Lessons from one Tunnel Boring Machine project in Kunming city, China

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Abstract: During a Tunnel Boring Machine (TBM) project in Kunming city, Southwestern China the engineering geological conditions encountered at a distance of 7km consisted of folded, faulted, weak rocks, high ground stress and groundwater problems. The problems of collapse, squeezing, debris flow, water loss from reservoir and accidents resulting from the TBM jamming were encountered. As a result a lot of measures, e.g. chemical reinforcement, adit excavation and advanced test jack hammer excavation outside of shields were adopted to cope with these difficult ground conditions. An adjustment to the tunnel line had to occur after 4km of boring in these difficult ground conditions. This paper presents lessons learnt from this case study. In particular increased costs and time delay due to the transfer of water from a reservoir to Kunming city are reported.

Decisions made on what excavation method (blast and cast or a TBM) are strategic decisions that define the success and progress of a tunnelling project. The difference of the deformation and failure mechanism that occur to the surrounding rocks under a TBM tunnelling method from that under blast and cast method should be clarified when undertaking a project of this nature.

Résumé: Au cours d'un projet utilisant un équipement de forage de tunel, réalisé près de la ville de Kunming en Chine du sud-ouest, des conditions géologiques particulières ont été rencontrées à une distance de 7 km, consistant en roches de consistance friable et déstructurées, accompagné d'un stress ausol élevé et de problèmes d'eau souterraine. Ces conditions ont engender divers problèmes de collapsus, d'écoulement de débris, de difficultés d' extraction, de perte d'eau des réservoirs, ainsi que des accidents liés au bourrage de l'équipement. Les mesures de correction ont consisté en renforcement chimique et tests approfondis de l'équipement en dehors des couches à risque. Il a été nécessaire de procéder à un ajustement du trajet du tunel après 4 km de forage en conditions difficiles. Cet article a pour but d'exposer les le?ons tirées de cette experience particulière, en particulier en termes de pertes financières et de retard d'exécution liées au transfert d'eau d'un réservoir à Kunming. Les décisions quant à la technique d'excavation (détonnation suivie de moulage, ou bien emploi d'un équipement de forage) sont stratégiquement critiques et conditionnent le succès et le progrès d'un programme de construction. Notre expérience démontre que les difficultés et échecs rencontrés lors de l'utilisation d'un équipement de forage sont différentes de celles engendrées par la technique de détonation/moulage, et qu'elles sont fonction de la qualité et de la structure des éléments géologiques rencontrés. Ces derniers doivent donc faire l'objet d'une analyse approfondie avant de décider quelle technique d'excavation adopter.

Keywords: tunnels, weak rocks, collapse, environmental geology.

INTRODUCTION

Although the Tunnel Boring Machine (TBM) is new and advanced in most cases of favorable geological conditions, its disadvantage of low suitability to complicated geological conditions makes its usage in a limited range (Pelizza *et al.* 2001). Most tunnelling projects are expected to be completed in a short time. This provides more chances for the TBM to be considered or even accepted without comprehensive investigation and comparable design. One example for limits of excavation by TBM is Dul Hasti in India (Christophe *et al.* 2005). TBM tunnelling was undertaken from 1992 to 2003 covering a distance of 11300m. The conventional drill and blast method is proved to be more efficient. Similarly, the Shanggongshan Tunnel transferring water from a reservoir to Kunming city is another example that shows the decision to use the TBM was poor. Complicated geological conditions (Shang *et al.* 2004b) and poor understanding of secondary behaviour of the surrounding rock mass resulted in many problems and accidents during TBM tunnelling. The problems as squeezing (Shang *et al.* 2005*a*), water flow (Shang *et al.* 2005*b*) and TBM blocking (Shang *et al.* 2005*c*) were coped with on site. The time delay and increased costs, even the adjustment of the tunnel alignment were lessons for decision making on selection of tunnelling method.

