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ADVANCED SOIL AND SOFT ROCK TUNNELING TECHNOLOGY IN JAPAN

By

G. Wayne Clough
Professor of Civil Engineering

Prepared For
U. S. Department of Transportation
Urban Mass Transportation Administration
Office of Technology Development and Deployment
Office of Rail and Construction Technology
Washington, D.C. 20590

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PREFACE

During the period September 11 to 26 of 1979, Professor G. Wayne Clough undertook a trip to Japan to study the advanced shield tunneling processes being used and developed there. This report summarizes the information obtained during the visit. Funding for the trip was provided by Research Contract #DOT-TSC-1726 with the United States Department of Transportation and Stanford University, for which Professor Clough is the principal investigator.

Organization and planning of the site inspections and personal contacts, were made for Professor Clough by a number of very helpful individuals and organizations. Special thanks are due Mr. Yoshihisa Ohbayashi of Ohbayashi-Gumi Ltd., Dr. Yashio Ozawa of Nikken Sekkei, Ltd., Mr. I. Kitamura, Secretary General of the Japan Tunnelling Association, and Mr. Keiicha Fujita of Hazama-Gumi, Ltd. The hospitality and assistance afforded by these gentlemen was outstanding and contributed greatly to a successful visit. Many other people at each site offered assistance and openly and frankly discussed their projects. Names of these individuals and their organizations are given in Appendix A. To all of these engineers and their companies the author offers his thanks.

The conclusions drawn in this report are the responsibility solely of the author and are not intended to reflect those of the U.S. Government.

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INTRODUCTION

In the United States, it is becoming more common that underground transport facilities are constructed in soft ground by tunneling in lieu of cut and cover methods. This is particularly true in sensitive neighborhoods or highly developed business communities. It is important that in such circumstances undue surface settlements are not caused by the tunneling. Unfortunately, conventional procedures for controlling settlements when tunneling in soft grounds are becoming increasingly expensive and, in some cases, environmentally unacceptable. Thus, a need exists for new methods which can be used for soft ground tunneling in urban areas.

This situation, only recently developing in the United States, has been faced for some time in Japan and Europe. As a result, considerable research and development has been done overseas. In the past five years, the most extensive work has been forthcoming from Japan. This is not surprizing since the Japanese undertake substantially more soft ground tunneling each year than any other country. Murayama (17) reports that in 1976 and 1977 some 345 km (221 miles) of shield tunnelling work was completed in Japan, a figure five times larger than that for the United States (15).

The Japanese have specialized in the development of tunnelling procedures for difficult soft ground conditions, and in working in weak and broken rock. It is the purpose of this report to describe important aspects of this technology since it most likely will find significant application in the United States in the near future. In fact, only in the past year, two tunnel projects have been undertaken in San Francisco by the Japanese firm Ohbayashi Gumi, Ltd,, using advanced tunneling techniques.

The information presented in this report was obtained from observations made on a three week trip to Japan, internal documents provided to the author by Japanese firms, and published literature. The report does not represent a comprehensive state-of-the-art review, but covers the predominate spectrum of soft ground tunneling technology being used as of 1979-1980. A limited amount of information is also provided on weak rock tunneling based on two site visits to projects of this type.

PART I -- TUNNELING IN SOFT GROUND; ADVANCED SHIELD TECHNOLOGY

The problems associated with soft ground are typically two-fold: (1) The material being tunneled is weak; and (2) the ground water table is often above the crown of the tunnel. To deal with the first problem, the shield technique was developed in the 1800's by Brunel; a protective structural shield (usually circular) is used at the face of the tunnel to allow excavation and linear erection to take place. To handle water and water laden soil, various procedures have been used in the past, including breast boards to provide face support, dewatering to remove water from previous soil, and compressed air throughout the tunnel to prevent water flows into the tunnel and support the face. These methods have disadvantages which have been widely discussed, and during the last 25 years, tunnel machine designers have worked at developing advanced shields to eliminate the need for them.

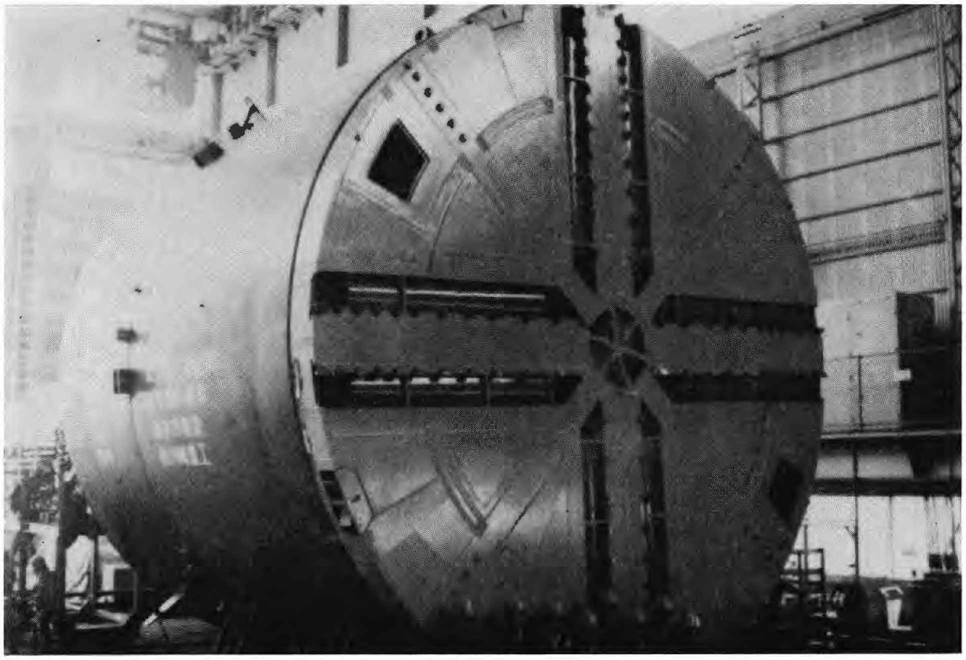
The basic idea of most of the early attempts was to use a "blind" shield with a rotating excavation wheel at the face of the shield to remove soil. The term "blind" is used to reflect the fact that the rotating excavator wheel is essentially solid, with only narrow slits open for the soil to pass into the shield. Thus, the miners cannot see the soil in the face of the tunnel and are working "blind". Examples of shields of this type were used in the 1960's reasonably successfully in Bay Mud soils in constructing the tunnels for the San Francisco Bay Area Rapid Transit System (22). However, compressed air must be used in the event sands are encountered below the water table to prevent the entry of water or soil through the excavator wheel slits. For best operation they should only be used in clays.

In order to overcome the problem of dealing with more diverse soil conditions, considerations turned to the idea of adding a bulkhead just behind the excavator wheel of the blind shield and pressurizing the space between the bulkhead and the wheel with air. The air pressure presumably would balance any free water pressure, and stabilize the soil at the slit openings which would possibly tend to flow into the shield. Also, because the compressed air would be confined between the bulkhead and the face of the tunnel, the tunnel workers would not have to be subjected to the air pressure. This system has been used in several cases but has been plagued by a low productivity (19). Subsequently, designers turned their attention to the possibility that the space between the bulkhead and the excavator wheel could be filled with a slurry kept under pressure. This led to the development at the slurry shield in England, Germany and Japan in the early 1970's (2, 7, 13, 24), and its successful application to many projects. With their large volume of soft ground tunneling, the Japanese implemented the use of the slurry shield to a greater extent than others, and Japanese industry pursued further developments at a rapid pace. In the mid to late 1970's three new shield techniques were introduced and quickly adopted into practice. During the period 1976-1977, some 65 advanced shield machines were used in Japan (17), and based on the observations during the author's trip, this usage appears to have increased. The following paragraphs are devoted to describing the characteristics and operational principles of the new shields. Subsequently, special issues such as starting and terminating the advanced shield work,liner supports, and performance data are reviewed. Also, specific comments on each soft ground tunnel project visited are presented.

The Slurry Shield

The basic principle of the slurry shield is that the soil at the face of the tunnel will be kept stable, and any water flow blocked, by means of a soil-water slurry kept under a pressure. Photographs of the front ends of two slurry shields designed by the Tekken Construction Company are shown in Figure 1. The upper photograph is of a large diameter (10 m) slurry shield designed to operate in sandy and silty soil. The cutter head or excavator wheel has eight rectangular openings with cutting teeth mounted to either side. As shown, the openings are blocked by gates; these gates are usually open during excavation and only closed if the shield stops. The two almost square openings near the outer edge of the head are manholes, and these are normally closed except in the event of a special problem. This particular shield has provisions for eight manholes. Close observation of the rim of the lower left side of the rim of the cutter head reveals two pointed teeth slightly protruding from small openings. These teeth can be extended in the event an overcut is desired, an option only desirable if a steering problem develops.

The slurry shield shown in the lower photograph of Figure 1 has a unique cutter face in that there are normal rectangular openings with cutter teeth on only one axis. Six tri-disk cutters are located along the other axis. This arrangement was especially designed to work in a soil with large gravels and cobbles; the tri-disk cutters were expected to break the cobbles and gravels down to a size which could be brought into the shield through the rectangular openings. The project where this shield is being used is discussed in a later section of this report.



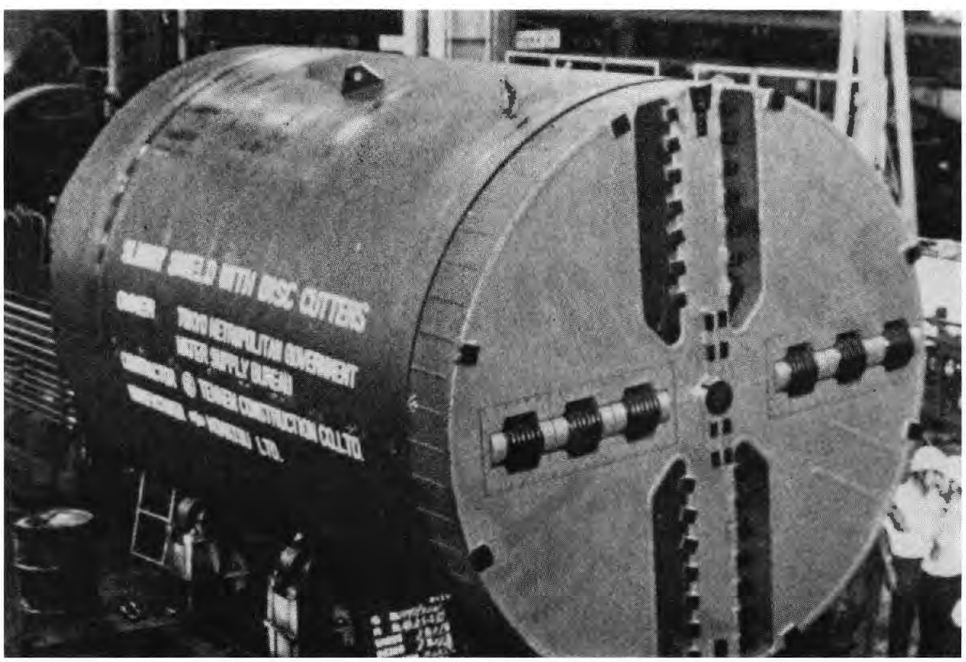


Figure 1. TEKKEN SLURRY SHIELDS: UPPER PHOTOGRAPH, 10m DIAMETER SHIELD; LOWER PHOTOGRAPH, 3.6m DIAMETER SHIELD WITH TRI-DISK CUTTERS ON ONE AXIS FOR BREAKING COBBLES.

Basic Shield Equipment

Figure 2 shows cross-sections of two basic types of slurry shields. The difference between the two lies in how the cutter head is rotated; one is driven by a central shaft, while the other uses a number of motors located around the periphery of a drum which rotates and which is attached directly to the cutter head. The drum type is typically used for larger diameter machines where greater power is required.

The space between the cutter head and the bulkhead is occupied during operation by the slurry and the soil cuttings. Clean slurry is brought into the bulkhead area via a pipe passing from the surface down through the tunnel. As cuttings come through the cutter head openings, they mix with the slurry and the contaminated slurry is pumped out through an outlet pipe located in the lower portion of the bulkhead. In order to keep the cuttings in the slurry, the slurry density is kept above a minimum level and it is stirred by the agitator shown in Figure 2 just inside the bulkhead. In addition to occupying the bulkhead area, the slurry, under pressure, is in contact with the tunnel face via the open slots in the cutter head.

In the central area of the shield, jacks are located which are used to propel the shield by pushing against the in-place liner element. The liner segments are assembled with the help of a power erector located in the tail of the shield. The operator of the shield works in the area between the bulkhead and the erector.

At the rear of the shield are located the small, but important tail seals (see Fig. 2). These seals are flexible and are situated between the tail of the shield and the liner segments. They are very important to the proper operation of the shield process since they prevent flow of ground water, slurry or grout into the work area. Early versions were made

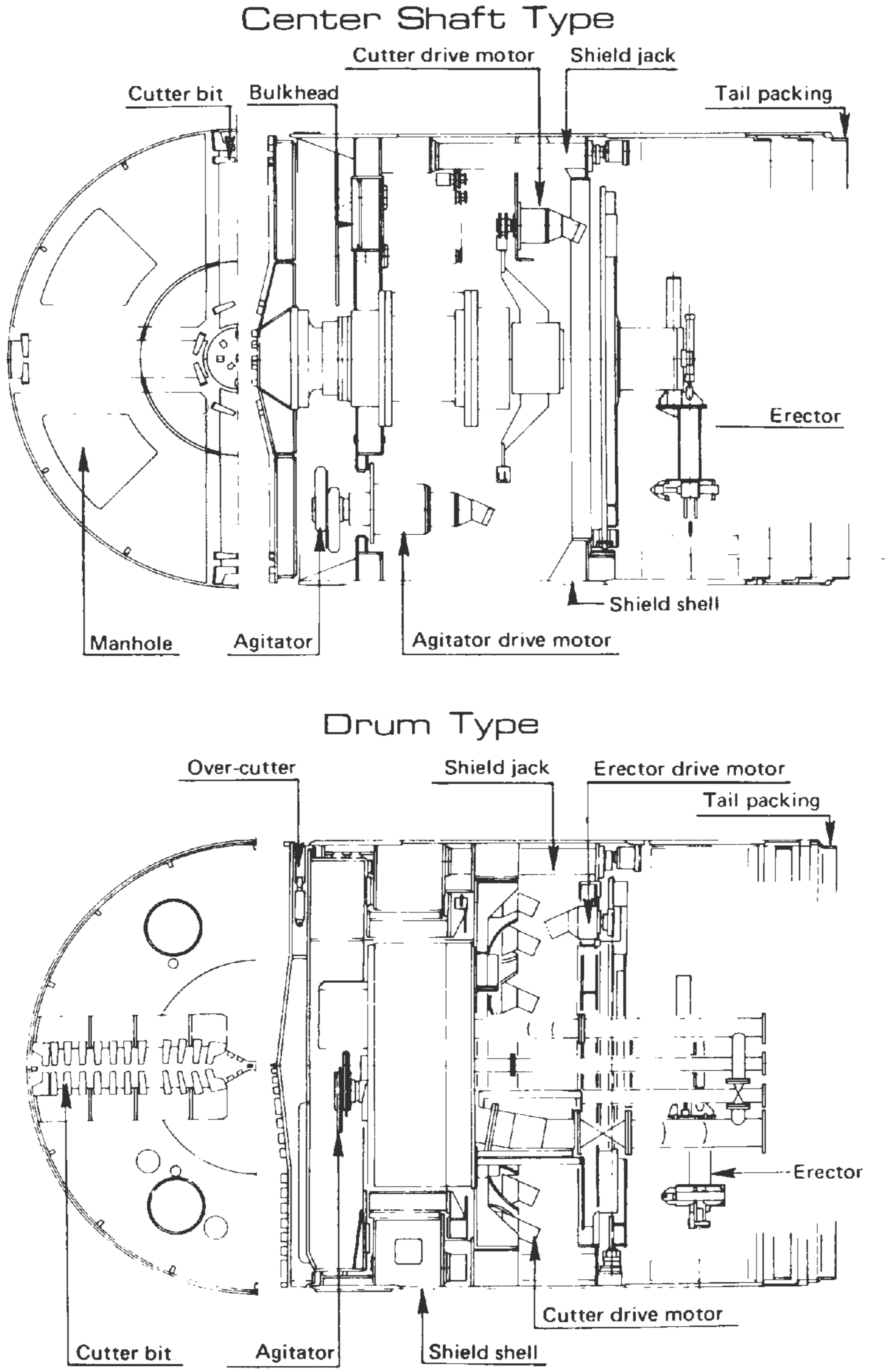


Figure 2. CROSS-SECTIONS OF MITSUBISHI CENTRAL AND PERIPHERAL DRIVE SLURRY SHIELDS.

of rubber, but these were not rugged enough and new designs are made of laminated rubber and steel sheets or fine wire mesh (see the photograph in Figure 3). Replacement of the seals during tunneling is difficult, and they are usually selected so as to last for the entire project. Ohta, et al. (20) report a case where provisions were made to freeze the soil outside the shield to allow for seal replacement, but this is not a common practice.

