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Applications of New Technology

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Chapter 45

SHIELDED TBM's - MATCHING THE MACHINE TO THE JOB

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ABSTRACT

A shield on a tunneling machine has two basic purposes. Firstly to provide temporary support in unstable ground, maintaining the integrity of the bore and protecting the operators, and secondly, in conjunction with other sealing devices, to prevent the ingress of water.

In any specific tunnel, unstable ground and water may or may not occur together. Further, there are a number of different ground behaviors that may be termed unstable and these must be defined in order to determine the most suitable type of machine. Beyond the shield itself, the cutterhead and the mucking system design are critical in successfully traversing difficult geology. In any but the shortest tunnels, variations in the geological conditions and the requirement of an acceptable advance rate can impose increasing degrees of sophistication in the machine design.

In this paper we will review current designs of shielded type machines and their application, and discuss new developments which blend hard and soft ground tunneling technology. We will also indicate that in some conditions, although first impressions seem to favor a shielded machine, in fact an open gripper TBM may be the wisest choice.

REVIEW OF BASIC SHIELD DESIGNS

The essential variations in the design of shielded machines are to be found in the shield structure itself, the means of cutting and then removing the rock or soil, the way in which it is propelled forward, and the way in which it is steered.

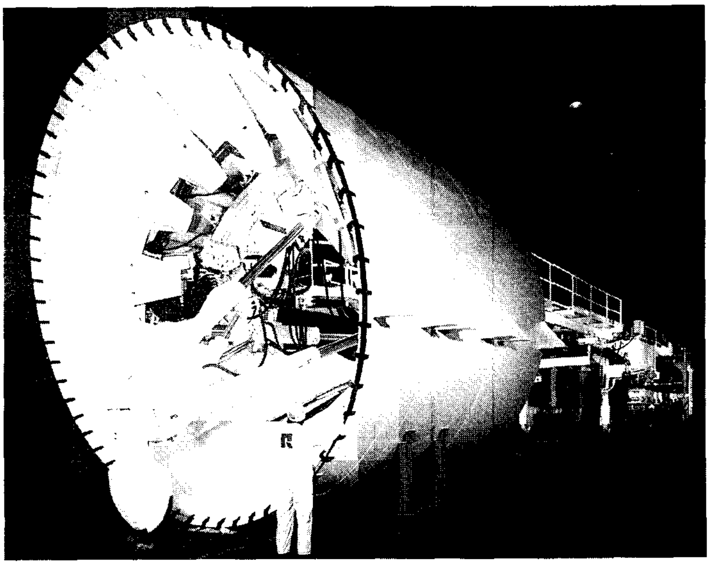

Figure 1. Excavator Shield 211S-237 for Seattle Metro (6.48 meters)

Excavator Shields

The simplest machine is an excavator type for soft ground. A boom mounted blade or pick is used to dislodge the soil which is then swept onto a conveyor. Breasting doors hinged around the upper periphery of the leading edge of the shield can be used to control the inflow of the material. If working below the water table, the machine may have to be operated under air pressure using a bulkhead behind the machine. Although this type of machine is not as fast as one with a rotary type cutterhead it does have some advantages. The shield can have a non-circular section, the face is accessible so that boulders or man made obstacles such as steel piling can be removed, and it is relatively cheap. On large diameter machines in very loose soil control of the face with an open machine is poor. Providing water inflows are not excessive, control can be achieved by using benches at the forward end of the shield.

These rely on the natural angle of repose of the soil to control the inflow. If the face characteristics vary between firm and running conditions then reconfiguration of the front end during the drive will be necessary.

Figure 1 shows the shield used on the Seattle Metro. In this case, accessibility to the face was required because of the presence of steel tie-backs along the alignment which had to be manually cut away, on the other hand when the machine ran into wet ground, the face became uncontrollable,and an extensive and complicated dewatering program became necessary, and the tunneling operation was delayed.

Rotary Type

Rotary type machines offer high advance rates and the ability to bore in rock of any strength. Drag bits are used as the cutting tools in weak rock, disc cutters in the harder materials. If boulders are expected in weak ground then a combination of discs and drag bits is advisable. In variable ground conditions, the ability to adjust the cutterhead speed is desirable. In fractured or very soft conditions a combination of low speed with high torque availability is required while in competent rock the ideal combination is high speed and lower torque. The simplest and most economical way this can be achieved is with two-speed constant power electric motors, but infinitely variable adjustment is the ideal. Hydraulic drives offer this capability, but will probably be superseded by variable frequency electrical systems in the near future.

Single Shields. The simplest configuration of shield derives its propelling force from a set of jacks in the rear that thrust against the tunnel lining, which is installed inside the shield. Figure 2 shows a single shield hard rock machine built for the island of La Reunion. This has a reversible cutterhead for correction of the roll of the machine caused by cutterhead torque reaction.