This paper presents the various problems and difficulties of TBM tunnelling in Shanggongshan Tunnel. Some aspects, such as the TBM jamming in an inter-layer shearing zone in folded rocks of marl interbedded with limestone have been presented previously (Shang *et al.* 2004a). Compared with blast and cast method, the TBM tunnelling facing new challenges ought to be paid more attentions by engineering geologists and decision makers.

TUNNELING SITE AND ENGINEERING GEOLOGICAL CONDITIONS

Layout of the tunnel and the TBM

Shanggongshan Tunnel, with a total length of 13.769km (Figure 1), a diameter of 3.00m, sits in NNE of Kunming city, Yunnan Province, SW China. It was commenced at the end of April 2003. The final breakthrough is to the TBM Sino (Zdn) made up of dolomite and marl. The surrounding rocks excavated are moderately weathered, in some cases strongly weathered. The tunnel line is under groundwater table (Figure 2).

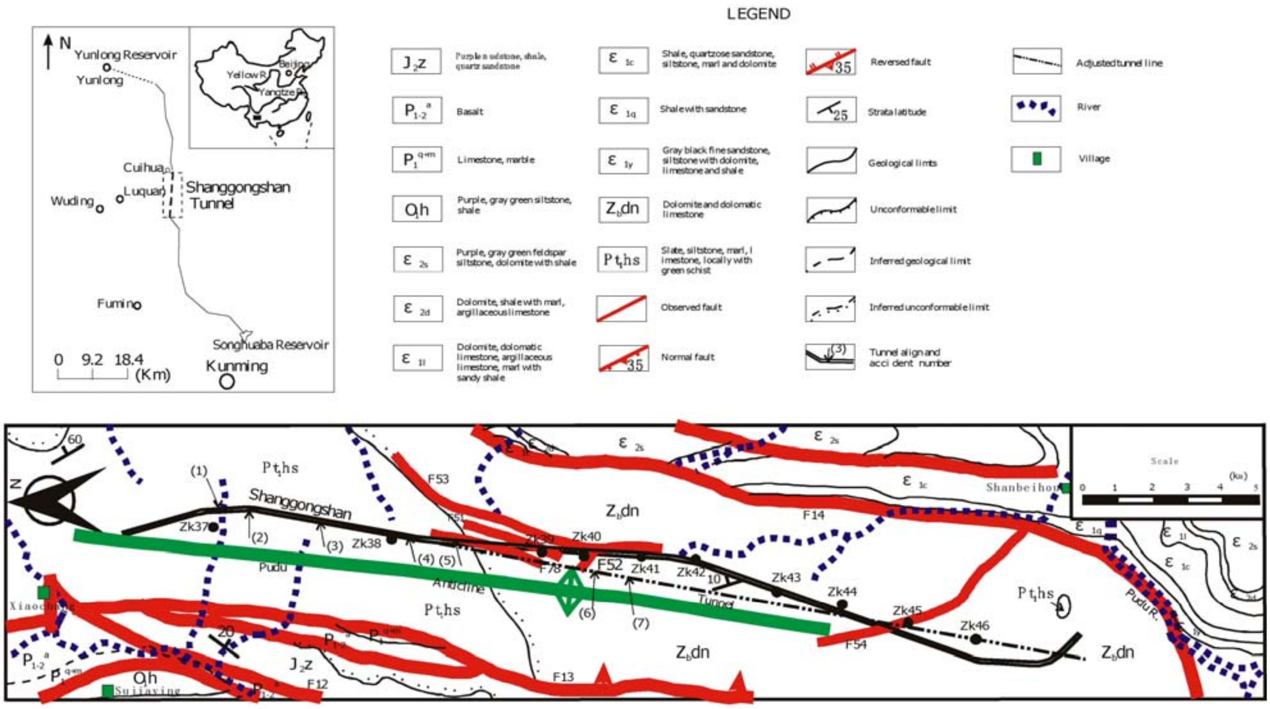

Figure 1. Sketch map of the Shanggongshan Tunnel for water transferring to Kunming city

