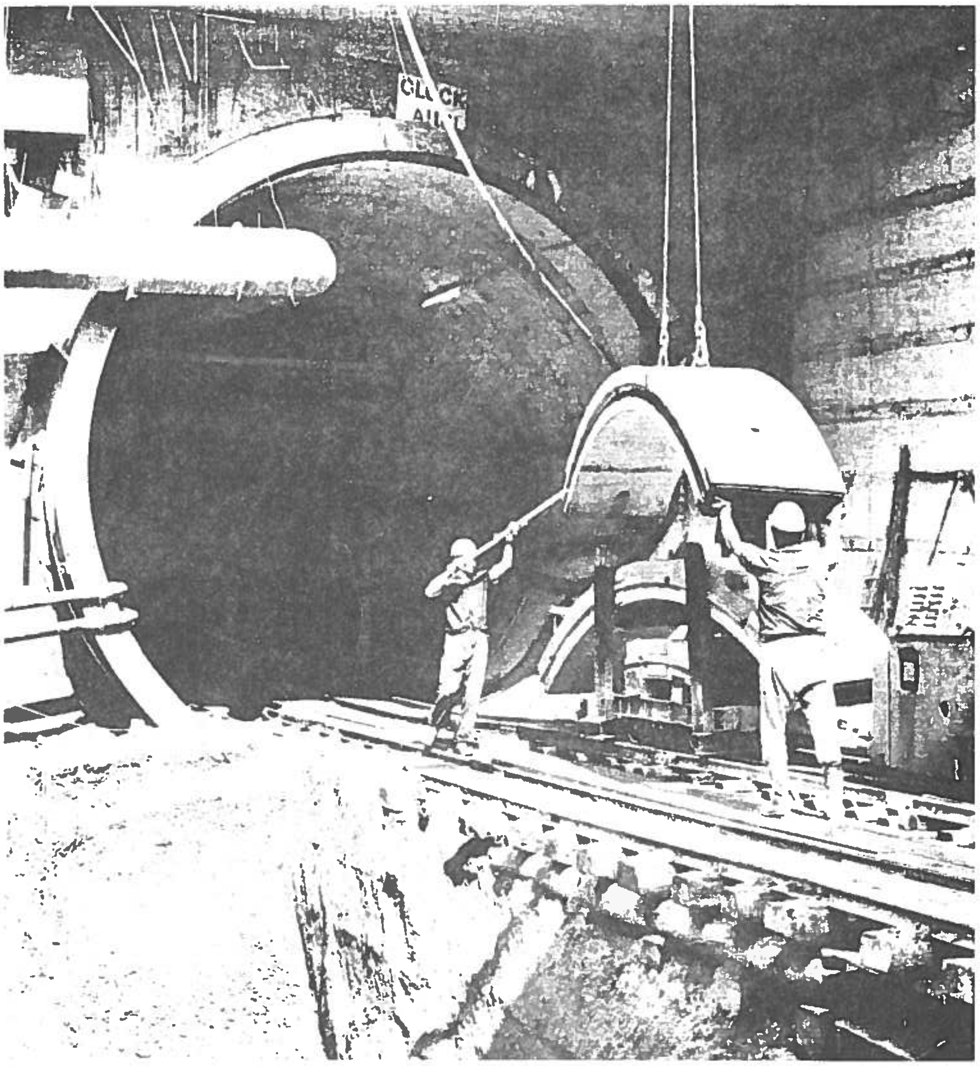
As far as can be ascertained from literature available on the construction of the tunnels, and from direct inquiry to the contractor, the water sealing system demonstrated satisfactory performance.

Segment store in the casting yard **FIGURE 25**

The segmented lining was lifted and placed by a ring erector assembly having a lifting capacity of 4 tons and a roller path diameter of 3.50 m. This assembly could be moved 55 cm in the horizontal. This type of erector allows unhampered removal of cuttings when the segments are handled (Fig. 19). The segments were transferred to the erector from above (Fig. 15). The sectionalized travelling platform comprised the following items: ring erector assembly, segment conveyor with pusher, hydraulic pumps for driving, pillar crane, grouting units, control panel, transformer and cable reel for the high-tension cable (Fig. 14). The hydraulic equipment was supplied by Messrs. R. Schäfer & Urbach G.m.b.H., Ratingen, Germany.

Removal of Cuttings

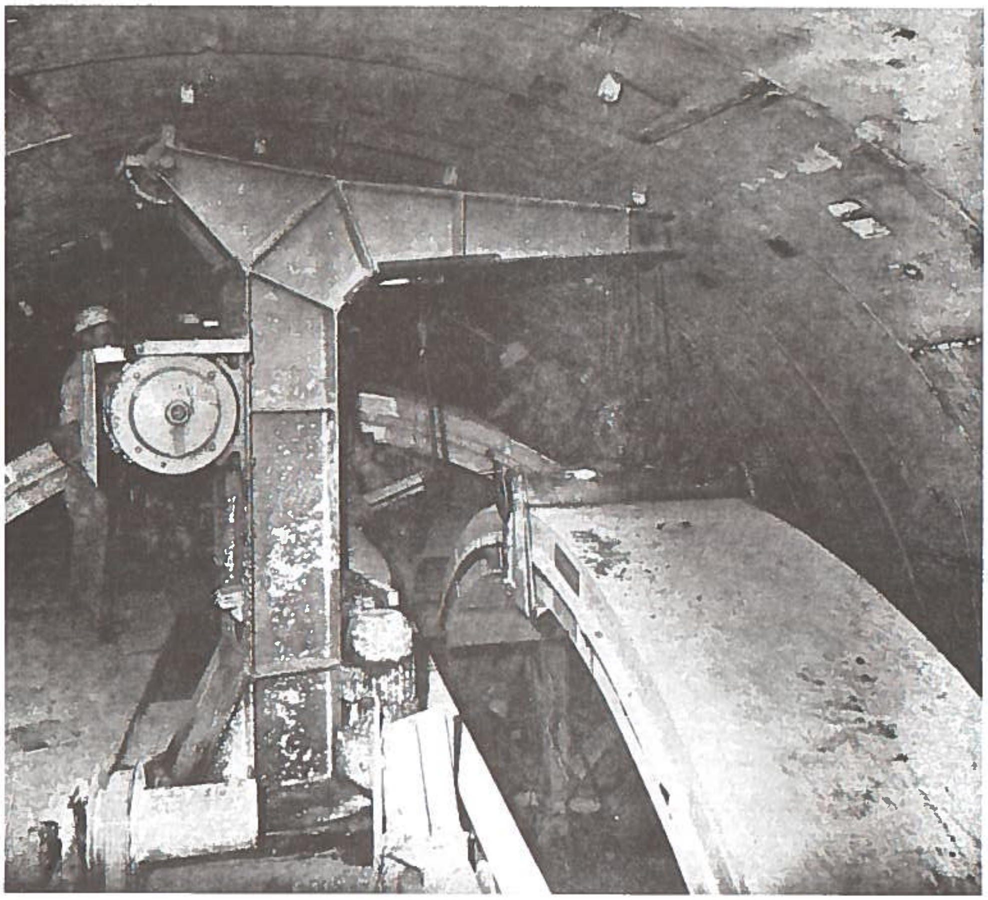
A two-track system was used in view of the lengths of the tunnels and the great number of operations required



Loading of segments on to hauling vehicles

FIGURE 26

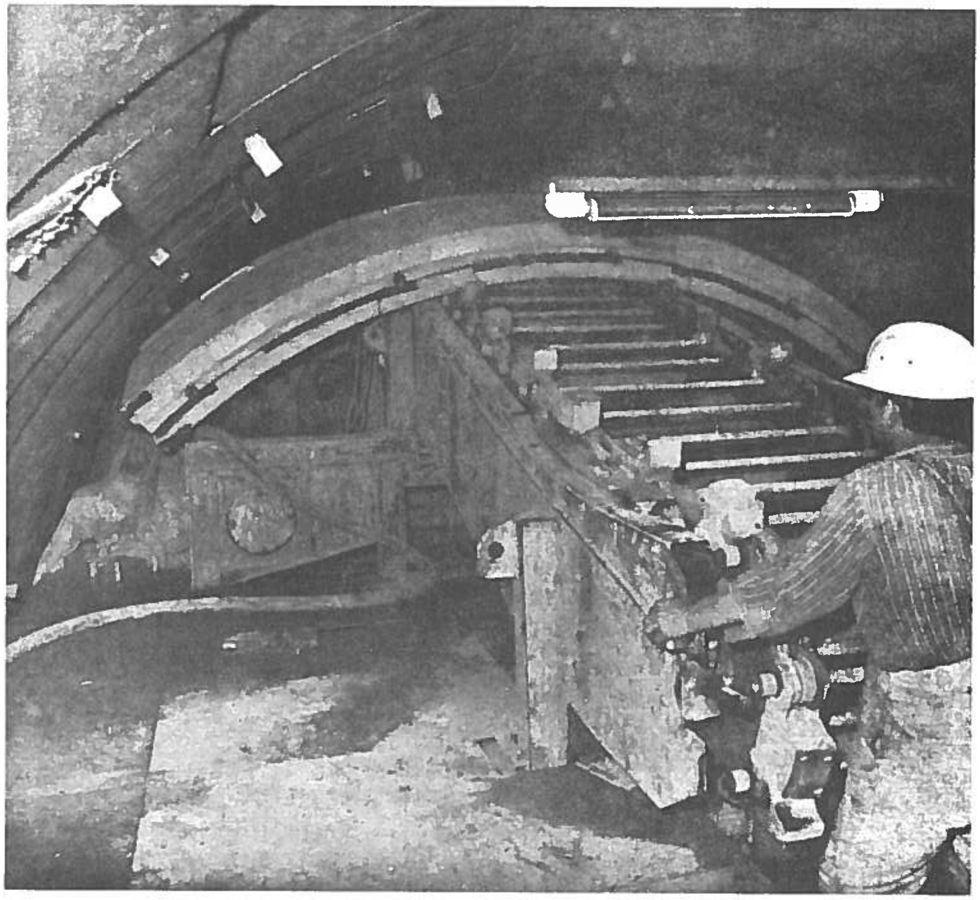
for transporting segments, grout and other materials as well as the removal of cuttings (Fig. 21). A train for the removal of cuttings comprised five $3^1/_2$ cu.m. skips. The loading conveyor was as long as the train (Fig. 20). Flameproof diesel locomotives were used for traction. The upgrade of 3.7 % in both sections required two locomotives of 40 h.p. and 60 h.p. for hauling a loaded train, so that two ventilation lines of 600 mm dia. were necessary. The cuttings were dumped into a pit (Fig. 22), grabbed by a M 154-type crane-excavator with a single-line 2 cu.m. grapple, lifted through the starting pit (Fig. 23) and loaded on to lorries which carted the spoil away to the waste area. The grapple was of special steel and therefore very light. This handling system was approved by the competent mining authority.



