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Sub-horizontal reinforcement of weathered granite before tunneling beneath a spillway

Yufeng Shi [a,b], Junsheng Yang [b], Shuying Wang [b,*]

[a] School of Civil Engineer and Architecture, East China Jiaotong University, Nanchang 330013, China
[b] School of Civil Engineering, Central South University, Changsha 410075, China

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ABSTRACT

Sub-horizontal jet-grouted columns and pipe roof are usually adopted to reinforce weak ground ahead of tunnel excavation face, but they bear a low tensile strength and poor waterproof capacity, respectively. A combination of sub-horizontal jet-grouted columns and pipe roof was proposed to reinforce weak ground before Jiangmen tunnel passed beneath a spillway for drainage of Yu-long Reservoir. Due to the pipe roof added below the jet-grouted columns, numerical simulation demonstrates that stress in the jet-grouted columns, ground surface settlement, convergence and stress of primary liner are reduced, and the stability of the excavation face is increased substantially. The umbrella formed by jet-grouted columns works as a shell, and the pipes in the pipe roof behave as beams in the longitudinal direction of the tunnel. Due to their respective features in the working mechanism, Jiangmen tunnel stayed safe when it passed beneath the spillway. The field measurements are comparable to the numerical results, although there are some differences in their values due to some influence factors.

1. Introduction

With development of civil infrastructures, there is a growingly number of tunnels. Sometimes, it is inevitable that complex geological conditions are encountered by tunnels, whose construction easily induces ground failure ahead of excavation face. The complex geological conditions can be swelling rock, squeezing ground, high geostress, fracture zone, etc. To ensure ground stability and control ground settlement, the tunneling in different geological conditions requires different reinforcement technologies. For example, in the squeezing ground and geostress zone, high strength support are often required, and special construction sequences are sometimes considered [1–3]. Comparatively, for tunneling in the weak ground (such as fracture zone, fully-strongly weathered rock), the common reinforcement methods include pile roof, horizontal jet-grouted columns, curtain grouting and ground freezing [4–6] to reduce ground settlement and ensure the stability of tunnel excavation face. However, the ground freezing, curtain grouting methods are high in cost and time-consuming [7]. The stability of tunnel in weak ground can also be improved by reinforcing excavation face with pipes or bolts [8–12], and as an new developing method, the ADECO full-face excavation has been becoming a competitive tunneling method to control ground deformation [11–12]. However, with a comparison, the horizontal jet-grouted columns and pipe roof are still relatively more popular than other technologies [7].

As presented in [13], the horizontal jet grouting columns are employed to reduce the surface settlement in urban tunneling. They found that the settlement obtained for the staggered excavation scheme was only slightly larger than the settlement in the ground reinforced with jet-grouted columns for a layer of stiff gravel over a relatively soft sand layer. However, the settlement was reduced significantly with the jet-grouted columns for a soft sand layer over a relatively stiff layer of gravel. Coulter and Martin [14] presented the effect of jet-grouted columns on surface settlement above the Aeschertunnel, Switzerland. It was indicated that volume loss was limited to 0.35%. They stressed that the local shear bands induced by high jetting pressure produced narrow settlement trough compared to that observed using the conventional New Austrian tunneling method (NATM). To form a long umbrella ahead of excavation face, the horizontal jet-grouted columns were designed to have a low inclined angle in the longitudinal direction. With this low inclined angle, sub-horizontal jet-grouted columns are normally called. The sub-horizontal jet-grouted columns was applied to pre-confine the tunnel core in Cassia twin road tunnels [11], and only a settlement of 1 cm developed at the end of tunneling. Thus, the (sub-) horizontal jet-grouted is an effective method to control ground settlement and improve the stability of the ground ahead of excavation face. However, as pointed out by Lignola et al. [15], the jet grouted columns are often far from having a perfect shape,

* Corresponding author.
E-mail address: sywang@csu.edu.cn (S. Wang).

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because they are intrinsically affected by defects, resulting in that unforeseen risk may be hidden in design and construction of ground improvement.

The effectiveness of the pipe roof for improving the tunnel stability and reducing the ground settlement has been investigated by some researchers. Volkmann et al. [7] proposed a technology to measure the inclination of the pipes using in place inclinometer chains. Yang et al. [16] reported mechanism of double-layer pipe roof, which was used to reinforce the ground above a shallow multi-arch tunnel passing beneath an existing national road of China. Volkmann and Schubert [6] compared effectiveness of the spiling method (fore poling) and pipe roof method (long-span fore poling) in supporting working area against ground failure. When facing inhomogeneous ground conditions, the probability of failure was higher with the spiling method. Histake and Ohno [17] studied the effect of pipe roof umbrella on the displacement above an excavation face using centrifuge model tests, indicating that the maximum ground settlement was reduced by 75% due to the pipe roof installed ahead of excavation face. Yeo et al. [18] studied the Fort Canning Tunnel, Singapore using three-dimensional (3D) numerical models, also indicating that the tunneling induced ground settlement was largely reduced with the pipe roof umbrella. Forrest et al. [19] studied the pipe roof umbrella system in a Western US underground coal mine using two-dimensional (2D) and 3D numerical models, in which beam elements were embedded, and the results showed than bending moment in the embedded beams changed with the pipe spacing and the diameter of the pipes. The pipe roof umbrella can also be used with a combination of longitudinal fiberglass pipes grouted into the excavation face to improve the face stability [9]. The contribution of the pipe roof umbrella to ground settlement and tunnel stability was also presented in the references [20,21]. Thanks to steel pipes, the pipe roof has a higher shear tensile strength than jet-grouted columns. However, the pipe roof cannot effectively form a waterproof system to prevent groundwater from flowing into the tunnel [22]. Besides the pipes, the annular gaps are filled with grout through holes in the pipes [7]. However, mostly the pipes are not grouted with high pressures like during jet-grouted columns.