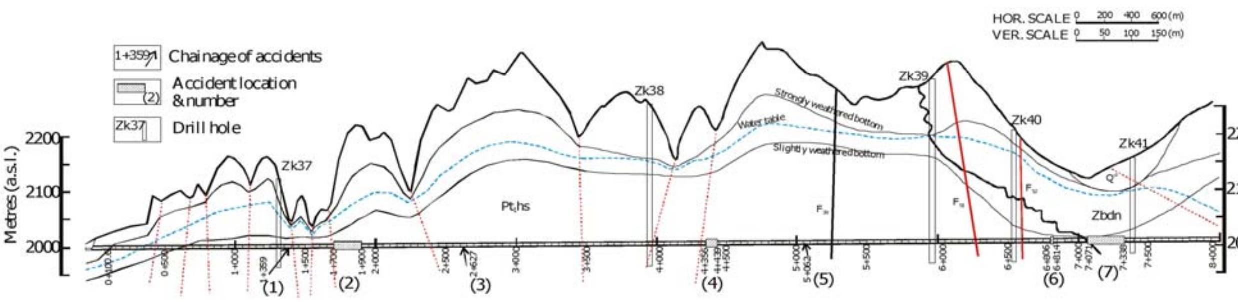

Figure 2. Shanggongshan Profile (former half part)(the graduation unit along the tunnel is 50m)

It is the longest one of the 16 tunnels in the Water Supply and Diversion Project, with a total length of 86km, a water head of 100m, of Zhangjiu River for water use in Kunming city. The designed water supply volume is 40×10^4t/d to 60×10^4t/d (Huang and Li 2003). The longitudal extention of the tunnel axis is S17.6°E - S18.7°W. The buried depth of the tunnel is generally 100 - 200m, with a minimum of 10m and a maximum of 368m (Figure 2).

This tunnel is unique as for the TBM method, the full face rock TBM of Robbison with a double shield (Type: 1217-303) in a diameter of 3.665m is used.

Engineering geological conditions

Located at the eastern side of the Puduhe Anticline and through the Shanggong Mountain, this tunnel is arrayed along one branch of Kangdian Fault System in a strike of SN.

This tunnel, located in the Xiaojiang-Puduhe active fault zone, is between two regional large reversed faults (F_{13} and F_{14}), whose spacing is less than 3 km (GIYGB 1969; Shang *et al.* 2004b; 2005*c*). The tectonic stresses are still active in this area.

The tunnel axis intersected with the strata in a cross angle of 0 - 40°. The strata consist of Heishantou Group of Proterozoic (Pt_1hs) argillaceous and sandy slates, quartz sandstones, and Dengying Group.

Table 1. Main accidents in Shanggongshan Tunneling

Number of accidents*	Time	Chainage (Km+m)	Length (m)	Problems and hazards	TBM status
(1)	July 29,2003	1+359		Deformation of segment, water flow, collapse	Stopped
(2)	Aug. 23~9Sept, 2003	1+700 ~ 1+900	200m	Water flow no less than 40l/s	Stopped
(3)	Oct 23, 2003	2+627.777		Soft rock squeezing	Blocked
(4) †	Feb 22~March 11, 2004	4+356 ~ 4+439	83m	Large deformation of surrounding rocks	Blocked several times. The back shield is pulled apart and plastic compression were observed and have to be repaired
(5)	July 2, 2004	5+062		Fault and water flow	Blocked
(6)	Oct. 19~23, 2004	6+806 ~ 6+814		Collapse of purple sandstones occurred in working face	Slow advancement
(7) ‡	March 2, 2005	7+071.198 ~ 7+338.664	260m	Karst water flow and disappear of springs and joint of reservoir water	Blocked 3 times. The maximum period is about 2.5 month

* Locations of (1)~(7) are marked in Figures 1 and 2.
† Gouges are sampled for mineral analysis and particle size distribution test. The silty slate is sampled for uniaxial compression test.
‡ Carbonate rocks are sampled for mineral identification as marls.

