A new perspective for support design of shallow tunnels in mudstone formation: basic philosophy and engineering practice

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Abstract. The traditional support design of rock tunnels mainly relies on the comparison of the geological condition and tunnel characteristics with those prescribed in rock mass classification schemes. The supporting patterns and supporting parameters can then be empirically determined in accordance with the classified grades of rock masses. However, a variety of rock mass classification schemes are used worldwide, which require different input indices. Different classification schemes may lead to varied design suggestions for the same project. Thus, determining the most reliable suggestion presents a challenge. In addition, most of the traditional rock mass classification schemes neglect the intrinsic and distinct properties of rock masses and often either underestimate or overestimate the necessary support requirements. In this study, a new design philosophy is proposed by emphasizing the importance of considering the intrinsic properties of rock mass. Based on a tunneling project in Pakistan, we first determined the basic mechanical properties of mudstone, which is the major formation in the tunneling region. Then, a series of model tests was conducted to analyze the tunnel stability under different scenarios, from which a reduced supporting system that was weaker and more flexible than those determined from the classic rock mass classification schemes was derived.

Practical application showed that the proposed supporting system was adequate and reliable. Apart from referring to the rock mass classification scheme, the current study highlights the importance of considering the mechanical properties of rock masses for tunnel support design.

Keywords: soft rock tunnel; tunnel supporting design; rock classification scheme; model test
1 Introduction

The engineering community generally believes that weathered mudstone has low strength and stiffness and is vulnerable to environmental factors, which leads to its high tendency of instability and deterioration. Numerous serious deformation and failure cases of weathered mudstone slope and roadway worldwide have been reported. Therefore, mudstone is usually classified as a weak rock by various rock classification methods, for example, it is classified to be below grade IV when using the basic quality index of surrounding rock (BQ) method [1]. At present, the design schemes of tunnel structure are mostly based on the classification of surrounding rocks, especially for tunnels shallowly buried in soft surrounding rock conditions, for which strong support measures should be usually adopted [2-5]. Based on the existing classification method, the support cost of tunnels in mudstone formation can be very high. Nonetheless, several microscopic phenomena, such as diagenetic cementation and engineering activation, etc., can greatly improve the engineering properties of mudstone. These events, however, are ignored in the existing rock classification schemes.

Based on the case study of China’s first foreign aid to construct the Hualong One nuclear power project (K-2/K-3 nuclear power plant in Karachi Nuclear Power Plant), this paper comprehensively analyzed the formation mechanism and engineering characteristics of mudstone on site by combining micro-scale analysis, model test, and site measurements. The rationales of different existing rock mass classification methods were evaluated. A reasonable design and construction plan was proposed at the end, and it was proven to be reliable and economic.

2 Project Overview

The K-2/K-3 nuclear power plant in Karachi, Pakistan is located west of Karachi and on the north shore of Arabian Sea. This power plant is China’s first foreign-aided Hualong One nuclear power project. The circulating water system of this project comprises a single intake tunnel of about 500 m (two in total) and a single drainage tunnel of about 2,200 m (two in total). As shown in Fig. 1, the tunnels mainly pass through medium and lightly weathered mudstones and partly through moderately weathered argillaceous sandstone. The current study focused on the mudstone section where the majority of tunnels are located, which includes medium weathered and breezy mudstones. The physical and mechanical properties of the rock formation are shown in the Table 1:

| Lithology   | density (g/cm³) | Shear strength fi (°) | Elastic modulus C | Uniaxial compressive strength | Compressional velocity | Rock quality | Softening coefficient |
|-------------|-----------------|----------------------|--------------------|-------------------------------|------------------------|--------------|-----------------------|
| Table 1. Physical and mechanical parameters of mudstone | | | | | | | |
|                | (MPa) | (GPa) | strength (MPa) | (m/s) | designation (%) |
|----------------|-------|-------|----------------|-------|-----------------|
| medium weathered mudstone | 2.28  | 0.20  | 0.63           | 1.91  | 21.10           | 1408 | 38.2 | - |
| lightly weathered mudstone   | 2.32  | 0.24  | 1.1            | 2.01  | 27.78           | 1799 | 46.6 | 0.11 |

The water intake and drainage tunnels were constructed by the mining method. Their equivalent...
excavation diameter is about 8.7–9 m, and the buried depth is 12–29 m. Both tunnels are shallowly buried with a low overburden. The shallow ground formation is 0.3–10.5 m thick and mainly consists of gravel sand and silt (medium permeability). The groundwater replenishment is mainly vertical infiltration of atmospheric rainfall, which is discharged into the nearby sea. Mudstone usually has good integrity and poor permeability. Thus, it can be considered as a marginal waterproof layer. The fracture pore water in the site bedrock mainly exists in argillaceous sandstone. Given that the water intake tunnel and drainage tunnel of this project pass through the same stratum, with the drainage tunnel having a longer length, only the drainage tunnel will be analyzed hereafter.