Figure 4 depicts a larger view of the slurry tunneling process, showing the shield, the slurry lines, the trailing support system and the surface facilities for processing the contaminated slurry. Because the muck is handled entirely through the outlet slurry line there is no need for conventional muck transport facilities. If the soil is gravelly, a rock crushing unit may be inserted into the slurry line to break down large particles to a size suitable for slurry transport; alternatively, a trommel can be used to separate the large particles out of the slurry.

A number of measurements are made on the slurry as it is transported into and out of the shield. These are essential in order to insure that the soil volume that is excavated equals the amount of the shield advance. It is necessary to measure the flow rate (by electro-magnetic flowmeter) and the density (by nuclear meter or differential density meter) in order to calculate the excavated volume. The measurements are recorded automatically at the ground surface and processed in a mini-computer, so that a frequent check can be made as to the operation of the shield.

The Slurry

Characteristics desired of a slurry for a slurry shield operation are that it should be:

Figure 3. FLEXIBLE STEEL AND WIRE BRUSH TAIL SEALS.

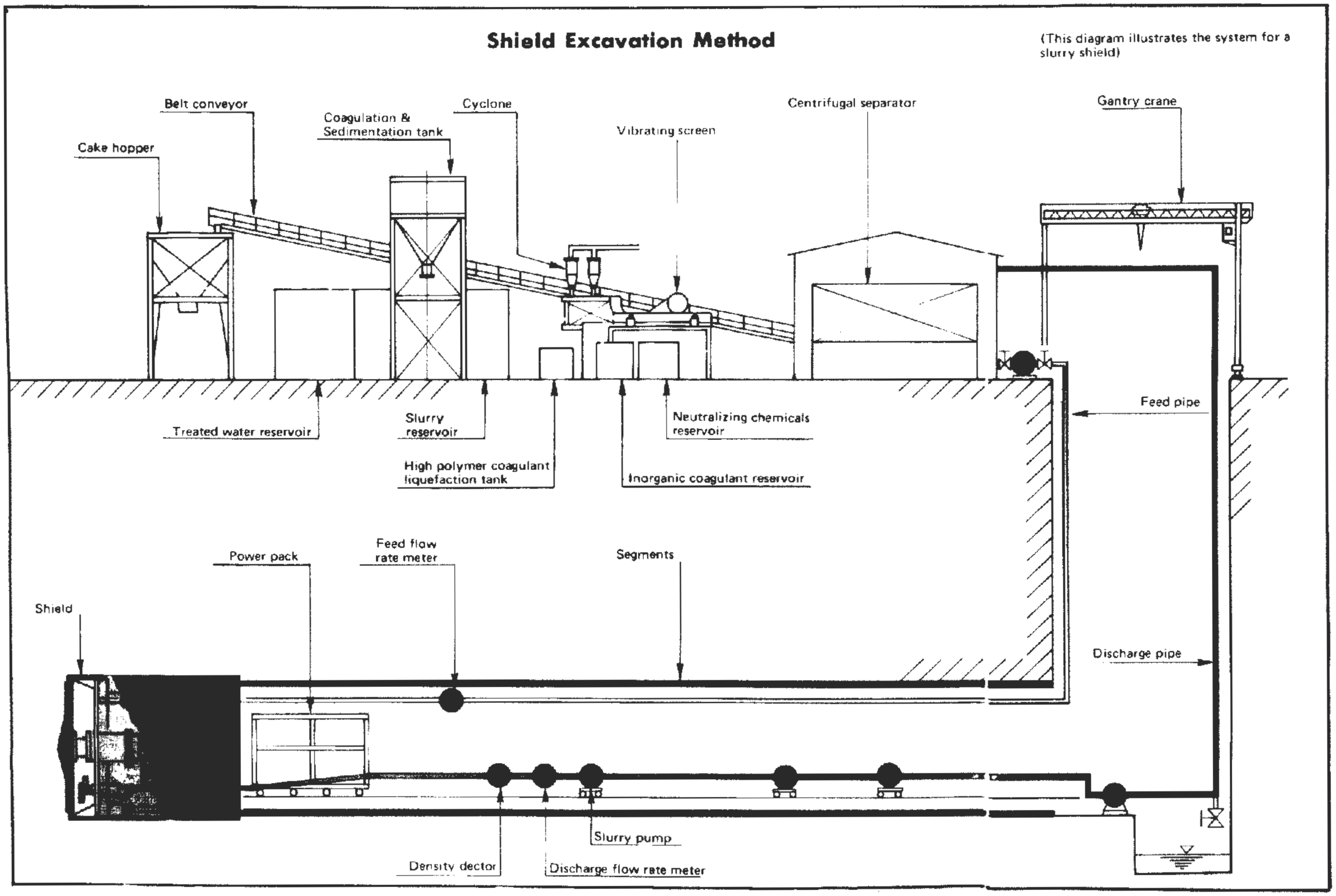


Figure 4. OPERATIONS OVERVIEW AND TREATMENT PROCESS FOR MITSUBISHI SLURRY SHIELD.

1. Stable
2. Able to hold solids in suspension
3. Impervious
4. Forms a "cake" quickly when put under pressure next to a pervious material
5. Mixes easily with water
6. Can be treated and separated from the muck.

Initially, slurries for this work were formed using bentonite clay and water. However, bentonite is not always readily available, and it is very plastic, leading to disposal problems. To resolve this difficulty, Japanese engineers studied techniques which would allow proper slurries to be formed using a wide variety of clays and silts. Miki, et al.(16) reported on successful alternatives created by mixtures of ordinary clays, water and an additive, Carboxyl Methyl Cellulose. Today, it is common that the slurry shield is operated using slurries formed with silts and clays obtained in the tunneling process. This represents an important step towards increasing the universality of the slurry shield.

The slurry is kept under a pressure inside the shield bulkhead slightly above that needed to maintain the stability of the soil and to prevent a flow of ground water. In this way there is always a tendency for the slurry to flow outward into the soil. Under such a pressure gradient, the slurry penetrates lightly into the soil and forms a thin "cake" on the soil face made up of fine particles from the slurry. This cake, which is constantly being removed by the cutters and then reformed, contributes to the stability of the face.

Methods for calculation of the proper slurry pressure are based on theory and experience. The water pressure to be balanced is obtained by knowing the water table and tunnel levels. The soil pressure is calculated by earth load analysis techniques proposed by Terzaghi (26) and Murayama (18), and the larger of the two is used. The combined water and soil pressures must be balanced for face stability if previous soils are being tunneled. In more impervious soils, consideration is given to the ability of the soil itself to maintain stability at the face in choosing the final slurry pressure. If the impervious soil is considered to have enough strength to hold the face without extra support, then the slurry pressure is set to counter only the water pressure. The amount of extra pressure above that required for stability and water control and needed to produce the slurry cake effect is determined by experience. This usually amounts to only 10 to 20 kN/m^2 (1 to 3 psi).

Slurry Treatment

The contaminated slurry returning from the shield must be treated to remove the soil cuttings and then be reprocessed for recirculation to the tunnel face. This operation has a significant impact on the rate of tunneling progress. Useful descriptions of the process of slurry treatment are provided by Takahasi and Yamazaki (24) and Kurosawa (12).

For soils with a range of grain sizes, there are a series of stages in the muck removal process as depicted in Figure 4. Typically, the coarsest particles are eliminated by passing the slurry through a centrifugal separator and vibrating screen. Then the slurry is sent into one or more cyclones to separate out the finer sand size particles. Finally, it is treated with flocculating agents, the soil flocs are allowed to settle out, and they are passed through a filter press to reduce their water content. The result of the pressing operation is a sludge material with a water content of about 30 to 40%. The flocculating agents are usually mixtures of organic and nonorganic substances which are selected on the basis of laboratory experiments. Representative organic flocculants are poly acrylamine or poly ethyleneamine. Inorganic flocculants are alum, poly aluminum chloride or calcium chloride.

The entire multistaged treatment process described in Figure 4 may not be needed in all cases. If the soil being tunneled is very fine grained, the vibrating screen operation may be left out. Alternatively, if the soil is predominately coarse grained, the filter press stage will not be needed. Because space around an urban tunneling project is often at a premium, considerable effort has gone into reducing the size of a slurry treatment plant. Where necessary, most of the units can be stacked vertically.

Control and Automation of the Tunneling Process

In order for the slurry shield concept to work, the slurry support at the face must be continuous. This means that the slurry supply system, the pumps and pressures they supply, the shield advance, the contaminated slurry removal, and the slurry treatment must proceed as an integrated, smooth operation. Such a complex situation can only be monitored by means of an automatic control system. Parameters which are tracked during tunneling include:

Incoming slurry density	Cutter head torque
Incoming slurry flowrate	Cutter head speed
Pressure at bulkhead	Outgoing slurry density
Advancing jack speed	Outgoing slurry flowrate
Advancing jack pressure	Pump speeds

Kurosawa (12) has provided a detailed description of how many of the key parameters are used to automatically adjust the shield operations. Referring to Figure 5:

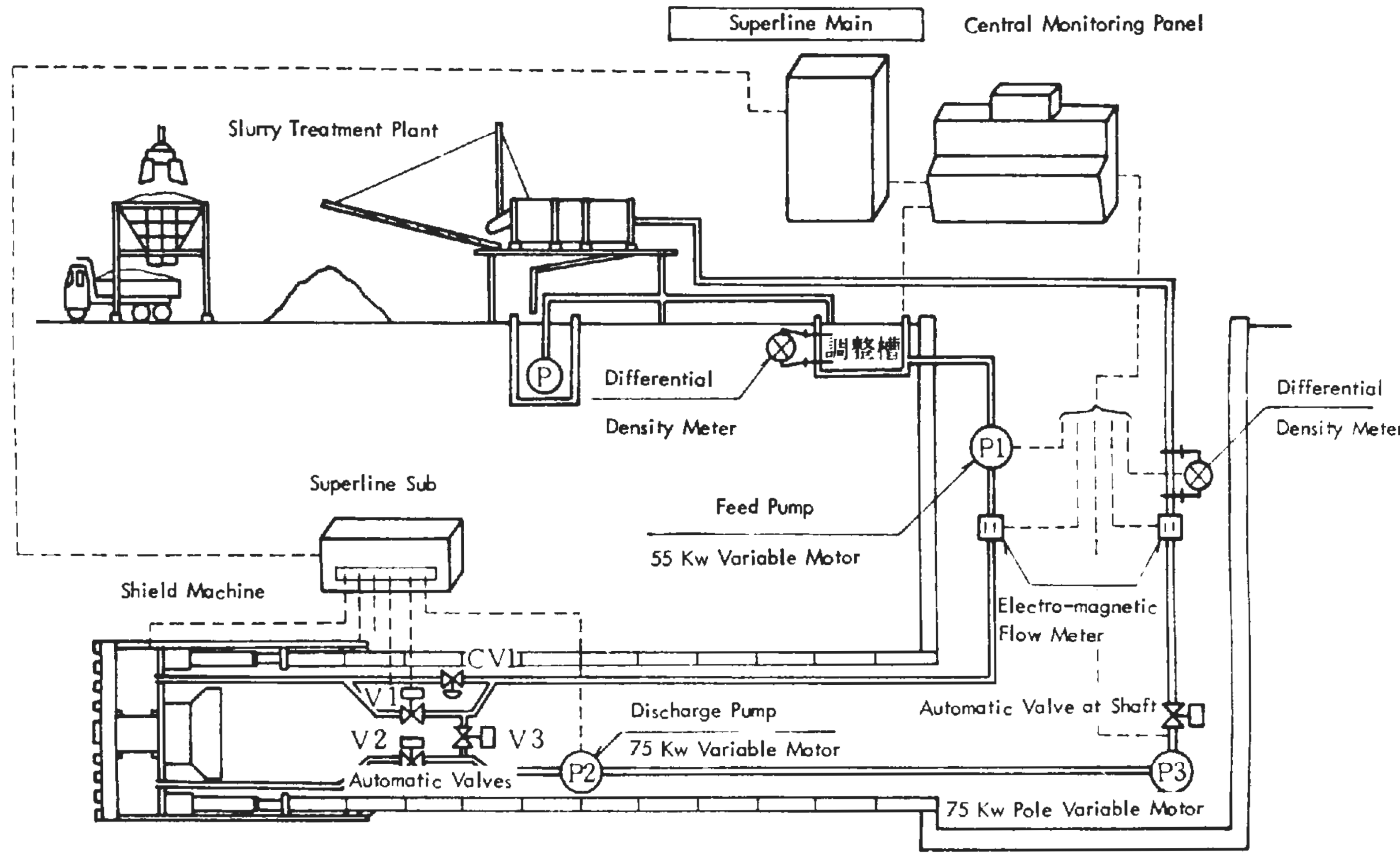


Figure 5. KEY POINTS IN AUTOMATIC CONTROL SYSTEM FOR SLURRY SHIELD (AFTER KUROSAWA, 12).

"The system maintains hydrostatic pressure of the slurry at the heading using the P_1 pump. The hydrostatic pressure at the heading is detected by a pressure sensor installed inside the slurry chamber, and is transmitted to the central control where the pressure regulator automatically changes the revolution of the P_1 pump so as to maintain the pressure to the pre-selected pressure level for stability at the heading. If shield advancement is suspended, the pressure is maintained by controlling the opening of valve V_1.

The flowrate of slurry in the discharge line is detected by an electro-magnetic flowmeter installed in the discharge pipe in the access shaft, and is transmitted to the central control unit where the flowrate regulator automatically changes the revolution of pump P_2 so as to change the actual flow rate to the pre-selected flowrate. This prevents sedimentation in the discharge line.

The excavated volume is estimated from soil properties and by measuring flowrate and specific gravity. This estimated volume is checked with the theoretical volume of the soil excavated to insure stability at the heading."

The control and monitoring systems are housed in a small building at the ground surface near the entrance shaft. A photograph of these facilities is given in the upper part of Figure 6. At a glance a technician can see indicator dials showing all the important parameters. He can communicate any important observations directly to the shield operator via a phone system. A minicomputer is used by some firms to record advance

Figure 6. CONTROL PANELS FOR SLURRY SHIELD: UPPER PHOTOGRAPH, ABOVE GROUND CENTRAL FACILITY: LOWER PHOTOGRAPH, SHIELD OPERATORS COCKPIT.

rates, excavated volumes, etc., in order to establish data which can be used to help bid and design future work. The shield operator also has a visual control panel inside the slurry shield which displays essentially the same parameters as the above ground control facility (see bottom photograph in Fig. 6). This allows for an additional source of checking of shield operations and enhances communication when changes have to be made.

