Interfacial Behavior in Tunnel Engineering

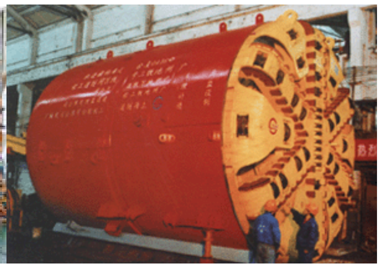
Northern Heavy Industries Group Co., Ltd.

Zongxi Cai
Department of Mechanics, Tianjin University
Tianjin, 300072, P.R. China

Mechanised excavation using full face tunnel boring machines (TBM) is now becoming a very popular method in tunnel engineering. Comparing with traditional excavation methods, technique with TBM has advantages such as that: the ground vibrations can be avoided (this is a very important reason for applying this method for tunnels in cities); the damage of the soil or rock mass in the tunnel periphery is small so it reduces the need for tunnel support; the rate of advance is increased so it reduced excavation time; the work site has better safety conditions; work is lighter for the workers; the "tunnel", as an industrial product, is of better quality; the rates of performance, in terms of excavated tunnel, is high; construction times and costs are guaranteed. On account of these advantages, only in China, there are now more than twenty cities which plan to apply this technique in underground engineering.

Full face tunnel boring machine is a very big machine system. The biggest one may be 400 meters long with 18 meters diameter. Basically, it is a movable factory. A TBM usually includes cutting head, pressure balance system, shield, mucking system, guiding system, advance and gripper system, segment erector system and power system and so on. It is really a complex system. More importantly, the work conditions of TBM are always very complicate. There are many ultimate geological situations, such as fault zones, clayey soil, important inflows of water, gas, rock and water at high temperatures, karst cavities and artificial stuffs and so on, have to be handled in real tunnel engineering. The ultimate dream of mechanized tunneling is a TBM capable of handling any type of ground. But in present, this is still a dream. To handling different type of geological conditions, now there are three typical types of TBMs: rock tunneling machines (which can be categorized as unshielded, single shielded and double shielded TBM) for rock formation, earth pressure balance (EPB) TBM and slurry TBM for looser ground.



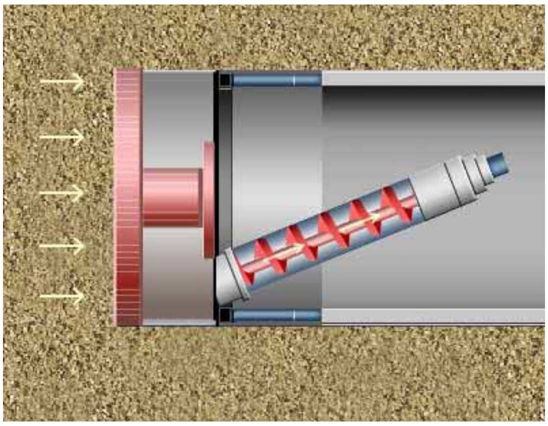


Rock tunneling machine EPB TBM Slurry TBM

Rock tunneling machines are designed for hard rock formations. The performance of this type of TBM main depends on the adaptability, efficiency and boreability of its cutting head. The interactive force between disc cutters and rock formation are the key parameter affecting adaptability, efficiency and boreability of a cutting head. Unfortunately, the mechanism affecting this interactive force is very complex. Experiments showed that the main factors affecting this interactive force may include the mechanics characteristic of the rock mass, the cutter spacing, the penetration depth and the distribution of disc cutters on the cutting head and so on. Usually, the cutter spacing mainly affects the normal force and finally the total thrust of a TBM, and the penetration depth affects the rolling force and finally the total torque and power of a TBM. But up to the present, since some special factors such as material nonlinearity, high gradient of temperature, seepage and instability of excavation face should be taken into account, the interactive behaviors between disc cutters and rock formation are not totally clear and so that the method to determine these interfacial forces is still an unsolved problem.