Steering of single shield machines requires a combination of the differential thrusting of the jacks and the ability to move the cutterhead in some way. The ability to move the cutterhead also allows compensation for cutter wear. In addition, when boring tight curves it is necessary to provide clearance for the shield. This particular machine has a one piece shield, and the cutterhead can be gimballed relative to it in order to overcut in any particular direction. In addition to the ability to move the cutterhead, an adjustable gage cutter can be extended to enlarge the bore diameter to open up shield clearance in a curve. Extension of the gage in hard rock can be achieved by using an additional single multi-row cutter, or shimming out the last four or five cutters. While it may be quicker to set up, the multi-row cutter may suffer heavy loads as it runs through muck debris in the invert. Soft ground machines use a radially extendable hydraulically operated cutter tool called a copy cutter, which can be set to overcut at any selected area of the periphery to open up shield clearance, however it is a major challenge to devise such a device for hard rock operation.

Steering problems have been experienced with some non-articulated single shields, basically designed for hard rock operation, when boring in weak fractured ground, because of the tendency of the machine to dive. An alternate approach is to provide an articulating joint in the shield. This method is preferred for soft ground machines, where it helps to counter the diving tendency, by providing a "planing surface" at the front end. An articulating joint however is more difficult to manufacture, particularly on the large diameter machines; it may have a tendency to bind, and requires a seal if the tunnel is below the water table.

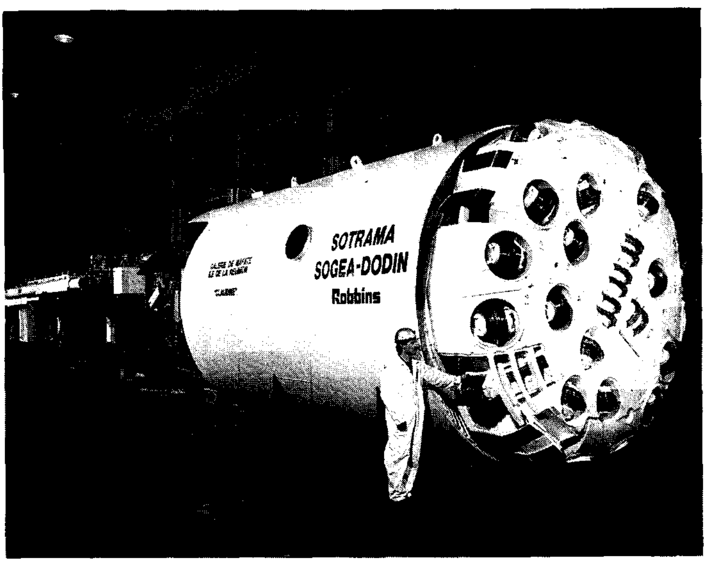

Figure 2. Single Shield 1411-260 for La Reunion (4.3 meters)

Besides articulation or overcutting, steering is also effected by controlling the hydraulic fluid flow either to individual or groups of the peripherally mounted jacks. In order to assess the ground forces acting on the machine and the necessary response, a display indicating the net center of thrust can be provided to the machine operator.

A disadvantage of the single shield is that with conventional cylindrical ring type segmental lining systems boring must stop while a new ring of segments is installed. This slows the overall advance rate. So-called "volleyball" segments, which are installed in a staggered fashion can be used to allow continuous boring and lining, but their use may not be acceptable for various reasons. The double shield system was developed to eliminate this problem in most conditions.

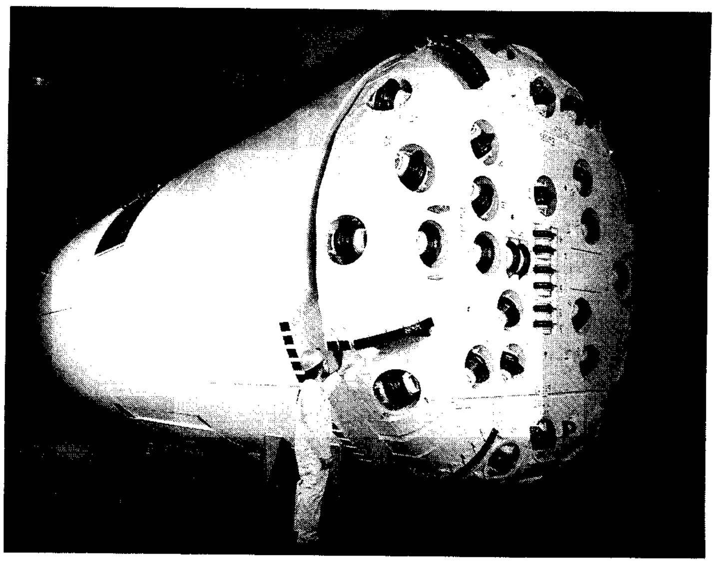

Figure 3. Double Shield 1811-256 for Yindaruqin, China (5.5 meters)

Double Shields. If the ground is firm enough that wall grippers can be used, then the lining can be installed as boring proceeds, thereby significantly increasing the overall advance rate. Also, as the propel forces are not reacted through into the lining, the machine can bore sections where lining is not needed. This is the principle of the double shield, conceived by Robbins and pioneered in the field by the Italian company, SELI. Figure 3 shows machine 1811-256 recently delivered to China.

