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An Insight into Mechanized Tunneling with Tunnel Boring Machines

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Abstract: ***History has seen the evolution of tunnelling starting with cave formation, for water management, underground transportation, and mineral extraction and for warfare purposes. Tunneling technology has advanced since the 1950 from the conventional drill and blast techniques to the most advanced and sophisticated mechanized tunneling with tunnel boring machines. The range of scenarios in which tunnel boring machines are deployed is continuously expanding, from clays to granular soils to highly fractured or monolithic rock masses, from partially to fully saturated ground, and from mountain ranges with high overburden pressures to sensitive urban areas with low overburden. Today, the application range of tunnel boring machines is being extended to an ever increasing variety of geotechnical conditions. This review paper gives an overall perspective of tunneling with tunnel boring machines and suitability of tunnel boring machines for soft ground conditions***

Keywords: Tunneling, Tunnel Boring Machines, Earth Pressure Balance Shield, Slurry Machines**.**

1. Introduction

Tunnels have played a vital role in the evolution and sustenance of man-kind through the ages. The ever increasing needs of the modern human race have driven the tunnelling technology to its pinnacle. This is being realized through rapid advancements in terms of geological and hydrogeological engineering, tunnel design, capacity, construction methods and speed and maintenance during operations. Several tunnel construction methods are opposed in a competition, each with its advantages and drawbacks. Tunnel Boring Machines have progressively overcome their initial flaws and are currently put at work in increasingly demanding projects. Civil engineers and tunnel builders simultaneously gain confidence in the technology and the extended capacity of TBMs, and actively fuel this search for higher performance and versatility. Tunneling techniques has advanced from the cut and cover method for shallow excavations, drill and blast methods for hard rocks to bored tunneling with Tunnel Boring Machines for diverse soil strata. Tunneling techniques have also been found wide applications in the form of immersed tunneling for crossing water bodies to jacked box tunneling used below a busy road or railway crossing.

2. Mechanized Tunneling with Tunnel Boring Machines

Mechanized tunneling are all the tunneling techniques in which excavation is performed mechanically by means of teeth, picks or disks. These tunneling techniques comprise of a wide range of techniques from the simplest excavation with backhoes to the most complicated Tunnel Boring Machines. Mechanized tunneling is now performed with a tunnel boring machine TBM and they can bore through hard rock to soft ground. TBM (Tunnel boring machine) is used for the excavation of tunnels with a cross section of circular as well as rectangular shape through the different types of rock and soil strata. Diameters of the tunnel excavated by using the TBMs may range from 1 m to almost 16 m to date. TBMs have limitations in term of fixed or predetermined tunnel diameter and shape. Once the shape and diameter of tunnel is decided then it is impossible to change it along the length of TBM drive. Anything from sand to hard rock can be bored by using the tunnel boring machines, therefore nowadays TBMs are using as an alternative to drill and blast methods in soil and hard rock mass. During the excavation process of tunnel, tunnel boring machines limit the ground disturbance and produce a smooth wall for tunnel. Modern TBMs consists of several systems such as a boring system which includes the disk cutter and cutter head, followed by a thrust system that provide forward movement and the gripper shoes that are pushed against the sidewall, muck removal system which removes the muck from the bottom of the cutter head and using the conveyor, transport the muck to the rear of the machine and support system which consists of the roof shield and drills for installing.

3. A Closer Look into TBM

The tunnel boring machine is a machine which has been developed in recent years and has revolutionised the tunnelling industry both making tunnelling a safer, more economical solution for creating underground space and opening the possibility of creating tunnels where it was not feasible before. A TBM can cut through rock at up to one kilometre a month. Powerful hydraulic rams force the machine’s cutting head forwards as the rock is cut away called the feed. Depending on rock strata and tunnel requirements, the tunnel may be cased, lined, or left unlined. This may be done by bringing in precast concrete sections that are jacked into place as the TBM moves forward, by assembling concrete forms, or in some hard rock strata, leaving the tunnel unlined and relying on the surrounding rock to handle and distribute the load. Tunnel boring machines (TBMs) and associated back-up systems can be used to highly automate the entire tunnelling process. There are a variety of TBMs that can operate in a variety of conditions, from hard rock to soft water-bearing ground. Some types of TBMs, bentonite slurry and earth-pressure balance machines, have pressurised compartments at the front end, allowing them to be used in difficult conditions below the water table. Mechanized tunnelling with TBM has the benefit of higher and sustainable progress rates for good quality hard rock conditions. Penetration rate us even higher for soft ground conditions. As lesser damage is caused to tunnel profile, less support is required. Lower ventilation requirements allow smaller tunnels to be constructed. As the blast and dust generation is less compared to other tunnelling techniques, the process ensures improved health and safety conditions to workers. [4] But the major disadvantage is its high upfront cost and the time required for assembling and mobilization of the components and backup systems. Moreover it can provide only a circular geometry for the tunnel. The presence of a high proportion of highly altered and weathered bed rock may demand more tunnel support systems, thus hampering the TBM progress. It has limited flexibility in response to the extremes of geological conditions. [1]