Segments are handled by pillar crane **FIGURE 27**

The Precast Concrete Interlocking Segments

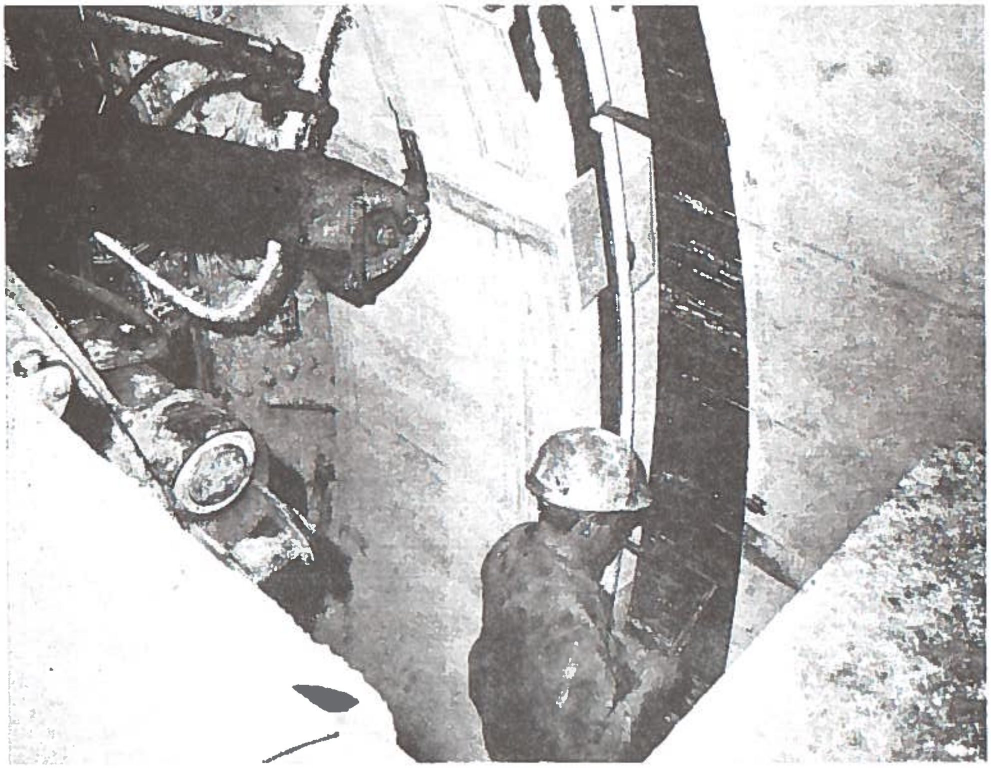
Designers specified an outer ring that is composed of precast concrete interlocking segments 30 cm high and 87.5 cm wide. The minimum compressive strength of the concrete was specified as 8,534 psi. for an apex load of 45 ton/square metre (load range 1) and 6,400 psi. for a load of 30 ton/square metre (load range 2). Each ring consists of four equal segments and a keystone (Fig. 35). This keystone has a quarter of the length of a segment or a seventeenth of the circumference of the lining. The segments have four seventeenths of the circumference. This division corresponds to the arangement of the jacks in the shield. There were thus five joints in each ring which were arranged as hinges by Neoprene plates and sheet metal sleeves (Fig. 30). This division of the ring was advanta-



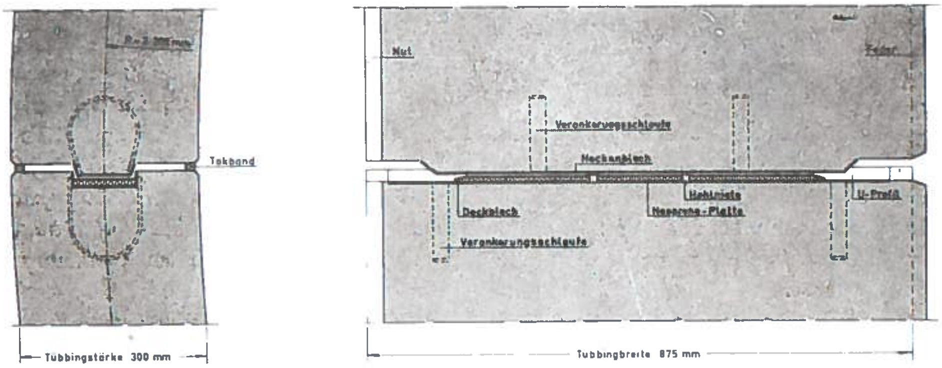
The segment conveyor pushes segments to the point of placing **FIGURE 28**

geous in so far as the keystone could be located anywhere if a taper ring had to be used for direction adjustment. Any necessary change of direction could be realized with a limited number of segment sizes. Generally, the transverse joints of adjacent rings were staggered by two seventeenth of the circumference (Fig. 39). The ring joints were of the T & G type.

In the statical analysis, the ring was considered to be a chain of hinges elastically and entirely radially supported in the ground. This purely radial support was taken into account only in the zone of outward deformations and combined into elastic forces. The circular system was thus replaced by a plane and polygonal system in which the reactions and the loads combined into single forces apply to the intersections. The determination of the load was based on the work of H. Schulze

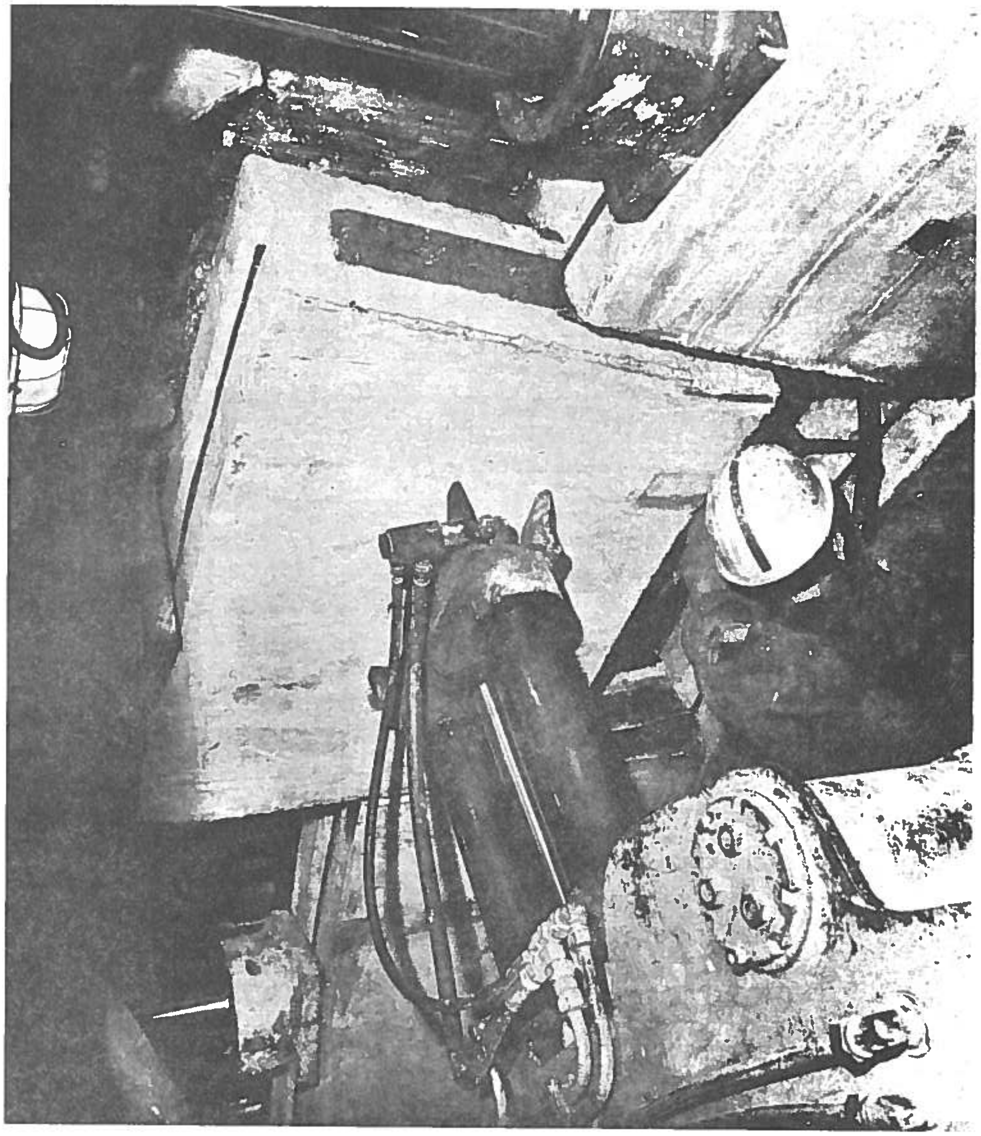


Placing segments by ring erector **FIGURE 29**



Hinge design **FIGURE 30**

Tokband	**Sealing strip**
Tübbingstärke	Thickness of segment
Nut	Groove
Feder	Tongue
Verankerungsschlaufe	Anchoring loop
Nockenblech	Buckled plate
Deckblech	Cover plate
Hohlniete	Hollow rivets
Neoprene-Platte	Neoprene plate
U-Profil	U-section
Tübbingbreite	Width of segment

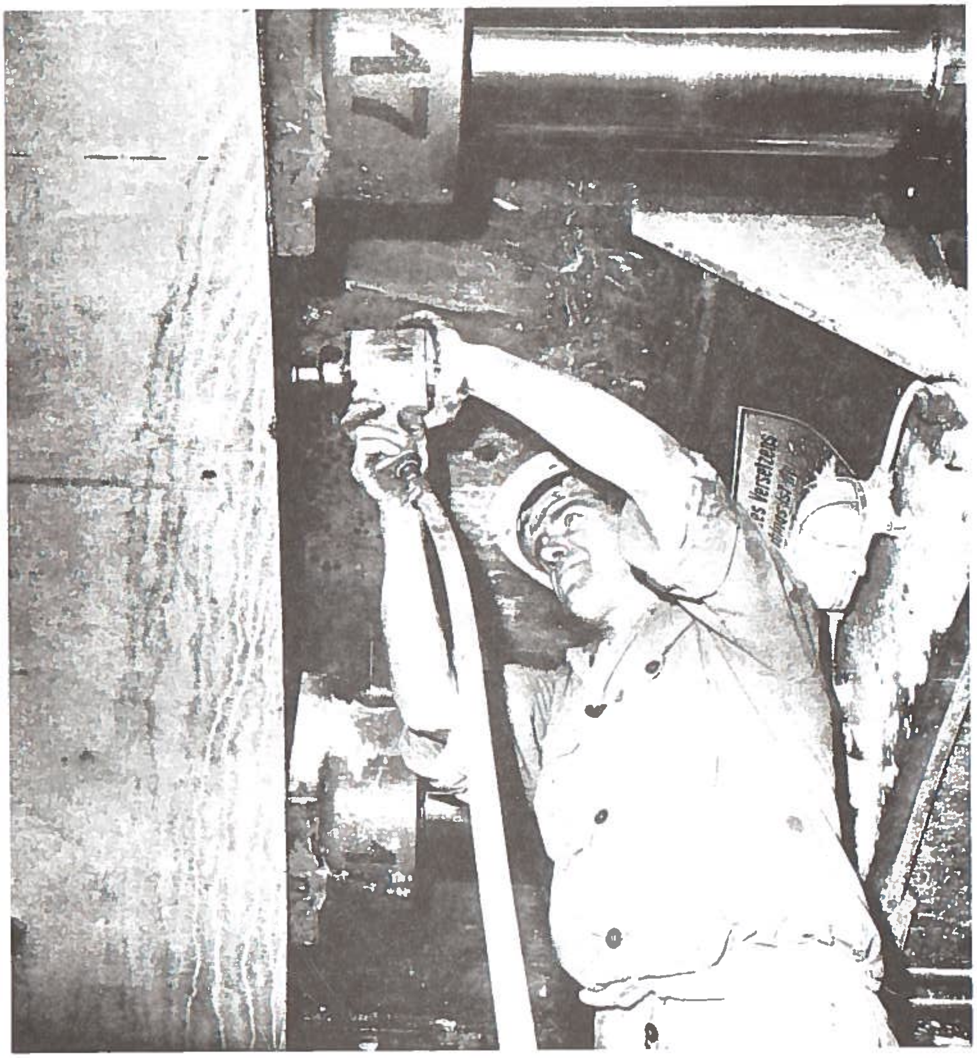


Placing the keystone by jack
Patent applied for

FIGURE 31

and H. Duddeck and took only the radial loads into account. However, because of the displaceable joint locations, this work could not be used for the computations. For this reason and in view of the considerable statical indeterminacy of the system consisting of an outer and an inner ring, the intersection values were calculated electronically.

