Study on ground suitability and construction countermeasures of metro shield in China

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Abstract. Because of unsuited shield type selection, equipment configuration and construction measures, lots of construction problems appeared like clogging, excessive settlement, spewing, abrasiveness, oversized grains and abnormal working parameters. Ground conditions and construction measures encountered in numerous metro projects across China are categorized in order to improve the selection of shields specific to complex ground conditions. Firstly, according to grain-size distribution, diversity of complex ground is classified as four types. Secondly, oriented by ground suitability problems, the four types are divided into eight sub-classes based on the critical geological parameters or conditions. In order to provide an overall view for planning of shield selection, the map of China consisting of metro cities is regionalized according to the above classification. In the end, construction countermeasures for each type are put forward including shield type selection, equipment configuration, soil conditioning and tunneling parameters. Conclusions drawn from the paper can improve current classification for shield tunneling and provide practically targeted references for engineers.

1. Introduction
Metro shield tunneling has been extensively adopted in China as an effective way to relieve traffic congestion ([1-2]). By the end of 2020, metro lines of 39 cities in mainland China had been in operation with 7122 kilometers and 46 cities with 5306 kilometers were under construction. When faced with kinds of construction problems during tunneling, the improvement of shield’s suitability is a prerequisite to tackle ever-wider ranges of ground conditions ([3-4]).

At present, the available studies specific on ground suitability of shield machine mainly focused on three kinds of problems: (1) stratigraphic classification ([5-7]), (2) performances of shield/TBM tunneling ([8-9]) and (3) countermeasures of construction problems ([10-11]). Nevertheless, the above researches were mainly about rock classification and working performance prediction of rock tunnel boring machine. Moreover, studies about countermeasures about shield construction mostly concentrated on a specific project. Therefore, it remains lack of comprehensive investigations on ground suitability of metro shield to a large extent, which makes it difficult for engineers to take a reliable pre-arranged planning.

In this study, soil classification, problems of ground suitability and construction countermeasures are comprehensively taken into consideration. Soils are classified nationwide which is designed to allow an easy transition from soil engineering properties to basic predictions of construction problems during shield tunneling. Then corresponding construction measures (including shield selection, equipment configuration and soil conditioning) are systematically summarized and proposed on the basis of experiences of practical project cases. Conclusions drawn from the paper can provide...
practically targeted references for engineers to make a reliable pre-arranged planning and ensure the construction proceed favorably in diversity of geological conditions.

2. Classification of ground suitability

Most of the current methods of soil classification are categorized by grain composition and plastic index. For example, Chinese Code for investigation of geotechnical engineering (DGJ08-37-2012) had divided soil into clayey soil, silty soil, sandy soil and gravelly soil according to this method. Nevertheless, this classified method has no direct correspond relationship between soil classification and shield construction. Thus, without consideration of compound strata, a ground classification method with respect to shield is proposed in this paper. Firstly, soils are classified into four types (I, II, III and IV) according to grain size distribution. Based on the unified soil classification system (USCS) and experiences from soft-ground shield ([12-15]), the classification is determined by the content of particles passing through a no.200 and a no.4 sieve respectively (Fig. 1; Table 1). Then each type of ground is divided into two different sub-classes by geological parameters or conditions that affect shield construction significantly.

| Type | Basis of classification | Description (USCS) | Engineering properties | Primal hazards for shield |
|------|-------------------------|--------------------|------------------------|---------------------------|
| I    | More than 60% remaining above # 200 | Fine grains consist of clay of high plasticity, silt and clay/silt of low to moderate plasticity may contain a small amount of fine sand | Soft plastic clay is characterized by high water content, low shear strength and high sensitivity. Hard clay possess a relative high strength and great viscosity for adherence potential | Excessive and long-term settlements in soft clay, stickiness and clogging in hard clay |
| II   | 30% to 60% passing # 200 | Silty/clayey sand and fine sand | Cohesionless, poor stability and low strength | Instability of excavation face, spewing of water/sand and low potential for clogging and abrasiveness |
| III  | 12% to 30% passing # 200 and more than 50% passing # 4 | Coarse grains consist of gravelly sand and clayey/silty gravel | Cohesionless, high permeability and hardness | Moderate to high potential to be abrasive |
| IV   | Less than 12% passing # 200 and 15% to 50% passing # 4 | Sandy gravel, gravel cobbles and potentially boulders | Lacking of fine gains, high content of large particles | Cutters damaged by impact failure and soil discharge hindered by screw conveyor, hysteresis ground collapse |
2.1. Type I

According to the relevant studies ([16-17]), when the percentage of particles passing through the no. 200 sieve is more than 60%, the clogging risk should be considerably estimated. When water content of these highly plastic clays changed, soil particles tend to develop sticky behaviors (adhesion on metal surfaces), which may lead to clogging on cutterhead, soil chamber and screw conveyor. For example, clogging occurred on the cutterhead of a metro shield project in China (Fig. 2). With clay cake on the surface, the sticky clay can’t be penetrated and discharged smoothly, leading to higher cutter torque more than 3300kN\cdot m, lower advance rate less than 5mm/min and upheaval of ground as 5mm ([18]).