3 Supporting Scheme of Surrounding Rock

3.1 Recommended support schemes under various surrounding rock classification standards

At present, numerous classification methods are used for surrounding rock at home and abroad, among which the BQ method, Q-system (Q), rock mass rating (RMR), geological strength index (GSI), and rock structure rating (RSR) have the greatest influence [6-10]. Table 2 summarizes the above major classification methods. The GSI method is mainly a visual rapid assessment method combined with a scene, and it presents difficulty carrying out quantitative analysis. The RSR method is mainly adopted by specified projects in the United States, and its follow-up applications are extremely limited. Therefore, from the perspective of quantitative analysis and wide application, BQ, Q, and RMR were adopted for further discussion. BQ, Q and RMR divide rock quality into five grades according to the calculated values and Table 3 shows the intervals of rock classification based on the three methods respectively. Of these three methods, China mainly adopts the modified BQ, and the other two methods are commonly used rock classification methods overseas. Furthermore, among these methods, the BQ method and Q-system offer suggestions for tunnel support measures.

Table 2. Summary of different rock mass classification schemes

| Classification scheme | Formula | Major indices |
|-----------------------|---------|---------------|
|                       |         | intact rock strength | complete-ness | joint condition | joint orientation | under ground water | initial in-situ stress | ranking number |

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BQ-system:

\[ BQ = 100 + 3R_c + 250K_v; \]

\[ [BQ] = BQ - 100 (K_1 + K_2 + K_3) \]

Q-system:

\[ Q = \left( \frac{RQD}{J_n} \right) \left( \frac{J_w}{SRF} \right) SRF RQD, J_r, J_w \]

RMR system:

\[ RMR = A_1 + A_2 + A_3 + A_4 + A_5 + B \]

RSR system:

\[ RSR = A + B + C \]

GSI system:

\[ Experienced \]

Table 3. Overall quantitative classification index of rock mass

| Classification Scheme | I (very good) | II (good) | III (fair) | IV (poor) | V (very poor) |
|-----------------------|---------------|-----------|------------|-----------|---------------|
| BQ-system             | (550,700]     | (450,550] | (350,450]  | (250,350] | (0,250]       |
| Q-system              | (40,1000]     | (10,40]  | (1,10]     | (0.1,1]   | (0.001,0.1]   |
| RMR system            | (80,100]     | (60,80]  | (40,60]    | (20,40]   | (0,20]        |

In accordance with the surrounding rock conditions of this project, the classification results of surrounding rock under different classification schemes were obtained as shown in Table 4. The moderately weathered mudstone is generally characterized as the rock with very poor stability and needs strong supports. The slightly weathered rock is also classified as a rock with poor stability and with a necessity of strong support measures.
Table 4. Recommended supported measures of different rock classification systems

| Lithology           | BQ  | Q      | RMR | Recommended Supported measures                        |
|---------------------|-----|--------|-----|-------------------------------------------------------|
| moderate weathered  | 150 (V) | 0.51  | 40  | BQ-system: Fiber reinforced shotcrete: >20cm          |
| mudstone            | Very poor | Very poor | Poor | Reinforced ribs: @60cm                                |
|                     |      |        |     | System rock bolt: L=3m, @0.6m                          |
| slightly weathered  | 187.5 (V) | 2.96  | 50  | BQ-system: Fiber reinforced shotcrete: >20cm           |
| mudstone            | Very poor | poor | Fair | Reinforced ribs: @60cm                                |
|                     |      |        |     | System rock bolt: L=3m, @0.6m                          |
|                     |      |        |     | Q-system: Fiber reinforced shotcrete: 12~15cm          |

Combining the initial support suggestions of different classification methods, the tunnel support measures in the preliminary design stage are shown in Fig. 2.

![Fig. 2. Cross-sectional illustration of the initial support of the drainage tunnel (Unit: mm)](image)

3.2 Microscopic analysis of weathered mudstone

The mudstone used in this project was mainly grayish-yellow or blue-gray and comprised a layered argillaceous structure. The single-layer mudstone has a thickness of 0.1–0.5 m, which represents a medium-thick layer with well-developed micro-layers. Mudstone joint fissures were absent, and the joint fissure surface was rust-colored, with a thin-layered argillaceous sandstone interposed locally. According to the previous rock mineral determination, the mudstone contained...
50%–30% clay (mud), 35%–45% silt, 15% calcite (calcium), 15% dolomite, and 5%–6% iron, clay mineral hydromica (20.3%–26.9%), montmorillonite (11.2%–11.4%), and kaolinite (10.3%–11%). The degree of cementation of mudstone is closely related to the content of montmorillonite and the characteristics of sodium-based calcium, which has a significant effect on its shape. The mudstone showed strong and evident water absorption and swelling properties. After absorbing water, the microstructure of the mudstone will change. More attention should be paid to its water absorption given the high content of montmorillonite in this project.