Grouting of the Liner

The importance of grouting of the tail void created behind the liner when the shield advances is readily appreciated for conventional shield operation. This situation is even more critical for a slurry shield, especially if ground movements are of concern. The problem is increased because the tail void of a slurry shield is likely to be larger than that of a conventional shield due to the presence of the tail seals in the slurry shield. A photograph of typical tail seals is shown in Figure 3. When in their deflected position behind a liner segment, the seals occupy a space of about 50 mm (2 in) which exists continously around the liner. This gap, plus the thickness of the skin of the shield, forms a significant tail void. Because the slurry at the face of the tunnel apparently does not generally migrate around the shield to help support the tail void, grouting must be done as quickly as possible after shield advance.

Grouting systems are closely coordinated with shield movements and the grouts used are quick-set clay-sand-cement mixes. Gel times for the grouts are on the order of a minute or less, and the components of the grout are only mixed in the tunnel just prior to injection through the liner. Ideally, the grout gains strength rapidly, since the shield advances by jacking against in-place liner segments which should be reasonably restrained by the grout, or otherwise the rings can be misaligned. Where data have been reported, segment alignments vary some ± 30 mm from theoretical values (12, 16). A limited number of tapered segments are usually prepared which can be installed if the misalignment problem is serious (12).

In addition to helping support the liner, the rapid gelling of the grout also helps prevent migration of the grout around the shield and into the face area. If the grout does mix into the slurry, it upsets the delicate chemistry of the slurry, since the grout is usually highly basic. Flocculation of the slurry can result, destroying or damaging its ability to carry solids and impermeabilize the soil at the face of the tunnel.

Usage of the Slurry Shield

The first slurry shield projects were undertaken by the firm Tekken Construction Co., Ltd. in the early 1970's and these were primarily small diameter tunnels (24). Since that time, the use of the slurry shield has greatly increased. In 1976-1977 some 53 slurry shield projects were underway (10, 17) and by 1978, the Tekken Construction Company alone had had 59 slurry shield jobs (25).

One of the most impressive aspects of the expanded use of the slurry shield is the diversity of conditions to which it is being applied. Projects have been described where mixed alluvial soil (5, 20), gravelly sands (25), and wooden obstructions (12) have been encountered. The slurry shield has worked under 41 m (135 ft.) of water head (12), and has passed beneath urban structures (9). Recently, a slurry shield was built with a diameter of 10 m (33 ft) to construct an extension to the Tokyo subway system (see the upper photograph in Fig. 1).

Probably the greatest restraint on the application of the slurry shield has been the development of alternative advanced shields which are cheaper to build and operate. As one engineer put it during the writer's visit, the slurry shield is the "Cadillac" of shields. Under certain critical soil and groundwater conditions it may be necessary, but not for all cases. The future of the slurry shield apparently remains open at this time, and depends on relative advances between the different technologies.

The Earth Pressure Balance Shield

The earth pressure balance (EPB) shield was introduced in Japan in about 1976 and its popularity has grown substantially (9, 17). The basic principle behind this shield is that the face of the tunnel is stabilized by keeping excavated soil in contact with the face at all times and under enough pressure to prevent soil movement (11, 23). A photograph of the front end of an earth balance shield is shown in Figure 7; its appearance is no different from that of a slurry shield. The cutter head is designed to rotate and cut the soil by means of the cutter teeth on either side of the open rectangular slots. The muck falls into the slots and inside the shield machine. No slurry or additives are mixed with the excavated soil.

The earth balance shield in its simplest form is primarily applicable to soils where there is no groundwater problem, or, if there is a high groundwater table, to soils with a relatively low permeability. In a subsequent section, modifications will be discussed which have been developed to extend the range of applicability of this shield.

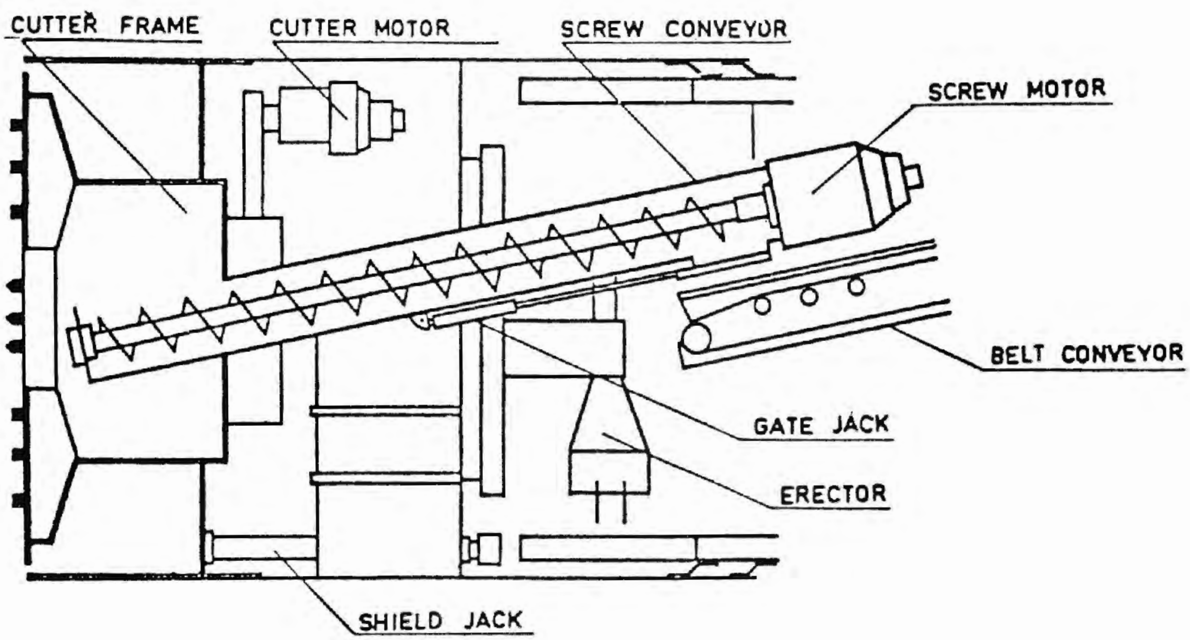


Figure 7. FRONT VIEW AND CROSS-SECTION OF EARTH PRESSURE BALANCE SHIELD.

Basic Shield Equipment

A section drawn through the axis of an EPB shield is shown in the lower portion of Figure 7. Unique aspects of the shield equipment are the spoils chamber located between the cutter head and the bulkhead, and the screw conveyor used to remove the muck from the spoils chamber and transfer it to a conveyor at the rear of the shield. In this drawing, the cutter head is rotated by a drum where the motors are located around the periphery of the shield. However, as with a slurry shield, either a drum or center shaft drive can be used. Just inside the tail of the shield, a power erector is located to assist in putting the liner segments together. As with the slurry shield, tail seals are needed between the tail of the shield and the liner segments. The seals prevent ground water or grout flow into the work area. A close-up view of the business end of a screw auger is given in the left photograph in Figure 8. The edges of the auger are built-up to resist the abrasive effects of the soil. The right photograph in Figure 8 is of the rear of the EPB; the screw auger, propulsion jacks and liner erector are clearly visible. The key to the operation of the EPB shield is the screw auger and the rate at which it removes soil from the bulkhead area.

In principle, the bulkhead area or spoils chamber should be filled with soil at all times so that the soil from the face is not able to flow into the shield. The speed of rotation of the screw auger must be adjusted to the speed of shield advance and cutter head rotation so that soil is removed at the same rate as new spoil is brought into the shield. This process is coordinated by an automatic control system which will be discussed later. The shield is advanced by means of the jacks which react against the in-place liner. The advance is carried out as a steady forward movement to keep a constant pressure on the soil face. Theoretically, this pressure balances the external earth pressure, thus the name "earth pressure balance shield."

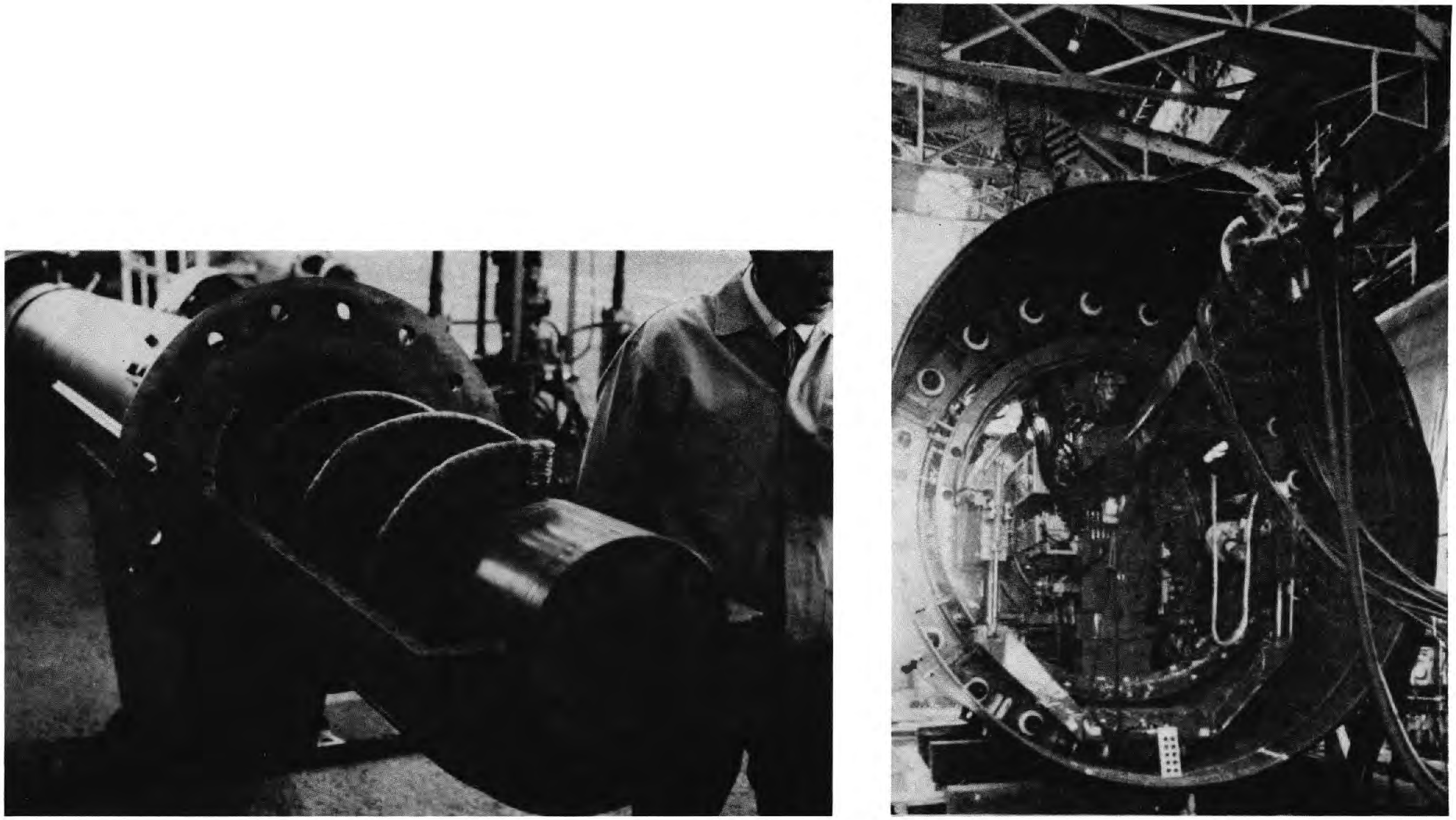


Figure 8. DETAILS OF EARTH PRESSURE BALANCE SHIELD: LEFT PHOTOGRAPH, CLOSE-UP OF FRONT OF SCREW AUGER: RIGHT PHOTOGRAPH, REAR VIEW OF SHIELD.

At the rear of the screw auger is an adjustable opening through which the soil must pass downwards to the conveyor belt muck removal system. This opening and how it is controlled is important to the condition of the muck, and it can be used to shut down the soil movement if a fluidized soil mass should attempt to flow through. There are at least three different types of controls used for adjusting the opening of the screw conveyor outlet. The rotary hopper is marketed by Mitsubishi Heavy Industries. This device receives the soil from the auger in a small hopper or bucket; at a specified interval the bucket is rotated until it empties its contents onto the conveyor. After emptying it rotates to its original position and fills with soil again and the process is repeated. An alternative control involves simply opening and closing a sliding gate. A third commonly used scheme involves using a cone valve which works on the same principle as a hydraulic flow needle valve. As the cone is forced into the cone shaped opening at the end of the auger, the soil flow can be curtailed.

It should be noted that by restricting the soil as it passes through the auger, all of the valve types can be used to squeeze the muck before it drops onto the conveyor. The basic idea is to provide enough resistance at the opening that the muck is compressed by the screw conveyor to some degree. This reduces the water content of the muck as well as its volume. The inventors of the cone valve, the Hitachi Sozen Company, argue that it is especially well adapted to this purpose.

Figure 9 presents a view of the entire EPB shield tunneling process. The muck from the shield conveyor is dropped into muck cars and taken out to the shaft where the muck cars can be directly lifted out.

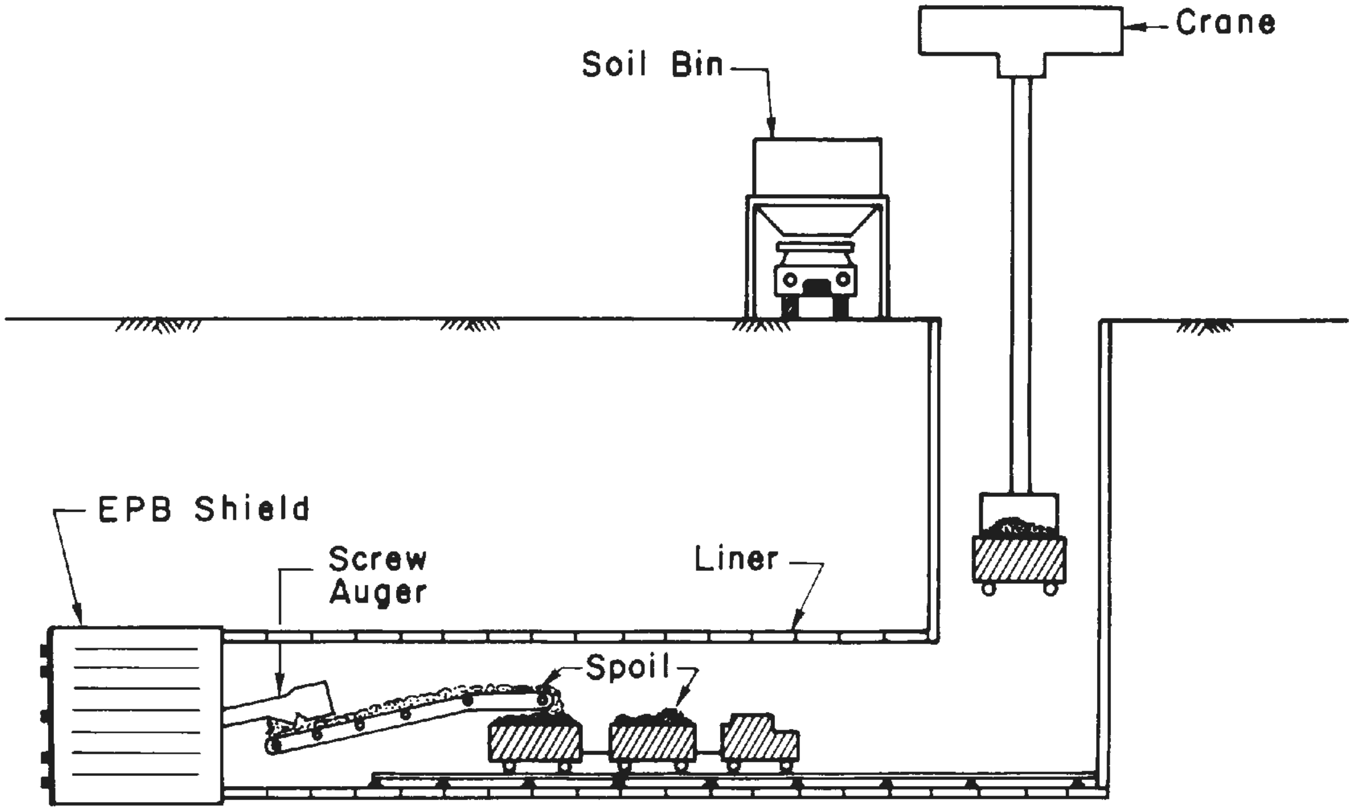


Figure 9. MUCKING PROCESS AND MUCK HANDLING FOR EARTH PRESSURE BALANCE SHIELD.

