Engineering 5 (2019) 384–392

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Engineering Achievements

Challenges and Development Prospects of Ultra-Long and Ultra-Deep Mountain Tunnels

Hehua Zhu [a], Jinxiu Yan [b], Wenhao Liang [c]

[a] *College of Civil Engineering, Tongji University, Shanghai 200092, China*
[b] *China Railway Academy Co., Ltd., Chengdu 611731, China*
[c] *China Railway Construction Co., Ltd., Beijing 100855, China*

1. Introduction

Social development has led to the placement of high standards on ultra-long and ultra-deep mountain tunnels. Disasters may be encountered during the construction and maintenance of such mountain tunnels due to high geostress, high geotemperature, high hydraulic pressure, and special adverse strata, in addition to various other problems caused by engineering activities. To deal with uncertain geological conditions during mountain tunnel construction, comprehensive geological prediction, refined monitoring, and dynamic design and construction methods based on information technology should be adopted. For the operation and maintenance of ultra-long tunnels, the concepts of dynamic evacuation rescue, active protection, energy conservation, and environmental protection should be fully embodied in order to address significant problems related to ventilation, rescue situations, and energy consumption. Moreover, integrated construction and maintenance should be carried out to achieve digital sensing and intelligent maintenance. New ideas and technologies should be adopted to improve the quality and efficiency of the whole process of construction and operation, and to enable the construction of environmentally friendly tunnels, thus achieving the ultimate goals of safety, efficiency, greenness, and intelligence for ultra-long and ultra-deep rock tunnels.

With the development of society, the economy, and transportation networks, the construction of ultra-long and ultra-deep tunnels through mountains has become increasingly inevitable. Ultra-long and ultra-deep tunnels are generally defined as tunnels that have a length exceeding 10 km and a depth exceeding 500 m [1]. Mountain tunnels mainly consist of road tunnels, railway tunnels, and hydraulic tunnels. Although an ultra-long and ultra-deep tunnel potentially features the advantages of safety, environmental friendliness, and speed, the cost and difficulty of project establishment, construction, and operation are considerable. Table 1 lists the ultra-long and ultra-deep mountain tunnels that have already been built or are under construction around the world. According to an incomplete survey, there are 56 ultra-long and ultra-deep mountain tunnels in China and 21 abroad. Among these tunnels, the 57.1 km Gotthard Basis Tunnel is the longest and deepest in the world, the 32.7 km New Guanjiao Tunnel is the world's longest tunnel above 3000 m, the 18 km Highway Tunnel of Qinling Zhongnan Mountain is the world's longest double-line highway tunnel, and the 16 km Qinling Tianhuashan Tunnel is Asia's longest single-hole two-lane high-speed rail tunnel.

With the increasing demand for and ongoing progress in tunnel construction technologies, the construction of ultra-long and ultra-deep mountain tunnels will usher in new development opportunities. Due to the high geostress, high geotemperature, and ultra-long construction and operation, these complex tunnel projects must handle unprecedented challenges in terms of design, construction, operation, and maintenance, which demand new ideas and engineering measures.

2. Geological problems and disasters

Ultra-long and ultra-deep tunnels, which possess the advantages of safety, convenience, environmental protection, and reduced sensitivity to the natural environment and human activities, have been extensively constructed for transportation, water conservancy, energy, and other infrastructure fields in alpine and mountainous areas. However, as their length jumps from several kilometers to dozens of kilometers and their depth leaps from hundreds of meters to several kilometers, ultra-long and ultra-deep tunnels will encounter a complex geological environment that greatly differs from shallow rock mass conditions. It is increasingly likely that an ultra-long and ultra-deep tunnel will pass through multiple geological and tectonic units, and that the tunnel construction, operation, and maintenance will be confronted with the geological problems of high geostress, high geotemperature, high hydraulic pressure, and special adverse strata. These challenges will make the tunnel construction environment very difficult, and may induce geological disasters such as rockburst, large deformation of the surrounding rock masses, landslides, and even water and mud inrush.

2.1. High geostress

Initial geostress is one of the most important features that distinguishes rock mass from other materials. The geostress increases with the depth of the tunnel. A high-geostress environment (with a maximum principal stress of $\sigma_1 > 20$ MPa, or a strength–stress

https://doi.org/10.1016/j.eng.2019.04.009

Table 1
Summary of major ultra-long and ultra-deep mountain tunnels (built/under construction).

