Support System for Tunnelling in Squeezing Ground of Qingling-Daba Mountainous Area: A Case Study from Soft Rock Tunnels

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Tunnelling or undertaking below-ground construction in squeezing ground can always present many engineering surprises, in which this complicated geology bring a series of tunnelling difficulties. Obviously, if the major affecting factors and mechanism of the structure damage in these complicated geological conditions are determined accurately, fewer problems will be faced during the tunnel excavation. For this study, reference is made to four tunnel cases located in the Qingling-Daba mountainous squeezing area that are dominated by a strong tectonic uplift and diversified geological structures. This paper establishes a strong support system suitable for a squeezing tunnel for the purpose of addressing problems exhibited in the extreme deformation of rock mass, structure crack, or even failure during excavation phase. This support system contains a number of temporary support measures used for ensuring the stability of tunnel face during tunnelling. The final support system was constructed, including some key techniques such as the employment of the foot reinforcement bolt (FRB), an overall strong support measure, and more reserved deformation. Results in this case study showed significant effectiveness of the support systems along with a safe and efficient construction process. The tunnel support system proposed in this paper can be helpful to support design and provide sufficient support and arrangement before tunnel construction in squeezing ground.

1. Introduction

The railway/highway tunnels are considered one of the most efficient and environment-friendly ways to improve the transportation infrastructures and have been developing rapidly all over the world in recent decades [1–4]. In reality, determining the viable support system is a key factor affecting the cost and safety of underground works. When a tunnel is excavated, a support system is installed to ensure the stability of the excavated underground caverns by controlling the displacement of the rock mass, so as to address the safety issues that may arise [5–8]. In recent times, an increasing number of the complex geological conditions have been confirmed in underground space development [9–12], this is especially so in the squeezing ground areas which have resulted in a series of tunnel construction problems such as extreme deformation, support structure failure or even collapse, and examples can be easily found in the Zhegushan and Laodongshan tunnels in China [13, 14], tunnel 35 of the Ankara-Istanbul high-speed railway project in Turkey [15], and Kaligandaki tunnel in Nepal [16]. The continuous hazards yield brand-new challenges to tunnel construction in squeezing ground [17–19].

With regard to the uncertainties existing in rock mass properties, the design of tunnel support in squeezing ground has always been a sophisticated task [20, 21]. Many scholars have done research on tunnel support structure where the achievements are mainly carried out from three aspects of empirical method, analytical method, and numerical method [22–24]. As for tunnel support design, although analytical and numerical methods are generally considered to be the most effective and scientific way, they also have
obvious shortcomings and limitations in use. For example, most analytical methods are established based on the assumption that a tunnel is a circular cavern, and some necessary simplifications are made to simplify the calculation [25, 26]. These assumptions are sometimes distant from the realities of the engineering conditions in most cases, because the shape and faced stress conditions of the tunnel vary greatly from one construction site to another. The analytical method is widely used in tunnels regarding the characterization, support evaluation, and back analysis [27, 28]. Gao et al. [29] optimized the lining structure used in a soft rock tunnel by employing a finite difference software of FLAC 3D, and based on a comparison with field test data, they finally proposed an economical and simplified construction support system. A yielding support system was proposed by Wu et al. [30] to cope with the extreme deformation problem for a soft rock tunnel excavated in squeezing ground. Kanik and Gurocak [31] conducted a deep study on empirical rock mass classification system and established an optimal support unit through a comparative numerical analysis. The analytical methods provide a lot of support for tunnel design and construction simulation; however, an accurate rock mass model is difficult to establish due to the discontinuity, anisotropy, heterogeneity and inelasticity of rock mass [32–35]. The complex nature and different strata make rock mass a difficult material for a simulation of the numerical method [36–38].

Of course, the research and discussion of the effective support system from engineering practices have never stopped. Aksoy et al. [39, 40] recently have developed new approaches to identify the time-dependent deformation behaviors of rocks under different loads so as to guarantee the stability of constructions built in rock masses. Kong et al. [41] emphatically analyzed the mechanism of primary support failure in a deep tunnel regarding a sidewall collapse during construction phase. Dadashi et al. [42] analyzed and revised the support structure parameters after a soil mechanics property evaluation, and then a support system using shotcrete, steel mesh, and lattice beam was proposed for a squeezing tunnel based on the parameters obtained from the back analysis. Oliveira and Diederichs [43] discussed the brittle failure simulation of the sandstone and influence of the high geostress on tunnel support design. Panthi and Nilsen [44] believes that the best way to deal with severe squeezing is to preestablish a strategy including planning and design phases to minimize the stability problem and optimize the support and stability measures. In this view, a reasonable structure system becomes very useful in designing tunnel support. There are many literatures reporting tunnel support design or optimization regarding rock mass properties and support structures [45, 46]. However, the number of literatures reporting extreme-deformation-induced support structure failure is limited, and thus, a comprehensive supporting system is required to relieve the damage of tunnel structure in squeezing ground.

In this paper, study area with full of surprises during underground construction activities due to frequently geological changes in Qingling-Daba mountainous area is introduced firstly (Figure 1). Tunnels in this area are being constructed in squeezing ground with high tectonic activity and a large number of jointed rocks. The maximum deformation in four tunnel cases selected for study had reached 100.8 cm during tunnel excavation, causing the support structure failure, which requires a reshaping work for tunnel support system. In the view of this, the main purpose of this paper is to explore features of the structure damages in a squeezing condition through on-site investigation. Based on the discussion of structure failure and field test results, we establish a strong support system suitable for a squeezing tunnel that includes the temporary support measures and some necessary key techniques. The effectiveness of the proposed tunnel support system was verified by an analysis on the recorded data of the rock mass deformation throughout the construction phase.

2. Study Area

Main body of the Qingling-Daba mountainous area is located in southern Shaanxi province, in which its administrative division includes Hanzhong, Ankang, and Shangluo. The southern Shaanxi is mostly located in the two major mountain systems of Qinling and Bashan, except for a small number of basins, Hanzhong and Ankang regions are dominated by complex and diverse topography and landform as well as the intricate flatland and hill. The mountain area is 47.9 thousand square kilometers, accounting for 69.42% of the total area.