3.1 Parts of a TBM

A tunnel boring machine (TBM) typically consists of one or two shields (large metal cylinders) and trailing support mechanisms. At the front end of the shield a rotating cutting wheel is located. Behind the shield, inside the finished part of the tunnel, several support mechanisms which are part of the TBM are located: soil/rock removal, slurry pipelines if applicable, control rooms, and rails for transport of the precast segments. Depending on the type of TBM, the muck will fall onto a conveyor belt system or into skips and be carried out of the tunnel, or be mixed with slurry and pumped back to the tunnel entrance. The component parts of a TBM are

- Cutter head-Cutter head consist of cutter housings with disc cutters that can excavate the rock or soft ground by the rotation of the cutter head. There are several types of bits for TBM, such as teeth bit, peripheral bit, centre bits, gouging bit, wearing detection bit, etc. Arrangement of bits on the cutter head is decided based on construction conditions, past experience in similar geology, cutting depth and the number of passes of rotating bits.
- Shield Body Structure- The front shield body consist of excavation area and operation area by the bulk head. The rear shield consist of thrust system, which consist of hydraulic cylinders, which drive the TBM forward and articulation cylinders which would be used in rectification and making a turn. A shield is provided with probe drill injection ports, additive and grease injection ports. Man lock is installed at the flange seat above the bulkhead for TBM under closed model use. At the end of the shield, tail shield is provided which prevent water and grout flowing into the tunnel shield.
- Segment Erector- The erector mounted on the rear shield can rotate, slip and lift the precast concrete segments which is used as tunnel lining.
- Segment hoisting devices- Segment hoisting devices system consist of segment feeder device and single hoist beam. Single hoist beam unloads the segments from the segment car and provide it to the segment feeder. The segment feeder transports them to the erector area
- Muck Removal System- While cutter head is working and excavating in TBM, the muck is collected by the Screw conveyor constructed as an empty slot around the perimeter of the cutter head, which is delivered to the conveyor belt, which will be finally delivered to the wagons mounted on rails.
- Gantry- Backup gantries are arranged in the sequential order behind the segment erector. Six to seven back up gantries are arranged to the shield each gantry having specific attachments for various purposes.
- Systems in TBM- Various systems are arranged in the TBM in the shields and back up gantries for specific purposes. The systems in TBM are oil lubrication system for machine operations, tail grease injection system for preventing water and soil flowing back to tunnel shield, grouting system for injecting grouts into the grout holes provided in the tunnel lining, additives injection system for injecting additives like bentonite slurry as in case of slurry TBM, industrial water system, ventilation and de dust system, hydraulic system, electricity system, gas detection system, TBM guidance system etc. The component parts of a TBM is shown in figure 1

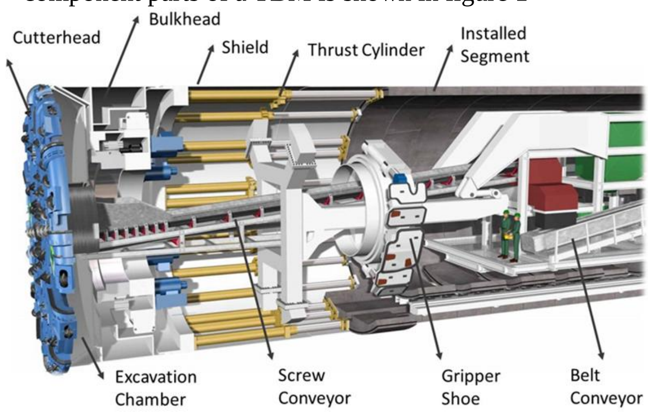

Figure 1: Parts of a TBM

3.2 Operating Sequence of a TBM

The TBM moves forward as it excavates the tunnel by extending the pushing jacks at the back. The rear section of the TBM is braced against the tunnel walls and used to push the TBM forward. When the advancement of the machine reaches the distance of the length of a ring, the excavation is stopped and the pushing jacks are retrieved, a concert circular ring in form of a numbers of segments are then put together at the tail of the shield. The pushing arms are once again extended in full contact with the concert ring just erected and excavation is resumed. The cycle of excavation and ring erection is repeated as the TBM advances to form the lining of the tunnel. The support mechanisms which are part of the TBM will help in muck removal, injection of slurry wherever applicable, injection of grouts and transportation and erection of precast segments. [2]