A number of shields have been built in this style with considerable success. These machines are used where a mix of competent and weak rock is anticipated. In the weaker sections, if the wall strength is inadequate for grippers, then a set of auxiliary thrust cylinders in the rear section of the machine can be used to thrust against the lining. Between the front section, which incorporates the cutterhead and cutterhead support structure, and the rear section incorporating the grippers and auxiliary thrust cylinders, is a telescoping section and an articulating joint. Within this section are located the main propel cylinders which carry the thrust from the gripper section to the cutterhead support. These may be distributed in a lattice arrangement which allows the cylinders to react and control the roll of the cutterhead support, and provides very accurate control of the positioning of the cutterhead for steering. The steering action of these machines in the wall gripping mode is very positive as the rear section is gripped tightly in the bore.

A potential problem with this configuration is the possibility of muck jamming in the telescoping section, particularly in the crown and in the invert. Clean out holes are provided, but muck removal can still be difficult. The necked down telescopic section can be eliminated by reducing the diameter of the rear shield relative to the front, but this increases the backgrouting requirements behind the segments.

It is also difficult to provide a seal on the telescoping joint, so that the design is not suitable for operation under water inflows.

Another consideration is that the machine is quite long, and could get trapped in rapidly squeezing ground. This subject is dealt with later on in this paper.

Alternative Gripper Shield Configurations. The basic principle of the double shield as described above is the telescoping action that provides relative motion between the cutterhead and the gripper system. Another way of accomplishing this is to articulate the shield and to slide the cutterhead support inside the front section. This is the principle of the T1 Channel Tunnel machine described later on. This is more expensive, but is relatively easy to seal against water pressure. One problem is that the periphery of the cutterhead becomes exposed as it leaves the shield.

There are other ways of accomplishing the telescoping action, including the concept of building an articulated shield around a standard gripper type machine, with provision for a protected window in which the grippers can slide longitudinally, but they are at the expense of increased complication.

GEOLOGICAL CONSIDERATIONS

Shielded machines are used where there is a possibility or a certainty that "difficult" ground will be encountered. The range of that difficulty is wide, however machines are being developed that are able to successfully cope with variations in conditions along a single drive. Traditionally, the major machine manufacturers have specialized mainly in either the hard rock or the soft ground category. Now that there is increasing demand for "universal machines", the range of application of their products is broadening.

Classification of Difficult Ground

The following types and condition of ground can be termed as difficult for excavation:

Fractured, faulted, blocky, raveling

The above in combination with water

Running and wet soils

Squeezing

Boulders

Clay and other sticky soils

In order to cope with these conditions, mechanical systems of increasing sophistication are required. With any "loose" ground, the main problem is controlling the flow of material. Control of this flow is important for two main reasons: the prevention of subsidence where this is harmful to existing structures such as buildings and roadways, and the prevention of the creation of voids and chimneys which make it impossible to install an adequate tunnel lining. It also causes unnecessary overloading of the machine muck handling system.

MACHINE CONFIGURATIONS RELATED TO GROUND CONDITIONS

At this point we would like to raise a note of caution. Because of all the perceived advantages of shields in dealing with difficult conditions, there may be a tendency to specify one when in fact an open machine may be better. This would be in cases where limited stretches of bad ground are predicted, but which can be adequately dealt with by erection of temporary support such as ring beams, rock bolting, and shotcrete. An open machine is simpler, cheaper, easier to steer, and in all except the worst conditions less likely to become trapped. Naturally the geotechnical experts have to be conservative in their assessment of the conditions. Unfortunately this often leads to specifying a machine which is not ideally suited to the task.

Fractured Ground - Control with the Cutterhead

Dry, blocky or raveling ground can usually be controlled by mechanically restricting the flow into the cutterhead by reducing the openings of the muck entry buckets with grill bars. Pieces too large to enter will be broken up by the cutters. To make the bucket entry readily adaptable to hard competent rock and fractured conditions, the degree of opening can be controlled with hydraulically adjustable shutters. These are not easy to design as they must move easily without jamming yet be extremely rugged. Besides having these features, cutterheads designed for blocky ground operation should be as smooth as possible, using recessed cutters, to allow the muck to move across the face easily without hanging up. In addition a variable speed cutterhead assists in controlling muck inflow.

Water Inflow

The situation becomes much more difficult if water is present. The source of water and the pressure at the tunnel can varies over a wide range. In mountainous areas underground streams can flow through fractured ground. When tunneling under large bodies of water there is always the possibility of unlimited water entering the tunnel through fissures connected to the water source.

If the amounts of water are limited then pumping out the initial inflow followed by grouting off of the source may is an effective option. Probe drilling ahead to detect the presence of water followed by pre-grouting can choke off the water inflow before it becomes a major inconvenience. In these cases, providing there is no other major reason to employ a shielded machine, an open gripper TBM can cope well. The reliability of the geological report must be assessed critically. The tunnels at the Seabrook nuclear power plant in New Hampshire were successfully driven under the sea bed, experiencing considerably less inflow than had been predicted. On the other hand, during the driving of the Walgau tunnel in Austria, water inflows encountered in fault zones were far greater than had been anticipated, and a great deal of time was lost mining ahead of the machine (open gripper type) to stabilize the ground.