Four bolts were used for fixing a segment. The 17 bolts required for a ring were staggered by 10 cm in relation to the jacks. Plywood panels were glued to the segment faces at the respective points to ensure uniform transmission of the jack forces and to eliminate detrimental edge stresses in the concrete due to the thrust.



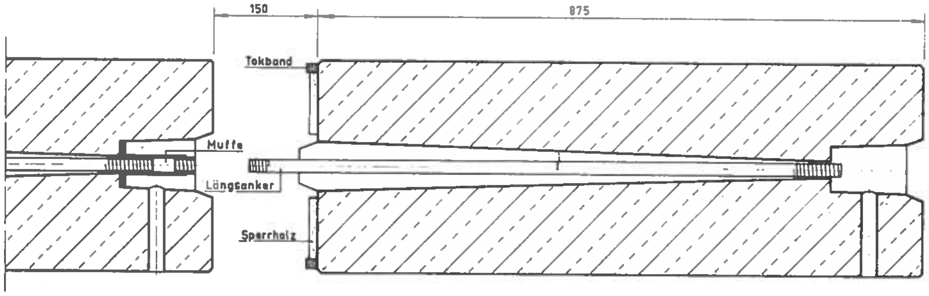
Tightening of the longitudinal ties

FIGURE 32

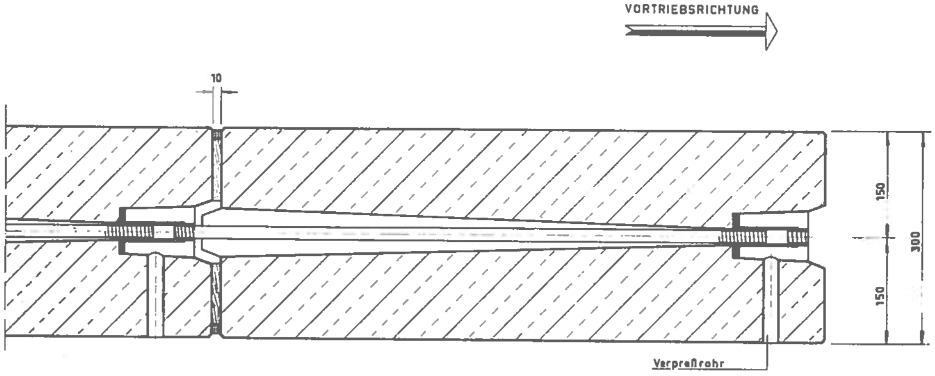
The about 1 cm wide ring and transverse joints were sealed from inside and outside with a view to preventing leakage of grout even at high pressures.

The standard rings are 87.5 cm wide. Taper rings were used for negotiating curves and for correcting direction. The geometry of the smallest radius of curvature resulted in a conicity of about 2 cm, and in order to allow corrections even in such case, the conicity was fixed at 4 cm, so that the taper ring was only 85.5 cm wide at the narrow face in the keystone zone and 89.5 cm on the opposite side (Fig. 39).

The segments were factory precast on



Situation vor der Montage



Situation nach der Montage

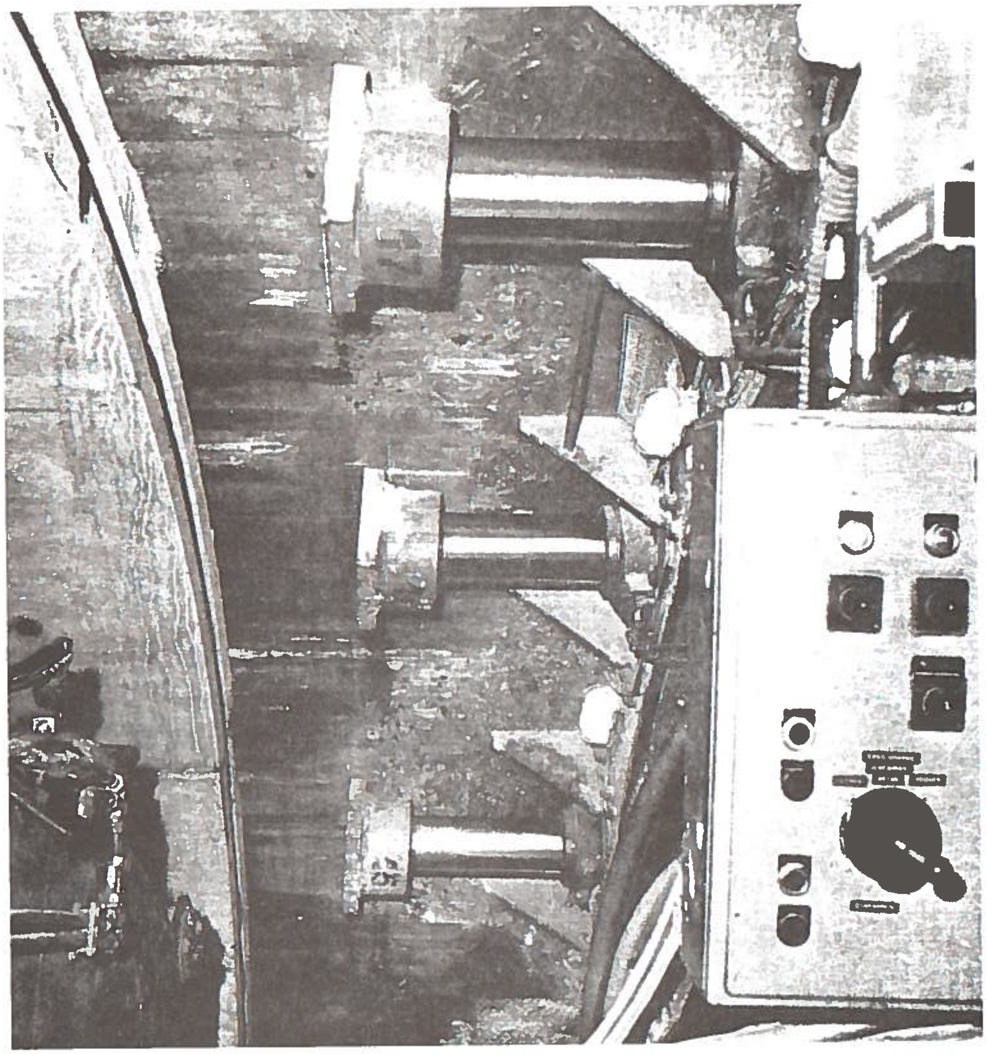
Placing of the segments

FIGURE 33

Situation vor der Montage	State prior to placing
Tokband	Sealing strip
Muffe	Sleeve
Längsanker	Longitudinal tie
Sperrholz	Plywood
Vortriebsrichtung	Direction of driving
Situation nach der Montage	State after placing
Verpreßrohr	Grouting tube

two 30 m long casting beds which were cambered to suit the inner radius of the segments. Pressed carbboard laid on the beds facilitated stripping. The segments were cast in braced steel moulds and the recesses for the ties were obtained by re-usable steel cones.

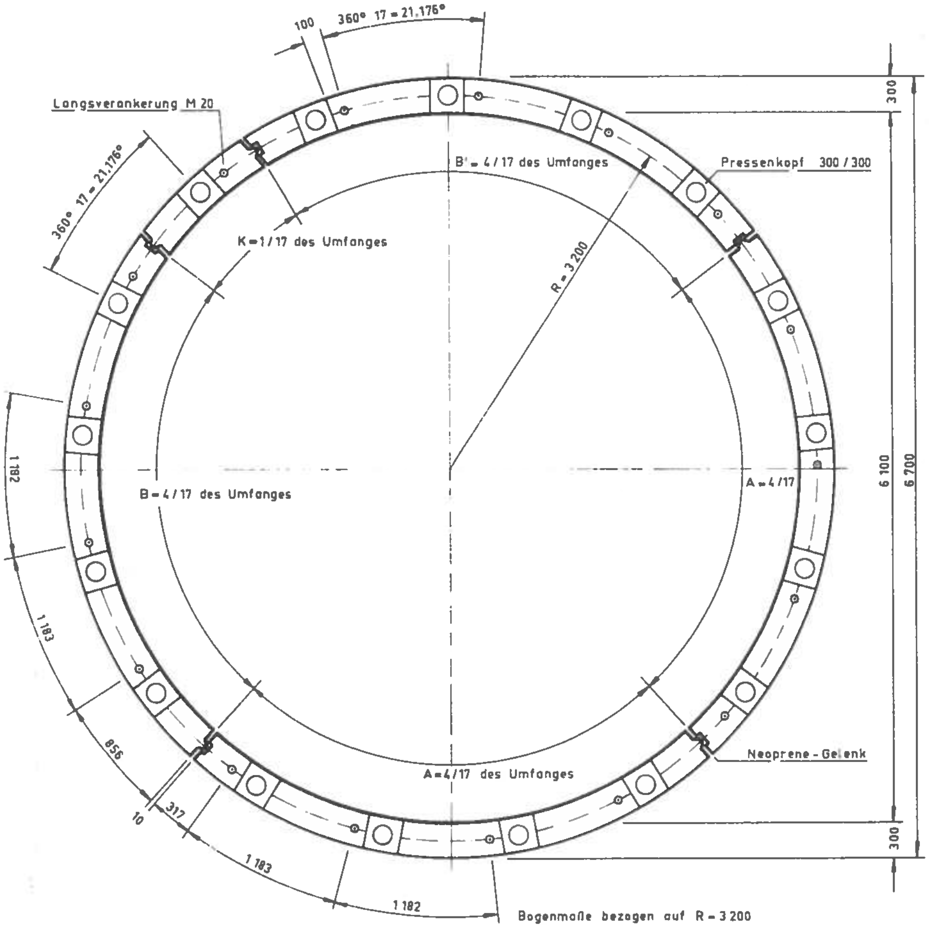
All segments of a ring were equally reinforced, so that the amount of steel determined for the most unfavourable system and which would have been necessary only at a particular point was provided all over the ring. A reinforcement against tensile splitting was provided for the single loads in the longitudinal and transverse directions.