The study area stretches across three comprehensive stratigraphic zones, which was named north China, Qinling, and Yangtze, respectively. The area is located at the region between the southern margin of the Zhongchao platform and the northern margin of the Yangtze platform. Due to the action of compressive stress in north-south direction, large, deep, and dense faults are widely developed in the platform margin and geosyncline-folded system. There are significant signs of neotectonics in southern Shaanxi, and differential movement of fault blocks is obvious after inheriting the Himalayan orogeny at the end of the tertiary period. It has a profound impact on the formation and development of the landforms which can be reflected by the formation of mountainous regions with high mountain, deep valley caused by continuous rising, and wide and flat basins induced by continuing decline since Quaternary. The differential uplift and movement of the fault caused deep gullies, broken topography, and strongly dynamic geological action in the area [47]. A geological profile of the study area is presented in Figure 2.

Surface runoff in the area is mainly three river systems, Hanjiang river, Danjiang river, and Jialingjiang river, and the site is located in the upper reaches of the three river systems. Groundwater in the area is mainly recharged by precipitation and surface water infiltration, which is characterized by a very uneven distribution due to the variation of hydrogeological conditions and can be divided into four types based on their different kinds of water-bearing media [47].

2.1. Pore Water of Quaternary in Loose Rocks. It is mainly distributed in intermountain basins and broad valley section
along the river. The aquifer is composed of alluvial sand, gravel, and pebble layer in the Quaternary, and it is further divided as phreatic water and confined water, the former is mainly distributed in intermountain basins and broad valley section along the river and the latter is mainly distributed in intermountain basins.

2.2. Fractured Pore Water in Clastic Rocks. It is mainly distributed in the southern region of the Hanzhong and Machi-Ankang basin and is mainly stored in sandstones and conglomerates in the period from Mesozoic to Cenozoic. Rare fissures can be found in storing rock, which are often filled with mud and sand. The main source is atmospheric precipitation while there is surface water supplement in some valley areas.

2.3. Karst Fissure Water in Carbonate Rocks. Karst fissure water is the main form of groundwater, which is in great quantities, but not a large distribution area, accounting for more than half of the total reserves. It is mainly distributed in Ningqiang county, Zhenba county, and the eastern region of Xunyangba. It is stored in limestone, siliceous limestone, dolomite, and shale with its main source being atmospheric precipitation.

2.4. Bedrock Fissure Water. It is dominated by a small distribution area found in metamorphic muddy clastic strata of the southern region of the Qinling mountain area and Hanzhoung city. The water is often found in schist, phyllite, shale, and various magmatic rocks and is mainly supplied by atmospheric precipitation. However, undeveloped rock fissures coupled with steep terrain cause most part of the precipitation lost in the form of the surface runoff, which is unfavourable for groundwater recharge.

3. Engineering Geology and Tunnelling Problems Faced in Studied Tunnels

3.1. An Outline of the Studied Tunnels

3.1.1. Mingyazi Tunnel. The Mingyazi tunnel has a maximum depth of 320 m that is dominated by deep gully around the site where it has a gentle ridge. The tunnel sites are all exposed to bedrock except for some residual soils of Holocene accumulated in gentle slope and gully. The bedrock is Devonian sandstone with limestone, Cambrian limestone with siliceous rock, chlorite schist, flaky carbonaceous shale, phyllite, and fault breccia (Figure 3). The tunnel excavated in the area where five deep and large fault zones developed. The fault plane is of steep upper wall and flat lower wall, forming a shovel shape while the zones are filled by mud, breccia, broken stone, etc. The wide fault zones cause extensive fragmentation and even mud-gravel occurrence of the rocks. The groundwater in tunnel site is bedrock fissure water and Quaternary loose layer pore water [48].

3.1.2. Xiangshan Tunnel. The Xiangshan tunnel is a single-hole two-way road tunnel and is located in a structural erosion mountain area. The strata in the area are slope gravel soil, pebble soil, silty clay, schist weathered from slightly to strongly, and fault crushed rocks. The tectonic system is a strong compression zone consisting of compressive faults with compact folds stretching in an east-west direction, and its axis is obliquely intersected with tunnel line at a large angle. A regional reverse fault that has a large width was detected in this area; it has a tendency to dip at angles of 15°

Figure 1: The study area and case tunnel locations.
and 16°, respectively. The rocks are fractured while fault boulders and gouges can be easily found in fault zone and adjacent influence region (Figure 4).

The tunnel passed through two intensely jointed zones, J1, J2, and J3 and the spacing of joint sets are 20–25 cm, 25–30 cm, and 30–35 cm, respectively. They are all shear joints and extend in a far distance in which are filled by a small amount of calcite. Surface water is not developed and mainly supplied by meteoric water, spring water, bedrock fissure water, and pore water of Quaternary loose accumulation layer. Groundwater in tunnel site is mainly composed of bedrock fissure water, which is directly
recharged by atmospheric precipitation and drained into valleys by seepage.

3.1.3. Yingfeng Tunnel. The geomorphology of the Yingfeng area where the tunnel is situated is a low-hilly landscape formed by the movement action of the tectonic denudation and shallow cutting. The site surface is covered with Quaternary residual silty clay and gravel soil, and exposed bedrock is Silurian slate with different weathering degrees that embedded in Meiziya formation (Figure 5).

The tunnel site is dominated by the northern Dabashan Caledonian fold, which mainly consists of anticlinorium and synclinorium. The tunnel had to pass through two fault zones and intensely jointed zones. F1 and F2 are the fault zones, and J1 and J2 are the intensely jointed zones. For the J1 and J2 jointed zones, the spacing of each joint set is 15–20 cm. The surface water in the tunnel area is mainly gulley water and stream water, which is recharged by precipitation. The surface flow changes obviously depending on the season. The groundwater in tunnel area consists of Quaternary pore water and fissure water and its sources mainly are the surface runoff, evaporation, and spring drainage [49].

3.1.4. Yezhuping Tunnel. The passage way for this tunnel runs through the mountainous landscape that is formed by structural erosion and water cutting. The rock formation in tunnel is mainly quartz schist and Devonian slate, and its overlying layer consists of Quaternary diluvium. The tunnel location is in the Shanyang-Fengzhen fault zone, which has three active faults named F1, F2, and T1. Figure 6 presents a geological section profile along the Yezhuping tunnel. There are three well developed sets of jointed zones with severe occurrence changes in tunnel site. The spacing of three joint sets are 0.15–0.2 m, 0.5–0.6 m, and 0.45–0.5 m, respectively [50].