4. Types of TBM

Tunnel boring machines can excavate from hard rock to soft ground, depending on the type of TBM used. TBMs in general are classified as hard rock TBMs, soft ground TBMs and TBMs used in difficult ground situations. Hard rock TBMs are further classified into reaming machines and gripper TBMs. Soft ground TBMs are mainly shielded TBMs which is further classified into Open Face TBMs, Compressed air shield, slurry shield and Earth Pressure Balance Shield. Hybrid Shield TBMs are used for difficult ground situations such as soil rock mixed ground conditions or varying ground conditions. The various types of TBM for different ground conditions are shown in Figure 2

- Reaming Machines- These type of TBMs do not have a shield and they can be used for digging hard rocks. They are provided with a reaming machine at the cutter head face which facilitates drilling into the hard rock.
- Gripper TBM- A gripper TBM is a classic well known tunnel boring machine. This type of TBM is also described as open TBM. The area of application of this type of TBM is mostly in hard rock with medium to high stand-up time. Gripper TBM have capability to excavate hard rock of UCS up to 300MPa. Since no protection or support is given to rock masses while excavating, they may have difficulty in poor rock masses.
- Open Face TBM- This type of TBM has the cutter face open and is used for firm soil and soft rock which has good stand up time to support the excavation.
- Compressed Air Shield- When open face shield excavating groundwater-bearing soil, water penetration can be prevented by having the shield and a section of the tunnel protected by a lock system using compressed air. The required pressure is monitored continuously and adjusted automatically where necessary by a compressed air system consisting of two control circuits. The health consideration under compressed air pressure limits the usage
- Slurry Shield- TBM excavation face is supported by pressurizing bentonite in cutter head chamber. Circulation of the fluid flushes out the muck. Pressure is maintained by controlling discharge rates. Slurry TBM allows equal distribution of pressures against mixed face conditions. It has good performance in sands and gravels. Sequence of discharging the excavated muck for this type of machine consist of pouring the slurry into the cutter chamber while the soil is excavated, mixing excavated soil with the slurry and pumping the slurry mix to a slurry treatment plant where the soil is separated from the slurry and circulating the slurry back to the tunnel face for reuse.[6]
- Earth Pressure Balance Shield Machine (EPBM) - TBM excavation face is supported by pressurizing soil (earth) inside the cutter head chamber. Earth pressure in the chamber is regulated by the rate of earth discharge through the screw conveyor. Clay-water slurry is injected into the cutter chamber and is mixed with excavated muck. The slurry mix is pressurized to stabilize the tunnel face and create the driving force of the machine. It is very well adapted for excavating silty and clayey grounds.
- Double Shield TBM-It is a hybrid shield TBM which is used for rock -soil changing ground conditions. It combines the features of gripper and shield in one TBM, and enables fast excavation even in varying rock formations. In poor ground condition, it works as a single shield machine. When in rocks, grippers are used for forward movement.
- Mix Shield TBM- The cutter head has combined features for hard rock and soil excavation. It enables the shield TBM to excavate through both rocks and soils, and rock-soil mixed face. Mix-shield can be EPBM or slurry based. It is flexible in excavation of rock, soil, and mixed ground. Face pressure features are maintained by either EPB or slurry. [5]