Pushing the jacks forward

FIGURE 34

On the site, the segments were first handled by a tower crane (Fig. 24). They were then transported by special trucks and transferred by a pillar crane to the segment conveyor belt (Figs. 27 and 28) and then hydraulically pushed on to the ring erector assembly which placed them into position where they were held in grouting holes provided with tubes. The ring erector assembly placed the segments to within 15 cm of the previous ring (Fig. 33). The



Arrangement of the segments

FIGURE 35

Längsverankerung
Longitudinal ties

K = 1/17 des Umfanges
K = 1/17 of the circumference

Pressenkopf
Jack head

Neoprene-Gelenk
Neoprene hinge

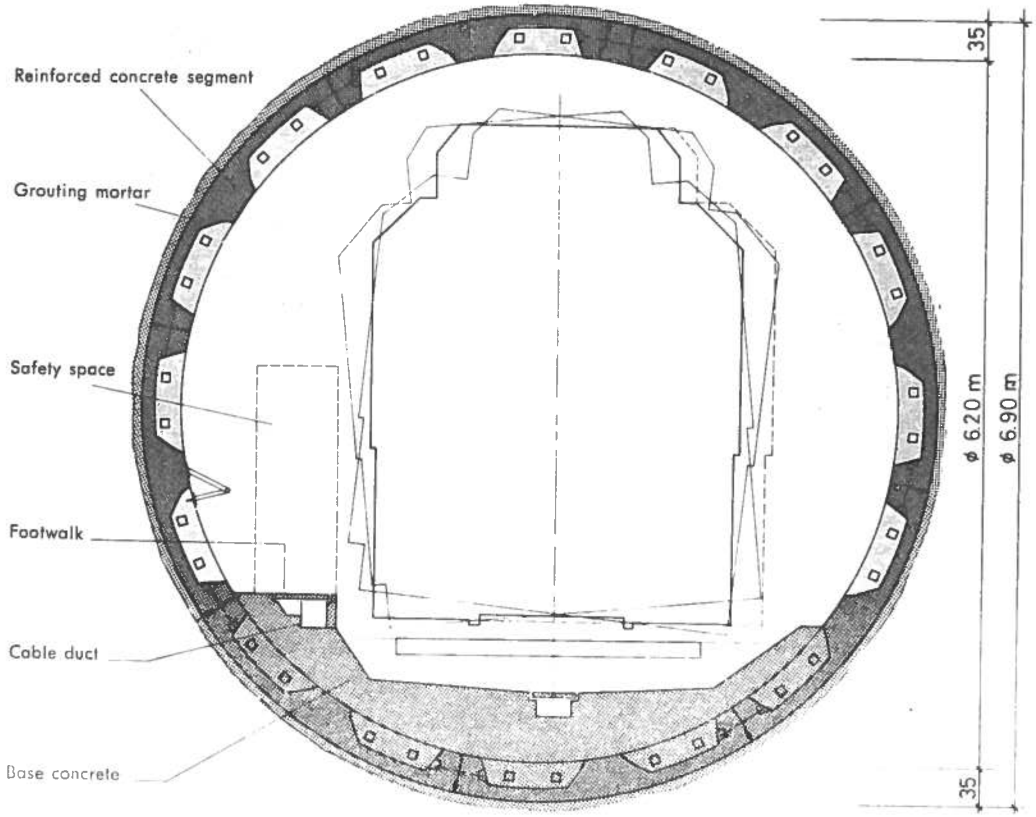
Bogenmaße bezogen auf R = 3200
Arch dimensions related to radius = 3,200

longitudinal ties were thereupon screwed into the sleeves, the segments placed in position and the sleeves tightened by impact wrench (Fig. 32). During the placing of a segment, the four corresponding jacks were retracted whereas the other jacks were in forward position to drive the shield. The tapered keystone was placed in the tapered opening at about 45 cm from the previous ring, pushed by the jack into position after placing the tie rod (Fig. 31); then the sleeve was tightened.

Grouting of the cavity between lining and ground **FIGURE 36**

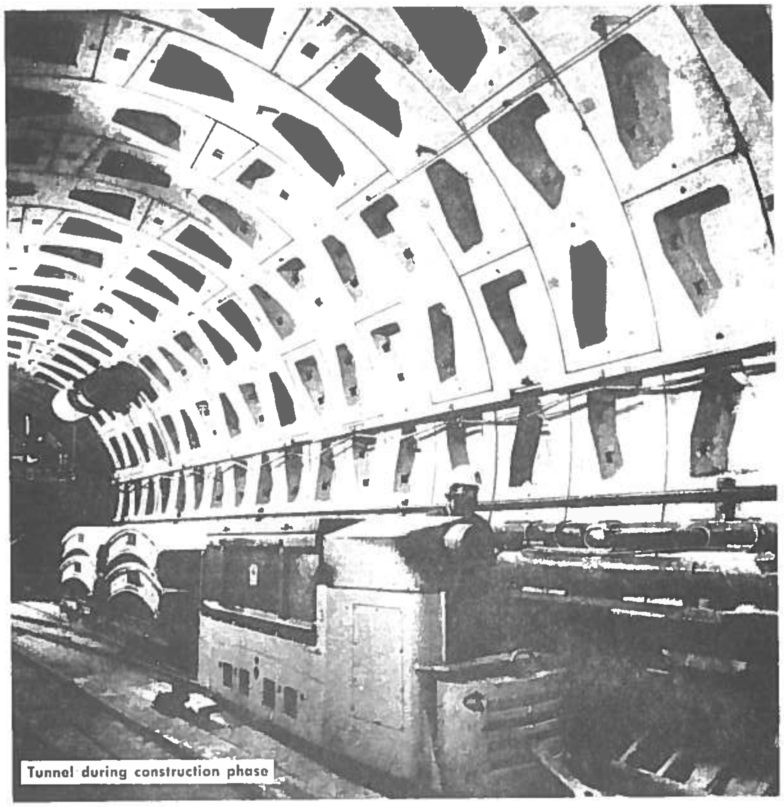
Sealing within the tail of the shield during placing operations was provided by a trailing plate and wood wool ropes (Fig. 29).

After the tail of the shield had travelled past a ring, the cavity between the lining and the ground was pressure-grouted from bottom to top through the grouting holes in the segments (Fig. 36), followed by injection of a neat cement-water grout. The segment joints and the recesses for the ties were fully grouted prior to the application of the levelling rendering. The water running from the joints was intercepted by split plastic pipes and conveyed to the construction drainage system at the low point of the tunnel outside of the insulation. This drainage system was grouted at a later stage.

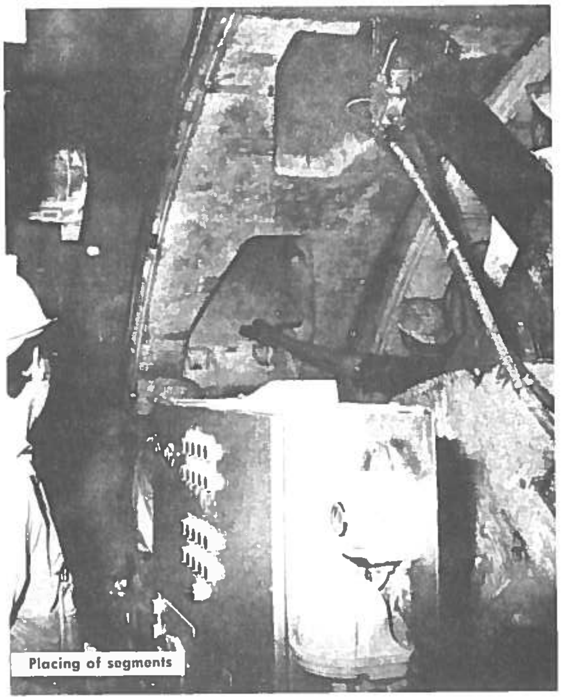


Typical cross section of tunnel line

TYPICAL CROSS SECTION OF TUNNEL LINE

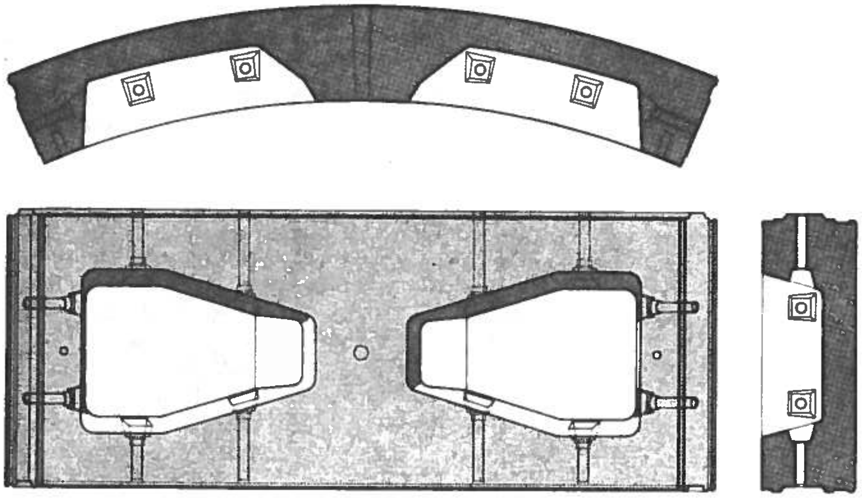


Tunnel during construction phase



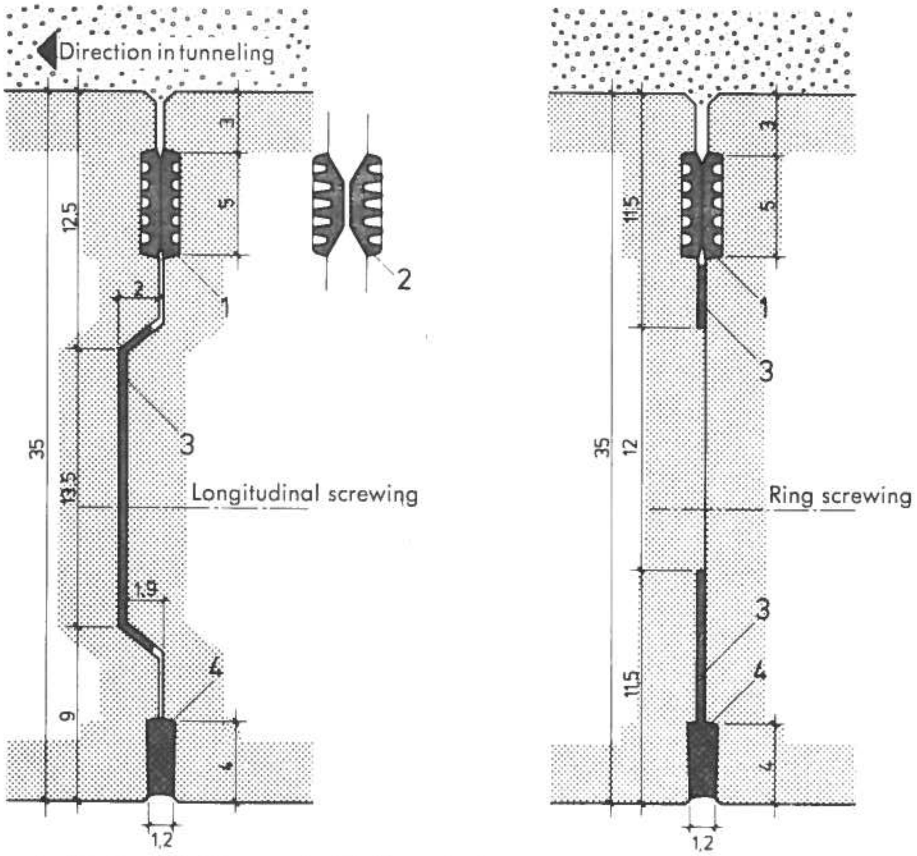
Placing of segments

CONSTRUCTION DETAILS



Precast segment

Forming of joints



1 Compressed solid rubber seal, 2 Compressed solid rubber seal prior to mounting, 3 Plastic packing, 4 Sealing of joints

PRECAST CONCRETE SEGMENT AND JOINT SEAL DETAILS

TUNNEL CONSTRUCTION IN JAPAN

Discussion

A list of concrete segment lined subway tunnels installed in Japan (18 in Tokyo, 1 in Yokohama) is reproduced on page B-22. The tabulated data includes the tunnel ring diameter and width, the height of the water table above the tunnel invert, and information on the water sealant systems used and their performances.

Extracts from the letter which transmitted the data are reproduced on pages B-20 and B-21. This provides additional details on the water proofing systems used and some information on the segment manufacture. Although details of the segments of the linings were not included, it appears from other sources that the segments in all the lining systems are bolted in the four faces, either according to the details of the Teito HST Authority, or the Sakuragicho Subway Yokohama tunnel examples indicated in Section 3.

On page B-23 some segment details of the systems of interest are shown. This is manufactured by the Nippon Pressed Concrete Corporation, which was recently visited by Mr. Ben C. Gerwick Jr., whose comments are reproduced with the details.

The water sealing systems described on page B-22 consist typically of one or two gasket bands on one circle face and on one radial face of each segment, and caulking to the segment inside edges.

Generally one of two products have been used for the gasket bands:

- Nittetsu Seal, which is described as a "tar-plastic." Details of its properties and application are summarized with English translation on pages B-24 and B-25.