PROBLEMS AND DISTINCTIVE FEATURES IN TBM TUNNELING

In a distance of 7km mainly in Pt_1hs, there occurred accidents such as TBM blocking, water flow, segment and shield failures. Most obvious events are listed in Table 1, and presented in the plane and profile maps (Figures 1 and 2).

Weak rocks and squeezing

Generally all of the slates functioned as soft rocks. The weak rocks mainly consisted of faulted rocks, jointed rocks, buried weathered crust and soft rocks.

In most of the sections, the surrounding rock is thin-layered sandstone intercalated with argillaceous slate of the Pt_1hs, and the bed is steeply inclined with a dip angle of 65°. Therefore the rock mass has a thin-layered sandwich and cataclastic structure. The uniaxial strengh of the 6 silty slates most commonly seen is from 25.3 MPa to 94.8 MPa, with an average of 53.4MPa (Table 2).

Table 2. Physical and mechanical properties of slightly weathered slates in tunnelling

Specific gravity	Density/g.cm-3	Void ratio	Water absorption/%	Compressive strength/MPa Dry/wet	Elastic modulus/10^4MPa Dry/wet	Poison ratio Dry/wet
2.74	2.72	0.73	0.25	58.8/57.1	3.61/0.93	0.26/0.11

From Table 1 it can be seen that TBM blocking due to squeezing is mostly associated with argillaceous slate (Shang *et al.* 2005*c*), to interlayer shearing between sandstones and argillaceous slates (Shang *et al.* 2004b). As often emerged weak rock, the gouges greatly contribute to squeezing as its components contain higher content (15.15%) of smectite, and the clay proportion is higher (<0.002mm taking account of 28.4%) (gouges sampled at the most catastrophic squeezing case (4), see Table 1). According to classifications of rock mass quality, rock masses in the TBM getting stuck section belong to weak rock.

As for the depth of TBM blocking in weak rocks, it is generally greater than 200m. By means of FLAC3D on plastic-elastic numerical simulation, the displacements of surrounding rocks versus depth indicates that there exist obvious increase once the depth is greater than 200m, and rocks at vault and lateral parts show displacement values larger than 3cm (Figure 3). The squeezing caused TBM blocking quickly just because the space between surrounding rocks and TBM shield is about 5~10cm in two sides.

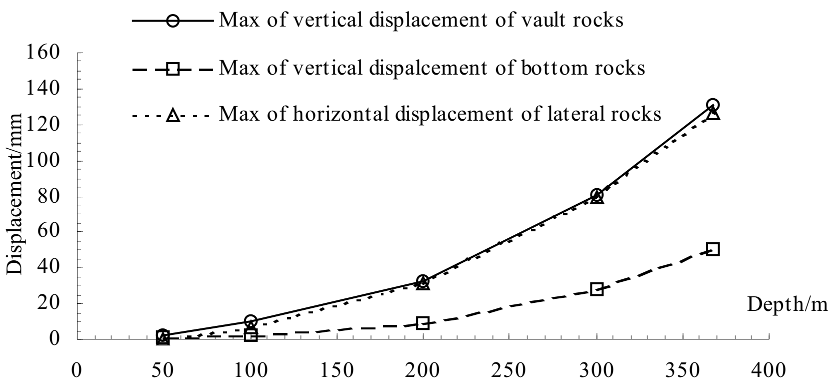

Figure 3. Displacements of surrounding rocks versus depth from numerical simulation

Folds and faults

In this section, the Puduhe Anticline is dominant (Figure 1). Before excavation, the number of known faults is about 5. After excavation over a distance of 7km, there are more than 14 faults.

In structural geology, the stratum was subject to intense inter-layered shearing and several inter-layered shearing zones with different thickness were formed.

For example, there is an approximately 45 cm wide inter-layered folding zone in one side adit, and another case of a broader cleavage shearing zone at chainage 2+627.777 (see (3) in Table1) (Shang *et al.* 2004b). These weak rocks are affected by faults, folds and joints commonly encountered during excavation, whose distribution is under the control of the Puduhe Fold and two faults at its eastern and western boundaries (Figure 1). The most serious case (4) is just within a reversed gentle dipped fault in a length of about 100m.