3.2. Structure Damage and Failure Identification

3.2.1. Occurrence Mode of Structure Damages. As mentioned above, the tunnels are mainly constructed in strong compression zones with active tectonic activities, causing various adverse conditions affecting tunnelling such as development of folding and fault and shearing action. The severe geological deformation and weathering degree of rock mass as well as unreasonable excavation methods all breed structural damage or total failure. The support structure deformation degree of the case tunnel can vary and mainly depend on ground stress property and rock mass quality, where it is summarized into four modes for support structure damage from a collection of construction experience in case tunnels, i.e., drop block, structure crack, structure failure, and invert uplift. Some on-site photos are illustrated in Figure 7, followed by detailed characterization in Table 1.

3.2.2. Features Associated with Extreme Deformation. As shown in Table 2, the abovementioned problems occur in tunnel support structure; it not only results in the reshaping of the tunnel but also requires an adjustment in the excavation method and support parameters to ensure safety during construction. This challenge negatively impacted the project scope by increasing both time and construction cost. To develop efficient measures for support system usage, it is necessary to explore main features of structure problems in terms of extreme rock mass deformation, to collect useful data to analyze in an effort to support design and construction.

(1) Large Deformation. The excavated tunnel in soft rock of squeezing ground, especially in fault fracture zone, is mainly dominated by extreme rock mass plastic deformation; displacement around tunnel can be from a few millimeters up to decimeters, as this was noted at the Mingyazi tunnel where the maximum movement recorded was 100.8 cm.

(2) Sharp Displacement Rate. The rock mass movement of the excavated tunnel cases always produces an amazing displacement speed. In the case of the Xiangshan tunnel, the average displacement rate was estimated cm per day with the highest movement recorded being 5.4 cm and still maintained a considerable rate after completion of primary support. The rate of the Yezhuping tunnel in the fault fracture zone is as large as 2-3 cm/d in the early stage.

(3) Long Duration. Soft rocks in squeezing ground are always characterized by rheological and low-strength properties, which extend the time required for rock mass to reach stability. For example, after 120 consecutive days of
Figure 5: Geological section profile along the Yingfeng tunnel [49].

Figure 6: Geological section profile along the Yezhuping tunnel [50].

Figure 7: On-site photos explaining structure damage modes. (a) Drop block, (b) structure crack, (c) structure failure, and (d) invert uplift.
monitoring Yingfeng tunnel, it was deemed unstable based on it exhibiting extreme deformation characteristics. A vault settlement rate of more than 10 mm/d at ZK1 + 589 section of Yezhuping tunnel lasted for 15 days after tunnel excavation, which was characterized with obvious creep deformation characteristics.

(4) Unsymmetric Deformation. Due to sensitivity difference in different parts submitted to disturbance, the aggregated displacement in different parts varies greatly, in which the deformation value of a certain part is several times than that of the other part. On the other hand, the sensitivity of different parts is different.

3.2.3. Safety and Harm Assessment. Structural support problems can cause significant cost overruns, project delivery delays, and even safety issues for working personnel. Some of these unfavourable issues were recorded in studied tunnels. For example, the Yingfeng tunnel had experienced the most reshaping works among the four case tunnels as a result of the rock mass collapse and failure of the support structures. Moreover, huge extra economic investment was sacrificed for these works, taking one of them as an example, about a total of 190,000 dollars was required to successfully complete the reshaping work at the zone between the YK10 + 680 and YK10 + 660. For the Yezhuping tunnel, the excavation was forced to stop for 40 days after the primary support was failure due to water inrush on February 13, 2017. A more serious case was the consecutive collapse events occurred in July, which caused two 20-day shutdowns. Rock mass in some excavation sections of Xiangshan tunnel was extremely broken, resulting in large-scale collapse and sidewall instability during tunnel excavation, and ultimately these problems were only addressed after the implementation of enhanced advance support measures. Once these difficulties occur, they will bring about considerable concerns for designers and engineers.

Of course, if such issues are left unchecked or uncorrected, they have the potential to create hazardous conditions in the future for both operations and maintenance of the plant. Extreme-deformation-induced ground surface cracks or even collapse in shallow tunnels may destroy natural environment and threaten surface buildings around region.

4. Support System Design Based on Geotechnical Analysis

The geological report should be a key element in the decision-making process, as this would help to better address the best methods for a cost efficient excavation, design of support system, and the overall construction. In this section, the shared adverse geological conditions intensified structure damage among the four case tunnels is discussed, and it can help to design the viable and efficient support system.

4.1. Rock Structure. Dense fractures and poor integrity in rock mass easily produce sliding failure along weak structural planes, which significantly promotes rock mass deformation and structure damages. The existence of rock structural planes also brings about change of stress...
distribution in rock mass and weakens the overall rock mass. The geotechnical information among the four tunnels is summarized in Table 3.

Figure 8 reveals broken rock mass and weak intercalated layer excavated in tunnel site. In fact, the stability of tunnel rock mass and its failure mode mainly depend on spatial combination among the abovementioned adverse factors. For example, the existence of multiple structural planes in Yezhuping tunnel results in an extremely broken rock mass in tunnel face. Also, another case could be found in the Yingfeng tunnel, where a weak intercalated layer reduced the structural properties of the rock mass, which resulted in rock mass undergoing both the material and structural deformation, and finally leading to a considerable cumulative deformation.

4.2. Rock Strength. To a certain extent, rock strength determines degrees of rock mass deformation and structure damages. Engineering practice have already proved on rock mass in grade VI or V (six grades are determined, in which is varying from good to poor [51]) is more easily faced with extreme deformation problems than other rock mass in favourable characteristics during the tunnelling. The test results of the uniaxial compressive strengths of the rocks in dried and saturated conditions are presented in Table 4. Dried rock samples exhibited unsatisfactory strength values of less than 10 MPa, this strength got even weaker as the rocks were saturated with water. These features may aggravate the rock mass's stability, which can eventually result in structural cracks, extreme deformation which may lead to total failure.

For this study, the rock mass was evaluated by the classification system recommended in China Code for Design of Road Tunnel [51], for which is proposed on the basis of the combining qualitative and quantitative methods. The qualitative characteristics include the hardness degree and intactness index, as well as the quantitatively basic quality index BQ is supplemented. The BQ can be obtained by the following equation:

\[
BQ = 90 + 3R_C + 250K_V,
\]

where \(R_C\) is the uniaxial compressive strength of the rock mass and \(K_V\) is the intactness index of the rock mass.