Fig. 2. Clogging occurred on cutterhead.

For evaluating the potential of clogging in advance, a practicable approach was proposed by Holman and Thewes [19] using consistency index ($I_c$) and plasticity index ($I_p$). The consistency index is defined by the following equation:

$$I_c = \frac{w_l - w}{w_p - w_l} = \frac{w_l - w}{I_p}$$

(1)

Where the parameter $w = $ natural water content, $w_l = $ liquid limit and $w_p = $ plastic limit of the clay.

As shown in Fig.3, clays with $I_c > 0.5$ are assessed as medium to strong clogging while $I_c \leq 0.5$ has little potential for clogging. Therefore, the consistency index is chosen to discern clogging risk in this type of ground. In addition, the risk of clogging increase with an increase of plasticity index, as the plastic consistency range is cover by many possible water contents.
In contrast, tunneling in soft clay has little potential for clogging due to the high content of water content. However, the soft clay possesses poor self-stability, high sensitivity and low shear strength, ground surface settlement is difficulty to control after soil disturbance by tunneling. Furthermore, ground settlements last for a long duration after construction because of the notable rheological behavior. It is a critical threat to both the surface and subsurface facilities, particularly in urban areas ([20]). Taking a representative city Shanghai for example, long-term ground settlements per year of local areas exceeded 30mm ([21]).

2.2. Type II
This type of ground is mainly consisted of silty sand and fine sand performed slightly abrasiveness for cutters. In generally, it can be cut and discharged by shield machine with high efficiency. The main problems of shield tunneling in this type of ground are instability of excavation face and spewing. Because of its cohesionless and high permeability coefficient ranging from $10^{-3}$~$10^{-2}$cm/s, it’s prone to be spewing under the action of free water. Once the spewing phenomenon happened, control of the liquid sand and groundwater inflows can be problematic, which may lead to excavation face collapse and excessive ground deformation. Based on experience of Shenzhen and Guangzhou in China, it may be a common phenomenon during shield tunneling without effective soil conditioning in this ground.

Zheng et al ([22]) presented an evaluation method to predict spewing based on a simplified model with two indices critical hydraulic conductivity and water table height of the cutterhead (see Fig.4). As shown in Fig.4, the potential for spewing predicting was divided into three regions including no spewing, moderate spewing and spewing. Additionally, the parameters of some typical spewing accidents during the construction of subway were validated with this proposed evaluation criterion.
Fig. 4. Critical hydraulic conductivity with varying water table heights of the cutter head (Zheng et al., 2015 [22]).

There exits variability for permeability among different soils, it should be estimated the possibility of spewing according to the practical geological conditions and then taking reasonable construction measures. For this sub-classification, hydraulic conductivity of 10^-2cm/s was selected as the critical value and the corresponding height of water head was 2m.

2.3. Type III
Differing from type II, this type of ground is mainly consisted of gravelly sand and sandy gravels, a typical incohesive ground charactized by relative larger granules. By abundant engineering experiences in China ([10-11, 23-24]), the primary risk in this ground is severe abrasion on cutters and the cutterhead structure of shield machines. When serious wear damage occurred, downtime for the replacement of cutting tools and worn parts is unavoidable (Fig. 5). Thus, the abrasiveness of ground not only controls the rate of machine wear, but also the factor of time and economic. At present, there are three common ways for assessing the abrasiveness of ground including the Cerchar test, LCPC test and NTNU test ([24]). The Cerchar abrasivity test is only practical test for a whole piece of rock or stone sample. While the NTNU test applied only to soil particles smaller than 4mm. The LCPC test is chosen to evaluate the abrasivity of the ground, which is suitable for 4-6.3mm fractions so that coarser grains need to be crushed in advance and their grain fractions need to be determined by sieving. According to the research of Hashemnejad ([25]), that the index EQC (equivalent quartz content) was the most important parameter determining the abrasivity of samples. Fig. 6 shows the relationship EQC value and abrasiveness level for this type of ground ([25]). Base on this estimation for abrasivity, we could get the critical EQC value between medium abrasive and very abrasive as 30.