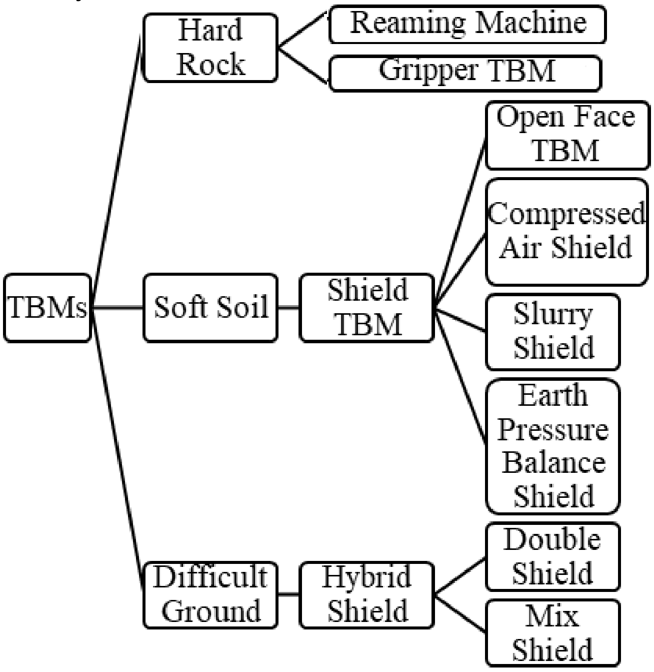

Figure 2: Types of TBM

5. Choice of TBM for Soft Ground Conditions

Anticipated ground behaviour in soft ground tunnels was first defined by Terzaghi based on Tunnelman's ground classification of soils. Soft soils behaviour to tunnelling in general, according to Tunnelman's ground classification for soils are classified as

- Running ground-need instant support all around. When exposed at steeper slopes greater than the angle of repose of the soil, they run like granulated sugar or sand dunes Water bearing sands and cohesionless soils come under this category
- Soft ground- Require instant support for roof like soft clay
- Swelling ground-ground absorbs water and slowly increases in volume and squeezes into the tunnel. Highly pre consolidated clay with plasticity index exceeding 30 comes under this category.
- Ravelling ground- Flakes of materials begin to drop out of the tunnel wall, once the ground is exposed. The ground cam be slow ravelling to fast ravelling depending upon which the support conditions vary. Residual soils with small amount of binder may be fast ravelling below the water table, while stiff fissured clays may be slow ravelling to fast ravelling depending upon the overstress.
- Squeezing ground- Ground has low frictional strength. Ground squeezes or extrudes plastically into the tunnel. Clay of very soft to medium consistency in shallow to medium depths come under this category.

- Firm ground- roof will stand for a few minutes and sides for a much longer period. Heading can be advanced without initial support and final tunnel lining can be done before the ground starts to move. Loess above water table, hard clay, cemented sand and dry earth comes under this category.
- Self-supporting ground – soil stands supported for a short period and for short lengths of 1200mm to 5000mm sand stones and cemented stones.

In selecting the type of TBM, it is important to consider geological and ground water conditions that affect the tunnel face. In specific case of tunneling in soft ground detailed geotechnical explorations should be carried out to decide the type of TBM to be used –whether EPBM or slurry. Geological condition along the tunnel route is a primary factor for deciding the type of machine. Soft ground characteristics can be analyzed after a detailed investigation which include

Soil identification
The main parameters to be identified are:
- Density, wet and dry
- Water content
- Grain size distribution
- Pore volume
- Abrasiveness (grain shape and hardness)
- Atterberg limits (when clay is present)
- Mineralogical analysis – where relevant
- Elastic modulus and Poisson ratio
- Cohesion
- Permeability
- Angle of friction
- -Undrained shear strength
- Determination of the initial stress conditions
- Study of mechanical characteristics
- Study of the hydraulic characteristics [3]

6. Choice between Slurry TBM & EPB

The choice of type of closed face TBMs and its applicability is a critical decision on soft ground tunneling projects. The decision will be guided by thorough assessment of the ground types and conditions to be encountered, particular experience of the contractor, logistics and configuration of the work, but the initial choice is guided by the grading envelope of soils to be excavated. The choice of an EPB or Slurry TBM is decided by the following factors.

6.1 Selection Criteria Based on Particle Size Distribution and Plasticity

A Slurry TBM is ideal in loose water bearing granular soils that are easily separated at the separation plant. By contrast Slurry TBMs have problems dealing with clays and some silts. If the amount of fines (particles smaller than 60 mm or able to pass through a 200 sieve) is greater than 20% then the use of a Slurry TBM becomes questionable although it is not ruled out. In this situation it will be the difficulty in separating excavated spoil from the slurry. An EPBM will perform better where the ground is silty and has a high percentage of fines both of which will assist the formation of a plug in the screw conveyor and will control groundwater inflows. A fines content of below 10% may be unfavourable for application of EPBMs

6.2 Permeability

As a general guide the point of selection between the two types of machines is a ground permeability of $1x10^{-5}$ m/s. Slurry TBM is applicable to ground of higher permeability and EPBs for ground of lower permeability. However, an EPBM can be used at a permeability of greater than $1x10^{-5}$ m/s by using an increased percentage of conditioning agent in the plenum.