Control and Automation of the Tunneling Process

A fully automated EPB shield process as proposed by Mitsubishi Heavy Industries, Ltd. is shown in Figure 10. Parameters that are monitored are:

Earth pressure at the crown of the shield

Earth pressure on the interior bulkhead

Cutter pressure or torque

Cutter rotation speed

Shield advance rate

Screw conveyor pressure or torque

Screw conveyor rotation speed

Rotary hopper pressure or torque

Rotary hopper rotation speed

Conveyor belt speed

Weight of muck passing over conveyor belt

Some of these parameters are measured simply to be used as periodic checks while others are integrated into an automated advance scheme. All of them can be monitored by a technician at the surface in a control room as well as by the shield operator, in the same manner as was described for the slurry shield.

The two earth pressure detectors shown in Figure 10 have different missions, neither of which is related to insuring that the earth pressure balance per se is maintained. The cell on top of the shield is a cautionary surveillance tool which is used to insure that the soil above the shield is still there. If a serious run should occur and was not somehow detected by other means, then presumably an opening could develop in and around the crown. The crown pressure cell would show this event by a reduction in

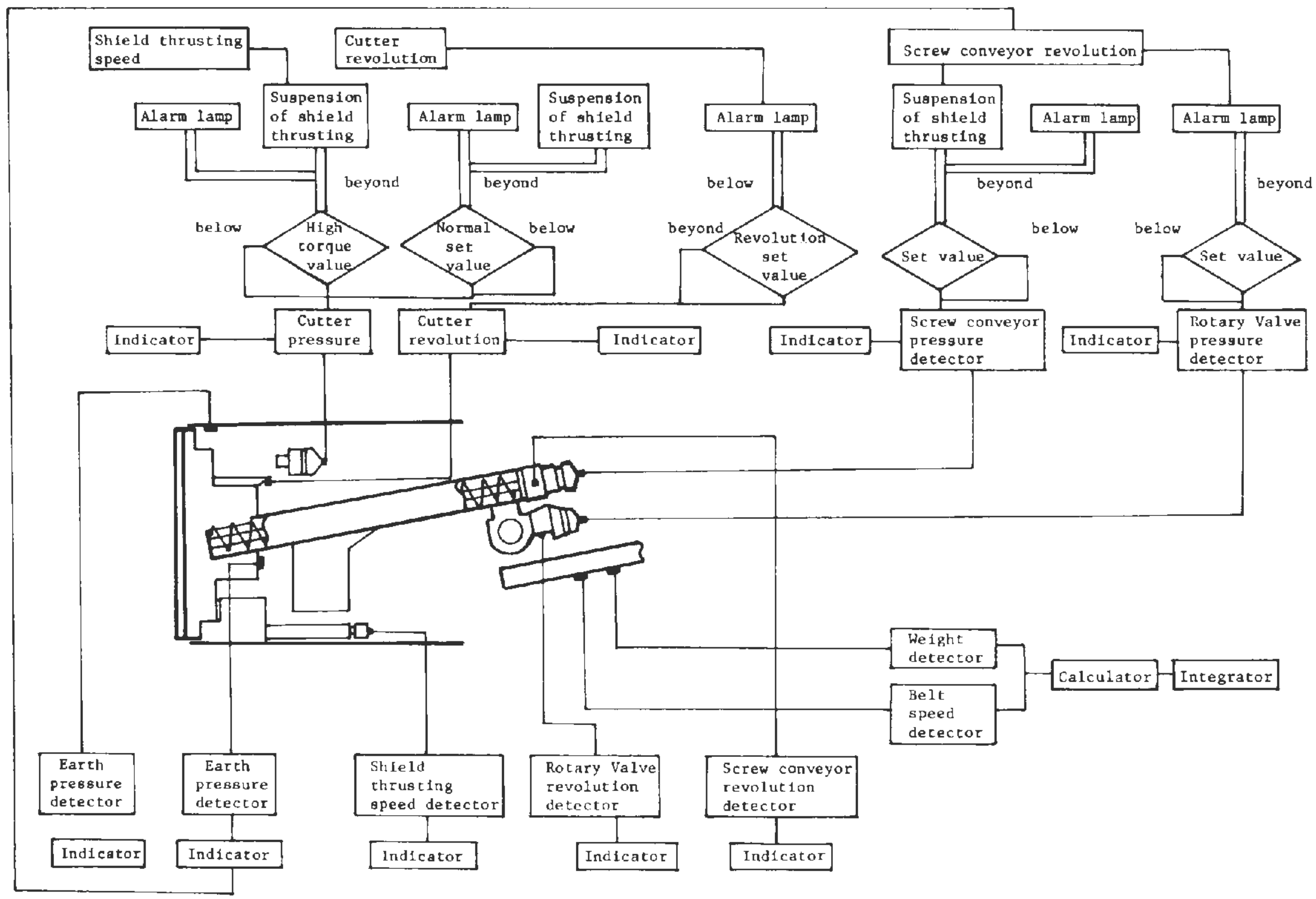


Figure 10. CONTROL FLOW CHART FOR MITSUBISHI EARTH PRESSURE BALANCE SHIELD.
NOTE: Double lines = Automatic; Single lines = Manual.

pressure level, and the shield could be halted before a collapse occurred. The internal pressure cell on the bulkhead is designed to help insure that the spoils chamber is entirely full. Because this is a key element in insuring that the soil cannot run into the shield, this sensor is tied into the automatic control unit for the screw conveyor speed. If the bulkhead pressure level should be measured as too low, then the screw conveyor speed is reduced to allow the spoils chamber to fill up. Should it be too high, then the screw conveyor speed is increased to remove muck faster so as to prevent overloading of the cutter head drive or pushing of the soil outwards from the shield.

Of course, the earth pressure cells do not directly measure parameters which can be used to insure that the amount of soil being removed is equal to the volume of the shield advance. To check this, two approaches are used, one of which is indicated in Figure 10. This procedure utilizes a weight detector on the conveyor belt itself, and by knowing the speed of the belt, the amount of muck removed is estimated continuously. The amount of muck being removed can only be approximately equated to an in-place soil volume since the process of excavating and squeezing the muck changes its density. However, by experience a reliable relationship can be established. The second approach to determining the soil volume removed involves weighing the muck as the muck cars are lifted from the shaft, and equating this to an in-place soil volume. This alternative is not as desirable as the first one, since it is not continuous and the information is not developed as rapidly.

It is interesting that while the EPB shield itself is simpler than the slurry shield, the monitoring process is no less complex. The reason for this probably lies in the fact that the EPB process involves more risks than that of the slurry shield. The face support provided by the EPD shield is not as easy to insure, and the fluid pressure of the slurry provides a more continuous resistance to soil movement than the system of the EPB shield.

Shield Modifications and Supplementary Actions Taken To Assist in Ground Control

If the ground water table is above the tunnel crown and the soils are relatively pervious, the EPB shield is likely to have difficulties in ground control. Modifications to the shield to help prevent uncontrolled runs through the screw auger system can be made. One relatively simple idea for areas with only limited quantities of potentially running soil involves adding a bypass to the auger so that in the event of encountering a flowing soil condition, the soil in the auger can be shunted into a line which has a squeeze pump or a moino pump attached to it (11). These pumps can control the flow of the viscous soil and reduce its water content.

An alternative major modification to the bypass idea has been developed to allow use of the EPB shield where extensive deposits of running soil are encountered along the tunnel alignment. This involves adding a capability to exert water pressure through the screw auger on the tunnel face. This system, known as the "EPB shield of the water pressure type," was designed by the Sato Kogyo Co., Ltd., and it will be described in the next section.

Outside of altering the EPB shield design, it is common practice to control potential pockets of flowing ground by injecting chemical grouts in the pervious soils. The grout gels after a period of one hour or less and solidifies and impermeabilizes the soil. At several projects visited by the author this procedure was being used in areas where ground movements could potentially damage nearly structures. Details are given in a subsequent section of the report, entitled "Comments on Specific Soft Ground Site Visits." The injection operations were of a significant scale, and in one case reached $8,000,000. This is larger by far than any comparable chemical stabilization program undertaken for tunneling in the United States. To the writer's knowledge, the larger previous tunnel stabilization contract in the United States was about $800,000 for the G1 project of the Washington, D.C. Metro. This illustrates the great concern on the part of Japanese engineers about preventing unnecessary surface settlements.

Grouting of the Liner

As with the slurry shield, grouting of the tail void for the EPB shield is a critical operation. Again the tail seal problem exists in that it must occupy about 50 mm (2 in) between the tail of the shield and the liner. This leaves a larger void than would occur in conventional shield tunneling, and necessitates use of prompt grouting with quick-set agents.

Usage of the EPB Shield

The application of the EPB shield in Japan appears to be on the increase. Where the soil conditions are right for its use, it is cheaper than the slurry shield because the shield itself is less expensive and the complex procedure for slurrying the muck and treating it is avoided. Recently, the Ohbayashi Gumi Company has won the bid for the N2 contract of the San Francisco Outfall Sewer System using an EPB shield. A significant factor in this outcome was that the insurance rates using the EPB shield were considerably less than those for conventional shields with compressed air in the tunnel.

Greater use of the EPB shield is likely in the future, especially if improvements continue to be developed for handling a more diverse set of ground conditions. Additional research will be required before it is known exactly where the EPB can and cannot be applied. The instrumentation effort to be undertaken by the Stanford Research Team under DOT sponsorship at the site of the N2 Sewer Contract in San Francisco is directed towards this goal.

The Earth Pressure Balance Shield of the Water Pressure Type

As mentioned in the previous section, one of the limitations of the ordinary EPB shield is in handling pervious soils beneath the water table. During the late 1970's, Sato Kogyo Co. Ltd. developed a modified EPB process for such conditions using water pressure applied through the screw auger to prevent the flow of ground water (1, 6, 14, 23). The new shield is called the EPB shield of the water pressure type. Hereafter in this report, it will be designated WPB (water pressure balance) shield.

Basic Shield Equipment

An illustration of the WPB shield equipment is provided in the section shown in Figure 11. As can be seen, the shield is very similar to a conventional EPB shield except that a "mucking adjustor" is located at the outlet of the screw conveyor. The upper pipe into the mucking adjustor carries water under pressure which passes through the pervious soil in the screw auger, past the bulkhead, and to the tunnel face via the openings in

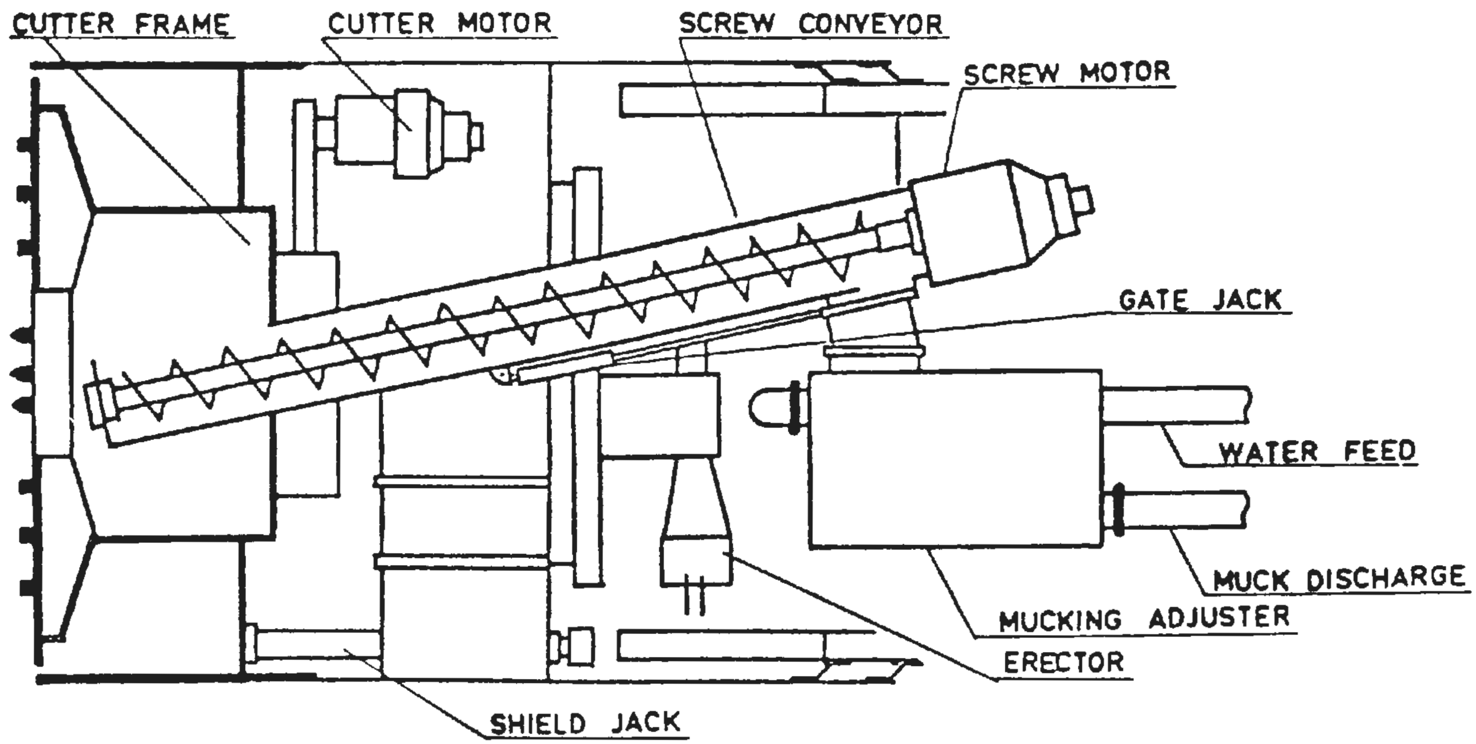


Figure 11. CROSS-SECTION OF WATER PRESSURE BALANCE SHIELD (AFTER ISHIHARA, 6).

the cutter head. The pressure of the water in the mucking adjustor is set to balance that of the ground water trying to pass into the shield and thus, the water flow is prevented. This allows use of the EPB shield principle in soils which are pervious and under the ground water table.

As the muck passes from the screw auger into the mucking adjustor, it is subjected to a high speed water jet which creates a fluid slurry that is pumped out to the surface. Large particles are separated from the slurry in the mucking adjustor by passing it through a grate. In order to reduce the water content of the muck before transportation, the soil-water slurry is subjected to treatment in essentially the same fashion as is described for the slurry shield.

Control and Automation of the Tunneling Process

From the description of the WPB shield it can be seen that the technique combines the excavation procedures of the EPB shield and the slurry transport and treatment methods of the slurry shield. The controls for the WPB tunneling process also draw upon the technology of the other two shield procedures. At the face, the earth pressure balance type system is used where the rate of shield advance, the speed of rotation of the screw auger, and the soil conditions in the spoils chamber are linked together to insure proper advance. In addition, the water pressure in the spoils chamber is measured to insure that the pressure inside the shield equals that applied outside. During slurry transport, the slurry flowrate and density is checked in the same manner as for the slurry shield, in order to insure that the shield advance volume equals the volume of soil excavated.

Usage of the WPB Shield

The WPB shield is applicable to relatively pervious soils. Sato Kogyo Co.,Ltd. (6, 23) has conducted an extensive research program and developed the following guide parameters which may be used to determine when it is necessary to use the WPB shield instead of the EPB shield:

Coefficient of permeability $\geq 10^{-3}$ cm/sec

Coefficient of uniformity $\leq$ 8-10

Amount of particles smaller than 74 microns $\leq$ 10%

The addition of the water pressure balance scheme to the EPB shield considerably extends the range of conditions where it can be used. The capabilities of the WPB shield allow it to compete directly with the slurry shield where soil and ground water conditions are difficult for tunneling.