In situations where large amounts of water can be expected, and grouting would either be ineffective or consume excessive time, a fully shielded and sealed machine is necessary. In this case a gasketed tunnel lining must be continuously installed within the shield, and a sealing arrangement provided between the outside of the lining and the inside of the shield. The mucking system must be provided with some form of pressure lock device to prevent the free flow of water from the face through the machine.

Channel Tunnel Machines. Figure 4 shows the Robbins machine built for the French side seaward service tunnel for the Channel Tunnel (T1). It was known that that off the coastline the ground was fissured right through from the sea bed to the tunnel alignment. Rather than relying on grouting, the machine was designed to work in a fully submerged condition. Fissured areas were expected for only about half of the the total boring distance, but the machine was actually designed to operate under the pressure which would be experienced at the lowest part of the tunnel, 10 bars, in case water inflow was experienced at that point. The excavation was through a competent chalk marl, so face stability in itself was not a problem.

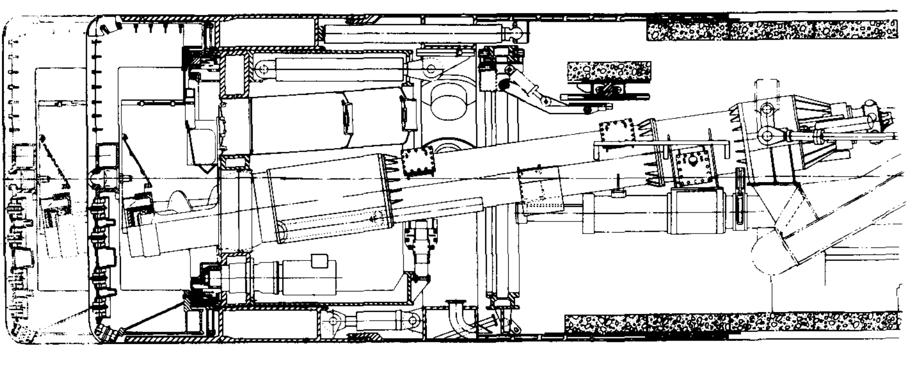

Figure 4. Channel Tunnel Marine Service Machine 1810-235 (5.6 meters)

The muck is extracted through a screw conveyor and, under pressurised conditions, discharged to atmosphere via a positive displacement pumping unit, known as a piston discharger. The unit actually contains two adjacent pistons to provide adequate throughput capacity. The cycling rate and valve timing are controlled electronically. In concept the unit is similar to a concrete pump. The unit has the virtue of simplicity and positive control of the pressure. The valve action ensures that at no time is the high pressure connected to atmosphere resulting in a catastrophic water discharge. Problems arising with the unit are the fact that a considerable amount of water is discharged along with the muck, and that the pressure in the cutterhead chamber drops momentarily during the intake portion of the discharge cycle. This fluctuation caused some problems to the pressure balanced lubrication system of the cutterhead bearing. This system was incorporated to decrease the pressure differential across the seals.

Any pressure lock system using sliding gates as valves is susceptible to muck jamming. However, the chalk marl, because it is weak, is easy to shear through and no problems have been experienced on this score.

Because the majority of the tunneling was expected to be in dry conditions, the machine is designed for dual mode operation. The cutterhead support is mounted on a telescoping drum, sliding inside the forward section of the articulated shield. If there is no water under pressure at the face, boring is accomplished by advancing the drum relative to the shield. Wall grippers in the rear section of the shield absorb the thrust and torque loads. This enables the lining to be installed simultaneously with boring. The principle is the same as in the more conventional double shields referred to previously, except that in this case sealing is essential, and it is far easier to provide a sealing arrangement with the internal drum rather than on an external telescoping surface. The disadvantage is in increased complexity and cost, plus the fact that the periphery of the cutterhead becomes exposed as it extends beyond the shield. The latter was not considered a problem in unpressurised conditions, but under pressure it was considered risky. Under pressure therefore the machine bored in the closed mode with the cutterhead retracted and was propelled forward by jacking against the lining.

Sealing at the rear end of the machine between the inside of the shield and the concrete lining is accomplished by the use of four rows of wire brush seals continuously injected with a special grease.

<u>Emergency Water Control.</u> The marine running tunnels on the English side of the Channel Tunnel were bored by machines built by the Robbins-Markham Joint Venture. These are substantially conventional double shield types, not being designed to bore under water pressure as are the French side machines. The geology on the English side was expected to be competent, although there was concern that unrecorded and / or unsealed exploratory boreholes might be encountered which could lead to flooding of the tunnel. Two emergency means of isolating the water are provided. The first is a "piston ring" seal on the periphery of the front shield, which can be hydraulically expanded against the tunnel wall, actually digging into the soft chalk. The second is a means of sealing off the belt conveyor entry. A bulkhead seal attached to the front end of the belt conveyor, normally located forward of the cutterhead support structure, can be moved into the sealing position by retracting the conveyor. At the time of writing no such emergency has arisen.