Numerical simulation via FLAC3D shows that the location of faults in the cross section of tunnel has a different influence on the displacement value. When the fault crosses the tunnel in the middle, then the displacement variation is very large. And the values of vault and lateral rocks are bigger than those in the bottom part (Figure 4).

Water flows

When excavated in sandstones or sandy slates, water flow volume is often larger. In 7 severe accidents in TBM tunneling, 4 of them are attributing to larger water flow. The most serious is that in the contact zone between the slates and the dolomite. In that case, a debris flow was formed in lateral adit when passing through this section, and a fault system acted as a water channel connecting surficial and underground water. As a result, waters in reservoirs at lower elevation and springs disappeared when the discharge in tunnel was undergone (Shang *et al.* 2005b).

Slow advancement and TBM blocking

In the past 22 months (June 2003~March 2005) at a distance of 7.338km, the mean advanced rate is about 334m/month, or 11m/day. This rate is very small, and in some sections the TBM moved forward without excavation after the blast and cast completion. In so many unfavourable engineering geological conditions, the TBM often blocked and lateral adit excavation was adopted for freeing the TBM and consolidating surrounding rocks. Thus much more time was spent on conventional excavation of adit, meanwhile TBM stopped (Figure 5). Taking account of the lower grade of rock mass quality, the advanced rate is too small to have advantages when compared with the conventional blast and cast method.

Segment failure and back shield deformation

Squeezing in weak rocks often resulted in segment failures in lateral sides and even shield failures at invert parts following lateral excavating after TBM blocking.

The segment failure is asymmetric in the two sides. In cases of faulted rocks the failure usually occurred in the side adjacent to the upper section of a reversed fault. The steel support was also failed in the upper section of a reversed fault as observed in the accident point (4). The segment failure after the TBM and the steel support failure in lateral adits occurred in middle height and were asymmetric. This phenomenon is very similar to that in Figure 4.

DECISION MAKINGS AND MEASUREMENTS

Consolidations

In the TBM tunnelling, collapse often took place in weak rocks, in some case with water flows. It is difficult to adopt bolting and grouting in such a small space. So the consolidation is to be undertaken with polyurethane foam from mixing of two liquids that become solid in a shortr time. In practice this method is effective, but when water flow is larger, this method is neither usable nor effective and economic. For the case of adit excavation, steel frame supports were used for supporting fractured or faulted rocks.

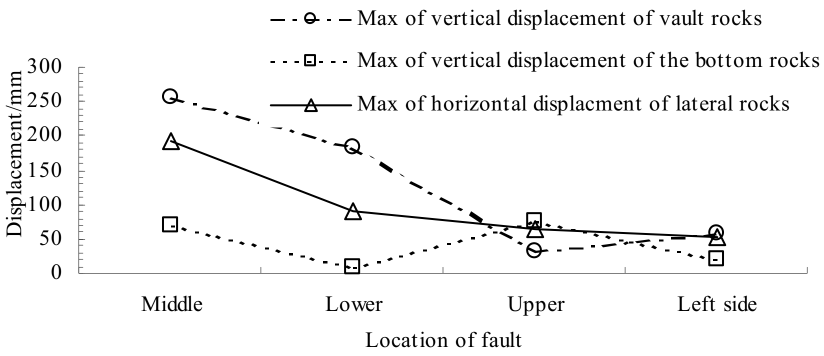

Figure 4. Location of faults in tunnel cross section versus displacements of surrounding rocks via numerical simulation