Usage of the WPB shield is less than that of the EPB or slurry shield. Sato Kogyo Co., Ltd. has patent rights to the concept and is the only contractor presently using it. They have employed the WPB shield in a number of challenging projects, two of which are described in a subsequent section of this report. Sato Koygo engineers list the following advantages for the WPB shield:

1. The pressure distribution used to support the face is more consistent with the actual one than is the case for an EPB shield.
2. There is no requirement that a slurry with a specific material composition be used at the tunnel face.
3. Should migration of the tail void grout to the face occur, there will be no problems with slurry flocculation as may occur with the slurry shield.

4. It is cheaper than a slurry shield.

The true significance of these advantages will presumably be defined by competition in the market place.

The Mud Pressurized Shield

The mud pressurized shield, or "mud shield" for short, utilizes and extends concepts from the slurry and EPB shields. It has been described recently by Murayama (17), who participated in its development with the Taiho Construction Company. Photographs of the front and rear views of the mud shield are given in Figure 12. The most noticeable aspect of this shield is the absence of a closed face cutter head. Instead, an open-spoke cutter is used which extends slightly in front of the shield. Just behind the cutter is a bulkhead, penetrated at the bottom by a screw auger which removes the soil cuttings into the shield.

Face stability with this shield is achieved by the following actions:

1. As the soil is broken free by the spoke cutter, a special slurry is poured into the area between the cutter and the bulkhead. The mixture of the soil and the slurry is not fluid, but rather behaves as a very plastic mass.
2. A pressure is applied to the plastic mass which is adequate to prevent instability of the tunnel face.
3. The plastic mixture of soil and slurry is removed by the screw auger at a rate so that it equals the advance volume of the shield.
4. The slurry admixture impermeabilizes the soil after mixing, preventing water flow through the screw auger even under high water heads of up to 200 kN/m^2 (28 psi).

This process represents a bold departure from previous concepts.

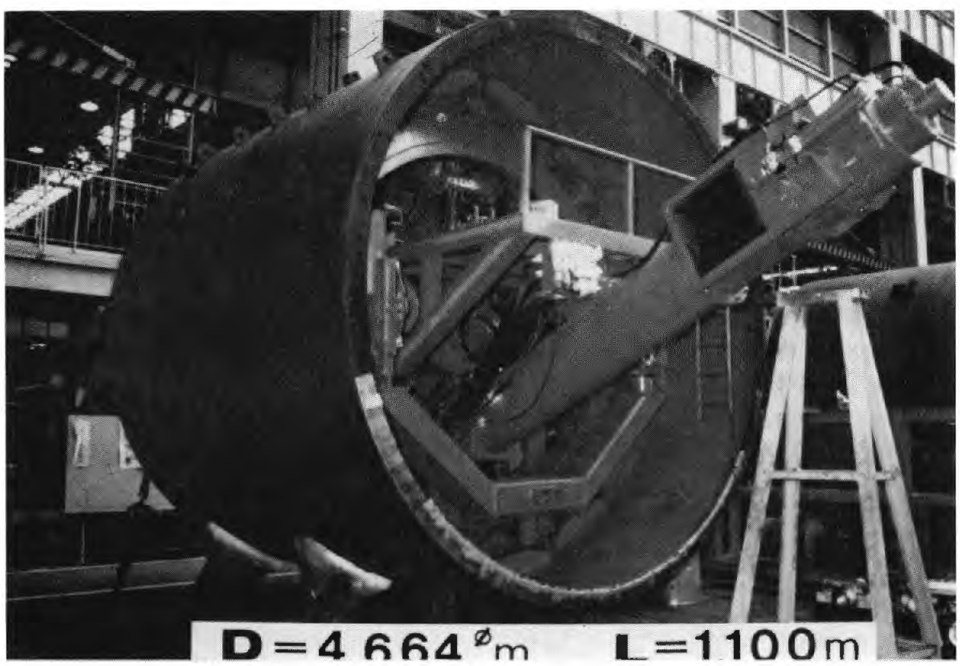


Figure 12. MUDSHIELD: UPPER PHOTOGRAPH, FRONT VIEW: LOWER PHOTOGRAPH, REAR VIEW (PHOTOGRAPHS COURTESY OF TAIHO CONSTRUCTION CO.).

Basic Shield Equipment

The basic idea of soil handling in this case is quite similar to that of the EPB shield. A screw auger removes the muck and drops it onto a conveyor belt for transport (see Figure 12). And, as with the EPB shield, there is a pressure cell mounted on the bulkhead. This pressure cell serves to tell the operator how much pressure should be applied to the plasticized mud in order to maintain face stability. Because the mud is impervious, the cell will read the total pressure (earth + water) acting on the face.

The nature of the slurry material added to the excavated soil is apparently a trade secret. It is added via several valves set into the bulkhead and is controlled by the shield operator. In order to insure blending of the slurry and the excavated soil, mixing wings are attached to the back of the rotating cutter spokes (see Figure 12).

The muck is taken from the tunnel via conveyor belt and muck cars. Because it is in a plastic state, it may be hauled away directly, without need for any special treatment or conditioning.

Usage of the Mud Shield

The mud shield was first used in 1976 and is patented by the Taiho Construction Company. According to a brochure published by this company, it has been employed on six jobs of mostly small diameter, the largest being 4.13 m (13.6 ft.). It has tunneled in sands and clays and under up to 9 m (30 ft.) of water head. During a meeting between the author and Professor Murayama, it was pointed out by Professor Murayama that the mud shield is soon to be used for even larger diameters and water heads.

Obviously, the mudshield can compete directly with the EPB, WPB and slurry shields. It has a number of advantages relative to the others:

1. The cutter head torque required is relatively low since the face is not closed, reducing the area over which friction forces are mobilized.
2. A continuous face support is achieved by the plastic soil-slurry.
3. The earth and water load at the face are truly balanced by the pressure applied to the plastic soil-slurry mass.
4. It is applicable to a wide range of ground conditions.
5. The muck is easily handled.

Starting and Terminating Advanced Shield Tunneling

All of the advanced shields operate using some type of closed system when the tunneling is under way. For example, for the EPB shield, the spoils chamber must be full of soil, and cuttings should be entering the shield as fast as the screw auger removes them. However, at the portals of the tunnel, the system cannot operate until the shield is fully covered by soil. Thus special procedures are needed to start and terminate the process. Typically, the starting operation is the most difficult.

Starting the Shield Process

There are many variations used for starting an advanced shield, but basically there are two primary categories. The first involves digging a large shaft, lowering in the shield, and burying it under a backfill. The second, and more common, involves excavating a shaft, lowering in the shield, and advancing the shield through the shaft wall. In order to get the shield through the shaft wall, a number of special provisions are undertaken to prevent ground water inflow, and to seal the shield in so as to start the production cycle as soon as possible. First, if the soil is pervious, a zone adjacent to the shaft wall is usually chemically grouted to form a stabilized mass within which the shield will pass. If the soil cannot be grouted, but stability is still a problem, it may be frozen. Second, an external rubber seal is placed on the face of the wall so as to completely encircle the shield as it passes into the soil. This prevents water flow into the shaft, and allows the tunneling cycle to begin before the tail seals of the shield itself are in the soil. Third, provisions are usually made to have removable elements or a weak, easily demolished zone in the shaft wall where the shield is to enter. Kurosawa (12) reports of the use of a special glass fiber concrete in a slurry wall of a shaft which could be cut by the bits on the cutter head of a slurry shield.

As the shield passes into the soil, it is primed with soil or slurry to initiate the production cycle. A temporary set of liner rings are usually erected in the shaft behind the shield and given structural support. These segments are used for the shield to react against as it advances. As the shield moves forward liner segments are erected in the conventional manner.

Terminating the Shield Process

In most cases the basic shell of the shield is left in-place after it breaks through at the exit shaft. This is simply dictated by economics and the fact that the removal of the shield would be a difficult and tricky process. In order to break through the shaft wall, there are the problems of potential leakage around the shield and developing a means for the cutter head to penetrate the shaft wall. The leakage is overcome by chemically grouting pervious soils adjacent to the shaft wall. Penetrating the wall is accomplished in a similar manner to that used at the entry shaft. That is, removable or weak elements are built into the wall at the location of the shield penetration.

Liner Systems

In Japanese soft ground tunneling, the use of precast concrete segments for tunnel liners is pervasive. Steel liner plate is used primarily only where the length of the tunnel is very short or where sharp turns are encountered. The precast concrete segments are waterproofed in a very simple manner by gluing rubber or vinyl strips onto the periphery of each segment. Examples can be seen in the upper photograph of Figure 13. In the case of the middle segment of the stack shown, two black rubber strips have been glued into slightly recessed grooves around the segment. The upper segment in this stack has had glue applied in the grooves, but the rubber strips have not been set in place. The use of the grooves as guides for the rubber strips is by no means universal. In many jobs the strips are glued directly onto the surface of the segments. In one case, observed by the author, a practice was made of gluing a 10 cm (4 in.) thick foam piece to cover the entire back of the segment. Engineers on the job felt that the foam would help to fill the tail void created by the shield advance.

On most of the jobs visited, the segments were bolted together in a conventional fashion using straight bolts. In one project of the Tekken Construction Company, curved bolts and holes were used. This type of segment is demonstrated in the lower photograph of Figure 13. The use of the

Figure 13. PRECAST CONCRETE LINER SEGMENTS: UPPER PHOTOGRAPH, CONVENTIONAL SEGMENTS WITH GROOVES FOR WATERPROOFING: LOWER PHOTOGRAPH, SEGMENTS WITH CURVED BOLT HOLES.

curved bolts is said to allow the bolt tightening process to be automated since a mechanical torque wrench can reach the upward curving bolt head.

In Figure 14, a finished portion of a tunnel using the precast segments is shown. The pipes in the lower right of the photograph are the inlet and outlet lines for a slurry shield which is operating ahead of the location of the photograph. Leakage through the liner is very small; generally, this was the case in all the jobs visited by the writer.

Comments on Specific Soft Ground Projects Visited

In Table 1 a listing and short description is presented of each project visited during the author's trip in September of 1979. A total of seven soft ground sites were seen; operation of the EPB, WPB and slurry shield could be observed.

Deiribashi - Ebie Trunk Line; Contractor - Ohbayashi Gumi

Located in Osaka, this project is representative of a relatively uncomplicated small diameter (4.2 m, 13.9 ft) sewerage tunnel. The soils are largely silty clays and well adapted to the use of an EPB shield. Because the tunnel has a small diameter, a center shaft drive is utilized in the shield. Precast concrete segments are employed for the liner and an average daily advance rate of 6 m (20 ft.) is being achieved using a two shift work schedule.

Tennojo - Benten Trunk Line; Contractor - Ohbayashi Gumi

This job is particularly challenging in that it involves a large diameter (6.76 m, 22.3 ft.) 1400 m (4620 ft.) long sewerage tunnel which passes at a relatively shallow depth (8 m, 26.4 ft.) beneath busy streets in commercial and residential sections of Osaka. The soils vary from

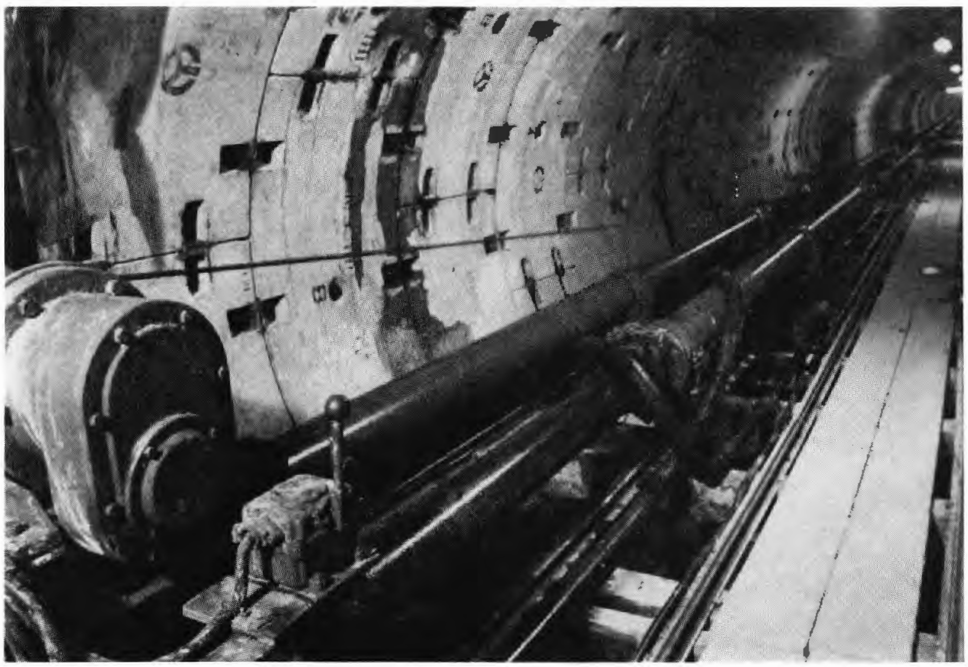


Figure 14. FINISHED TUNNEL WITH PRECAST CONCRETE LINER SEGMENTS AND SLURRY LINES FOR MUCK TRANSPORT (PHOTOGRAPH COURTESY OF SATO KOGYO CONSTRUCTION CO.).

TABLE 1. TUNNEL SITE VISITS

Project	Location	Diam.	Length	Ground Conditions	Cover	Depth to GWT	Tun-neling Procedures	Contractor	Purpose	Primary Tunnel Supports	Daily Advance Rate
		m	m		m	m					m
Deiribashi-Ebie Trunk Line	Osaka	4.2	537	Silty Clay	7	1.5	Earth Bal-ance Shield	Ohbayashi Gumi	Sewerage Transport	Precast Concrete Liner	6
Tennojo-Benten Trunk Line	Osaka	6.75	1400	Sands, silts and silty clays	8m	1.5	Earth Bal-ance Shield	Ohbayashi Gumi	Sewerage Transport	Precast Concrete Liner	Just Beginning
Kanamachi Water Supply Tunnel	Tokyo	3.7	100	Fine sand	25	1	Water Bal-ance Shield	Sato Kogyo	Water	Precast Concrete Liner	6.5
Shinozaki Trunk Line-Phase 5	Tokyo	5.24	1630	Fine sand	11	1.5	Water Bal-ance Shield	Sato Kogyo	Sewerage Transport	Precast Concrete Liner	7.2
Hikarigaoka-Yabara Water Supply #1	Nerima-ku Tokyo	3.55	418	Sandy gravel	8	1	Slurry Shield with Rock Cutter	Tekken	Sewerage Transport	Precast Concrete Liner	5.4
Hikarigaoka-Yabara Water Supply #2	Nerima-ku Tokyo	3.55	418	Dense sand	25	1	Slurry Shield	Tekken	Sewerage Transport	Precast Concrete Liner	7.2
Subway Line #8 Hikawadi #2 Section	Nerima-ku Tokyo	10.0	884	Sands, gravelly sands, & clayey silt	10-18	2.5	Slurry shield	Tekken	Subway	Precast Concrete Liner	Just Beginning
Shirasaka No.1 and 2 Tunnels	Matsumoto	8.5	3000	Fractured mudstone and shale	0-150	-	New Aus-trian Method	Kumagai Gumi	Railroad	Steel Sets, Rock Bolts & Shotcrete	Just Beginning
Seian Under-sea Tunnel	Connects Honshu to Hokkaido	11.4	54000	Sandstone, siltstone, mud-stone, tuff	Up to 400m	*	Grouting-Drill & Blast	Consortium	Railroad	Steel Sets & Lagging	**

*Passes under Seikan Sea under up to 240 m of water head

**Highly variable; tunnel under construction for 15 years sands to silts and silty clays, with a water table near the ground surface. An EPB shield is being used which is unique in that two screw augers are built into it. The use of the two augers was done to provide a backup to that progress could be maintained in the event of an outer malfunction. A bypass valve system is attached to the screw augers with a squeeze pump in line to help handle any possible soil runs.