- Top Sealer, which is described as a "synthetic butyl rubber." Details of its properties are summarized on pages B-26, B-27, B-28, and B-29. Page B-30 indicates details of some of the gasket band variants that were used.

The caulking materials for all the projects are described as an epoxy or tar epoxy. Typical of these is Shoresin (tar epoxy) which is discussed on pages B-31 and B-32. Pages B-33 through B-35 indicates caulking joint details, installation techniques, and test values when the material is installed in wet conditions. During application, the caulking grooves are first cleaned, as far as possible, and dried with air jets, and the two-component material is mixed and introduced into the grooves in a caulking gun.

It would appear, from the comments on the waterproofing properties of the combined systems, that the results were generally satisfactory. The individual performances of the gaskets and the caulking were not evaluated, but it is suspected that due to the relative softness of the gasket materials, their function is to provide temporary water tightness until the installation of the caulking.

Most of the tunnels were constructed in water-bearing granular silty soils, the water lying between 20 and 50 ft above the top of the tunnels.

Extract from transmittal letter of "List of Reinforced Concrete Single-Lined Subway Tunnels" (Japan).

"The enclosed list of Reinforced Concrete Single-lined Subway Tunnels is prepared for your information on the "year of construction", the "head of water" above the bottom of tunnel and "seal of joint and attained waterproofing". This list is based on the descriptions compiled by the Compiling Committee on Examples of Shield-driven Railway Tunnels and published by the Permanent Way Society of Japan.

In the enclosed list, the tunnels marked * indicate that it is mostly lined with reinforced concrete segments while other segment material (ductile iron) is used partly. The tunnels marked ** indicate that the tunnel is partly lined with reinforced concrete segments and mostly lined with other materials.

Slight leakage of water resulting from "fair" waterproofing is left as is until it cures by itself. Chemical grouting into the ground surrounding the segmental lining is made to remedy the "poor" waterproofing of the tunnel indexed No. 203 on the Keiyo Line.

Required allowable compressive strength of concrete for segments is as follows:

Sobu Line (Index No. 103):	200 kg/cm^2
Keiyo Line (Index No. 203):	180 "
Tokaido Line (Index No. 107):	200 "
Eidan Lines (Index Nos. 302 through 322):	160 "
Yokohama Line (Index No. 501):	180 "
Shin-Tamagawa Line (Index Nos. 901 through 903):	160 "

However, the attained compressive strength is considered to be higher than the value indicated above and actual ultimate compressive strength is somewhere around 450 kg/sq cm or more.

Quality control of concrete for segments during production is made according to the "Standard Concrete Specification" of the Japan Society of Civil Engineers and the "Guidelines for Design and Manufacture of Factory-made Reinforced Concrete" of the same society.

Almost all reinforced concrete segments in Japan are factory-made using steel forms of dimensional error less than one-half of the allowable dimensional error of manufactured segments.

The allowable dimensional errors of concrete segments according to the "Guidelines for Shield Tunneling Method" of JSCE are as follows:

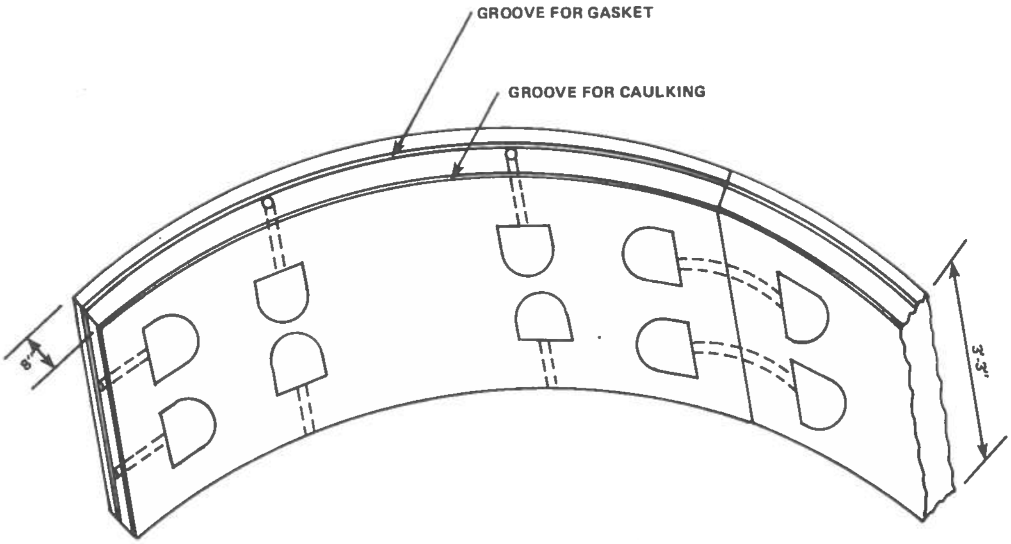
Dimensions of assembled segmental ring at horizontal position	Outside diameter (m)	6-7	8 or more
	Error in bolt-pitch circle(mm)	±10	±15
	Error in Outside diameter(mm)	±15	±20
Thickness	a (mm)	-0	
Width	b (mm)	±1.0	
Length	c (mm)	±1.0	
Distance between bolt holes	d, d'(mm)	±1.0	

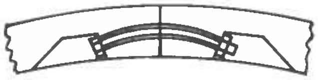
Concrete for segments after placed in forms is compacted either by vibrating or pressing. Typical curing procedure for segment concrete of a manufacturer (Nippon Pressed Concrete) is as follows:

1. Steamtreating for 6 hours at maximum temperature of 100 degree Centigrade.
2. Cooling in air down to room temperature.
3. Wet-curing for a week.
4. Curing in air for predetemined period."

LIST OF REINFORCED CONCRETE SINGLE-LINED SUBWAY TUNNELS

Index Number	Name of Line	Name of Work Section	Year of Completion	ODxlength(m)	Head of Water (mm)	Type of Segment	Water proofings Caulkings	Water proofings Bands	Attained Water-proofings	Owner	Contractor	Manufacturer of Segments
103	Sobu	Kodenma-cho, Tokyo	1971	7.06x435 7.06x455	(10)	Slab	Esdine (Tar epoxy)	1xNittetsu seal (Tar)	Good	Japanese National Railways	Sato Kohgyo	Sato Koghyo
107	Tokaido	Shiodome, Tokyo	1973	2x7.06x836	10	Box			Fair		Kumagai	Nihon Press Concrete
203	Keiyo	Keihin sanku, Tokyo	1972	2x7.10x834	22	Box	Shoresin (Tar epoxy)	2xTop-sealer (rubber)	Poor	Japan Rwy Construction Corporation	Tekken Kensetsu	Fujimi Kohken
302	Eidan No. 5	Tomioka-cho, Tokyo	1967	2x6.75x800	22	Box	Tohodaito (Epoxy)	2xNittetsu seal	Fair	Teito Rapid Transit	JV Kashima & Nishimatsu	Kashima Kensetsu
303	Eidan No. 5	Susaki, Tokyo	1967	2x6.75x727	12.5	Box	Suriironji (Epoxy)	2xNittetsu seal (Tar)	Poor	Teito Rapid Transit	JV Kumagai & Sato	Nihon Press Concrete
305	Eidan No. 9	Senju Midori-cho, Tokyo	1969	6.5x792 6.5x807	15	Box	Suriironji (Epoxy)	2xNittetsu seal (Tar)	Good	Teito Rapid Transit	Taisei Kensetsu	Toyoda Concrete
306	Eidan No. 9	Sumidagawa, Tokyo	1969	6.5x683 6.5x679	19.5	Box	Suriironji (Epoxy)	2xTop-sealer (rubber)	Good	Teito Rapid Transit	Maeda Kensetsu	Nihon Press Concrete
312	Eidan No. 9	Minami-Aoyama II, Tokyo	1971	2x6.5x315	12	Box	Shoresin Tohodaito	2xrubber type	Excellent	Teito Rapid Transit	Sato Kohgyo	Sato Kohgyo
309	Eidan No. 9	Kasumigaseki, Tokyo	1972	2x6.5x353	2	Box	Suriironji (Epoxy)	2xrubber type	Good	Teito Rapid Transit	Kashima Kensetsu	Kashima Kensetsu
313	*Eidan No. 9	Minami-Aoyama III, Tokyo	1971	2x6.5x165	14	Box	Tohodaito (Epoxy)	2xrubber type	Good	Teito Rapid Transit	Maeda Kensetsu	Fujimi Kohken
316	*Eidan No. 8	Bancho, Tokyo	1973	9.8x445	10	Box	Suriironji (Epoxy)	2xTop-sealer (rubber)	Fair	Teito Rapid	Nishimatsu Kensetsu	Nihon Press Concrete
317	*Eidan No. 8	Hirakawa-cho I, Tokyo	1973	9.8x341	11	Box	Suriironji (Epoxy)	2xTop-sealer (rubber)	Good	Teito Rapid Transit	Tobishima Kensetsu	Showa Prefab
320	Eidan No. 8	Nagata-cho II, Tokyo	1974	6.5x661 6.5x616	0-12	Box	Shoresin (Tar epoxy)	2xTop-sealer (rubber)	Good	Teito Rapid	Sato Kohgyo	Sato Kohgyo
321	Eidan No. 8	Hibiya-bori, Tokyo	1973	2x6.5x648	14.5	Box	Shoresin (Tar epoxy)	2xTop-sealer (rubber)	Fair	Teito Rapid Transit	Maeda Kensetsu	Fujimi Kohken
322	Eidan No. 8	Kasumigaseki, Tokyo	1974	6.5x578	14	Box	Shoresin (Tar epoxy)	2xButyl-sealer	Good	Teito Rapid Transit	Tobishima Kensetsu	Nihon Press Concrete
501	Yokohama **No. 1	Miyamoto-cho	1971	6.3x595 6.2x621	(10-17)	Box	Shoresin (Tar epoxy)	1xNittetsu seal	Good	Yokohama City	Kumagai Gumi	Nihon Press Concrete
502	Yokohama **No. 1	Kanno-shita II	1974	6.2x509 6.2x503	13-17	Composite Slab of RC&Ductile	Shoresin (Tar epoxy)	1xShield sealer	Fair	Yokohama City	Aoki Kensetsu	Ishikawajima Harima Juko
901	Shin-Tamagawa	Shibuya, Tokyo	1975	6.5x1098 6.5x1086	14.5	Box	Esdine (Tar epoxy)	2xTop-sealer	-	Tokyu (Priv. Rwy)	Kumagai Gumi	Nihon Press Concrete
902	Shin-*Tamagawa	Komazawa (2), Tokyo	1975	6.5x658 6.5x650	12.5	Box	Tohodaito (Epoxy)	2xTop-sealer	-	Tokyu (Priv. Rwy)	Kashima & Tokyu	Nihon Press Concrete
903	Shin-*Tamagawa	Komazawa (1), Tokyo	1975	6.5x667 6.5x742	12.5	Box	Tohodaito (Epoxy)	2xTop-sealer	-	Tokyu (Priv. Rwy)	Kashima & Tokyu	Nihon Press Concrete





DETAIL OF CROSS JOINT BOLT
(CIRCLE BOLTS SIMILAR)

The segment details indicated are those of a concrete lining system manufactured by Nippon Pressed Concrete Corporation (near Tokyo). This firm reportedly produces 70 percent of the concrete tunnel liners in Japan.

Concrete strength is 700 Kg/cm^2 guaranteed (cylinder) = 10,000 psi. This is obtained by that company by applying pressure to the concrete during curing, which should significantly increase the tensile strength.

However, similar strengths can probably be obtained in the best concrete plants in the United States by using selected aggregates, and one of the new super water-reducing admixtures such as Mighty.