Running and Wet Soils - Pressure Bulkhead Machines

These types of ground conditions are found frequently in urban conditions as many cities are located on alluvial type deposits. When tunneling in such areas it is important to avoid ground settlement which can damage existing structures. Running and flowing wet ground cannot be adequately controlled by reducing the opening of the muck entry. It is necessary to employ some form of pressure control from within the cutterhead chamber to prevent the face from collapsing.

Sources of pressure that can be used are air, fluid, and the excavated muck itself.

Compressed Air. Compressed air can be applied to the total machine by being confined behind a bulkhead to its rear. This is commonly done in the case of excavator type machines. In this case the machine operators have to work in the elevated pressure zone. To avoid this problem Robbins manufactured a rotary machine for the Paris Metro in 1964 that confined the air to the cutterhead and the primary mucking system. A cyclic airlock hopper system at the rear of the machine was used to discharge the muck to atmospheric pressure. The machine successfully bored some 2800 meters, but suffered some problems that are inherent with compressed air tunneling. Air seals needed frequent replacemnt. Lignites in the ground were easily ignited in the oxygen rich atmosphere. The air pressure is uniform across the face whereas the water pressure depends on the height, requiring a compromise setting.

As in any compressed air application, there is always the possibility of air loss through the ground and, under low cover, a catastrophic blowout. However, interest in this method is being revived as disposal of the mud additives used in slurry and EPB machines discussed below becomes more environmentally sensitive.

Slurry Machines. A moderately viscous fluid under pressure is easier to seal than air under the same circumstances. Slurry machines, using a fluid mix of water and bentonite, are in common use, particularly in Japan and Europe. The fluid is used for two purposes; to provide a pressurized medium for face control and to transport the muck out of the cutterhead chamber. In urban situations, where tunnel lengths are of the order of a kilometer, the slurry system is also used to carry the muck right out of the tunnel to a separating plant on the surface. A recent development for longer large diameter tunnels has been to incorporate a primary muck extraction system on the backup system itself, with a secondary, smaller capacity circuit for fines separation extending back to a plant at the portal. The pressures and flows in the slurry circuit are dynamically related, and a complex control system is required. One problem facing slurry tunneling is the increasing amount of restrictions on the disposal of bentonite contaminated muck.

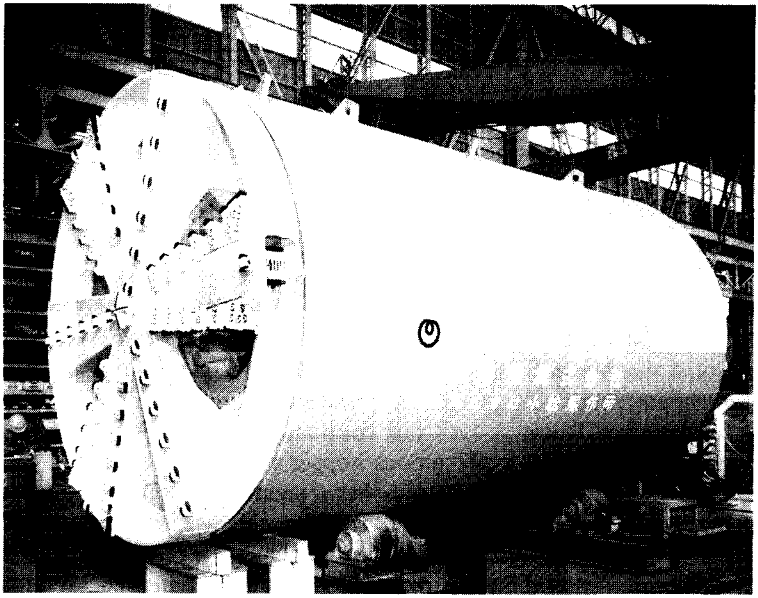

Figure 5. Komatsu Earth Pressure Balance Machine (3.26 meters)

Earth Pressure Balance Machines. The third option of face control, by controlling the flow of the excavated material itself, is realized in the Earth Pressure Balance machine (EPB). This type of machine has been developed by the Japanese to an advanced level of sophistication, and now holds some two thirds of the market in pressurized bulkhead machines in the small to medium diameter range (up to about 8.5 meters) in Japan. Figure 5 shows a Komatsu EPB shield. The muck is extracted from the cutterhead through a screw conveyor, the speed of which can be adjusted to maintain the cutterhead chamber full of muck and thereby providing a continuum of soil from the face back to the screw exit. The amount of water percolating through the excavated soil depends on the fines content, and if that is insufficient, then clay or chemical additives are injected. The additives also improve the viscosity of the coarser materials to facilitate their passage through the cutterhead chamber and screw and provide greater control. The additives themselves are the subject of much research. As in the case of slurry machines, dumping of contaminated muck is becoming restricted because of environmental concerns, and non-toxic, biodegradable, and post-treatment additives are being developed.