Tunnel type	Tunnels (project)	Location	Start–completion dates	Length (km)/ maximum depth (m)	Construction method
Mountain railway tunnels	Gotthard Base Tunnel	Switzerland	1996–2013	57.10/2450	TBM + drill and blast
	Brenner Base Tunnel (Brenner Railway)	Italy to Austria	2011–under construction	55.00/1600	TBM + drill and blast
	Lötschberg Base Tunnel (New Alpine Railway Passage)	Switzerland	Jul 1999–Apr 2005	34.60/2100	TBM + drill and blast
	Gaoligong Mountain Tunnel (Dali–Ruili Railway)	China	Dec 2014–under construction	34.50/1155	TBM + drill and blast
	Koralm Tunnel (Koralm Railway)	Austria	2011–under construction	32.90/1250	TBM + drill and blast
	New Guanjiao Tunnel (Qinghai–Tibet Railway)	China	Nov 2007–Apr 2014	32.65/900	Drill and blast
	Ping An Tunnel (Chengdu–Lanzhou Railway)	China	Oct 2013–Feb 2017	28.44/1700	Drill and blast
	Guadarrama Tunnel (Madrid–Bayadorid High-Speed Railway)	Spain	2002–2007	28.38/900	TBM
	West Qinling Tunnel (Lanzhou–Chongqing Railway)	China	Aug 2018–Jul 2014	28.24/1400	TBM + drill and blast
	Semmering Base Tunnel (Gloggnitz–Mürzzuschlag Railway)	Austria	Apr 2012–under construction	27.30/800	Drill and blast
	Hakkōda Tunnel (Shinkansen Line in Northeast Japan)	Japan	Jun 1999–Feb 2005	26.46/540	Drill and blast
	South Lvliang Mountain Tunnel (Shanxi–Henan–Shandong Railway)	China	May 2010–Jun 2013	23.40/550	Drill and blast
	Yuntunpu Tunnel (Chengdu–Lanzhou Railway)	China	Oct 2014–under construction	22.92/750	Drill and blast
	Lushan Tunnel (Inner Mongolia–Jiangxi Railway)	China	May 2015–Aug 2018	22.77/500	Drill and blast
	Zhongtianshan Tunnel (Nanjiang Railway)	China	Apr 2007–Feb 2014	22.45/1728	TBM + drill and blast
	Daishimizu Tunnel (Joetsu Shinkansen)	Japan	Dec 1971–Jan 1979	22.22/1300	Drill and blast
	Qingyunshan Tunnel (Xiangtang–Putian Railway)	China	Aug 2008–Sep 2011	22.17/890	Drill and blast
	Yanshan Tunnel (Tang Zhang Railway)	China	Nov 2010–Sep 2014	21.18/557	Drill and blast
	Wushaoling Tunnel (Lanzhou–Xinjiang Railway)	China	Mar 2003–Aug 2006	20.05/1100	Drill and blast
	Simplon Tunnel (Simplon Pass Route)	Italy–Switzerland	I:1898–1906 II:1912–1921	19.80/2150	Lower pit + parallel pit
	Gaogaishan Tunnel (Xiangtang–Putian Railway)	China	Oct 2008–Jun 2012	17.60/819	Drill and blast
	Muzhailing Tunnel (Lanzhou–Chongqing Railway)	China	Mar 2009–Jul 2016	19.06/715	Drill and blast
	Qinling Tunnel (Xi'an–Ankang Railway)	China	Jan 1995–Sep 1999	18.46/> 1000	TBM
	Yingpanshan Tunnel (Chengdu–Kunming Railway Double Line)	China	Dec 2013–Feb 2018	17.90/833	Drill and blast
	Dalata Tunnel (Sichuan–Tibet Railway (Lalin Section))	China	Oct 2015–under construction	17.32/1760	Drill and blast