LINING SYSTEM
NIPPON PRESSED CONCRETE CORPORATION

<table>
<tr><td colspan="2">製　品　名　日鉄シール#S　NITTETSU SEAL #5</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>1. 系　TYPE　統</td><td>タール合成樹脂系シート状シール材　STRIP SHAPE TAR-PLASTIC GROUP</td></tr>
<tr><td>2. 特　MERITS　徴</td><td>1. 日鉄シール#Sの凝集力と接着剤の接着力とのバランスが良くとれている
GOOD BALANCE OF COHESION AND STRONG ADHESION
のでセグメントに対し強い接着力がある。
2. 適度の弾性と流動性を兼ね備えているので止水効果が優秀である。
SUITABLE ELASTICITY AND PLASTICITY
3. 貼り付け作業が簡単である。
EASY APPLICATION.
4. 耐老化性、耐油性が優れている。
EXCEL IN WEATHERPROOF AND ANTI-OIL.
5. 価格が安価である。
ECONOMICAL.</td></tr>
<tr><td>3. 推　奨　用　途
USE</td><td>1. シールド工法に於けるセグメントのパッキン
SEALING FOR SHIELD TUNNELS
2. ボックスカルバートのパッキング
SEALING FOR BOX CULVERTS</td></tr>
<tr><td>4. 形　状
DIMENSION</td><td>
<table>
<tr><td rowspan="2">標準形状
STANDARD</td><td>厚さ（mm）
THICKNESS</td><td>3</td><td>5</td><td>5</td><td>7</td><td>7</td><td></td></tr>
<tr><td>幅　（mm）</td><td>30</td><td>20</td><td>30</td><td>20</td><td>30</td><td></td></tr>
</table>
</td></tr>
<tr><td>5. 施　工　方　法
APPLICATION</td><td>1. 下地処理　PRELIMINARY PREPARATION
(a) 塗装面がスチール又はダクタイル鋳鉄の場合には、土埃、油、水分は充
CLEAN, FREE OF DUST, OIL, WET
分に拭き取って下さい、特にスチールセグメントの場合は防錆塗料が予め
STEEL SEGMENTS, REMOVE ANTI-RUST COATING
塗装してある場合がありますが、塗料の上に貼り付けますと、スチールセ
WIRE-BRUSHING, ETC.
グメントとシール材の間が剥離致しますので塗料はワイヤーブラシ等を用い充分擦り落して下さい。然し実際の場合なかなか落しにくいので、出来たらシール材を貼る面には塗料は塗らないようにして下さい。
(b) 塗装面がコンクリートの場合にはコンクリート表面のレイタンス
WIRE-BRUSHING, ETC.
（Laitance）をワイヤーブラシ等で充分除去して下さい。勿論、油、土
MAKE FREE OF OIL, DIRT, SAND, WET.
砂、水分等はの場合と同様「日鉄シール」の接着力を低下させる原因になりますので、充分清浄な面にしてから塗装して下さい。
2. 接着剤塗布　COATING PRIMER
シール材の箱の中にはいっている接着剤を100cc（約5勺）位の容器に小分
COAT WITH A 40-MM-WIDE BRUSH
けし、巾40mm位の小刷毛でシートの巾より両側約2.5mm位広めに均一にシー
2.5MM WIDER ON BOTH SIDES THAN THE SEAL
ト貼り付け面に塗布して下さい。
STD. AMOUNT OF PRIMER
接着剤の使用量は7〜10g/mが標準になっております。
3. 日鉄シールSの貼り付け　ATTACHING NITTETSA SEAL
接着剤塗布後約5〜10分間位放置致しますと接着剤中の溶剤が揮発致しま
5〜10 MIN. AFTER COATING PRIMER ATTACH SEAL-S
すのでこの時に日鉄シールSを剥離紙と共にシートが接着剤塗布面に充分密
TOGETHER WITH PAPER COVER
着するよう剥離紙の上から手で強く押しつけます。
剥離紙は接着後のシートを直射日光や土、埃、雨露から保護し、シートの相互接着力をそこなわないためのものでありますので、セグメント等の組立直前まで剥がないで下さい。</td></tr>
</table>

日鉄シールＳの性状表 PROPERTIES OF NITTETSU SEAL S

1. 比重 SPECIFIC GRAVITY		1.25
2. 伸張率（ＪＩＳ K6301）% ELONGATION RATIO		500 ～ 550
3. 抗張力（ＪＩＳ K6301）kg/cm² TENSILE STRENGTH		15 ～ 20
モジュラス kg/cm² MODULUS	100 %	1.8
	200 %	6.1
	300 %	9.8
4. 引裂強度（ＪＩＳ K6301）kg/cm² TEARING STRENGTH		7～8
5. 接着力 kg/cm² BONDING STRENGTH	引剥接着力 AGAINST PULL	4.1
	剪断接着力 AGAINST SHEAR	5.8
6. 圧縮率と圧縮応力 kg/cm² COMPRESSION RATIO AND COMPRESSIVE STRESS	30 %	1.1
	40 %	2.1
	50 %	3.0
	70 %	29
	80 %	160

7. 復元率 RECOVERY RATIO	圧縮率 COMPR.	30 %		50 %		80 %		
	圧縮時間 TIME (HRS) / 復元時間 RECOVERY TIME	0	2	0	2	0	2	
	1 分 MIN.	99	92	94	86	91	46	
	5 分	100	97	99	96	97	65	
	2 4 時間 HR.	100	100	100	100	100	72	

8. 耐水圧力（T字型継手試験器による）kg/cm²		5 以上 WATERPROOF CAPACITY
9. 耐薬品性 RESISTANCE AGAINST	耐油性 OIL	異常なし NO CHANGE
	耐酸性（5%H_2SO_4）	ACID 〃
	耐アルカリ性（5%NaOH）	ALKALI 〃
10. 耐候性 WEATHERPROOF		表面の光沢は消失するが弾力性は変化なし NO CHANGE IN ELASTICITY

Ⅱ. 特長 MERITS TOP SEALER

1）シールド工法用シール材のトップ製品である
TOP-RANKING PRODUCT FOR SEALING (SHIELD TUNNEL)

シールドセグメント用シール材として，満足して頂くためには如何にあるべきか，を永年研究してまいりました．研究員は土木技術者と起居を共にして実情を丹念に調査しいろいろな悪条件においても止水効果が完全に発揮できるよう改良をつづけたシール材のトップ製品であります．

2）シールド工法の専門家によつて生み出された製品であります
DEVELOPED BY TUNNELING EXPERTS

トップシーラは当社のみならず，シールド関係の多くの技術者から現場施工に必要ないろいろな条件を提示していただき，御使用される方々と一緒に実験，施工，討論をくり返しつつ，御使用される皆様によつて育てていただいた．いいかえせばシールドの専門家によつて生まれたシール材と申せます．

3）各官庁および多くの建設会社の公認されている製品であります
AUTHORIZED BY GOVERMETIAL OWNERS AND CONTRACTORS.

トップシーラーは各官庁の厳しいテストに合格した製品で，帝都高速度交通公団，日本鉄道
TOP SEALER QUALIFIED THROUGH STRICT TESTS, EMPLOYED BY TEITO RAPID TRANSIT.
建設公団，日本国有鉄道その他各官庁に御採用いただいている製品です．
JAP. RWY. CONTR. CORP., JAP. NAT'L RWY. ETC.

4）性能

A 材質 …… 瀝青物を含まない合成ゴム（ブチルゴム）です．
QUALITY **SYNTHETIC BUTYL RUBBER WITHOUT BITUMINUOUS COMPONENT**

B 接着性 …… 自己接着性にすぐれ，接着性は抜群です．
BONDING QUALITY **GOOD IN SELF ADHESION AND EXCEL IN BONDING QUALITY**

C 硬度 …… 施工性に適した硬度です．
HARDNESS **SUITABLE HARDNESS FOR APPLICATION**

D 耐久性 …… 施工後は半永久的な性能を有します．
DURABILITY **POSSESS SEMI-PERMANENT FUNCTION AFTER APPLICATION**

Ⅲ. 用途 USE

1. シールド工法用シール材
   SEALING MATERIAL FOR SHIELD METHOD
2. コルゲートパイプ継目用シール材
   SEAL MATR'L FOR JOINTS OF CORRUGATED PIPES
3. 用排水溝継目用シール材
4. 潅漑用コンクリートU字管シール材
   SEAL. MAT'L FOR CONCRETE U PIPES
5. カルバートボックス用シール材
   SEAL MAT'L FOR CULVERT BOXES
6. その他一般土木用シール材

Ⅳ. 物　　性
MECHANICAL PROPERTIES

1）伸　張　率 ELONGATION RATIO

試料厚み5m/mのシートを用意し JISK－6301（加硫ゴム試験法）に定められたダンベル1号形に打抜く，打抜いた試料を 500㎜/min 速度の引張り試験機にかける試料が切断するまで引張る．

伸張率の算出方法

$$E_B = \frac{L_1 - L_0}{L_0} \times 100$$

E_B　伸張率 %

L_0　標線間距離 m/m

L_1　切断時の標線間距離 m/m

測定温度 20°C
AT TEMP.

伸張率% ELONG. RATIO	1000

2）抗　張　力 TENSILE STRENGTH

試験方法は 2）に準ずる．

抗張力の算出方法

$$T_B = \frac{F_B}{A}$$

T_B　抗張力 ㎏/㎠

F_B　最大荷重 ㎏

A　試験片の断面積 ㎠

測定温度 20°C
AT TEMP.

抗張力 ㎏/㎠ TENSILE STRENGTH	0.6

3）荷重による圧縮度合の変化 VARIATION IN COMPRESSION UNDER VARIOUS LOADINGS

測定方法 TEST EQUIP.　定荷重式硬度測定器（高分子計器製）による．

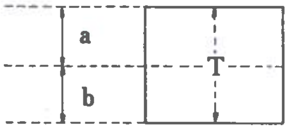
試料寸法 SPECIMEN　10 m/m 巾 WIDE ×2.47 m/m 厚 THICK ×20 m/m 長 LONG

測定温度 TEMP.　20°C

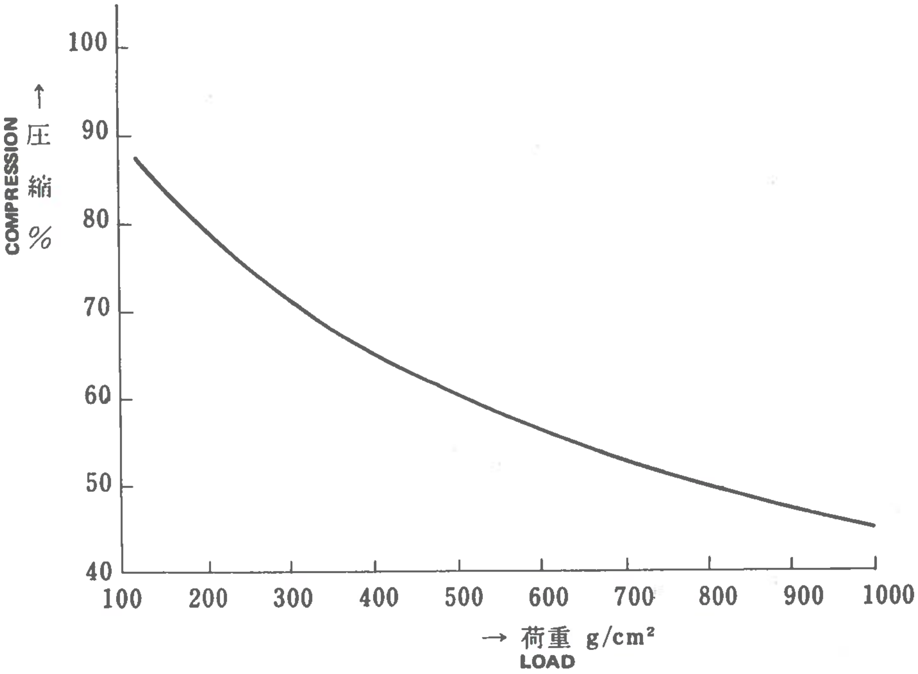
圧縮時間 COMP. TIME　15分 MIN.