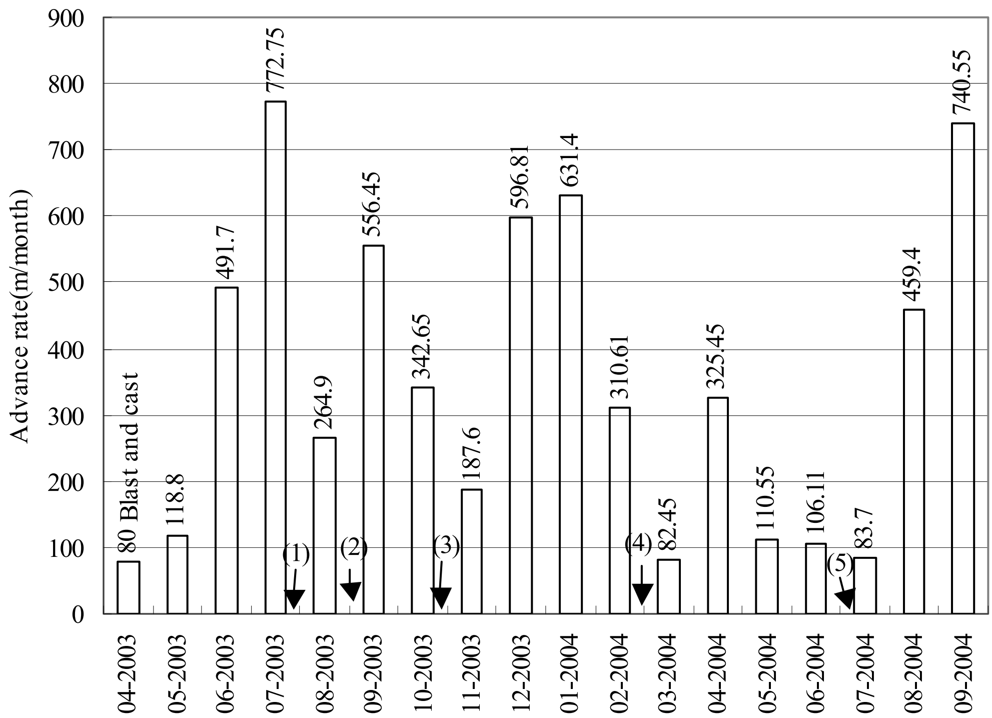

Figure 5. TBM advancement in Shanggongshan Tunneling in the past two years

Drainage

The drainage capacity increased after some accidents. One way is to upgrade the discharge capacity of the pumping machine; another is to temporarily keep the flowed water at a free space in the middle of the tunnel. Meanwhile, the TBM quickly moved forward and sealing rod between segments and anti-filter layers outside of the segment were set up to prevent groundwater from moving into the tunnel.

Lateral excavation and advanced drilling

In squeezing and collapse section, lateral excavation was used to free the TBM shield and make consolidations. In the case of facing fault or large water flows, advance drilling was used. In accident (4), advanced drilling was carried out in a length of about 20m. In practice, taking the geological record from shield windows, TBM machine working parameters and the excavated rocks together are helpful on advanced prediction, because the advanced drilling is more difficult to use in TBM tunnelling.

Adjustment of tunnel line

As shown in Figure 1, after excavation of 4.35 km, it was found that at least three parallel faults were in front of the working face. And the most serious case (4) resulted in much time being spent dealing with the faulted rocks and a large squeezing span. So after consideration and comparison of geophysical exploration results, the previous tunnel line was adjusted to a new straight line. Following excavation, examination indicates that this adjustment is acceptable to escape from dense faulty belts.

DISCUSSION

From triaxial to uniaxial compression on shield

When TBM was blocked, in most cases a lateral adit excavation was to be undertaken. This made the loading on shield transferred from triaxial to uniaxial when squeezed rocks at its both sides were moved out ($_3$=0), and the loading only at its top and bottom as vertical stress. Then in a unit longitudial length (1m) of the tunnel, the inferred centralized force on the shield

$$P=\sigma\bullet A=(\sigma_1-\sigma_3)\bullet l\bullet 1=\sigma_1\approx\gamma hl \qquad (1)$$

$$l=1/4\bullet\pi\bullet D \qquad (2)$$

In equations, γ, h: bulk density and thickness of overlaying rocks, respectively; l: circular contact length of shield with surrounding rocks in the vault; D: diameter of the cutterhead in m.