Squeezing Ground

One of the most difficult geological conditions to deal with is squeezing ground. This is usually found in weak rock under high cover. Typical examples include layers of clay or severely fractured and sheared rock found at the edges of a fault. The parameters of interest are the rate of squeeze, the amount of inward movement until stability is achieved, and the squeezing pressure, all of which are extremely difficult to predict. If the rate of inward movement of the tunnel walls is relatively slow, then the machine can move ahead before it becomes trapped. Of course, if for some reason the machine cannot advance, due to breakdowns (or in some unfortunate cases due to the labor force insisting in taking time off), then it may inevitably become trapped. Machines having rigid shields are the most difficult to free in such circumstances, and the longer the shield the greater the problem.

For this reason, if squeezing ground is predicted, the advisability of using a shielded machine should be carefully reviewed. An open machine with conventional adjustable roof and side supports has great flexibility, and is less likely to get trapped. On the other hand, in such conditions the tunnel wall may not be able to withstand the gripper forces. Temporary methods of wall reinforcement, such as the use of liner plate, or the use of auxiliary thrust cylinders reacting against invert segments may be employed. Some form of temporary support such as ring beams and shotcrete will have to be installed. A segmental tunnel lining is the best protection against squeezing, but it is not usually practicable to erect lining ahead of the grippers.

If a significant proportion of the tunnel geology is unsuitable for the use of an open TBM, because of fractured or running ground, then a shielded machine will be necessary. This raises the question as to whether a double or single shield should be used. The shorter single shield is less likely to get stuck, but it is inherently slower than the double, as it relies for its thrust and torque reactions on the lining. If it is intended to install segmental lining only when necessary for ground support, then an auxiliary gripping reaction ring can be temporarily attached behind the shield when lining is not being placed.

Solutions to the Squeezing Ground Problem.

We will review some of the options available if the use of a shielded machine cannot be avoided.

<u>Bentonite Injection.</u> Bentonite injection on the outside of the shield can be used to reduce the ground friction. The problem is ensuring an adequate dispersal of the fluid across the shield surface to cover an effective area.

Overcutting. The bored diameter can be temporarily enlarged beyond the normal amount of overcut outside the shield body diameter. This increases the time period available before the ground moves in to grip the shield. The disadvantages are that the extra overcut means a considerable increase in the backgrouting requirements behind the segments, and the means of achieving the additional overcut result in additional complexity to the cutterhead and cutterhead support arrangement. Assuming the machine is built for mainly hard rock use then the cutter spacing adjacent to the gage must be kept to the normal proportions. This means either that a number of the cutters must be shimmed out in a progressive manner or that a single radially adjustable multi-row cutter must be used. In addition the cutterhead must be elevated in some manner so that the invert cut is not below the bottom of the shield resulting in the machine diving.

Stepped or Tapered Shields. With a double shield, the rear section, instead of being the same diameter as the front, can be stepped down to match the diameter of the telescoping surface. This will reduce the chances of trapping the rear shield, especially as the rear shield is exposed to the incoming ground for greater time than the front as the shield advances. Also, the muck jamming that can occur in the normal telescopic configuration can be avoided. Tapering of the shield towards the rear is also an option, on single and double shields. The disadvantage is that the necessary enlargement of the tunnel bore relative to the outside diameter of the lining necessitates a great deal of extra backgrouting.

The previous approaches are open to the objection that in the case of a prolonged standstill, shield entrapment may be inevitable. However the chances of this happening may be accepted in view of the fact that the mechanical arrangement required is less complex than the alternatives below.

Contracting Shields. In ground defined to be "squeezing", inward movement following removal of support is not instantaneous, and even a relatively small inward movement of a few millimeters should be enough to release the machine. Contracting the shield can be accomplished by incorporating longitudinal splits on each side of the shield at the springline and lowering the entire upper section relative to the lower, using hydraulic power. On freeing the machine it is imperative that the shield be expanded back to its original diameter as quickly as possible, to avoid running out of contracting capability in case of further squeezing. Splitting the shield in this way is not simple; it is not easy to provide radially adjustable telescoping and articulating sections, and the shear and torsional loads normally absorbed by the rigid cylindrical body must be reacted through sliding keyed surfaces. This approach assumes that the main direction of squeeze is vertical, which may not in fact be true as in-situ stresses can in fact be lateral, depending on the geological history. In any specific case the opinion of the geotechnical consultants should be solicited.