	Sangzhuling Tunnel (Sichuan–Tibet Railway (Lalin Section))	China	Dec 2014–Jan 2018	16.45/1347	Drill and blast
	Qinling Tianhuashan Tunnel (Xi'an–Chengdu High-Speed Railway)	China	Jan 2013–Jul 2016	15.99/1016	Drill and blast
	Dagushan Tunnel (Lanzhou–Urumqi High-Speed Railway)	China	Mar 2010–Feb 2014	15.92/1085	Drill and blast
	Daiyunshan Tunnel (Xiangtang–Putian Railway)	China	Dec 2008–Mar 2012	15.60/638	Drill and blast
	Zhujiashan Tunnel (Xuzhou–Lanzhou High-Speed Railway)	China	Jan 2013–Aug 2016	14.95/715	Drill and blast
	Daqinling Tunnel (Xi'an–Chengdu High-Speed Railway)	China	Feb 2013–Sep 2016	14.84/1185	Drill and blast
	Beacon Hill Tunnel (Xuzhou–Lanzhou High-Speed Railway)	China	Mar 2013–May 2015	14.75/708	Drill and blast
	Dayaoshan Tunnel (Hengyang–Guangzhou Railway)	China	Nov 1981–May 1987	14.30/910	Drill and blast
	Tianping Tunnel (Chongqing–Guiyang Railway)	China	Apr 2013–Jul 2016	13.98/900	Drill and blast
	Maijishan Tunnel (Xuzhou–Lanzhou High-Speed Railway)	China	Jan 2013–Apr 2016	13.93/675	Drill and blast
	Shin–Shimizu Tunnel (Joetsu Shinkansen)	Japan	Unknown–1967	13.50/1200	Drill and blast
	Mont Cenis Tunnel (Turin–Modane Railway)	Italy–France	Aug 1857–Dec 1870	13.70/1800	Drill and blast
	Tuan Tunnel (Chengdu–Kunming Railway Double Line)	China	Mar 2014–Nov 2017	13.37/550	Drill and blast
	Ba Yu Tunnel (Sichuan–Tibet Railway (Lalin Section))	China	Dec 2014–under construction	13.07/2080	Drill and blast
	East Qinling Tunnel (Nanjing–Xi'an)	China	Jan 2005–Jan 2007	12.27/580	Drill and blast
	Zongfa Tunnel (Chengdu–Kunming Railway Double Line)	China	Sep 2014–May 2017	11.97/570	Drill and blast
	Yuanliangshan Tunnel (Yuhuai Railway)	China	Mar 2001–Feb 2004	11.07/780	Drill and blast
	Arlberg Railway Tunnel (Arlberg Railway, western Austria)	Austria	Jun 1880–Jul 1885	10.65/1311	NATM
	Qiyueshan Tunnel (Yichang–Wanzhou Railway)	China	Dec 2003–Dec 2009	10.53/670	Drill and blast
Mountain highway tunnels	Laerdal Tunnel (Oslo–Bergen Highway)	Norway	1995–2000	24.51/1400	TBM + drill and blast
	Zhongnanshan Tunnel (Xi'an–Ankang Expressway)	China	Mar 2002–Jan 2007	18.02/1640	Drill and blast
	Jinpingshan Tunnel (Traffic Channel of Jinping Hydropower Station)	China	Oct 2003–Aug 2008	17.5/2375	Drill and blast
	Gotthard Road Tunnel (The North–South Trunk of the Swiss State-Owned Highway)	Switzerland	May 1970–Sep 1980	16.92/1000	Drill and blast
	Muzhailing Tunnel (Weiyuan–Wudu Expressway)	China	Apr 2016–under construction	15.23/629	Drill and blast
	Arlberg Road Tunnel (S16 Arlberg Highway)	Austria	Jul 1974–Dec 1978	13.98/736	
	Micangshan Tunnel (Sichuan Ba Shan Expressway)	China	Oct 2013–Aug 2018	13.81/1070	Drill and blast
	Xishan Tunnel (Taigu Expressway)	China	May 2009–Oct 2012	13.65/700	Drill and blast