Because of the high water table, the critical nature of the project, and the fact that an EPB shield is being used, chemical grouting was carried out prior to tunneling in order to stabilize the regions with sandy soils. An outline of the cross section of the theoretical zone which was grouted is given in the lower portion of Figure 15. A silicate grout was used and injected with a two pipe scheme. There were two components to the grout, one of which passed down one pipe, and the other down the second pipe. At the exit point of the two pipes, the components mixed and the grout gelled very rapidly. Subsequent to the formation of an initial small mass of hardened grout around the tips of the pipe, the injections were continued. In theory, the fluid grout components split the previous mass, pass just outside of it and harden themselves. This was repeated until a fixed quantity of grout was injected to equal about 30% of the soil volume being treated, an amount equal to the void space in the sand. Successive bulbs of hardened grout were built up around the tip of the injection pipe.

When visited by the author, the chemical grouting work was finished and tunneling was just getting under way. Precast concrete segments are being used for the liner; the segments for this job are shown in the upper part of Figure 13.

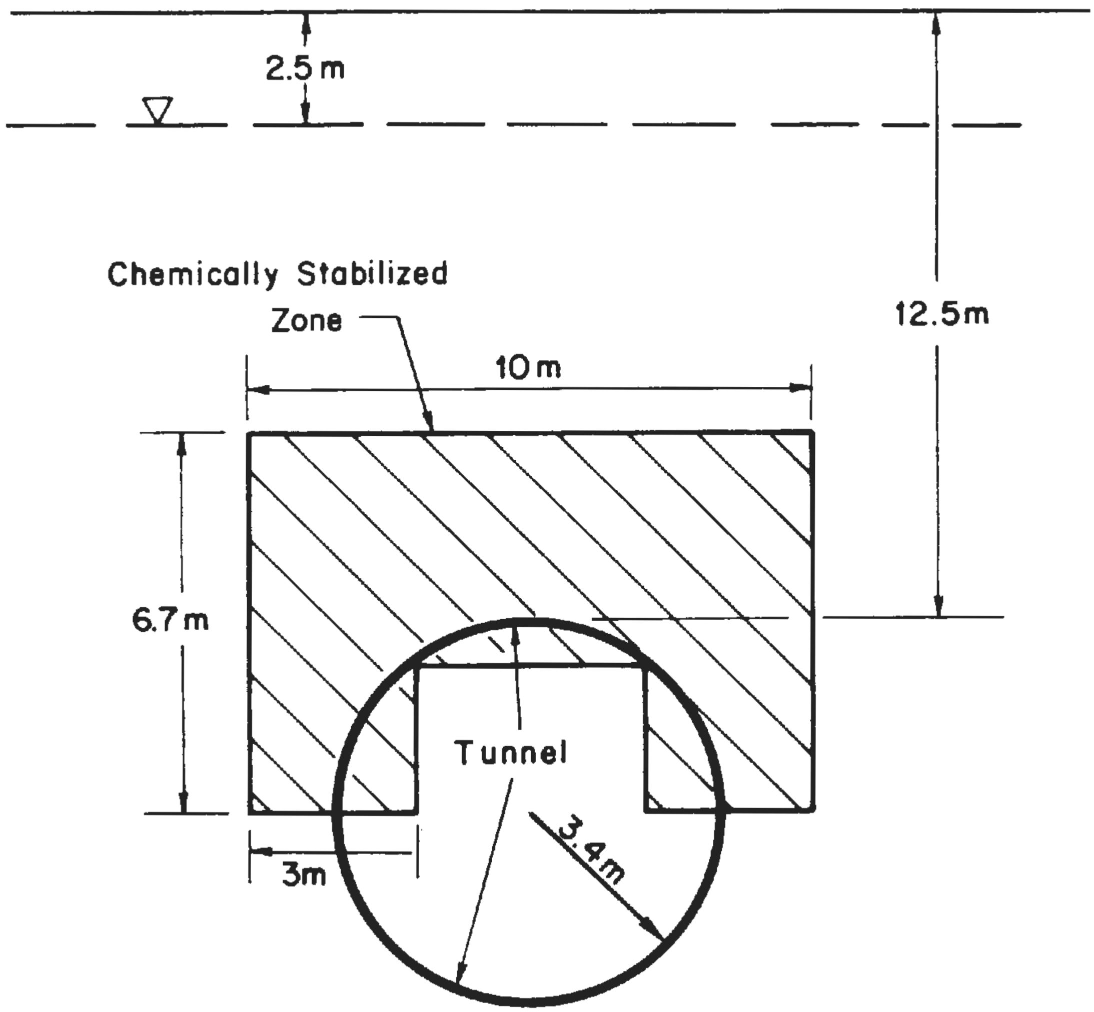


Figure 15. CHEMICALLY STABILIZED SOIL ZONES FOR TENNOJO-BENTEN TRUNK LINE SEWER: USED ONLY IN AREAS WITH RUNNING SOILS IN CROWN.

Kanamachi Water Supply Tunnel and Shinozaki Trunk Line Phase 5; Contractor--Sato Kogyo

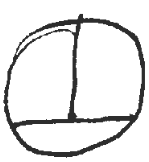
These projects are examples where the WPB shield is being used. Only in the case of the Kanamachi Water Supply Tunnel was active tunneling observed; the work on the Shinozaki Trunk Line has recently been completed. Both of the projects are interesting in that the ground conditions consist of sands with a high water table, and the tunnels run beneath narrow residential streets. Concrete segments are used in both cases on the liner support. Average daily advance rates were quoted as 6.5 m (21.5 ft.) and 7.2 m (23.8ft.) for two shift operations for the Kanamachi and Shinozaki tunnels respectively. No problems with ground settlements apparently occurred. Some precautionary chemical grouting was required by the owners of the projects where the tunnel passed near critical structures.

Hikarigaoka - Yabara Tunnels Nos. 1 and 2 and Subway Line No. 8 Hikawadi No. 2 Section; Contractor - Tekken

At both of these sites the slurry shield is being used in active tunneling. The Hikarigaoka-Yabara tunnels are identical small diameter tunnels (3.55 m, 11.7 ft.), with one located at a depth of 8 m (26.4 ft.) and the other at 25 m (82,5 ft.). With the ground water table near the ground surface, the lower tunnel is subjected to a high water head. The lower tunnel passes through a sand layer while the upper one is located in a sandy gravel layer with some large cobbles. In order to work in the upper tunnel, a special slurry shield was developed with rock cutter bits in addition to the standard soil bits (see Figure 1). The cutter bits break the gravel and cobbles down to a manageable size to pass into the slots of the cutter face. Just at the base of the bulkhead, the operator has a trapdoor access which allows him to remove large rock pieces without decompressing the slurry. Behind the shield is a rock crusher which breaks gravel sized particles down to about sand size. Following the crusher on the return line is a gravity separator which splits the slurry into a relatively clean fraction and a contaminated fraction. The contaminated fraction is sent to the surface for cleaning. The treatment plant consists of only a vibrating screen and a series of cyclones. No secondary processing is used since there are few fines in the slurry.

Because of a lack of fines in the soils at the Hikarigaoka-Yabara site, a silty clay is imported from a nearby cut-and-cover project to make up the slurry. Precast concrete segments are used for the liner and the average daily advance rates are 7.2 m (23.8 ft.) and 5.4 m (17.8 ft.) for tunnels No. 2 and 1 respectively.

The Hikawadi Subway Line project is unique in that the diameter is 10 m (33 ft.), the largest slurry shield tunnel yet attempted. A photograph of the shield is shown in Figure 1. At the time of the author's visit, the shield was just being assembled at the bottom of the tunnel shaft. The tunnel will pass through sandy soil layers with a high ground water head and with only 10 m (33 ft.) of cover in some locations. Upon completion of this project, a wall is to be run down the length of the tunnel to separate the inbound and outbound subway lines.



General Comments on Advanced Shield Tunneling in Japan

It is apparent that the field of shield tunneling has made rapid gains in Japan in the last decade. Shallow tunneling is possible under even the worst of soft ground conditions by a variety of techniques. The reasons for the successful development of shield technology appears to be as follows:

1. The market is large and thus there is a considerable economic incentive.
2. The time was right in that preliminary ground work had been done for more than a decade in preparing the way for advances.
3. The Japanese contracting firms have devoted substantial amounts of time and monies to research and development.

It is important to realize that the large Japanese contracting firms have well equipped research laboratories that are staffed by highly trained personnel. Paulson (21) has described these types of facilities and their operation in the Japanese economic market. Work done by the contractors at their laboratories and funded by them at Japanese universities have led to the development of the new technology.

At the present time, the slurry shield, the EPB and WPB shields, and the mud shield all offer tunneling procedures which can deal with similar ground conditions. As of 1979, the slurry shield had the longest experience record. It has the advantage of being a very sure method of dealing with difficult soil and water situations. Where the soils are relatively impervious, the EPB shield represents a useful tool in that it has no need for slurry treatment or handling, and the shield itself is inexpensive compared to the slurry shield. The WPB shield extends the capability of the EPB to tunnels in sands under the water table. This technique does not utilize a slurry at the face of the tunnel, but has the advantage of transporting the muck in slurry form. The mud shield is the most recent development, and utilizes an especially clever scheme for providing full and continuous support of the face. Muck handling is a relatively simple operation, and the basic shield equipment is comparable in price to the EPB shield.

In terms of rates of progress, all of the shields seem to work at similar speeds. Average daily rates for projects visited by the author ranged from 5.4 m (17.8 ft.) to 7.2 m (24.8 ft.) for two shift operations. Where ground settlement data have been reported they have generally been quite small for any of the shield types, typically less than 20 mm (1, 6, 16, 23, 24). One early slurry shield project was reported to have experienced 60 mm of surface settlement (24) but this appears to be an isolated case.

Given the similarity in the shield performance and ability to handle the different ground conditions, it would appear that only future competition and possible technological improvements will decide if one type is, in fact, preferable to the others.

PART II -- WEAK ROCK TUNNELING

The primary purpose of the visit by the author to Japan was to examine soft ground tunneling procedures. However, trips were made to two interesting projects involving tunneling in weak rock which are described in the following paragraphs. A summary of key data on the projects is given in Table 1.

Shirasaka No. 1 and 2 Tunnels

This project is located on the main island of Japan (Honshu) near the town of Matsumodo, about 100 km south of Tokyo. The tunnel is horseshoe shaped, 9.4 m (31 ft.) wide and 7.5 m (24,8 ft.) high, and is being built for a local railroad line. Kumagai Gumi Co., Ltd. is the general contractor. The rock conditions and topography along the tunnel alignment are given in Figure 16. The cover over the tunnel ranges from zero to 150 m (459 ft.). The rock is basically a fractured mudstone with numerous thin layers of shale, sandstone, and cemented gravel which intersect the tunnel alignment at steep angles.

Tunneling is being carried out using drill and blast procedures taking out half of the heading at a time. The primary supports consist of rock bolts, steel sets and shotcrete. A secondary finished concrete liner is poured subsequently. Design of the primary support elements is following the general procedures of the New Austrian Tunneling Method (NATM). The basic philosophy exercised is as follows:

1. Provide flexible supports as soon as possible at heading after blasting, which will prevent deterioration of the rock but allow enough squeeze to occur so that the rock mobilizes its strength.

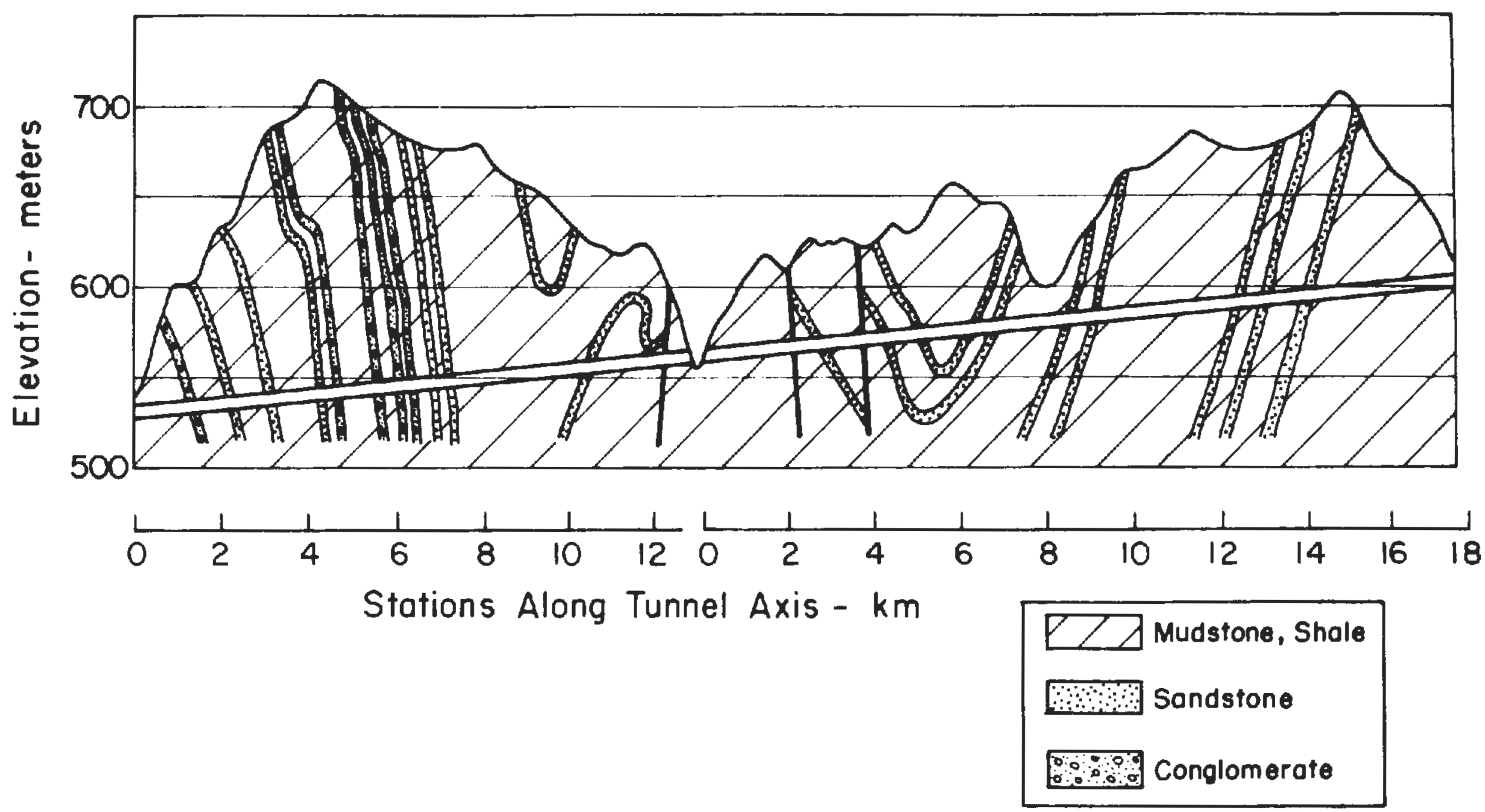
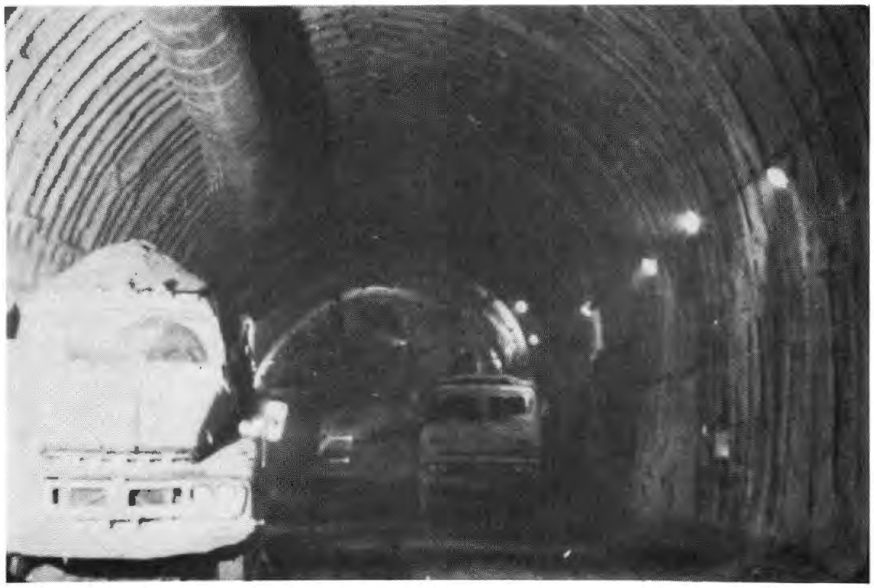


Figure 16. ROCK PROFILE AND TOPOGRAPHY - SHIRASAKA NO. 1 AND 2 TUNNELS.