Disc cutter Multi-disc cutters

In urban environment, ground control is of paramount importance since it directly affects surface settlement and as such often represents the governing design and construction criterion. Usually, for most urban tunnel engineering, the allowed uplift or sink of surface is only about 10mm and 30mm respectively. Clearly, the settlement of ground surface directly depends on face control during tunnel excavation. To deliver such a positive face control, the EPB TBM pressurizes the face of the excavated tunnel by stresses transmitted by the reworked soil cuttings present in the front chamber. It can successfully control and support a tunnel face in either a dry or a saturated fine grained soil if there no free water is present in the front chamber. The slurry TBM provides stress at the face hydraulically by bentonite slurry kept under pressure in the front chamber. It can reliably operate in practically all types of soils, fine or coarse grained, with or without free water. When applied in proper ground conditions, these two type TBMs can deliver a ground control superb to most other tunneling technologies if we can control the operate parameters properly which means a total understanding of the mechanics behavior of the excavation face.



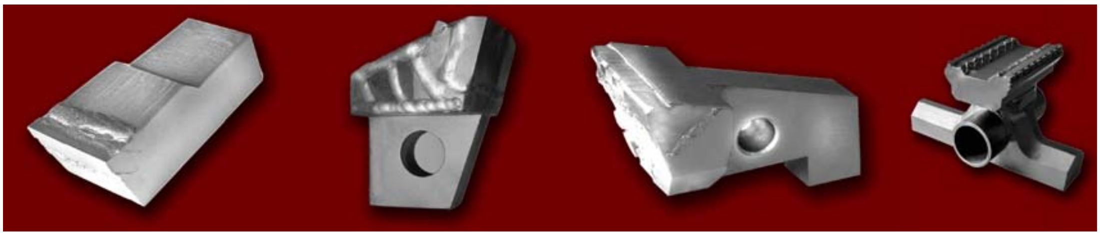
A Sketch of the front chamber

Collapsed ground

Since soil or rock formations in which tunnels are constructed are not very homogeneous and their behavior is not always very predictable, plus it is impossible to design a TBM which can cope with all the possible formations, there is still about 10% of the tunnel engineering which occurred accidents such as leak, collapse, sink and so on. Investigation shows that many serious accidents are induced by the instability of the excavation face. For EPB and slurry TBM, if the pressure present in the front chamber or the total trust or the mucking speed is too low or too high, the excavation face may lost its equilibrium and then induce the accidents. For rock TBM, improper total trust or mucking speed may induce shocks and then lead to damage of cutter tools or the cutting head and other accidents. Generally speaking, to understand the behavior of the excavation face is a basic challenge for the design of TBMs and the safety and efficiency of tunnel engineering under ultimate geological situations.

In the point of view of engineering, to understand the behavior of the excavation face is mainly to answer these questions:

(1). How to determine the loadings acting on a single cutter? These loadings are very important factors for the design of cutters and cutting head since they affect the boreability of a TBM directly. Under a given geological situation, for the reason of boreability, we wish to design a cutter that with smallest loadings. But for the reason of efficiency, the forces acting on the formation (which equal the loadings acting on the cutter) should be large enough. Firstly, it should be large enough to cut out the soil or rock mass of which contacting the cutter. Secondly, it should be large enough to put the reworked soil or rock into the front chamber. In real tunnel engineering, a cutting head is designed to excavate a whole segment of tunnel which may include many kinds of geological materials. It is a fundamental requirement to know the loadings acting on a particular cutter in a given geological situation so as to design a particular cutting head with various cutters to handle the possible geological conditions



Cutting tools

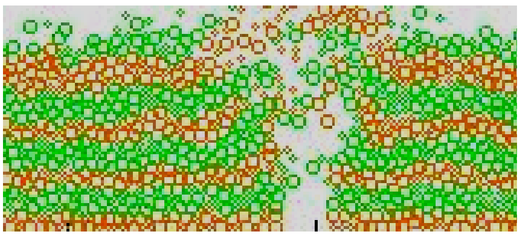
(2). How to determine the distribution of the interfacial force between the cutting head and the formation? The distribution of the interfacial force is a very important factor affecting safety and efficiency of tunneling. Since the excavation face is not always homogeneous, the distribution of the interfacial force is also not homogeneous. So, for a given geological condition, we have to understand the relationship between the distribution of the interfacial force and structure of the cutting head so as to design a particular cutting head to cope with this geological condition. For the reason of safety and efficiency, the possible distribution of the interfacial force should lead to that the penetration depth of each cutter is almost the same, faces at all openings of the cutting head can maintain its equilibrium. The difficulty of this problem comes from that the formation may be very complicate. It may contain soil, sand, stone, rock, artificial materials and so on, and the seepage of the underwater should also be take account.