Table 1 (*continued*)

Tunnel type	Tunnels (project)	Location	Start–completion dates	Length (km)/ maximum depth (m)	Construction method
	New Erlang Mountain Tunnel (Ya Kang Expressway)	China	Aug 2012–Sep 2017	13.46/1500	Drill and blast
	Hongtieguan Tunnel (Lin Chang Express)	China	Jun 2009–Sep 2013	13.12/600	Drill and blast
	White Horse Tunnel (Jiu Mian High-Speed)	China	Apr 2016–under construction	13.01/1092	Drill and blast
	Fréjus Road Tunnel (Bardonecchia–Modane Route)	Italy–France	1974–1980	13.00/1800	Drill and blast
	Snow Mountain Tunnel (Taiwan Highway No. 5)	China	Jul 1991–Apr 2004	12.90/600	TBM + drill and blast
	Maijishan Tunnel (Baotian Expressway)	China	Dec 2005–Jun 2009	12.29/675	Drill and blast
	Gaoloushan Tunnel (Pingliang–Mianyang Expressway)	China	Jul 2017–under construction	12.25/1500	TBM + drill and blast
	Grand Canyon Tunnel (Ehan Expressway)	China	Sep 2016–under construction	12.17/1830	Drill and blast
	East Tianshan Tunnel (Barikun–Hami Highway)	China	Aug 2016–under construction	11.77/1225	Drill and blast
	Mont Blanc Tunnel (European Route E25)	Italy–France	1958–Aug 1962	11.61/2400	Drill and blast
	Old Camp Tunnel (Baoshan–Lushui Expressway)	China	Mar 2016–under construction	11.52/1268	Drill and blast
	Yunshan Tunnel (Dongying–Lvliang Expressway)	China	2011–2014	11.39/743	Drill and blast
	Yingpanshan Tunnel (Huali Expressway)	China	Dec 2016–under construction	11.31/868	Drill and blast
	Baojiashan Tunnel (Xi'an-Ankang Expressway)	China	Apr 2006–Jan 2009	11.20/700	Drill and blast
	Kan–Etsu Tunnel (Kan–Etsu Expressway)	Japan	1985–1991	11.06/1190	
	Hida Tunnel (Tokai–Hokuriku Expressway)	Japan	Oct 1996–May 2008	10.74/1015	TBM + NATM
	Tongzi Tunnel (Lanzhou–Haikou Expressway)	China	Mar 2018–under construction	10.50/649	Drill and blast
	Baota Mountain Tunnel (Pingyu Expressway)	China	Jun 2009–Jun 2012	10.20/700	Drill and blast
	Plabutsch Tunnel (A9 Motorway (Austria))	Austria	Unknown–1987	10.09/763	NATM
	Niba Mountain Tunnel (Iasi Expressway)	China	Dec 2007–Dec 2011	10.00/1650	Drill and blast
Mountain hydraulic tunnels	Tunnels in the water diversion project for the central area of Yunnan Province (Water diversion project for central area of Yunnan Province)	China	2017–2025	—/607.4	TBM + drill and blast
	Hanjiang–Weihe water conveyance tunnel	China	2012–2020	81.60/2012	TBM + drill and blast
	Pahang Selangor Raw Water Transfer Tunnel (Pahang Selangor Raw Water Transfer Tunnel Project)	Malaysia	2010–Feb 2014	44.60/1246	NATM + TBM
	Diversion tunnel of Jinping II Hydropower Station (Jinping II Hydropower Station)	China	Jan 2007–Aug 2011	16.67/2525	TBM + drill and blast
	Futang Hydropower Station Diversion Tunnel (Futang Hydropower Station)	China	Apr 2001–Feb 2004	19.32/700	Drill and blast

NATM: New Austrian Tunneling Method; TBM: tunnel boring machine.

ratio of the intact rock of $S_0 = R_c/\sigma_1 < 7$) significantly affects the pressure, deformation, and stability of the surrounding rock mass of ultra-deep tunnels, and can induce disasters such as rockburst and large deformation. For example, the diversion tunnel of the Jinping II Hydropower Station has a maximum depth of 2525 m, and 75% of the tunnel exceeds 1500 m. The measured maximum principal stress σ_1 is 46 MPa, and the strength–stress ratio S_0 of the rock mass is approximately 2.13. More than 700 rockbursts occurred during construction; in particular, an extremely strong rockburst occurred on 28 November 2009, in which the support system was completely damaged within a 28 m section along the tunnel axis. The tunnel boring machine (TBM) was permanently buried by collapsed rock, causing tragic casualties. Another significant example is the Muzhailing Tunnel of the Lanzhou–Chongqing Railway. The tunnel is 19.02 km long and its maximum depth is about 715 m. The measured maximum principal stress is 27.16 MPa, and the strength–stress ratio of the rock mass is 2.13. The core section of the slate/carbonaceous slate stratum ridge that the tunnel passes through is 2000 m deep. During construction, the large extrusion deformation was significant, and the lining structure was seriously damaged.