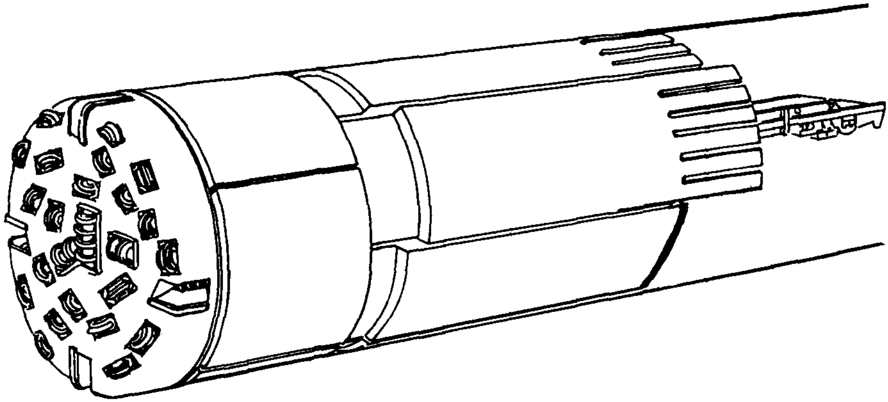

Figure 6. Walking Gripper Machine

An alternative to the split type shield is the "walking gripper" type. In this design the shield is split into a number of parallel sided segments, the alternate segments acting as two independent groups, one acting as a gripping set while the other set advances. This allows the machine to advance continuously without having a regrip cycle to reposition the grippers. The advancing set is pushed against the tunnel wall with just sufficient pressure to provide support to the wall. The number of segments can be as few as four, although in the case of the machine which became trapped in the Stillwater Tunnel, Utah, and which was modified to this configuration in situ, there were twelve segments. The modification was carried out on a double shield machine which became trapped in a squeezing situation in the Stillwater tunnel in Utah. Figure 6 shows a six gripper version. In this machine the cutterhead configuration is similar to a conventional open machine. In conjunction with the segmented rear section the machine is effectively a double shield. Although this machine provides the flexibility to cope with squeezing ground the inevitable gaps in the outer structure make it virtually impossible to seal againt the ingress of water and fine materials.

Boulders

Boulders encountered in a matrix of softer material have been a major problem for rotary tunneling machines. They will easily break drag tools and jam mucking systems.

Boulders up to 8 inches (200 millimeters) or so can usually pass through belt conveyor, screw conveyor, and slurry systems. Reducing larger ones to this size can either be done by restricting muck entry through the cutterhead by the use of grill bars or slots, relying on the disc cutters to break them down until they are small enough, or by using a crusher at the entry to the mucking system. The duty for a crusher is severe, increasing dramatically with the hardness of the rock. It may have to operate underwater, it must have an acceptable throughput and be accessible for the inevitable repairs.

In EPB applications where boulders are anticipated, a shaftless ribbon type screw conveyor is used in order to maintain throughput capacity within the same envelope, yet provide clearance for the boulders between the flights.

Clays

Apart from the squeezing and swelling (expansion due to stress relaxation and water absorption) characteristics of clays which can cause shield entrapment and difficulties in lining placement, the major problem in tunneling in clay and similar materials is the poor flowability caused by their inherent stickiness. In open mucking systems, buckets, chutes and hoppers can become clogged, and even in slurry systems coagulation of clay in the pipelines can cause blockages.

Mechanical handling of clay generally requires a cutting or scraping action which is often impossible to achieve in the bucket scoop and transfer chute areas of a cutterhead. If the machine is boring through varying geology the handling requirements of the more freely flowing materials and the clays cannot both be accomodated easily.

Lining materials such as stainless steels and teflon have been tried with limited success. Flushing with water jets can be effective, but excessive amounts of water in the muck can cause problems in the later stages of the muck handling system, with conveyor belts, muck cars, and final disposal. Chemical additives may be developed to alter the undesirable characteristics, but as in the case of the EPB and slurry type additives, they will have to be environmentally acceptable.

EXPANDING THE RANGE OF SHIELDED MACHINES

Hard / Soft Ground Machines

Demand is increasing for machines that can operate in hard rock and soft ground with little or no modification in going from one type to another. Robbins is answering this demand with the Wide Range Shield (WRS). This combines the lessons of long experience in hard rock machines with soft ground expertise gained from licensing agreements with Komatsu.

The machine illustrated in figure 7 can operate in an open (hard rock) mode or closed EPB mode. Muck extraction is by screw conveyor in both modes. A screw conveyor is essential for accurate metering of the discharge of muck in the EPB mode so that face stability is maintained. In the open mode a hopper is necessary to feed the muck to the conveyor entry, but as it would impede flow in the fluid EPB mode, the hopper can be rotated 180 degrees out of the way. The cutterhead power is higher than that generally associated with Japanese machines to reflect the higher performance required by contractors outside Japan. The cutterhead is provided with a wide speed range to allow maximum performance in each mode, by the use of variable frequency electric, or hydraulic drive. A constant horse power characteristic offers high speed and low torque for hard rock and low speed with high torque for the EPB mode. The shield is articulated to provide good steering control and to allow for cutter wear. The cutterhead is unidirectional to provide the optimal muck bucket configuration. Roll control is accomplished using a skew ring. This is an alternative to the use of a bidirectional cutterhead, which is a less complicated approach, but which may have reduced mucking efficiency as dual direction bucket scoops are required.