Fig. 5. Serious wear damage occurred on cutters.
2.4. Type IV

As for the ground of type IV, the content of fine grains (0.075mm) is less than 12% and more than 50% of the coarser grains remain above # 4 sieve (4.75mm). The engineering properties of this type differs greatly from the other three types, oversized grains and soil with low fine grained content highlight the risks of impact failure of cutters, blocking, hindered mucking and delayed settlement. Oversized grains (cobbles and boulders) have a great impact on the material of cutting tools. Moreover, hindered mucking frequently occurred in the outlet device and consequent blocking of cutterhead chamber had happened (Fig. 7).

On the other hand, lacking of fine grains means the larger particles can form a soil arching structure and work as skeleton, which is helpful to the control of ground settlement during construction. However, the stability of this ground is temporary, the effects of arching will gradually be weakened after construction, so the delayed settlement could develop as time passing and sudden subsidence of ground surface may occur sometimes.

There are two ways to deal with the oversize grains, ingesting by a properly designed mucking system or broken up by a suitably equipped cutterhead. Based on the construction practice in Beijing and Chengdu, the underground water condition in front of the excavation face had an obvious effect on the cutterhead chamber configuration and accessibility.

3. Ground regionalization and construction countermeasures

According to the classification of ground suitability for shield tunneling, the ground types that encountered in China’s subway construction can be distributed by regional areas (as shown in Fig. 8). Type I, fine grains ground is mainly distributed in coastal areas like Shanghai (liquid~soft) or along the middle and lower reaches of Changjiang River like Wuhan (firm~hard); Type II, mainly distributed in the northwestern china like Xi’an city; Type III, has a wide distribution in northeast and
south of China, such as Shenyang, Nanning and Guangzhou, etc.; Type IV, oversized grains ground is usually distributed in the upstream regions of rivers, like Chengdu and Lanzhou.

The regional distribution of ground type can provide overall references to make rational use of regional ground characteristics, carry out prearranged plan and offer a quick sense of construction countermeasures. Construction countermeasures including shield type selection, equipment configuration and soil conditioning for improving ground suitability of metro shield are summarized in this part.

![Fig. 8. Regionalized distribution of ground conditions in urban metro-shield tunnels.](image)

### 3.1. Type I

When $I_c \leq 0.5$, the drivage efficiency of shield machine working in this kind of ground is high and the cutters are worn lightly. In consideration of its excavability and stability, it’s usually configured panel or spoke-panel cutterhead with aperture ratio ranging from 20%~40% and excavated by scrapers as well as central fish-tail cutters (Fig. 9a). What's more, there is no need to take auxiliary measures by soil conditioning because of the good workability. Only in some silty sand ground, a small amount of foam agents or soapsuds is adopted. In addition, synchronous grouting should be emphasized and secondary grouting equipment need to be constantly configured for controlling the accelerated post-construction settlement.

![Fig. 9. Configuration of cutterhead and cutters in type I.](image)

If the physical property of this ground performs firm to hard, namely $I_c > 0.5$, soil conditioning like adding water is essential for transforming the physical state. In this case, the classification of Fig. 1 is particularly useful when estimating the conditioning effort with water for EPB machines. Fine-grained soils with very soft to soft consistencies ($I_c: 0.4-0.75$) can be directly used as a support medium ([26]).
However, consistency index > 0.5 are not reasonable since the evaluation of clogging is strong. The optimum of consistency index is determined as 0.4-0.5 for the support medium on excavation face and pressure-tightness of the screw conveyor. For example, the case of Hefei plotted in Fig need an increasement of 13% water content to reach the desired consistency range. Additives, like foam, are often used to minimize clogging as well to constitute a proper support medium. Taking a project case of Wuhan as an example, the cutter torque was effectively decreased from 3300kNꞏm to 2600kNꞏm and penetration speed increased from 5mm/min to 40mm/min by the utilization of foam with anti-adhesive agents. What’s more, to avoid the stickiness on the metal surface of cutterhead, spoke-type cutterhead with opening ratio above 60% is recommended generally and the central opening ratio should large enough for avoiding adhesive particles accumulate in the easy-clogging area (Fig. 9b).