4.3. Groundwater Conditions. Some waterproofing techniques and drainage measures must be adopted during excavation to alleviate or totally avoid the water-induced adverse impacts on safety during construction. The groundwater discharge in studied tunnels is presented in Table 5. The precipitation infiltration method is herein adopted to evaluate the groundwater discharge during tunnel construction; it is shown in the following equation [52]:

\[
Q = 2.74aFP,
\]

where \(a\) is the infiltration coefficient of precipitation, \(F\) is the catchment area, and \(P\) is the annual maximum precipitation.

Practically, some methods could fail if support structure was destroyed in some extreme unfavourable circumstances. A large amount of groundwater causes softening and disintegration on the rock mass leading to a significant weakening in the mechanical properties of rock mass. In the case of the Yezhuping tunnel, more time was taken than previously anticipated due to significant in flows of groundwater during excavation. The softening of rock mass reduces compressive strength and makes it more susceptible to disturbance; this can be noted in the case of the Yingfeng tunnel and is illustrated in Figure 9.

5. Key Techniques Used in Support System of the Tunnels

Extreme rock mass deformation must be controlled to prevent the support structure from significant displacement, damage, or even total failure. The control attempts can benefit from the reasonable selection of the support system, improvement of support system, and the implementation of necessary temporary supports. Apart from an ideal bench length in tunnelling with bench method, the stability of rock mass mainly depends on the applied support system in excavated soft rock tunnel, despite the fact that there is negligible self-stabilizing ability that could be used for supplement.

5.1. Preparation for CCM-Based Design. Analysis of the tunnel stability is needed to better understand the behavior between rock mass and support system. The convergence confinement method (CCM) can be considered as the most commonly used means for support design; latterly, another important support philosophy, Non-Deformable Support System [15, 53], has been introduced for this work. It can be not only successfully applied in urban tunnels, but also in squeezing and swelling rocks tunnels to address tunnelling problems [54]. However, many complex parameters in support design phase should be considered in order to obtain a very high-performance support system. In addition, time-dependent deformation features of the rock mass and right materials-failure models should be determined accurately. Practically, design and construction works notably benefit from the experience and engineering judgment. So, the in situ measurement-led CCM is suggested for preliminary investigation on support design, for which can provide more intuitive on-site information used for evaluation on stability of rock mass and structures.

CCM is considered one of the most convenient tools to describe interaction between rock mass and support structure after tunnel excavation. Its principle has been well documented and can be found in literatures of this field and can be referenced in support of acceptable levels of deformation within the tunnel profile [55–57]. This method needs to establish three basic curves: (1) longitudinal deformation profile describing relationship between tunnel deformation and distance from tunnel face [58]; (2) ground reaction curve describing the internal pressure and radial displacement of the tunnel; and (3) support reaction curve describing stress-strain behavior of support system [59, 60].
Longitudinal deformation profile in Figure 10 describes the rock mass deformation throughout tunnel excavation phase, it highlights some predeformation prior to the start of excavation, loss deformation, and measured deformation, in which the latter two parts accounting for a majority of the total radial displacement. Hence, the design of support system is very important in reducing or even eliminating structural damage that can be potentially caused by extreme rock mass deformation. Specifically, in severe cases, the predeformation in tunnel face can be controlled by

### Table 3: Description of the rock joint data of the studied tunnels.

| Tunnel name | Type     | Joint sets | Spacing  | Number | Remarks                                                                 |
|-------------|----------|------------|----------|--------|-------------------------------------------------------------------------|
| Mingyazi    | Shear    |            | 10–25 cm | 4      | Joints and fissures are well developed, rock mass structure is very loose and fragmented with sheet and block shape, in which are filled with fault gouges and loose sand. |
| Xiangshan   | Shear    |            | 20–35 cm | 3      | The joints are filled with a small amount of calcite veins, and weathering fissures are well developed along tunnel route. |
| Yingfeng    | Tension  |            | 15–20 cm | 2      | Developed joints exhibit a poor cementation filling with shale. The rock mass is cut by structural plane showing a layered fractured structure. |
| Yezhuping   | Shear    |            | 15–60 cm | 3      | The development degree and occurrence change of the joints vary greatly. |

**Figure 8:** On-site exposed rock mass after tunnel excavation. The left one is found in Yingfeng tunnel and the right is in Yezhuping tunnel [49, 50].

### Table 4: Unsaturated and saturated uniaxial compressive strengths of the rocks (unit: MPa) [1].

| Rock condition | Sample number | Maximum | Minimum | Average | Average softening coefficient |
|----------------|---------------|---------|---------|---------|-------------------------------|
| Unsaturated    | 81            | 20.5    | 4.35    | 9.36    |                               |
| Saturated      | 30            | 5.45    | 3.97    | 4.72    | 0.51                          |

*Note.* Softening coefficient = saturated uniaxial compressive strength/unsaturated uniaxial compressive strength.

### Table 5: Groundwater conditions in the four studied tunnels.

| Tunnel name    | Type                                      | Supplement source                                      | Groundwater discharge amount (m³/d) |
|----------------|-------------------------------------------|-------------------------------------------------------|-------------------------------------|
| Mingyazi       | Quaternary pore water and bedrock fissure water | Atmosphere rainfall and spring drainage | 4.2–1194                            |
| Xiangshan      | Bedrock fissure water                    | Atmosphere rainfall                                   | 36.4–1887.7                         |
| Yingfeng       | Quaternary pore water and fissure water   | The surface runoff, evaporation, and spring drainage   | 19.5–149.7                          |
| Yezhuping      | Bedrock fissure water and pore water      | Atmosphere rainfall                                   | 34.3–331.9                          |

Longitudinal deformation profile in Figure 10 describes the rock mass deformation throughout tunnel excavation phase, it highlights some predeformation prior to the start of excavation, loss deformation, and measured deformation, in which the latter two parts accounting for a majority of the total radial displacement. Hence, the design of support system is very important in reducing or even eliminating structural damage that can be potentially caused by extreme rock mass deformation. Specifically, in severe cases, the predeformation in tunnel face can be controlled by [49, 50].
5.2. Temporary Support Methods. Temporary measures are usually used as auxiliary or special construction tools in the case of the conventional support means or partial excavation measures failed to function effectively to ensure rock mass stability, especially for tunnels or underground projects with difficulties in soft rock, fault fracture zone, and other unfavourable geological conditions. The purposes of the temporary measures are to reduce the predeformation shown in Figure 10 and ensure rock mass stability in tunnel face and safety of tunnel structures and surrounding environment.