2.2. High geotemperature

In general, when the temperature of the surrounding rock mass exceeds 30 °C, a tunnel is called a high-geotemperature tunnel. Influenced by the geothermal gradient and by active tectonic movement, ultra-deep tunnels are often accompanied by the high-geotemperature phenomenon—and the greater the depth, the more severe the phenomenon. With the construction of major infrastructure projects such as the Sichuan–Tibet Railway in western China, a number of typical high-geotemperature tunnels have emerged. For example, the Sangzhuling Tunnel of the Lhasa–Linzhi Railway has a maximum depth of 1347 m, and its highest geotemperature is 89.9 °C, which is close to water boiling point in Tibet. The Gaoligong Mountain Tunnel of the Dali–Ruili Railway has a maximum depth of 1155 m, and its highest geotemperature is 45 °C. High geotemperature deteriorates the construction environment, reduces labor productivity, and threatens workers' health and safety. The additional temperature stress generated by high geotemperature will cause cracking of the initial tunnel support and secondary lining, harming the safety and durability of tunnel structure. Therefore, research into a concrete mix ratio and water-proof material that are suitable for high geotemperature is indispensable.

2.3. High hydraulic pressure

High hydraulic pressure problems are inevitable in ultra-deep tunnels in water-enriched mountainous regions and high-pressure water-transfer tunnels, especially when adverse geological conditions such as faults and karst are present [2]. Water and mud inrush problems caused by high hydraulic pressure in fault or karst zones endanger the safety of tunnel construction, disturb the balance of the surrounding groundwater, and destroy the ecological environment. The Dazhushan Tunnel of the Dali–Ruili Railway in Yunnan, China, provides an example. Excavation of this tunnel has still not been completed since its start in 2008 due to the huge amount of water inflow, which reached 7×10^4–$1 \times 10^5\ \mathrm{m^3 \cdot d^{-1}}$. Thus far, $1.5 \times 10^8\ \mathrm{m^3}$ groundwater has been discharged (equal to 15 West Lakes, referring to the famous lake in Hangzhou, China). As a result, the original ecological environment on both sides of the Lancang River has been damaged. For tunnels with high hydraulic pressure, advance grouting is usually used to reinforce the surrounding rock, form a high hydraulic-pressure-bearing body, and block permeable water passage. However, there are no scientific and systematic techniques at present for depressurization and discharge reduction.

2.4. Special adverse strata

Compared with short, medium, and long tunnels, ultra-long tunnels exceeding 10 km are much more likely to encounter various adverse geological conditions. Typical adverse geological conditions include faults, soft rock, karst, and coal stratum. The high hydraulic pressure problems of faults and karst have been discussed above. Gas outbursts caused by coal stratum can easily cause accidents such as explosions and suffocation in ultra-long tunnels, and rescue would be extremely difficult. This section focuses on seismic damage to tunnels crossing fault zones and the large deformation of soft rock.

(1) When a tunnel crosses fault zones, the stability of the surrounding rock deteriorates. In active fault zones, the tunnel line can be easily cut off directly by an earthquake. Tunnel structures are inevitably damaged or even partially collapsed by earthquakes, especially in areas of high seismic intensity. Yu et al. [3] investigated 55 tunnels in the epicenter area of Wenchuan after the earthquake, and found that the structures of 38 tunnels were damaged to different degrees; the damage was mainly located at the tunnel portals, and was also found in linings. Such damage probably resulted from inconsistent deformation of the tunnel structure and surrounding stratum. It is necessary to develop a structure ductile-design method for ultra-long tunnels in high seismic intensity zones. The design standard, design life, and structural type of tunnel lining structures should be determined by considering the surrounding rock geological conditions.