To study the changes in the microstructure of mudstone under different conditions of water immersion, we immersed the mudstone samples collected from the site in water for different time periods (0 s, 1, 5, and 30 min and 1 day). Then, the tungsten-filament scanning electron microscope (TFSEM) at the Department of Geotechnical Engineering of Tongji University was used to investigate the changes in the microstructures due to water absorption (Fig. 3). Table 5 lists the main features of TFSEM. For each sample, images at three different regions were collected.

![Tungsten Filament Scanning Electron Microscope (TFSEM)](image)

**Table 5. Main Technical Parameters of Tungsten Filament Scanning Electron Microscope (TFSEM)**

| Main parameter | Secondary electron resolution | Backscattered electron resolution | Magnification | Accelerating voltage | Maximum sample diameter | Maximum sample height |
|----------------|------------------------------|----------------------------------|---------------|----------------------|-------------------------|-----------------------|
| Value          | 3.0 nm                       | 4.0 nm                           | 5-30 \times 10^4 times | 0.3-30 kV            | 153 nm                 | 60 mm                 |
Table 6. Scanning results of mudstone samples with different immersion periods (magnified by 1000 times)

| Immersion time | Section 1 | Section 3 | Section 3 |
|----------------|-----------|-----------|-----------|
| 0              | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| 1 min          | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| 5 min          | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |
| 30 min         | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| 1 day          | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) |

Table 6 provides the scanning results of samples with different immersion times. The
microstructure of mudstone underwent tremendous and irreversible changes before and after immersion. Given the occurrence of secondary cracks and the influence of non-uniform tensile stress on the sample surface, pores and cracks gradually appeared on the surface of samples. The number and width of the sample’s surface cracks and the pore size increased with the increase in immersion time. The softening coefficient (ratio of unidirectional compressive strength of a rock specimen under saturated and dry conditions (or under natural water content)) of mudstone was 0.11. However, the mudstone involved in this project can still maintain a relatively good integrity after immersion in water for one day, indicating that the mudstone involved in this project had a strong anti-water disintegration property (low water sensitivity), which is beneficial to the safety of the project.

3.3 Laboratory model test of support scheme

To explore the influence of sharp deterioration of mudstone performance after water absorption on tunnel stability, the project also carried out the indoor model test of tunnel excavation under rainfall condition. The specific details of our model parameters and test conditions in this model test can be found in reference [11]. River sand, barite powder, clay powder, and iron powder were selected as aggregate, quicklime and gypsum were used as binders, and similar geotechnical materials were configured based on the recommended physical parameters in Table 7. Fig. 4 shows the established test model.

| Type          | Density / (g·cm⁻³) | Compressive strength /MPa | Elasticity modulus /MPa | Internal friction angle / (°) | Cohesive force /kPa |
|---------------|--------------------|---------------------------|-------------------------|-------------------------------|---------------------|
| Mudstone      | 2.0−2.3            | 0.1−1.4                   | 35−45                   | 40−55                         | 8−15                |
| C-1           | 1.94               | 0.1188                    | 39.77                   | 50.86                         | 11.93               |
| C-3           | 1.91               | 0.1151                    | 40.16                   | 47.43                         | 21.73               |
| C-4           | 1.89               | 0.0981                    | 31.08                   | 44.21                         | 9.62                |
Fig. 4. Laboratory model test of support scheme

The design of the experiment was a two-step scheme. First, the tunnel was excavated in the weathered mudstone stratum with low moisture content. After the excavation, the overall mode was left to rest overnight, and rain was used for replenishment. Therefore, model tests can be divided into excavation and rainfall processes. The low water content of the surrounding rock material during excavation can provide basic data for the analysis of mechanical response and deformation law during excavation. After the excavation, the stress of the surrounding rock was released through the space–time effect. Rainfall was implemented, that is, a certain amount of water was added in stages at a constant speed to make the surrounding rock moist and close to saturation. A detailed rainfall plan was formulated to reduce the influence of precipitation process on surrounding rocks. Four sprinklers were evenly distributed on the surface close to the model, and water was added slowly and symmetrically. Each precipitation lasted for 10 min, with a flow of 160–170 ml/min and a total rainfall flow of 1600–1700 ml. After the precipitation, the next precipitation time was determined based on the surface seepage. During the test, as the tunnel was excavated, no visible changes were found in the test block, the surrounding rock was stable, and the tunnel was not damaged in any way. Through grid calculation by PhotoInfor software, cloud map, allelic line map and displacement vector map of surface displacement can be obtained, and the three maps are combined into one map, as shown in Fig. 5.
Fig. 5 shows the cloud map of tunnel displacement caused by tunnel excavation in different rainfall periods. In the process of rainfall, water flow was fast at the beginning and can flow down in a short time. However, with the gradual saturation of surrounding rock, the rock formation in the wetting range formed a water-retaining layer. Thereby, the seepage slowed down and can only rely on the capillary action to flow slowly. In the end, after standing for a night with no support, the surrounding rock was still competent without evident collapse. At this stage, the entire testing model
was wet, and water had infiltrated into the tunnel periphery. However, the mudstone was still stable without significant displacement or local damage. In other words, during the excavation, the ground precipitation did not cause significant deterioration of the surrounding rock properties. The laboratory tests also verified that although the strength of the rock was low, full-section excavation can be stable under the condition of controlled excavation disturbance despite the lack of support measures. Therefore, the core of this project is to control the water that may appear in the tunnel during construction.