The tunnels considered are large with a span that exceeds 12 m. There are a few regions with excellent conditions, but most of the tunnels studied are excavated under challenging geological conditions. These tunnels were excavated using the bench method, and many special measures were adopted to stabilize the working face. There are a number of temporary support methods commonly used in these tunnels including advance grouting pipe, advance pipe umbrella, face bolt reinforcement, temporary invert, etc, which are summarized in Table 6.

Figure 11 illustrates some of the temporary measures utilized during construction in the Yezhuping tunnel, in addition to these two measures, other immediate shotcreting, and core retaining had been used for tunnel face stability. The variations and universality of engineering
geological behaviors have led to the variable scopes of applicability of temporary support measures. Guided by the recorded tunnel construction data, there are many concepts and principles for temporary support measures that can be used for tunnels constructed in various rock mass types. Therefore, this work requires detailed design and analysis of support system in order to adapt to the site conditions and particularities of each project.

For example, the 42 mm diameter advance pipes were constructed in Mingyazi tunnel to reinforce face before tunnelling in broken rock mass section while the 25 mm diameter grouting rock bolts were used in better section to ensure safety excavation. As for the Yezhuping tunnel, it was found to have large deposits of groundwater; therefore, a water stopping wall was firstly erected at a certain distance from the face to prevent the water from gushing, and then the curtain grouting was used to seal face of the excavated part. As shown in Figure 12, after the completion of the curtain grouting construction, the 100 mm diameter drainage holes were set along the inner tunnel annulus to reduce water pressure acting on primary support. The depth of the hole is not less than 5 m, and the holes were filled with hemp materials to prevent the holes from being blocked as water-flow-carrying sediment accumulation.

5.3. Detailed Support System. After achieving stability of the tunnel face, it is imperative to establish the final support

| No. | Method name                  | Function mechanism                                                                                                                                                                                                 | Main purposes |
|-----|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|
| 1   | Advance pipe umbrella        | Grouting slurry fully fills and saturates the cracks and improves strength and stiffness of rock mass, thereby improving its overall bearing capacity. The reinforcing ring formed by grouting slurry plays a “bearing arch” role to support weight of the upper strata.     | ✓ ✓           |
| 2   | Advance grouting pipe        | It improves structural and mechanical properties of soft and broken rock mass, fills joint fissures and cracks ahead the tunnel face, and forms an improved reinforcing belt with strong bearing capacity at the outer tunnel annulus.                      | ✓ ✓           |
| 3   | Face bolt reinforcement      | Reinforcement bolts are inserted into core soil to anchor the tunnel face where bolt materials usually employ the glass fibre-reinforced plastics (GFRP) for easy cutting off.                                | ✓             |
| 4   | Temporary invert             | Regarding the tunnelling with bench method, the steel sets and temporary invert at the bottom of the excavated bench are connected timely and followed by shotcrete construction to form a load-bearing ring, so as to improve the overall stability and bearing capacity. |               |
| 5   | Full-face grouting reinforcement | Full-face grouting is most used in tunnel face with extremely soft and broken rock mass, improving overall stability of tunnel face by usage of a large-scale grouting in working face. | ✓ ✓           |

Note. RMI and WSU refer to rock mass improvement and water sealing up, respectively.

Figure 11: Photos of temporary measures construction in site of Yezhuping tunnel [50].

Table 6: Typical temporary measures used in case tunnels.
A key support system for V grade rock mass shown in Figure 13 was employed in a case tunnel and the other supports of the case tunnels were presented in Table 8. During tunnelling, the design strategy combining big reserved deformation and strong support was widely used in the support system, which obtained a very good effect. The basic principle of these two combinations is maintaining the stability of rock mass with a certain support resistance, while allowing the support system to produce a certain displacement, so as to give full play to the combined function of supporting, yielding pressure, and load discharge simultaneously.

The complete support system of the tunnel brings an adequate structural support strength. Specially, the usage of advance grouting pipes in Xiangshan tunnel can resist the rock slippage of the vault under the action of concentrated shear stress. The risk reduction of bending failure and layer separation of rock mass in Yezhuping tunnel benefited from its reasonable selection of bolt insertion angle. The use of grouting bolt can effectively fill rock mass cracks, improving the stress release and ensuring the stability of deep rock mass. The mentioned measures form the support system with a considerable rigidity, which can constrain the loosening zone expansion of the rock mass.

In addition to the adoption of strong support measures, a large reserved deformation should be considered in some cases in order to deal with complicated geological conditions. It mainly works by the way of allowing a larger rock mass deformation and prevents tunnel from suffering risks of clearance interfering. The specific implementation of temporary measures and support techniques should be adjusted and modified based upon the site geology of the tunnel. It should be emphasized that in most cases, the recoded results had been validated by interpretation of convergence measurements and observation of support performance of support system installed in case tunnels.

6. Discussion
The design of tunnels requires a comprehensive strategy, which can be beneficial for saving time and cost and ensuring safety construction especially in squeezing ground; this idea is particularly important for extreme deformation control. The strategy for extreme deformation prevention and control in squeezing ground should be established on a dynamic basis, in which it emphasizes on dynamic information exchange and adjustment among deformation prediction, design ideas of support, field geological survey before tunnelling, and advance geological prediction during tunnelling. Recorded rock mass deformation, mapping geological information, laboratory testing of rock mechanical properties, and CCM can be used for evaluating in situ rock mass parameters and predesigning corresponding support system.

The key techniques, together with the abovementioned temporary support measures, have achieved an ideal deformation control effect and avoided structure damage of tunnel support system, which can be confirmed by in situ monitoring data from case tunnels shown in Figure 14. Compared with the aforementioned rock mass deformation hazards, the implementation of the proposed support system reduces the displacement rate of rock mass, the stability time for final deformation completion, and the total deformation amount.

6.1. Usage of FRB. The studied tunnels constructed in squeezing ground were excavated via using the bench excavation method; the separate installation of the steel sets for the top excavated section cannot form a closed support loop to deal with deformation problem. An illustration for the FRB is presented in Figure 15. The FRBs can be used to connect with steel sets bottom, so as to address the steel sets deviation caused by the insufficient load-bearing capacity of the arch springing or existence of the excavated space. It not only prevents the arch springing from shrinking and dropping, but also plays a role of advance or temporary support for the next bench excavation.

The monitoring data of the field tests conducted in Xiangshan tunnel indicated that a significant effect was achieved by using the FRB for controlling primary support structure deformation. The setting of FRBs could reduce the displacement rate by more than a half. After extreme deformation and support structure failure occurred in some sections of the Yingfeng tunnel, the FRB technique was used to protect tunnel system suffering from such structure damages and ensure safety construction. An ideal effectiveness was confirmed by the implementation feedback regarding the rock mass displacement shown in Figure 16.