圧縮度合算出方法

$$\text{圧縮度合}K = \frac{b}{T} \times 100\,\%$$



荷重 g/cm² LOAD	100	300	500	1000
圧縮度合 % COMPRESSION RATIO	88	73	61	45



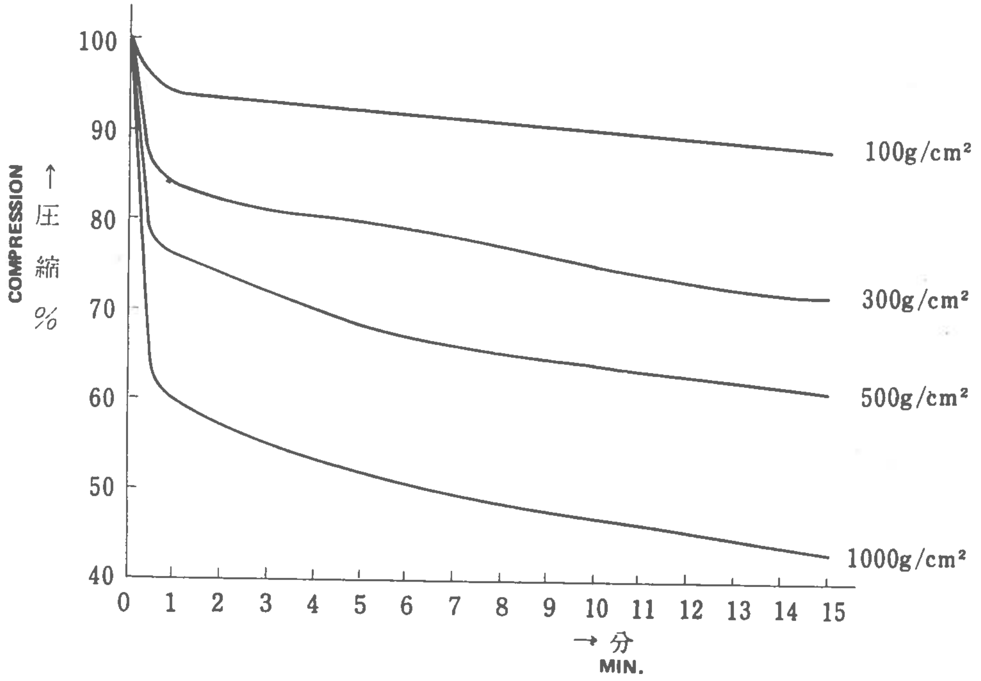
4）加圧時間による圧縮度合の変化 VARIATION IN COMPRESSION DUE TO VARIOUS TIME OF LOADING

EQUIP.	測定方法	定荷重式硬度測定器による
SPECIMEN	試料寸法	10 ㎜ 巾×2.47 ㎜ 厚×20 ㎜ 長
TEMP.	測定温度	20°C
COMP. TIME	圧縮時間	30 秒～15 分

算出方法は 1）に同じ

（数値圧縮度合 %）

時間（分） TIME (MIN.) LOAD 荷重(g/cm²)	0	30秒 SEC.	1	3	5	10	15
100	100	95	94	93	92	90	88
300	100	86	84	81	80	75	72
500	100	78	76	72	68	64	61
1000	100	64	60	55	52	47	43



5）荷重による復元度合の変化 VARIATION IN RECOVERY RATIO FOR VARIOUS LOADINGS

測定方法　定荷重式硬度測定器による．

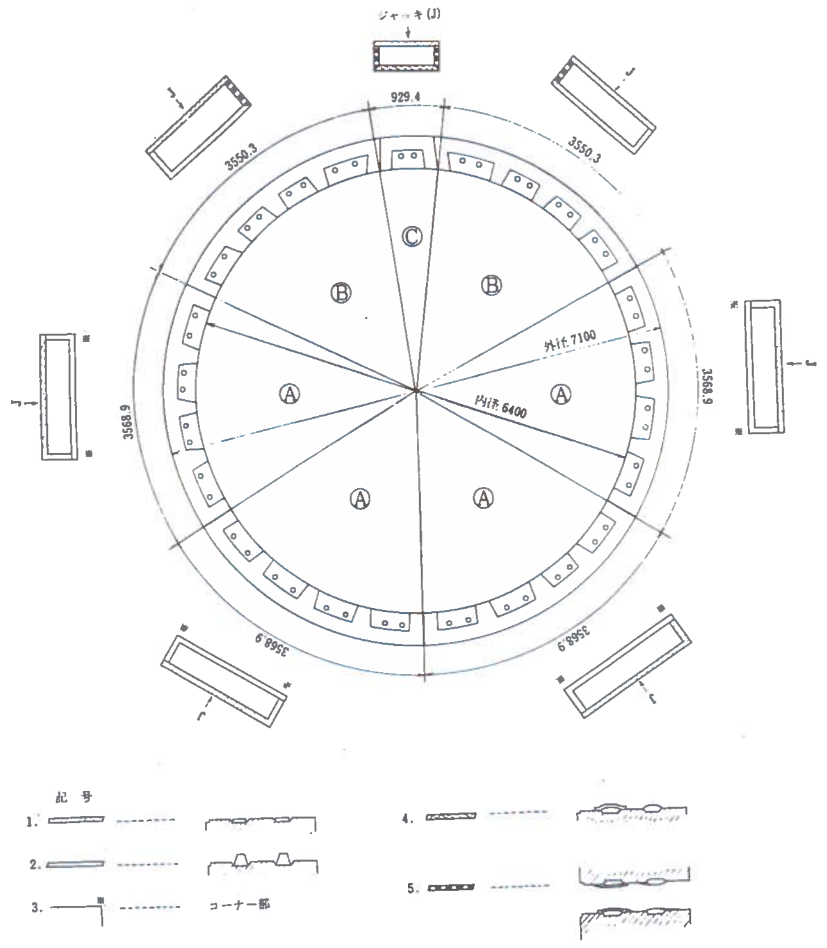
荷重 LOADS 100，300，500，1000 g/cm² をそれぞれ15分かけ，後に荷重を除き原寸 APPLIED 15 MIN. AND AFTER UNLOADING （高さ）の何%になつたか測定（15分） RATIO OF HEIGHT OF SPECIMEN TO INITIAL HEIGHT MEASURED

測定温度　20°C

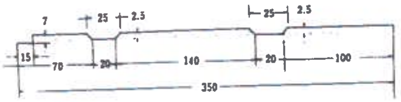
復元度合算出方法は 1）に同じ

荷重 LOAD (g/cm²)	100	300	500	1000
復元度合 (%) RECOVERY RATIO	92	75	67	49

RCセグメント用シール材施工図例

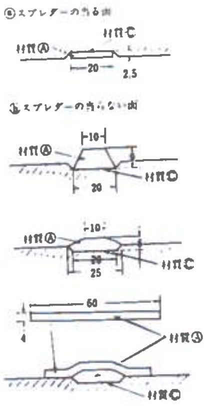


1. RC溝寸法

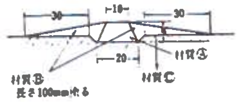


2. シール材寸法

2−1 推進方向



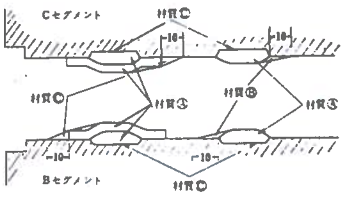
2−4 コーナー部



材質Ⓐ
トップ シーラー＃710B
材質Ⓑ
トップ シーラー＃30P
（一液性ブチルコーキング材）
材質Ⓒ
プライマー

2−2 接手方向
推進方向と同様

2−3 CセグメントとBセグメントの接合部



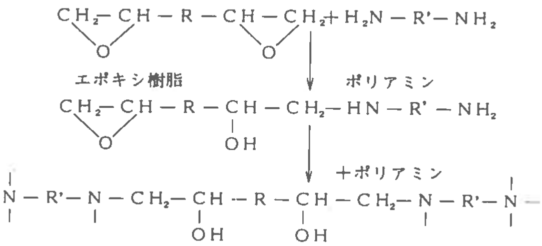
SHORESIN

はじめに

ショーレジン(株)
昭和49年1月

ショーレジン樹脂は石油を原料として合成によって得られる。多官能のエポキシ樹脂と我社が開発した特殊ポリアミン硬化剤とからなり、この二つを混合すると被着体表面の水分とも反応し特殊な生成物を形成してエポキシ基を開環すると同時に被着体のコンクリート、金属等の表面と結合します。したがって水中あるいは湿潤面でも強力な接着性が得られます。又エポキシ樹脂特有の優れた耐透水性、耐薬品性等を有しており、土木建築分野での防蝕、防錆、防水効果を発揮し、斯界に寄与しております。

ショーレジンの開環重合反応



製品案内

工法	品名	用途
コーキング材料	**ショーレジン TR-119** **ショーレジン TR-119L-1**	地下鉄、隧道等の目地コーキング用
	ショーレジン STE-500	樹脂充填全般用
塗膜材料	**ショーレジン TRC-14** **ショーレジン TRC-70** **ショーレジン STE-100** **ショーレジン STE-300**	タンクコンクリート槽等の防蝕、防水ライニング用
接着材料	**ショーレジン B-70**	アンカーボルト埋設用
	ショーレジン SRC-30 **ショーレジン TRC-14**	シート接着用
	ショーレジン TRC-70 **ショーレジン STE-100**	コンクリート打継、嵩上げ接着用
床材及び舗装材料	**ショーレジン PC-15**	歩道、陸橋、車道等の舗装用レジンモルタル
	ショーレジン RM-60	船舶用レジンモルタル
樹脂注入材料	**ショーレジン STE-150**	コンクリートクラック注入用
止水材料	**レジンクラッカー**	瞬結止水用

コーキング材料 CALKING MATERIAL

我社のコーキング材は特に地下鉄のシールド工法の経験から開発した２液型エポキシ系コーキング材でコンクリート、鉄、アルミ等の被着面に水中および湿潤状態でも、すぐれた接着性を示し、且つ耐候性も良好であります。それ以外のコーキング溝、クラック補修、間隙充填等にも用いその目的を達成して、斯界の皆様方によろこんでいただいております。

OUR CALKING MATERIAL DEVELOPED BASING ON EXPERIENCE IN SUBWAY TUNNELING WORKS, ARE 2-LIQUID-TYPE OF EPOXY GROUP AND IT POSSESS GOOD BONDING QUALITY AND WEATHER PROOFNESS EVEN UNDER WET CONDITION WHEN IT IS APPLIED TO CONCRETE, IRON, ALUMINUM, ETC.