Jiangmen tunnel was one of controlled projects in the Guang-Zhu special railway line for cargoes, with a length of 9185 m and double tracks. The tunnel passed beneath a cleugh, where a spillway was built for drainage of Yu-long reservoir, as shown in Fig. 1. The spillway was 20 m wide. The excavation scope of the tunnel was 11.6 m in height and 11.9 m in span. The tunnel had a minimum depth of only 3 m when passing beneath the spillway. To under passing the spillway safely, the ground ahead of excavation face had to be reinforced. This paper compiles the techniques adopted in construction of Jiangmen tunnel when passing the spillway to show how the ground ahead of the excavation face was reinforced. The working mechanism of the proposed technology is investigated using numerical simulation. Finally, the numerical results are compared with field monitoring results.

2. Geological conditions

Jiangmen tunnel locates in the area with hills and accumulation plain. Based on site investigation, the area is in a wide and gentle zone of fault-folded belts. The local tectonic formation is mainly dominated by northeast ruptures, which are joined by northwest ruptures. The ground in the tunnel section (DK111 + 140–DK111 + 160) beneath the spillway is weak and not good for tunnel stability. As shown in Fig. 2, the ground encountered by Jiangmen tunnel is a soft layer underlaid by a relatively stiff layer: fully-strongly weathered granite in up half tunnel scope and weakly weathered granite in down half tunnel scope. The ground under

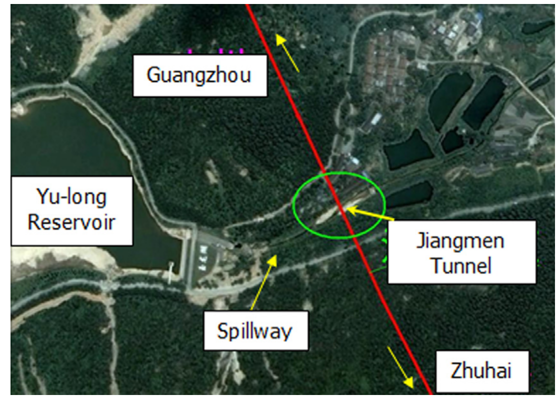

Fig. 1. Plan view of Jiangmen tunnel passing beneath the spillway for Yu-Long reservoir.

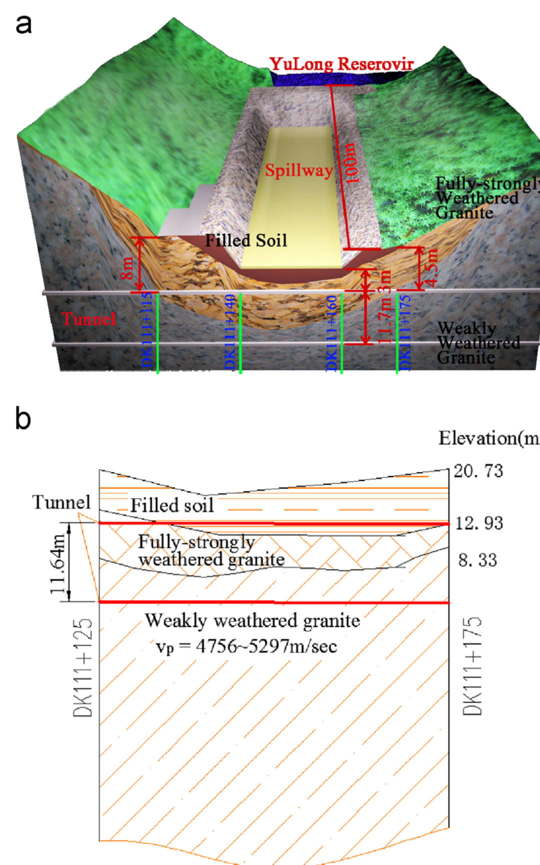

Fig. 2. Geological condition in tunnel section beneath a spillway: (a) three dimensional, review and (b) cross-section in the longitudinal direction of the tunnel.

the spillway may be described as follows (from the ground surface). (1) Filled soil: it consists of clayey soil and fine sand, and its thickness is about 3–8 m. (2) Fully-strongly weathered granite: this granite is easily disintegrated due to water and manifested as stiff sandy soil, as shown in Fig. 3. The standard penetration test (SPT) number is 31–46 and its average is 38. The cohesion and effective friction angle are 13 kPa and 29.8°, respectively. This layer is 4.6–8.1 m in thickness. (3) Weakly weathered granite: joints are developed in this layer, resulting in that the rock ground is manifested as blocks. This layer is so deep that the information of the lower layer is not required for consideration. The rock quality designation (RQD) of weakly weathered granite is about 85%. Based on laboratory tests, it has an elastic modulus of