6.2. Usage of Strong Support System. The usage of double steel sets was an effective way to prevent rock mass
Table 7: Three-bench temporary invert excavation method and its interpretation.

| Three-bench temporary invert excavation method | Step | Construction activities | Schematic pictures |
|-----------------------------------------------|------|-------------------------|--------------------|
| I | Excavate top bench, construct primary support (a), FRB (b), and Temporary invert (c). |
| II | Excavate middle bench, construct primary support (d), FRB (e), and Temporary invert (f). |
| III | Excavate bottom bench, construct primary support and FRB (g). |
| IV | Remove the temporary inverts (c) and (f), construction secondary lining. |

Note: Tunnel face excavation must select appropriate bench length according to the rock mass grade, section size and equipment configuration as well as other relative factors, so as to avoid collapse caused by the structure damage or failure. For example, a significant control effect for extreme deformation had been achieved when the 2 m, 4 m, and 6 m lengths of the top, middle and bottom bench were used for tunnelling in Xiangshan tunnel.

Figure 13: A support system for V grade rock mass. Note: the unit of FRBs, steel mesh, and seamless steel tubes is mm and the others is cm.
deformation and structure damage. A case tunnel employed H175-type steel sets with strong lateral rigorousness and strong bending resistance instead of the traditional I22-type steel sets to deal with the serious distortion of the arch sets. The second steel sets are constructed when there is 2/3 of the amount of the reserved deformation retained, and the short steel bar and wooden wedge are used to transfer the rock mass pressure between the first and second support steel sets.

Table 8: Support system of other three tunnels in V grade rock mass (the unit of bolts and steel frame is cm and the others is mm).

| No. | Tunnel name | Temporary support | Primary support | Secondary lining | Invert |
|-----|-------------|-------------------|-----------------|-----------------|-------|
| 1   | Yingfeng    | φ42 × 4 grouting tube (L = 500 cm) | C20 shotcrete (24 cm thick) φ22 rock bolt (L = 300) φ8 × 20 × 20 steel mesh 118 steel frame (@ = 90) | C25 secondary lining (45 cm thick) | C25 shotcrete (24 cm thick) |
| 2   | Yezhuping   | φ42 × 4 grouting tube (L = 450 cm) | C25 shotcrete (24 cm thick) φ22 rock bolt (L = 300) φ8 × 25 × 25 steel mesh 118 steel frame (@ = 80) | C30 secondary lining (45 cm thick) | C25 shotcrete (24 cm thick) |
| 3   | Mingyazi    | φ42 × 4 seamless steel tube (L = 450 cm) | C20 shotcrete (24 cm thick) φ42 FRB (L = 400) φ8 × 20 × 20 steel mesh 118 steel frame (@ = 70) | C30 secondary lining (45 cm thick) | C25 shotcrete (24 cm thick) |

Figure 14: Monitoring data of the rock mass deformation. (a) Mingyazi tunnel, (b) Yezhuping tunnel, (c) Xiangshan tunnel, and (d) Yingfeng tunnel [48–50].
6.3. More Reserved Deformation. The original designed reserved deformation varying from 10 to 15 cm failed to satisfy the requirement of the rock mass deformation, leading to structure crack, failure, and even partial collapse. For example, based upon the in-situ monitoring and field test, more reserved deformation was used for support system redesign in unfavourable sections of the Yingfeng and Xiangshan tunnels, which effectively addresses the deformation problems.

7. Conclusions

The wide distribution of soft rock and active geological structure in the Qingling-Daba mountainous area brings challenges and problems to the design and construction of tunnels in this region. Four case tunnels constructed in squeezing ground are studied in this paper, and the following conclusions can be drawn:

(1) The structure damage modes and affecting factors in four squeezing tunnels were studied for the purpose of improving stability of a tunnel excavated in rock masses by developing a support system.

(2) Four categories of damage for support structure are established from the previous experiences of the four case tunnels, i.e., drop block, structure crack, structure failure, and invert uplift.

(3) Main factors affecting structure damage are identified as rock structure, rock strength, and groundwater conditions, which is a key component for the design of a viable and efficient support system.

(4) For the proposed support system, temporary support measures are necessary for a tunnel excavated in squeezing ground; also the usage of key techniques such as strong support measures, FRB, and large reserved deformation provides helps for reducing damage risks of support structure for a tunnel in squeezing ground.

(5) The effectiveness of the proposed support system had been verified by in situ feedbacks and field test results presented in the paper, which will provide useful information and guidance for similar projects.
Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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References