3.2. Type II
For ground of type II, the shield selection and cutterhead configuration is similar to that of soft clay ground. To deal with the problem of spewing, dewatering, shield with air pressure and soil conditioning are often adopted. According to Fig. 4, dewatering is a direct way to reduce the high water pressure in front of the cutterhead when water head is above the critical value 2m in this type of ground. While the shield machine configured with air pressure chamber is mainly applied to balance the water pressure of excavation face for risk-aversion. On account of the convenience and efficiency, soil conditioning is generally adopted in practical construction. Based on the test results of Qiu ([27]), the injection of bentonite slurry could reduce the permeability coefficient by 67 percent while foam by 27 percent. So the bentonite slurry or water absorbent polymer is recommended when water head of the cutterhead is higher than 2m. In addition, two-stage screw conveyor and pressure holding pump are also applied in for control the occurrence of spewing.

3.3. Type III
According to general principle of shield type selection, the most suitable type in sandy gravel ground is slurry pressure balance (SPB) shield. However, in practical engineering of China, earth pressure balance (EPB) shield is usually preferred except parts of submerged tunnels are constructed by SPB shield. Taking Shenyang as an example, through investigation of 23 metro sections, 12 of them are adopted shield machine and only 2 were slurry shield. In addition, the slurry shield machines were both applied to undercross Hun River for avoid the risks of high water pressure.

EPB shield can be quite suitable for this type of ground by targeted soil conditioning to improve abrasion resistance and plasticity. In the very abrasive ground of Shenyang when EQC value is greater than 30, EPB shield could reach a consecutive tunneling distance as 1526m and average advance as 9.5m/d by means of foam and bentonite slurry conditioning.

As for configuration of cutterhead, spoke-panel type is often selected for two advantages: the appropriate opening ratio can ensure relative larger particles pass through smoothly and maintain the stability of excavation face at the same time (as shown in Fig. 10). To avoid excessive wear of cutters, rive cutters are placed in the front area and wear-resistant welding rod placed in the surrounding area to protect scrapers.
3.4. Type IV
Likewise, shield method is not quite suitable to oversized grains according to principle of shield type selection. However, the selection of shield should be considered under two kinds of geological conditions.

As for watery ground represented by Chengdu, composite EPB shield is widely used in the watery ground for the use of grains breaking by disc cutters (Fig. 11a). In the first stage project of line 1 of Chengdu Metro, there were adopted an EPB shield and a slurry shield respectively in the test section. It turned out that the mud pipe of SPB shield was seriously worn and the cutterhead was grinded repeatedly by the cumulative cobbles/boulders in front because of the blocked discharge of large particles. As a result, cutting tools consumption of slurry shield greatly outweighed EPB shield’s. The average advance of slurry shield was 79.6m per month while EPB shield was 237m per month and the driving cost of slurry shield was 38 percent higher than EPB shield’s. Consequently, EPB shield were fully adopted in subsequent lines of Chengdu Metro ([28]).

On the Contrary, due to the better stability of waterless grains, the ground of Beijing is directly excavated by large opening cutterhead with rip teeth cutters (Fig. 11b) and discharged by belt screw conveyor without breaking. Compare to the practice in Chengdu, this processing modes on oversized grains has a prevailing advantage, the continuous advancing distance without replacement of cutters is 1333m more twice that of Chengdu.

For soil conditioning, foaming agent and bentonite slurry are often used together for the purpose of power consumption reduction and fine grains supplement. In the British Tunneling Society (BTS) guideline for closed face tunneling, a minimum value of 10% fines is recommended ([29]); but this would rely on the addition of polymer. Without the addition of polymer, 20% fines is the considered minimum. The supplement of fine is beneficial for precaution of the delay settlements, the monitoring of deep settlements upper shield should also be strengthened at the same time.

![Fig. 11. Configuration of cutterhead and cutters in type IV.](image)

4. Conclusion
This paper aims at improve the suitability of shield specific to different types of soft ground encountered in China, diversity of grounds is categorized nationwide in China and corresponding construction measures are proposed on the basis of massive of practical project cases. Firstly, combined with grains distribution, ground encountered in China is categorized into four types and construction problems of ground suitability is analyzed specific to each type. Secondly, oriented by ground suitability problems, the four types are divided into eight sub-classes based on the critical geological parameters or conditions. In order to provide an overall view for planning of shield selection, the map of China consisting of metro cities is regionalized according to the above classification. In the end, construction countermeasures for each type of ground are summarized and put forward including shield type selection, equipment configuration and soil conditioning. Based on the study on ground suitability and construction countermeasures of metro shield in China, we can improve the current ground classification and provide practically targeted references for engineers.
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