(3). How to determine the total loadings (including trust, toque and pressure in the front chamber) of the TBM under a given geological condition? The total loadings are very important factors affecting the safety and the adaptability of a TBM. They are operative parameters in real tunneling. Generally speaking, to determine the total loadings, we have to consider problems including the stability of the excavation face, pressure equilibrium in the front chamber, advance speed and the formation deformations of nearby. Usually, high pressure in the front chamber exceed needed may induce ground surface uplift or leak accident. On the other hand, if the pressure in the front chamber is too low, the excavation face may lost its stability and then induce ground surface sink or collapse accident. Too large or too small total trust or toque also may induce many other accidents. So the best solution of this problem is to give the total loading curves as the geological condition changes. At least the region of the total loadings should be given.

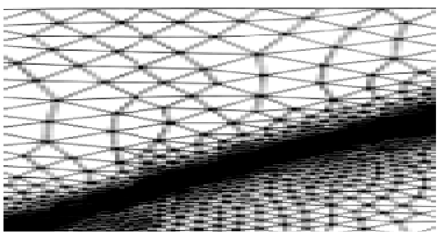
To solve above engineering problems, some basic mechanics and mathematics difficulty should be tackled, these may including:

(1). What's the best constitutive model for the analysis of the interfacial behavior in tunnel engineering? Up to the present, there are many constitutive models for varies geological materials. Basically, in the frame of solid mechanics, we can always find a suitable model for a particular geological material. Of course, most of these models can only be used for undisturbed soil or rock. But for the present problem we have to consider the disturbed soil or rock. Before cutting, the soil or rock mass can be really considered as solid. But after cutting, the behavior of the mass changes a lot and should not be considered as solid since it shall be put into the front chamber. It moves much similar as a granular flow. As mentioned above, to determine the interfacial forces, we have to deal with the whole progresses from the beginning of the mass to be excavated until it to be put into the front chamber. If we can find a constitutive model which uniformly suitable for the whole progresses, it may make significant improvement in the simulations of the interfacial behavior.

(2). What's the mechanism of the instability of the excavation face and if it is possible to derive analytical governing equations for this instability problem? During excavation, the formation stresses undergo a very rapid release and relocation, the pressures induced by the seepage of ground waters also changes a lot. If we can not control the pressure in the front chamber or the mucking speed properly, the excavation faces may lost its stability and further induce accidents. Frequently seen instability progress is beginning from the damage of microstructures of the formation, then strain localization appears in somewhere and finally the formation lost its stability. The difficulties to derive governing equations for instability problem may comes from such aspects: the coupled effects of multiple physical field including mechanical, temperature and seepage should be taken into account, the distribution of the interfacial force is not very homogeneous and may changes very rapidly, the disturbance of excavation affects either the stress state or the characteristic of the formation.



Damage of microstructures



Strain localization

Now, urban environment is extremely sensitive to any type of accidents. Tunnel Engineering is definitely one of the activities which easy to induce accidents. So it is very important to understand the interfacial behavior since if affects both the ground stability and ground deformation and finally the surface settlement.

Some useful links:

Tunnels & Tunnelling International
www.tunnelsonline.info

International Tunnelling Association
www.ita-aites.org

Tunnelling Association of Canada
www.tunnelcanada.ca

Italian Tunnelling Association
www.societaitalianagallerie.it

British Tunnelling Society
www.britishtunnelling.org

Tunnelling & Underground Construction Society (Singapore)
www.tucss.org.sg

Rapid Excavation and Tunnelling Conference
www.retc.org/index.cfm

Companies:

Herrenknecht
Construction & Tunneling Services
Robbins Company
LOVAT