[1] J. Lai, X. Wang, J. Qiu, J. Chen, Z. Hu, and H. Wang, “Extreme deformation characteristics and countermeasures for a tunnel in difficult grounds in Southern Shaanxi, China,” Environmental Earth Sciences, vol. 77, no. 19, pp. 77–706, 2018.
[2] J. Wang, Q. Huo, Z. Song, and Y. Zhang, “Study on adaptability of primary support arch cover method for large-span embedded tunnels in the upper-soft lower-hard stratum,” Advances in Mechanical Engineering, vol. 11, no. 1, pp. 1–15, 2019.
[3] R. Qiao, Z. Shao, F. Liu, and W. Wei, “Damage evolution and safety assessment of tunnel lining subjected to long-duration fire,” Tunnelling and Underground Space Technology, vol. 83, pp. 354–363, 2019.
[4] J. Lai, S. He, J. Qiu et al., “Characteristics of seismic disasters and aseismic measures of tunnels in Wenchuan earthquake,” Environmental Earth Sciences, vol. 76, no. 2, pp. 1–19, 2017.
[5] S. O. Choi and H.-S. Shin, “Stability analysis of a tunnel excavated in a weak rock mass and the optimal supporting system design,” International Journal of Rock Mechanics and Mining Sciences, vol. 41, no. 3, pp. 537–881, 2004.
[6] L. Duan, W. Lin, J. Lai, P. Zhang, and Y. Luo, “Vibration characteristic of high-voltage tower influenced by adjacent tunnel blasting construction,” Shock and Vibration, vol. 2019, Article ID 8520564, 16 pages, 2019.
[7] M. Kanik, Z. Gurocak, and S. Alemdag, “A comparison of support systems obtained from the RMR89 and RMR14 by numerical analyses: Macka tunnel project, NE Turkey,” Journal of African Earth Sciences, vol. 109, pp. 224–238, 2015.
[8] L. M. Duan, Y. H. Zhang, and J. X. Lai, “Influence of ground temperature on shotcrete-to-rock adhesion in tunnels,” Advances in Materials Science and Engineering, vol. 2019, Article ID 8709087, 12 pages, 2019.
[9] G.-H. Zhang, Y.-Y. Jiao, and H. Wang, “Outstanding issues in excavation of deep and long rock tunnels: a case study,” Canadian Geotechnical Journal, vol. 51, no. 9, pp. 984–994, 2014.
[10] Y. Fang, Z. Chen, L. Tao, J. Cui, and Q. Yan, “Model tests on longitudinal surface settlement caused by shield tunnelling in sandy soil,” Sustainable Cities and Society, vol. 47, article 101504, 2019.
[11] X. L. Luo, X. Meng, W. J. Gan, and Y. H. Chen, “Traffic data imputation algorithm based on improved low rank matrix decomposition,” Journal of Sensors, vol. 2019, Article ID 7092713, 10 pages, 2019.
[12] Z. Zhang, X. Shi, B. Wang, and H. Li, “Stability of NATM tunnel faces in soft surrounding rocks,” Computers and Geotechnics, vol. 96, pp. 90–102, 2018.
[13] L. Meng, T. Li, Y. Jiang, R. Wang, and Y. Li, “Characteristics and mechanisms of large deformation in the Zhegu mountain tunnel on the Sichuan-Tibet highway,” Tunnelling and Underground Space Technology, vol. 37, no. 6, pp. 157–164, 2013.
[14] C. Cao, C. Shi, M. Lei, W. Yang, and J. Liu, “Squeezing failure of tunnels: a case study,” Tunnelling and Underground Space Technology, vol. 77, pp. 188–203, 2018.
[15] C. O. Aksoy, K. Oğul, İ Topal et al., “Reducing deformation effect of tunnel with non-deformable support system by jointed rock mass model,” Tunnelling and Underground Space Technology, vol. 40, no. 1, pp. 218–227, 2014.
[16] P. K. Shrestha and K. K. Panthi, “Assessment of the effect of stress anisotropy on tunnel deformation in the Kaligandaki project in the Nepal Himalaya,” Bulletin of Engineering Geology and the Environment, vol. 74, no. 3, pp. 815–826, 2015.
[17] R. D. Dwivedi, M. Singh, M. N. Viladkar, and R. K. Goel, “Estimation of support pressure during tunnelling through squeezing grounds,” Engineering Geology, vol. 168, pp. 9–22, 2014.
[18] Y. Sun, X. Feng, and L. Yang, “Predicting tunnel squeezing using multiclass support vector machines,” Advances in Civil Engineering, vol. 2018, Article ID 4543984, 12 pages, 2018.
[19] S. He, L. Su, H. Fan, and R. Ren, “Methane explosion accidents of tunnels in SW China,” Geomatics, Natural Hazards and Risk, vol. 10, no. 1, pp. 667–677, 2019.
[20] S. Dalgic, “Tunneling in squeezing rock, the bolu tunnel, Anatolian motorway, Turkey,” Engineering Geology, vol. 67, no. 1, pp. 73–96, 2002.
[21] G. Tiwari, B. Pandit, M. L. Gali, and G. L. S. Babu, “Analysis of tunnel support requirements using deterministic and probabilistic approaches in average quality rock mass,” International Journal of Geomechanics, vol. 18, no. 4, pp. 1–20, 2018.
[22] G. G. Gschwandtner and R. Galler, “Input to the application of the convergence confinement method with time-dependent material behaviour of the support,” Tunnelling and Underground Space Technology, vol. 27, no. 1, pp. 13–22, 2012.
[23] P. He, S.-C. Li, L.-P. Li, Q.-Q. Zhang, F. Xu, and Y.-J. Chen, “Discontinuous deformation analysis of super section tunnel surrounding rock stability based on joint distribution simulation,” Computers and Geotechnics, vol. 91, pp. 218–229, 2017.
[24] C. Paraskevopoulos and M. Diederichs, “Analysis of time-dependent deformation in tunnels using the convergence confinement method,” Tunnelling and Underground Space Technology, vol. 71, pp. 62–80, 2018.
[25] W. Feng, R. Huang, and T. Li, “Deformation analysis of a soft-hard rock contact zone surrounding a tunnel,” Tunnelling and Underground Space Technology, vol. 32, no. 11, pp. 190–197, 2012.
[26] S. Hussain, Z. U. Rehman, N. Mohammad et al., “Numerical modeling for engineering analysis and designing of optimum support systems for headrace tunnel,” Advances in Civil Engineering, vol. 2018, Article ID 7159873, 10 pages, 2018.
[27] A. Kaya and A. Sayın, “Engineering geological appraisal and preliminary support design for the Salarha Tunnel, Northeast Turkey,” Bulletin of Engineering Geology and the Environment, vol. 78, no. 2, pp. 1095–1112, 2017.
[28] Z. X. Zhang, C. Liu, and X. Huang, “Numerical analysis of volume loss caused by tunnel face instability in soft soils,” *Environmental Earth Sciences*, vol. 76, no. 16, 2017.

[29] S. M. Gao, J. P. Chen, C. Q. Zuo, W. Wang, and Y. Sun, “Structure optimization for the support system in soft rock tunnel based on numerical analysis and field monitoring,” *Geotechnical and Geological Engineering*, vol. 34, no. 4, pp. i–11, 2016.

[30] G. J. Wu, W. Z. Chen, H. M. Tian, S. P. Jia, J. P. Yang, and X. J. Tan, “Numerical evaluation of a yielding tunnel lining support system used in limiting large deformation in squeezing rock,” *Environmental Earth Sciences*, vol. 77, no. 12, 2018.

[31] M. Kanik and Z. Gurocak, “Importance of numerical analyses for determining support systems in tunneling: a comparative study from the trabzon-gumushane tunnel, Turkey,” *Journal of African Earth Sciences*, vol. 143, pp. 253–265, 2018.

[32] A. Sainoki, S. Tabata, H. S. Mitri, D. Fukuda, and J.-I. Kodama, “Time-dependent tunnel deformations in homogeneous and heterogeneous weak rock formations,” *Computers and Geotechnics*, vol. 92, pp. 186–200, 2017.

[33] Z.-F. Wang, S.-L. Shen, and G. Modoni, “Enhancing discharge of spoil to mitigate disturbance induced by horizontal jet grouting in clayey soil: theoretical model and application,” *Computers and Geotechnics*, vol. 111, pp. 222–228, 2019.