2. Optimize the size of the support elements by making measurements of the performance of the supports during early construction.

In order to allow some squeezing of the rock, the steel sets are provided with a slip joint which can be locked when a pre-selected amount of movement has occurred. A close-up photograph of the joint is provided in the upper half of Figure 17. The dark positions of the joint in the picture are indicative of slippage since these were not covered by shotcrete initially. Also, a gap is left in the shotcrete about halfway between the crown and the springline of the tunnel. This is not filled until the slip joint is locked.

The measurements involve using load cells on rock bolts, extensometers drilled in at the crown, springline and halfway between the crown and springline, and survey points set around the tunnel periphery. Approximately 5 to 10 cm (2 to 4 in.) of squeeze has been observed on each side of the tunnel. A photograph of a completed section of the tunnel with all the primary supports in is shown in the lower position of Figure 17. The project engineer noted that the steel sets were much lighter and placed on about twice the spacing ordinarily used, thus resulting in a considerable material savings. However, he also noted that the work went slower using the NATM than the conventional technique. At the present, they consider that using the NATM yields a net savings. A previous project of Kumagai Gumi apparently was also successful in applying the NATM technique (27).



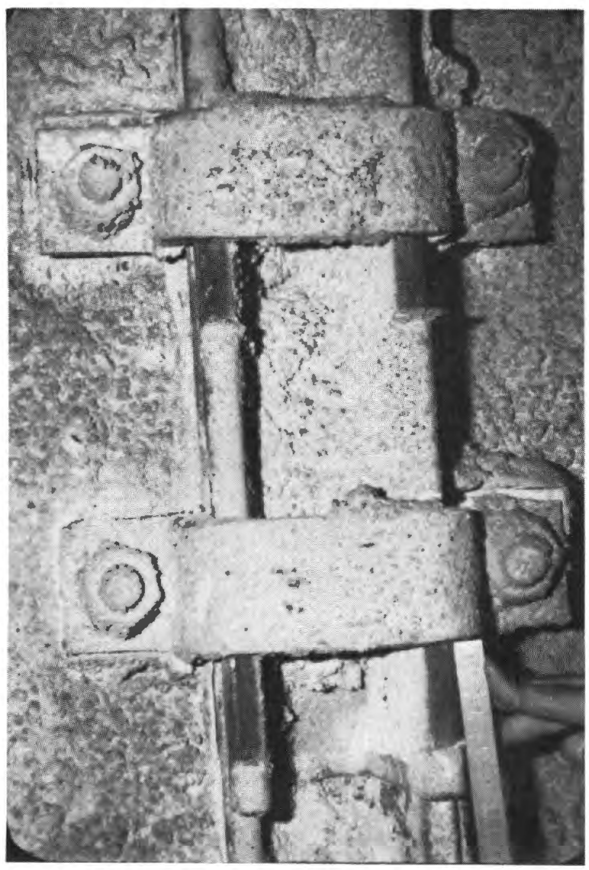


Figure 17. SUPPORTS FOR SHIRASAKA NO. 1 TUNNEL: UPPER PHOTOGRAPH, GENERAL TUNNEL INTERIOR SHOWING STEEL SETS AND SHOTCRETE: LOWER PHOTOGRAPH, SLIP JOINT ON SET TO ALLOW FOR SQUEEZE - DARK AREA ON SET SHOWS AMOUNT OF SQUEEZE (PHOTOGRAPHS COURTESY OF KUMAGI GUMI CORPORATION).

Seikan Tunnel

The Seikan Tunnel is one of the most extensive engineering undertakings in the history of mankind. Its purpose is to link the main island of Japan, Honshu, to the northern island, Hokkaido (see Figure 18), by passing under the Seikan Sea at the position of the Tsugaru Straights. The tunnel length, at 53.9 km (33.7 miles), is the longest in the world, and it has been under construction since 1971 with completion expected in 1983. In Figure 19 a section along the main tunnel alignment is shown; positions of the service and pilot tunnels can also be seen. In the approach areas on the Honshu side where the tunnel goes underground, the mountains reach as high as 400 m (1320 ft.) above the main tunnel and, as it passes under the Tsugaru Straights, it is some 240 (790 ft.) below sea level. The rocks along the tunnel route are of sedimentary and volcanic origin, consisting of sandstones, siltstones, mudstones, shales, rhyolites and andesites. A standard cross-section showing the relative positions of the main tunnel, the service tunnel and the pilot tunnel is presented in Figure 20. The main tunnel is horseshoe shaped with a width of 11.4 m (37.6 ft.) and a height of 9.7 m (29.1 ft.) and can accommodate two tracks of the Shinkansen (Bullet Train) service of the Japanese National Railway.

The long construction history of the tunnel has been described by many authors (3, 4, 8, 21) and will not be repeated here. The basic tunnel procedures have involved advancing from both the Honshu and Hokkaido sides simultaneously, primarily using drill and blast techniques, and staged bench and side drift removal of the rock. The author visited only the Hokkaido side, and at this time, only 4 km (2.5 miles) remained to be excavated from the center portion of the tunnel. At this location, the tunnel is essentially 240 m (790 ft) below sea level.

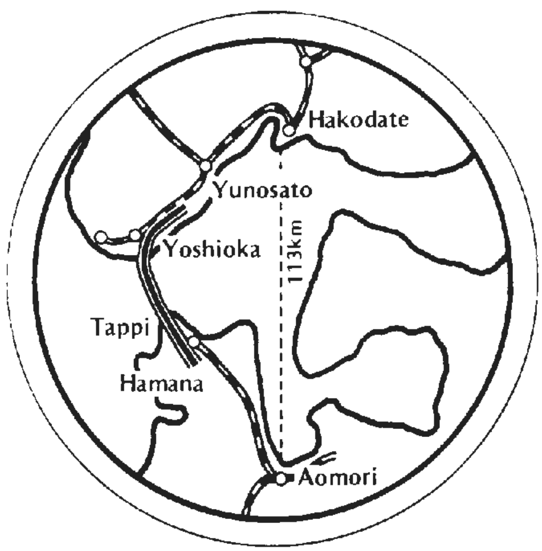


Figure 18. LOCATION OF SEIKAN TUNNEL

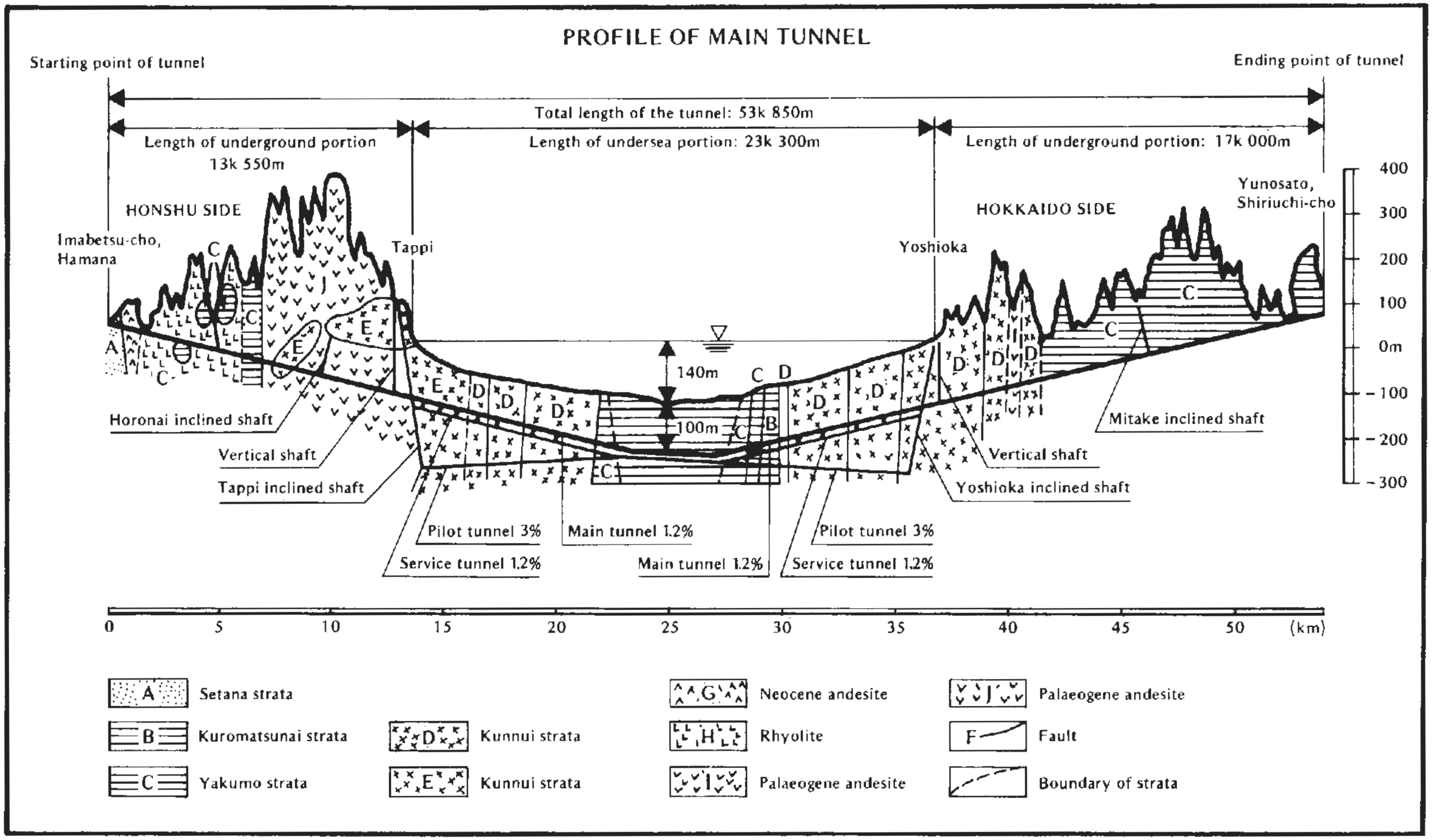


Figure 19. CROSS-SECTION ALONG AXIS OF SEIKAN TUNNEL.

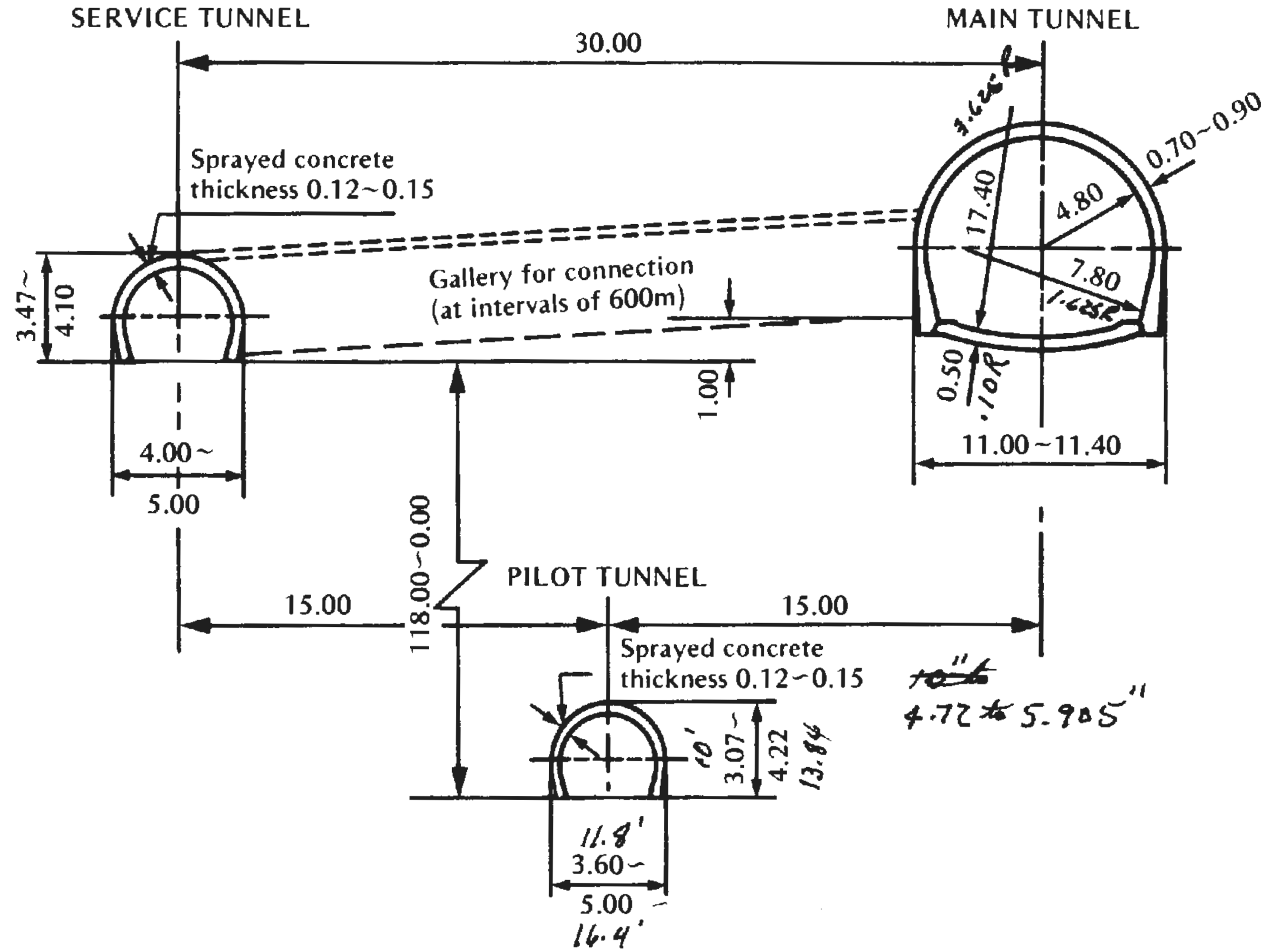


Figure 20. CROSS-SECTION OF MAIN, SERVICE AND PILOT TUNNELS - SEIKAN PROJECT.

Perhaps the greatest problem during the construction of the tunnel has been groundwater. There have been numerous serious water flows through the rock into the tunnels, and, by experience, the Seikan tunnelers have developed an extensive chemical grouting scheme to overcome these problems. The basic idea of the scheme involves injecting a quick set grout from the face of the tunnel through 40 to 50 holes, under high pressure, into the rocks ahead of the tunnel face, so that the grout seals fissures and "heals" inherently weak planes along which water can flow. Subsequently, tunneling takes place inside the zone which has been treated by grouting.

In Figure 21, a schematic drawing demonstrates the geometry of the protective cones created by the successive face grouting operations. For the main tunnel, the grout zone is extended 70 to 90 m (230 to 300 ft.) ahead of the face. The grout pipes are set so as to diverge from the centerline of the tunnel and create a cone shaped protective zone. At its extremity, the cone is about 60 m (200 ft.) in diameter. The geometry of the system of overlapping cones is designed so that the tunnel always is surrounded by a zone of treated rock at least twice as thick as the tunnel radius (see Fig. 21). The purpose of this is two-fold:

1. To prevent serious water inflow into the tunnel (small leaks continue to occur; while the author was there salty sea water was observed to seep into the tunnel); and
2. To strengthen the rock so as to form an outer structural shell around the tunnel liner which helps the liner carry the hydraulic pressures of the ground water (the liner could not economically be made thick enough to take the water pressures by itself).