In case (4), the plastic deformation of the back shield is from 5~12cm and became smaller when the lateral excavation moved ahead. In that case, h= 200m, γ=2.72g/cm^3. Then σ=5.44MPa. D=3.665m, then l=2.87m.Thus P=15300.544kN. According to

$$P=K\bullet\delta \qquad (3)$$

Here, K: stiffness coefficient of the shield in kN/mm δ:deformation in mm.

In this situation, δ=5~12cm, here it is as 100mm. So K=153.00kN/mm.

For the steel shield, this result is an inferred comprehensive value of stiffness coefficient of the shield. This value is smaller than its original value due to yielding force of the shield, which leads to large displacement as 10cm.

Difference of rock mass quality in ground surface and underground

Apart from the completely decomposed rocks and Quaternary deposits in import as grade V, in the former part of the tunnel at a distance of 7km, previous investigation and analysis evaluated the rock mass quality as good: II 30%, III 60%, IV 10%. But after TBM excavation, it was found that most of the rock mass was between grades III and IV, some even grade V as loose as fly ash. In the ground surface, most of slates exist as strongly weathered and completely weathered in yellow and brown, but in tunnels the slates exist as gray rocks, highly fractured. So on one hand the rock mass quality evaluation result is different in surface and underground. On the other hand, conventional evaluation index is not well suitable for TBM tunnelling. Barton (2000) once put forward Q_{TBM} for classification of the rock mass. In this case, a three-grade classification scheme was primarily put forward based on parameters of intact rock strength (uniaxial compression strength σ_c), abradability to cutterhead (taking the attrition value (A_b) of special wire CAI) and integrity of rock mass (integrative coefficient of rock mass K_v). A primary comparison of the results with those from conventional classification shows good correlation with TBM advanced rate (Figure 6).

CONCLUSIONS

Folds, faults, weak rock and ground water make engineering geological conditions too complicated to be coped well by using TBM method. The selection of the tunnelling method is a strategic decision.

Different identification of faults and rock mass quality in ground surface and underground is significant for decision making at primary stage on selection of tunnelling method. Conventional rock mass quality classification is not suitable for TBM method. The abradability of the rock mass, which will affect the budget and time of TBM method, should be particularly considered in classification.

The research and investigation of items such as asymmetric stress and deformation, water flow and effect on circumstances is distinctive for TBM method. Advanced prediction approach and accuracy is not well defined for TBM tunnelling. Engineering geological analysis is the basis of evaluation of TBM suitability and measures to be adopted.

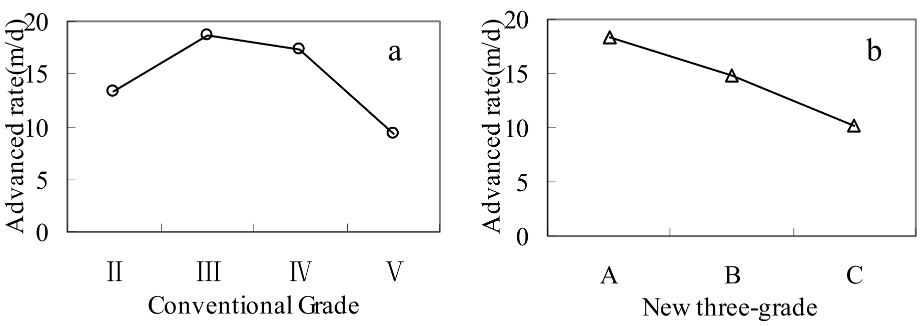

Figure 6. Correlations of TBM advanced rate to the conventional and to a three-grade scheme on rock mass classification
a. Conventional rock mass grades; b. a three-grade scheme on rock mass classification

Acknowledgements: Field investigation received assistance from engineers of Kunming Branch of CMC, Italy. This research received financial support from the Chinese Natural Scientific Foundation Committee (NSFC) (Project No. 40372125). The authors acknowledge the Special Funds for Major State Basic Research Project of China under Grant No. 2002CB412701.

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