[34] J. B. Wang, W. W. Li, and Z. P. Song, “Development and implementation of new triangular finite element based on MGE theory for bi-material analysis,” *Results in Physics*, vol. 13, article 102231, 2019.

[35] Y. W. Zhang, Z. P. Song, X. L. Weng, and Y. L. Xie, “A new soil-water characteristic curve model for unsaturated loess based on wetting-induced pore deformation,” *Geofluids*, vol. 2019, Article ID 5261985, 14 pages, 2019.

[36] L. Jing, “A review of techniques, advances and outstanding issues in numerical modelling for rock mechanics and rock engineering,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 40, no. 3, pp. 283–353, 2003.

[37] Z. J. Zhou, J. T. Lei, S. B. Shi, and T. Liu, “Seismic response of aeolian sand high embankment slopes in shaking table tests,” *Applied Sciences*, vol. 9, no. 4, 15 pages, 2019.

[38] Z. Zhou, Y. Dong, P. Jiang, D. Han, and T. Liu, “Calculation of pile side friction by multiparameter statistical analysis,” *Advances in Civil Engineering*, vol. 2019, Article ID 2638520, 12 pages, 2019.

[39] C. O. Aksoy, G. G. Uyar, and S. Şafak, “A new approach to time-load-deformation-stress hypersurface of rocks to stability analysis of underground openings,” *Arabian Journal of Geosciences*, vol. 11, no. 5, pp. 1–13, 2018.

[40] C. O. Aksoy, S. Şafak, G. G. Uyar, and V. Ozacar, “A new mathematical approach for representing the deformation mechanism of rocks under constant load,” *Geotechnique Letters*, vol. 8, no. 1, pp. 80–90, 2018.

[41] C. Kong, X. Gao, L. Cao, and K. Liu, “Analysis of the failure of primary support of a deep-buried railway tunnel in silty clay,” *Engineering Failure Analysis*, vol. 66, pp. 259–273, 2016.

[42] E. Dadashi, K. Ahangari, A. Noorzad, and A. Arab, “Support system suggestion based on back-analysis results case study: babolak water conveyance tunnel,” *Arabian Journal of Geosciences*, vol. 5, no. 6, pp. 1297–1306, 2012.

[43] D. Oliveira and M. S. Diederichs, “Tunnel support for stress induced failures in Hawkesbury Sandstone,” *Tunnelling and Underground Space Technology*, vol. 64, pp. 10–23, 2017.

[44] K. K. Panthi and B. Nilsen, “Uncertainty analysis of tunnel squeezing for two tunnel cases from Nepal Himalaya,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 44, no. 1, pp. 67–76, 2007.

[45] J. Pérez-Romero, C. S. Oteo, and P. de la Fuente, “Design and optimisation of the lining of a tunnel in the presence of expansive clay levels,” *Tunnelling and Underground Space Technology*, vol. 22, no. 1, pp. 10–22, 2007.

[46] Q. Lü, Z.-P. Xiao, J. Ji, and J. Zheng, “Reliability based design optimization for a rock tunnel support system with multiple failure modes using response surface method,” *Tunnelling and Underground Space Technology*, vol. 70, pp. 1–10, 2017.

[47] Y. Y. Zhou, “Study on formation mechanism of abrupt geological hazards of southern Shaanxi region in condition of strong rainstorm,” M.S. thesis, Chang’an University, Xi’an, China, 2013.

[48] Q. Han, “Stability evaluation of surrounding rock of the Mingyazi tunnel and its rapid excavation technology,” M.S. thesis, Xi’an University of Science and Technology, Xi’an, China, 2012.

[49] C. Y. Shi, “Study on the Large Deformation Control of the Weak Surrounding Rock in Tunnel,” M.S. thesis, Chang’an University, Xi’an, China, 2014.

[50] J. X. Wang, “Surrounding Rock deformation characteristics analysis and engineering disaster treatment research of Yezhuping tunnel crosses fault fracture zone,” M.S. thesis, Chang’an University, Xi’an, China, 2018.

[51] JTG D70-2010, *Code for Design of Road Tunnel*, China Communications Press, Beijing, China, 2010.

[52] TB 10049-2004, *Code for Hydrogeological Investigation of Railway Engineering*, China Railway Publishing House, Beijing, China, 2004.

[53] C. O. Aksoy, G. G. Uyar, E. Posluk, K. Ogul, I. Topal, and K. Kucuk, “Non-deformable support system application at tunnel-34 of Ankara-Istanbul high speed railway project,” *Structural Engineering and Mechanics*, vol. 58, no. 5, pp. 869–886, 2016.

[54] C. O. Aksoy and T. Onargan, “The role of umbrella arch and face bolt as deformation preventing support system in preventing building damages,” *Tunnelling and Underground Space Technology*, vol. 25, no. 5, pp. 553–559, 2010.

[55] H. B. Fan, Y. H. Zhang, S. Y. He, K. Wang, X. L. Wang, and H. Wang, “Hazards and treatment of karst tunneling in Qinling-Daba mountainous area: overview and lessons learnt from Yichang-Wanzhou railway system,” *Environmental Earth Sciences*, vol. 77, no. 19, 2018.

[56] V. Kontogianni, P. Psimoulis, and S. Stiros, “What is the contribution of time-dependent deformation in tunnel convergence?,” *Engineering Geology*, vol. 82, no. 4, pp. 264–267, 2006.

[57] Y. Cai, Y. Jiang, I. Djamaludtin, T. Iura, and T. Esaki, “An analytical model considering interaction behavior of grouted rock bolts for convergence-confinement method in tunneling design,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 76, pp. 112–126, 2015.

[58] S.-G. Song, S.-C. Li, L.-P. Li et al., “Study on longitudinal deformation profile of rock mass in a subsea tunnel,” *Marine Georesources & Geotechnology*, vol. 34, no. 4, pp. 376–383, 2016.

[59] J. Lai, J. Qiu, H. Fan, Q. Zhang, J. Wang, and J. Chen, “Fiber bragg grating sensors-based in-situ monitoring and safety assessment of loess tunnel,” *Journal of Sensors*, vol. 2016, Article ID 8658290, 10 pages, 2016.

[60] X. Liu, Q. Fang, D. L. Zhang, and Z. J. Wang, “Behaviour of existing tunnel due to new tunnel construction below,” *Computers and Geotechnics*, vol. 110, pp. 71–81, 2019.