4 On Site Construction Plan and Support Implementation

4.1 Restrictions on excavation technology and support measures

Considering that blasting construction causes great disturbance to the rock mass around a tunnel, and the compressive strength of the rock mass in this project was small, the milling excavator was used for excavation. To minimize the degree of disturbance to the surrounding rock and to shorten the exposure time of rock mass around the tunnel, we considered the whole section excavation by using a milling excavator after optimization, at which the entire tunnel cross-section can be formed once.

In the actual construction process, to speed up the progress of the project, we did not excavate the invert ground, and the I-steel arch was not closed into a ring. For such a construction scheme, the anchor bolts of the arch waist and arch foot parts are very crucial. The lock foot anchor rod adopted 2Φ42×4 with a length of 3.5 m.

4.2 Limitations on water-containing processes

The anchoring agent instead of cement slurry was used for grouting to avoid the degradation of strength and disintegration of the rock mass when it encounters water. The anchoring agent is water-free and has excellent characteristics, such as fast solidification and close bonding with the rock mass. Field practice showed that after grouting the system bolts with anchoring agents, the rock mass almost had no strength loss or disintegration, which was feasible.

4.3 Optimization of site support scheme

Table 8 shows the comparison of support before and after optimization. Notably, optimization of the support scheme cannot only improve the construction efficiency but also greatly reduce the support structure, which yields good economic benefits.
Table 8. Comparison of support measures before and after optimization of drainage tunnel

|                          | Original scheme             | Prioritization scheme |
|--------------------------|----------------------------|-----------------------|
| **Excavation method**    | Ring excavation reserved   | The whole section explosion |
| **Steel arch frame**     | core soil method           |                       |
| **Advance rock bolts**   | Spacing of 0.6 m           | Spacing of 1.0 m      |
| **systematic rock bolts**| Spacing of 0.6 m in arch   | none                  |
|                          |                            |                       |

4.4 Field monitoring data verification

The layouts of the horizontal convergence survey line in the two drainage tunnels were the same, and the monitoring results showed the same trend and value. Therefore, only the drainage tunnel was discussed. Fig. 6 shows the layout of the horizontal convergence survey line in the drainage tunnel. The displacement convergence map of the monitoring point corresponding to each monitoring section of the drainage tunnel is shown in Fig. 7.

Fig. 6. Schematic of the horizontal section of the monitoring point
As shown in Fig.7 the convergent deformations of tunnels at different monitoring sections were stable within 10–12 days. The convergent deformation was about 13–14 mm. Note the displacement of all monitoring points is relatively small. The site measured tunnel deformation further verifies that the reduced supporting strategy in comparison with that prescribed by the rock classification schemes is reliable.

5 Conclusion

The conventional design of support systems for rock tunnels mainly relies on rock classification schemes. Different rock classification schemes may provide various guidelines on the support design, which may be conservative, especially for soft rock masses. Based on a mudstone tunnel project, this study showed that the support design recommended by the rock classification schemes is alterable if the mechanical properties of rock masses and its performance subjected to tunneling activity can be fully understood.

(1) The microscopic analysis shows that the mudstone prevailing in the background project had low sensitivity to water absorption and can still maintain a high integrity after being immersed in water for one day.

(2) The model test showed that the mudstone tunnel can still remain stable after rainfall infiltration despite the absence of supports.

(3) Considering the good stability, the supporting system prescribed by the rock mass classification schemes was reduced. The construction technologies were modified to give a low disturbance and no hydration condition. The site monitored tunnel deformation indicates that the reduced supporting
scheme is reliable.

The relevant design and research have produced good benefits in the background project, and the optimization of steel arch frame, system bolt, and excavation method has saved about 35.8% of the total cost. This study highlights the importance of considering the mechanical properties of rock masses for tunnel support design. Relevant design methods and concepts can provide reference for subsequent similar projects.

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