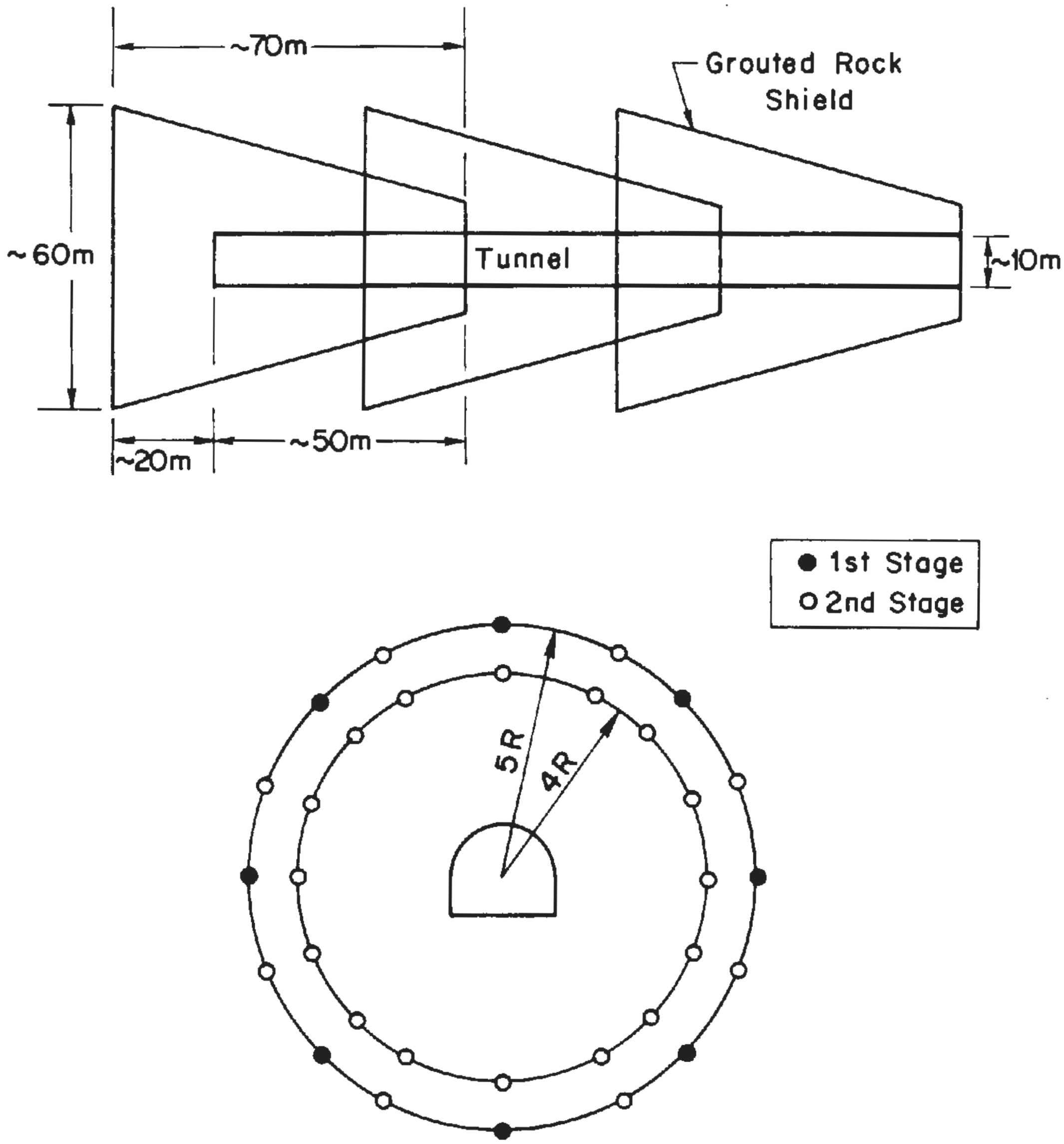


Figure 21. SCHEMATIC OF GROUTING ZONES USED FOR MAIN TUNNEL - SEIKAN PROJECT.

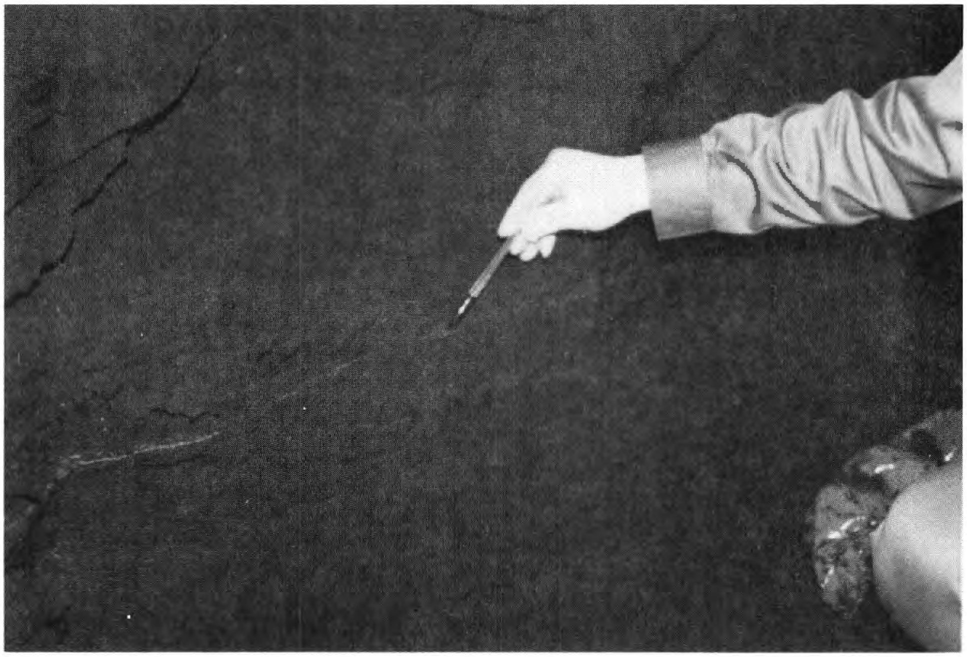
The time required for the grouting is of great importance to the tunneling progress since no tunneling can be done until grouting is complete. At the present stage, about one week is required for the grouting operation, and one week for tunneling to the point where grouting begins again. The 40 to 50 holes for the injections are drilled four at a time using a Gardener-Denver PR-123 percussion rotary rig. The holes are cased only over the first 5 m (16.5 ft.).

The grout mix was developed to be able to gel quickly and have an unconfined compressive strength of about 3900 kM/m^2 (560 psi). Rapid gelling is considered important in that the grout otherwise might migrate uncontrollably from the injection point. The strength is desirable because of the need to utilize the treated rock shell around the tunnel as a structural support element. The grout consists of a mixture of 50% sodium silicate solution (waterglass) and 50% portland cement "milk" (cement + water). This grout type is particularly useful because it is relatively cheap and non-toxic and does not give off any odors or fumes. The gel times are dictated by the water/cement ratio used for the cement "milk" as follows:

Water/Cement Ratio	Gel Time (minutes)
100	1.5
200	3
300	8

The "milk" with the water/cement ratio of 100 is the most commonly used form.

In the upper half of Figure 22, a photograph of the tunnel face shows the grout seams in the rock fissures. These were found throughout the rock. Pressures used to inject the grout into the rock reach 9800 kN/m^2 (1400 psi) even though the water pressures at this depth are



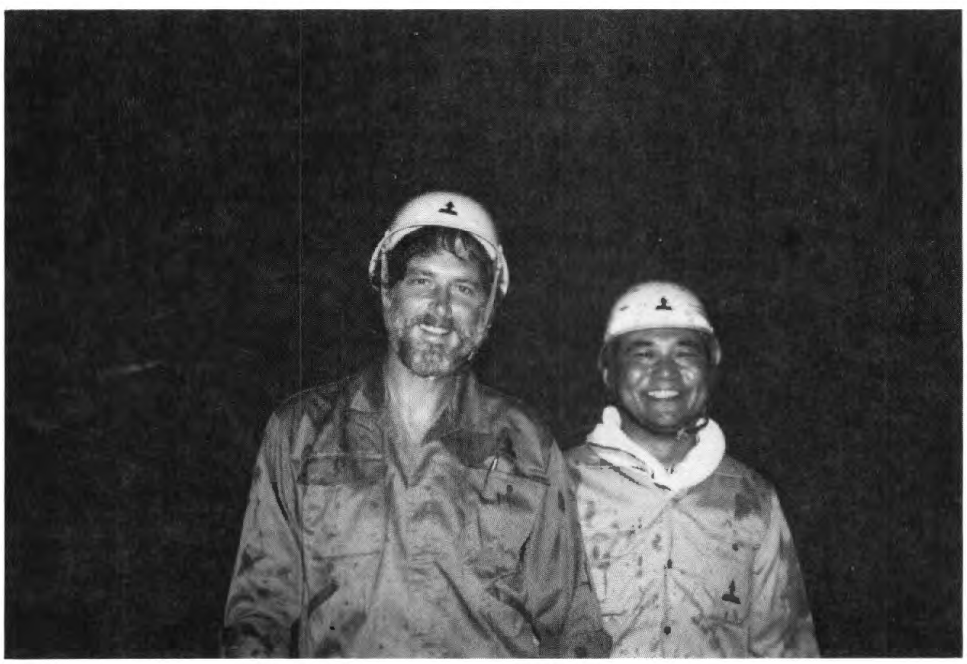


Figure 22. AT THE FACE OF THE NORTHERN SIDE OF THE SEIKAN TUNNEL, 240m BELOW SEA LEVEL: UPPER PHOTOGRAPH, GROUT SEAMS IN MUDSTONE; LOWER PHOTOGRAPH, AUTHOR WITH JNRR PROJECT MANAGER, MR. M. KUBOTA.

around only 2450 kN/m^2 (350 psi).

The lower half of the photograph shows the author at the tunnel face with Mr. M. Kubota, the Hokkaido side project manager for the Japanese Railway. This picture illustrates the fact that the tunnel is very warm at this great depth, with temperatures of around 29°C (85°F) and humidity of 100%. To reach the tunnel face, a crew train takes about 45 minutes; the grouting materials have to also be brought in via train.

SUMMARY AND CONCLUSIONS

This report presents observations made and information collected during a three week trip to Japan by Professor G. W. Glough in September of 1979. The purpose of the trip was to learn as much as possible about the soft ground tunneling procedures used in Japan which have advanced rapidly over the past decade. Motivation for the trip was provided by the fact that Professor Clough is in charge of an instrumentation program for an upcoming tunneling project in San Francisco where a Japanese Contractor, the Ohbayashi-Gumi Co., Ltd., will use a soft ground shield technique new to the United States. The information obtained is expected to help the research project team as well as serve as a guide to transportation officials in the U.S. who might well consider using the new tools developed in Japan.

Since the 1960's, there has been a concerted attempt by workers in a number of countries to develop shield tunneling methods for soft ground areas with a high water table which would eliminate the need for using compressed air in the tunnel. In the late 1960's and early 1970's, teams in England, Germany and Japan introduced versions of a shield which used a pressurized bentonite slurry to stabilize the face of the tunnel and prevent ground water flow into the work area of the shield. The slurry was kept between a bulkhead near the tunnel face and mechanical cutter head. The cutter head rotated and brought excavated soil into the bulkhead area through narrow rectangular slots. The soil mixed with the slurry and was pumped out to be ground surface where the two components were separated in a treatment plant. There were problems with the early models, but the designers persevered, and especially in Japan, it found increased usage after suitable modifications were made. One significant step has been the development of techniques to use a wide range of silts and clays for the slurry instead of bentonite. By 1978, over 70 projects had been completed using slurry shields in Japan.

The reasons for the rapid adoption of the new shield technique in Japan are:

1. Japanese environmental laws are very restrictive concerning use of conventional alternatives such as compressed air tunnels or cut and cover procedures.
2. The major population regions, namely the Tokyo Metropolitan Area and the Osaka-Kyoto-Area are located in wide alluvial plains where soft ground conditions prevail.
3. The large Japanese construction-design firms have excellent research facilities and have invested heavily in improvement of the slurry shield.

Along with the improvement of the slurry shield, Japanese engineers have developed newer types of equipment which are now competing for the soft ground tunneling market. The most frequently used of these to date is the earth pressure balance (EPB) shield. As with the slurry shield, the EPB shield utilizes a rotating cutter head with narrow slot openings, and the soil cuttings are temporarily held in a cuttings chamber whose back wall is a closed bulkhead. The cuttings are removed by means of a screw auger which passes through the bulkhead into the spoils chamber. By keeping a mechanical pressure on the cutter head, and the cuttings chamber full at all times, the earth at the face of the tunnel is kept stable. This "earth balance" is maintained by removing the cuttings by the screw auger at a rate exactly equal to that at which they enter the open slots of the cutter head. The system balance is monitored by an automatic control scheme.

The EPB shield can be used without special modifications in all soils but pervious sands below the ground water table. There are a number of techniques used if such conditions are encountered, including chemical stabilization of the sands if they are of limited extent. Alternatively, a version of the EPB shield can be used which applies a water pressure to the face of the tunnel via the screw auger system which balances the ground water pressure and prevents any tendency for ground water flow. The so called water pressure balance (WPB) shield has been used successfully in a number of difficult projects.

Finally, there is the "mud" shield which utilizes and extends concepts from the slurry and EPB shield. In this technique, the cutter head is replaced by a rotating four-pronged spoke wheel and the cuttings just in front of the bulkhead are mixed with a slurry. The slurry-cuttings mixture is not fluidized as in the slurry shield however, but becomes an impervious plastic mass. In this state the soil is removed from the bulkhead by means of a screw auger as in the EPB shield. The tunnel face is kept stable by means of a pressure applied to the plastic slurry-cuttings mixture. This type of shield has been used for primarily smaller diameter tunnels in six projects as of 1979. It is planned to use it in larger tunnels in 1980.

Daily advance rates reported for the different shield types are about the same, averaging around 6 m (20 ft.). General performance characteristics also seem similar; where ground settlements have been documented they have been small, generally less than 20 mm (0.8 in.), regardless of the type of shield. It appears that all of the shields are technically capable of tunneling under difficult soil conditions, although the slurry shield perhaps has an edge because of its more extensive experience record.

Along with the development of the new shields, liner supports have swung from steel to precast concrete. In all of the soft ground projects visited by the writer, precast segments are being used, except in areas where sharp turns exist. Waterproofing is provided by means of rubber or vinyl strips glued to the periphery of the precast segments. The segments were bolted together, and in one instance curved bolts were used which allowed automation of the bolt tightening process.

Two projects were visited by the writer where weak rocks were being tunnelled instead of soft ground. At one of the sites, the New Austrian Tunnelling Method was being used to choose the spacing and size of the supports. It was noted that a considerable savings in materials had been achieved, although labor costs were somewhat higher.

The other weak rock project visited was the famous Seikan Tunnel, which is the world's longest, and passes 240 m (790 ft.) beneath the Seikan Sea. Although the basic tunneling procedures being used are conventional, they have developed an extensive chemical grouting scheme to strengthen and impermeabilize the rock around the tunnel. A cone of grouted rock is created within which each tunnel advance takes place. The grout is a 50-50 mixture of sodium silicate and portland cement milk, a solution of water and cement. The grout gel time is 1 to 2 minutes and it sets up to have a considerable strength.

In sum, it may be said that the trip by the author resulted in an exposure to a wide range of advanced soft ground and weak rock tunneling techniques. The state-of-the-art of soft ground technology particularly seems to be changing rapidly. The slurry, EPB, WPB and mud shields appear to have considerable potential for applications in the United States.

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APPENDIX A

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Minato-ku, Tokyo 107, Japan

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