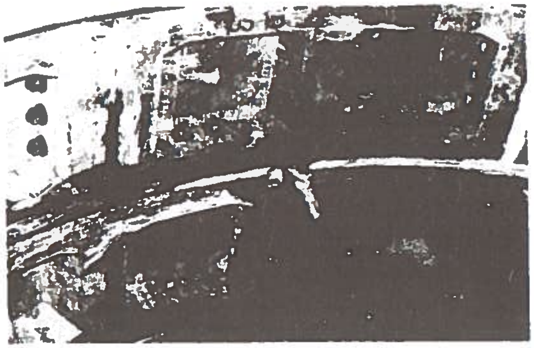
主材料 **MAIN**	一般目地コーキング、タールエポキシ樹脂、 **GENERAL CALKING TAR-EPOXY PLASTICS**	**ショーレジン TR−119** **SHORESIN**
	伸縮の大きいコーキング、タールエポキシ樹脂、 **FLEXIBLE CALKING TAR-EPOXY PLASTICS**	**ショーレジン TR−119L−1**
	水中での施工および特に接着力を必要とする場合 グレーエポキシ樹脂 **GRAY EPOXY PLASTICS** **MATERIAL APPLICATION UNDER WATER**	**ショーレジンSTE−500**
関連材料 **AUXILIARY MATERIAL**	伸縮の激しい場所、タールウレタン樹脂、 **FLEXIBLE PART TARURETAN PLASTICS**	**ショーレタンU−500** **SHORETAN**
	グレーウレタン樹脂、	**ショーレタンU−505**
	漏水の止水、瞬結セメント、 **INSTANTANEOUS WATER STOP** **QUICK-HARDNING CEMENT**	**レジンクラッカー** **RESINCRACKER**

用　途 USE

- 地下鉄シールドのセグメント目地
- 配管囲りの空隙充填
- プールや槽の水漏れ防止
- コンクリートのクラック、ジャンカの充填
- 金属接合部のシール
- 高速道路、一般道路の目地充填

特　長 MERITS

- 不定形、粘稠流動体で任意目地充填可能
- 硬化後の体積変化なし
- 水中湿潤でも接着性抜群
- 耐吸水性、耐透水性にすぐれシール効果大
- 耐薬品性、耐候性にすぐれています。



大阪市交通局　地下鉄６号線
セグメントコーキング工事
ショーレジンSTE－500

施工法

１．地下鉄シールドセグメントコーキング施工
CALKING APPLICATION ON TUNNEL SEGMENTS

シールドセグメントでは、継手組立時の誤差や、設計施工時のシール材、裏込注入だけでは必らず漏水がありますので、シール材、裏込注入材で止水しコーキングで防水する二段構えで行います。

A. 漏水の無い場合
CASE OF NO LEAKAGE

コーキングはいずれの場合も堀進後切羽から30〜40R後のジャッキ圧の影響を受けない部分からコーキングを開始します。

CALKING IS PERFORMED AT THE PLACE 30〜40 RINGS BEHIND THE SHIELD.

下地処理 CLEANING OF CALKING GROOVE

コーキング溝の汚れ(泥、レイタンス、油等)を除去しエヤーコンプレッサーにて乾燥するまで清掃させる。

CLEANED AND DRY BY AIR JET.

材料の混合 MIXING

所定の配合比でミキサーにて充分に混合する。

PREDETERMINED MIX IS MADE WITH MIXERS

材料の充填 FILLING MATERIAL

コーキング溝の頂部からインバート部へと水の流れにしたがってコーキングガン等で充填を行う。その後、パテナイフ、ヘラにて表面の仕上げを行うと共に材料の密着性を増す為に材料との境界の浮きを無くする。

CALKING IS STARTED FROM THE CROWN OF TUNNEL DOWNWARD. FILLING BY MEANS OF CALKING GUN AND LATER SURFACE SMOOTHED.

B. 漏水の有る場合
CASE OF LEAKAGE

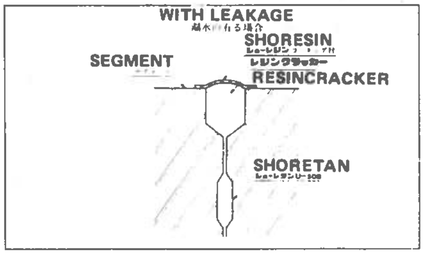
下地処理
SURFACE TREATMENT
下地処理後漏水箇所の確認をする。
CONFIRM LEAKING POSITION

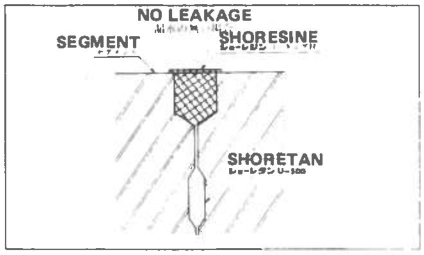
漏水部の処理
TREATMENT OF LEAKAGE
漏水は**レジンクラッカー**等でホース取りを行ない他
LEAKING WATER IS TAKEN OUT BY HOSING
の箇所に回らない様に処理をする。
WITH RESINCRACKER

材料の充填
FILLING MATERIAL
Aと同様に充分に2液を混合後コーキング溝の漏水の
SAME AS IN A.
無い部分に材料を充填する。

漏水部の止水
SEALING OF LEAKING POINT
止水はコーキング材料の硬化後(3日以降)に**レジンク**
AFTER (3 DAYS) CALKING IS HARDENED TEMPORARY
ラッカーで仮止水を行ない、その上を**ショーレジン**で防
SEALING IS MADE WITH RESINCRACKER AND SHORESIN
水シールする。
IS APPLIED OVER IT

この様な工法の併用でシールドにおける理想的な防水効果を得ることができます。



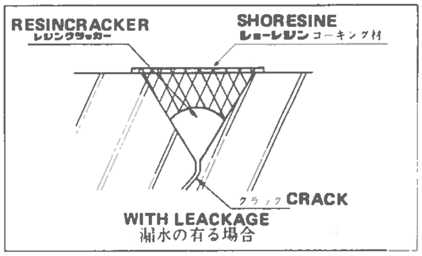


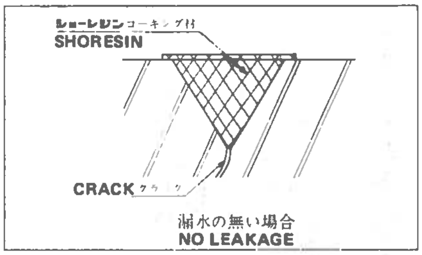
2. クラック補修コーキング施工
CALKING OF CRACKS

1. V斫り
V-CHIZELING
クラックにそって弱い箇所もV斫りを行う。
V-CHIZELING IS MADE ALONG CRACKS

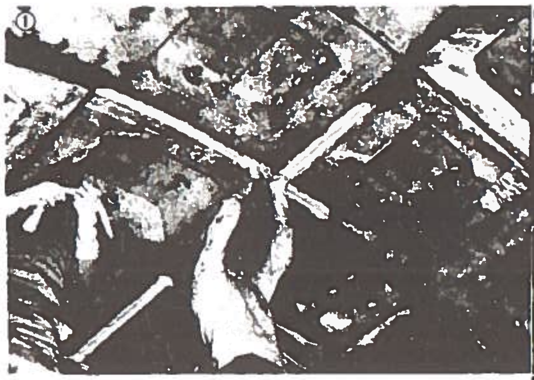
2. 下地処理
SURFACE CLEANING
施工面の汚れ(泥、レイタンス、油等)除去。

3. コーキング
CALKING
漏水の有る場合は**レジンクラッカー**で止水し、他の箇所に水が回らないことを確認する。その後**ショーレジン**コーキング材を金ベラ、コーキングガン等で充填し押え仕上げをする。

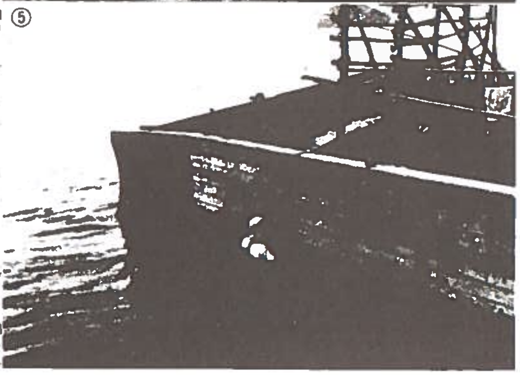




現場名



① ② 地下鉄3号線第5工区
セグメント目地コーキング
③ 屋上目地コーキング
会下山配水池
④ ⑤ 岸壁クラック補修工事
ショーレジン TR－119



設計所要量 DESIGN REQUIRED AMOUNT 'GR.' PER METER

目地の大きさ mm WIDTH OF JT. SEAM MM	SHORESIN ショーレジン TR－119	SHORESIN ショーレジン TR－119L－1	SHORESIN ショーレジン STE－500
縦/横 10/10	158	158	155
10/20	316	316	310
20/20	632	632	620
20/50	1,580	1,580	1,550

M当りの所要量g（ロスは含みません）
(NO LOSS INCLUDED)

性　状

配合比（重量）MIXING RATIO	主剤 PRIME COMPONENT	硬化剤 HARDNING AGENT
ショーレジン TR－119	9	1
SHORESIN ショーレジン TR－119L－1	9	1
ショーレジン STE－500	1	1

項目 ＼ 品名		ショーレジン TR－119	ショーレジン TR－119L－1	ショーレジン STE－500
外観 APEARANCE	主剤 PRIM. COMP.	黒色ペースト BLACK PASTE	黒色ペースト	黒色パテ BLACK PUTTY
	硬化剤 HARDNING	黒色液体 BLACK LIQUID	黒色液体	白色パテ WHITE PUTTY
比重（固体）SPEC. GRAVITY		1.58	1.58	1.55
可使時間 WORKABLE TIME	25℃	50分 MIN	60分	30分
指触硬化時間 HARDNING TIME	25℃	8時間 HRS	10時間	3時間

性　能 PROPERTIES

試験項目 TYPE OF TEST		ショーレジン TR－119	ショーレジン TR－119L－1	ショーレジン STE－500
引張強度 TENSILE STRENGTH	kg/cm²	70	20	100
伸び率 ELONGATION RATIO	%	10～20	30～40	5～10
圧縮強度 COMPR. STRENGTH	kg/cm²	400	400	400
曲げ接着強度 BENDING BOND STRENGTH kg/cm	水中 AIR CURED	30	20	35
	空中 WATER CURED	*60	40	*60

＊印はモルタル破壊

硬化条件23±1℃7日間養生、数値はいずれも3個平均値　試験方法はＪＩＳＫ－6911熱硬化性プラスチックス試験、ＪＩＳＲ－5201モルタル作成方法に準じて行った。

AT TEMP 23± 1°C. CURED 7 DAYS, AVERAGE OF 3 SPECIMENS. TESTS CONFORMS TO J1S STANDARDS

ショーレジンSTE－500の海水濁水中接着テスト
BONDING TEST OF STE-600 UNDER DIRTY OR SEA WATER

試料作成
PREPARATION OF SPECIMEN

試験方法はＪＩＳＲ－5201（モルタル曲げ強度）に準じ40×40×80mmのモルタル供試体を材令5週間に達したものを水中に一日間養生し、水中にて接着剤を片面塗布し2個を接着する。又水中で目地10mmに充塡接着した。

試験方法 TEST METHOD

試験機：TEST. MACHINE	島津オートグラフＩＳ－500
荷重速度 LOADING SPEED	50mm/min
試験温度 TEST TEMP.	20～25℃
水中温度 WATER TEMP.	18℃

試験結果 TEST RESULTS

試験項目 ＼ 養生期間 CURING TIME	圧着曲げ強度 kg/cm² BEND. BOND STRENGTH		10mm充塡強度 kg/cm² 10MM FILL STRENGTH	
	濁水 DIRTY WATER	海水 SEA WATER	濁　水	海　水
6時間 HRS	29.9	15.6	24.8	21.8
12時間	36.7	17.6	34.2	29.4
18時間	52.1	19.0	42.6	34.2
1日 DAY	50.1	23.3	47.5	47.8
2日	49.8	28.7	46.2	43.6
3日	50.5	41.5	48.4	46.5
4日	48.6	48.2	47.2	47.2
5日	49.2	48.6	49.2	45.6
6日	51.8	49.4	48.5	47.2
7日	56.8	50.2	49.3	46.8

PACKAGE UNIT
包装単位：主剤、硬化剤付セット

ショーレジン TR－119	5kg set
ショーレジン TR－119L－1	5kg set
ショーレジン STE－500	20kg set

Appendix C

REPORT OF INVENTIONS

A diligent review of the work performed under this contract has revealed no new innovations, discovery, improvement, or invention.