6.3 Hydrostatic Head

High hydrostatic heads of groundwater pressure along the tunnel alignment add a significant concern to the choice of TBM. In situations where a high hydrostatic head is combined with high permeability or fissures it maybe be difficult to form an adequate plug in the screw conveyor of an EPB. Under such conditions a Slurry TBM may be the more appropriate choice especially as the bentonite slurry will aid in sealing the face during interventions under compressed air

6.4 Settlement Criteria

Both types of machine are effective in controlling ground movement and surface settlement – providing they are operated correctly. While settlement control may not be overriding factor in the choice of TBM type, the costs associated with minimizing settlement should be considered. For example, large quantities of conditioning agent may be needed to reduce the risk of over-excavation and control settlement if using EPB in loose granular soils

6.5 Final Considerations

Other aspects to consider when making the choice between the use of an Slurry TBM or an EPBM include the presence of gas, the presence of boulders, the torque and thrust required for each type of TBM and, lastly, the national experience with each method. The overriding decision must be made on which type of machine is best able to provide stability of the ground during excavation with all the correct operational controls in place and being used. If both types of machine can provide optimum face stability, as is often the case, other factors, such as the diameter, length and alignment of the tunnel, the increased cutter wear associated with EPBM operation, the work site area and location, and spoil disposal regulations are taken into consideration. [3]

Applicability of Slurry TBM and EPBM to different ground condition is given in Table 1

Table 1: Slurry or EPBM for soft ground conditions [6]

Ground condition	*N value*	*EPB*	*Slurry TBM*
Alluvium clay clat	0-5 mm	I	s
Diluvium clay	7-20	I	s
Mud stone	>50	I	s

Loose sand	5-30	x	I
Dense sand	>30	S	I
Sand gravel	>30	S	I
Sand & gravel with boulders	>50	S	I
I- applicable, s-consideration required, x-not applicable			

7. Tunnel Supports

Most tunnels are supported at some stage of construction. For tunnelling in hard rock, the supports may be in the form of rock bolts, wire meshes, shotcrete or steel lattice girders as required depending on the rock quality designation. For shield tunnelling for soft grounds, a lining is erected inside the tunnel and the annular space between the shield and segments is injected with grout. As the cost of segments shares significant portion of total tunnelling cost, type of segment should be carefully selected from both engineering and economical point of view. Segments are classified into several types; reinforced concrete (RC), steel, cast iron (ductile), composite, and others. Reinforced concrete prefabricated segments are most commonly used for tunnels driven by TBMs. Reinforced concrete segment is an excellent lining member with high compressive strength against both radial and longitudinal forces. It also has high rigidity and water tightness. On the other hand, it is heavy and has less tensile strength and more fragile than steel ones. The segments are mostly precast and are connected each other to form circular rings, which are installed side by side continuously to form a cylinder. Precast segmental linings can be used as initial ground support followed by a cast in situ concrete lining (which is known as two pass system), or it can be one pass system in which the segmental lining serve as the initial ground support and also as the final lining of the tunnel. The lining must withstand the soil and water pressure acting on the tunnel. For two pass systems, segments used as initial linings are erected without bolting them together and have no water proofing. They are lightly reinforced. Grouting is done after jacking the segments with TBM, to fill the annular space between the segments and the ground. A water proofing membrane is laid over the initial lining and the final concrete lining is cast in place against the water proofing membrane. For one pass system, the precast segmental linings are heavily reinforced and fitted with rubber gaskets on all faces for water proofing and bolted together to compress the gaskets and the ring is completed, before the TBM advances. Grouting is performed to fill the annular space occupied by the shield. [3]

8. Conclusion

With the latest tunnel construction technology, engineers can bore through mountains, under rivers, and beneath bustling cities. Before carving a tunnel, engineers investigate ground conditions by analyzing soil and rock samples and drilling test holes. In tunneling projects, it is essential to control and predict the ground surface settlements observed during and after the excavation process that may cause damage to the structures present on the earth surface. Tunneling with TBM has proven to be the most efficient method of tunneling with minimal impact on the environment and ground settlements. This state of art technology limits all works underground in building the tunnel to keep the disturbance to land and mankind activities at ground level to a minimum throughout the period of construction. A precise engineering survey and a detailed geological and geotechnical explorations of the site should be conducted to decide the type of Tunnel Boring Machine to be adopted specific to the site conditions. Bored tunneling with TBM has proven to be effective in controlling the surface settlements compared to any other tunneling method.

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