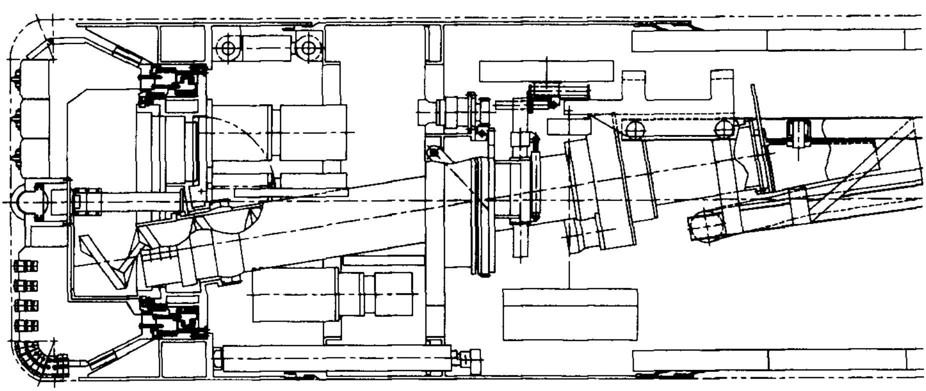

Figure 7. Wide Range Shield (Hard Rock / EPB)

Submerged and Slurry Machines

The T1 Channel Tunnel machine referred to above has been successfully operated under a water pressure of 9 bar using the piston discharger. However the particular tunneling medium, chalk marl, was easily sheared by the discharger valving. Underwater projects can be expected in the future in fractured hard rock, requiring pressure locking devices that can operate without the possibility of jamming on large, hard particles. In conjunction with the pressure lock an efficient muck dewatering system is needed.

Such a pressure lock and dewatering device also has a further use in a modified version of the conventional slurry system. Called a "Low-flow" slurry system, the pressurised slurry is used to stabilise the face, but not as a transportation means for the muck. Instead the muck is extracted from the cutterhead chamber by a screw conveyor and discharged through a pressure lock. This system offers a very positive control of the slurry pressure and does not require the high capacity pumps and large diameter pipelines of a standard system. A small capacity secondary system is used to separate out the fine particles which do not exit through the pressure discharge device. The screw conveyor can accomodate fairly large boulders. Figure 8 shows a conceptual layout of the system on an 11 meter machine. The full face cutterhead with recessed cutters will break up boulders to a size which can pass through the long narrow mucking slots. An additional feature of this machine is that it can be operated in open (competent ground) and closed mode (unstable face) with a quick changeover time. This is achieved by placing the screw conveyor and a belt conveyor side by side inside the main bearing cavity. To convert from the open mode to the slurry mode the belt conveyor is retracted and a pressure resistant bulkhead installed.

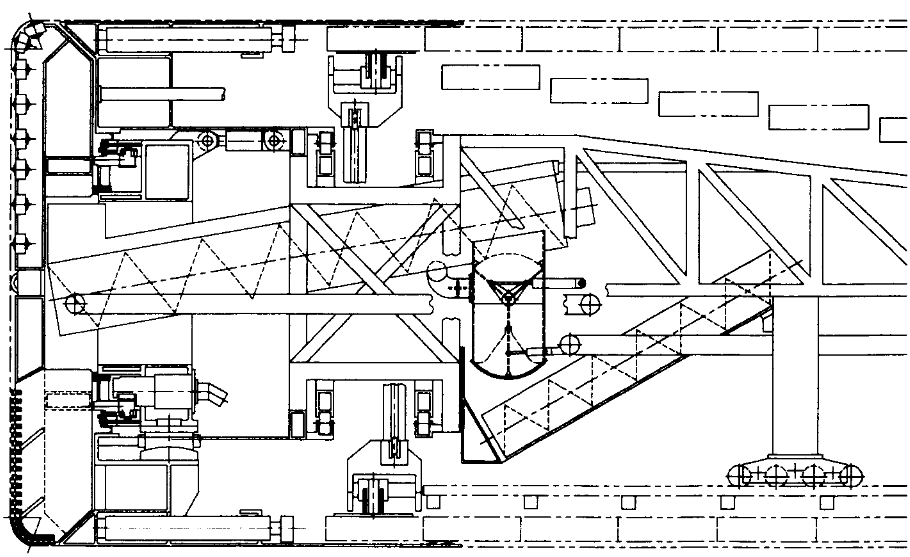

Figure 8. Low-flow Slurry / Mixed Ground Machine

CONCLUSION

A number of markedly different designs of shielded tunnel boring machine have been developed to cope with the tremendous variety of ground conditions that can be encountered. The limits of reliable and economical machine tunneling are being continuously expanded, thanks to the efforts of tunneling engineers all over the globe.

Now, the range of application of individual machines is increasing dramatically. Widening the range so that a mixed ground tunnel can be bored by one machine has the benefits of reducing equipment inventory and allows for more accurate project scheduling.

On any specific project however, careful consideration is necessary of the type of machine, narrow or wide range, shielded or unshielded, that most suits the true technical and economic priorities of the job.