(2) Soft rock can be classified into geological soft rock and engineering soft rock. *Geological soft rock* refers to loose, scattered, soft, and weak rock layers with low strength, large porosity, and poor cementation; it is significantly affected by the cutting and weathering of geological structural planes or by the inclusion of a large amount of expansive clay minerals. These rocks are mostly mudstone, shale, siltstone, and argillaceous ore, which are naturally formed complex geological bodies. *Engineering soft rock* refers to an rock mass that produces significant plastic or viscoplastic deformation under engineering forces. Under high geostress, soft rock is prone to significant creep and large deformation due to stress release during tunnel construction. During construction with a large excavation face using the New Austrian Tunneling Method (NATM)—a drilling and blasting method—it is difficult to control large soft rock deformation in high geostress areas if the initial lining is not built in a timely fashion. With TBM construction, the construction machines often get stuck due to large soft rock deformation in high geostress areas.

3. Challenges and engineering measures

3.1. Comprehensive advance geological prediction

For ultra-long and ultra-deep tunnels, the geological problems described in Section 2 have a higher probability and more serious consequences. To prevent and control these geological problems, the most important task is to ensure accurate advance geological prediction. For mountain tunnels over 500 m deep, it is very difficult to perform traditional vertical drilling, and the reference value of the results is limited. Instead, the comprehensive use of drilling and geophysical prediction based on conventional geological analysis is an effective method for advance geological prediction, and is an important future research direction [4,5]. In addition, the monitoring and prediction of specific geological hazards such as rockburst and large deformation are an indispensable means of ensuring safe tunnel construction.

A geological survey of the excavated tunnel section and the ground surface can identify the geological structure characteristics in front of the tunnel. The conventional geological analysis method is commonly used due to its low cost and acceptable results.

3.1.1. Drilling prediction method

Drilling prediction methods include probing ahead of the face with drilling and advance heading. These methods provide direct and accurate results and comprehensive predictions; however, they are time-consuming and expensive, and the prediction distance is short. The drilling prediction method is usually utilized in strata with complex geological conditions or rich water. By probing ahead of the face with drilling, the geological structure parallel to the tunnel face can be predicted well, but not the structure perpendicular to the tunnel face. The advance heading can be parallel to the main tunnel and in the main tunnel, as follows: ① Advance heading parallel to the main tunnel can provide direct and accurate prediction, and can be used for ventilation, slag transportation, drainage, and grouting. It can also be used to open up a new working face in order to expedite the construction or expand into a new tunnel. ② Advance heading in the main tunnel is a part of the main tunnel that is excavated in front of the tunnel face, and is more accurate than advance parallel heading.

3.1.2. Geophysical prospecting method

Geophysical prospecting usually uses electromagnetic waves, elastic waves (i.e., seismic and acoustic waves), infrared radiation, and the application of electric current to detect the rock mass structural planes, rock mass properties, and groundwater in front of the tunnel face. The prediction accuracy and range of geophysical prospecting technology are constantly improving, and this technology has become an indispensable part of tunnel advance geological prediction. Typical geophysical prospecting methods include the following: ① The elastic wave method predicts the geological conditions in front of and around the tunnel face by means of reflected waves propagating in the geological body; its detection distance can usually reach 100 m. Tunnel seismic prediction (TSP), true reflection tomography (TRT), tunnel seismic tomography (TST), the seismic negative apparent velocity method, tunnel geological prediction (TGP), the horizontal sound profile (HSP) method, and the land sonar method are typical elastic wave methods. ② The electromagnetic wave advance prediction method can be utilized to detect water over a distance of 30 m. It includes ground-probing/penetrating radar (GPR) that detects and transmits high-frequency electromagnetic waves, the transient electromagnetic method (TEM) that transmits a pulsed magnetic field to receive a secondary induced eddy current magnetic field, and infrared water exploration technology that receives the infrared electromagnetic waves emitted by an object. ③ The electrical method is based on the differences in the electrical properties of geological bodies. The bore-tunneling electrical ahead monitoring (BEAM) method and the three-dimensional (3D) induced polarization method [6] are two typical electrical methods that can be used to predict rock mass properties and water content. These two methods are usually combined with TBM construction for short-range advance prediction.

3.1.3. Monitoring high *in situ* stress and its induced disasters

At present, the mini-fracturing *in situ* stress test is the most effective method for measuring deep *in situ* stresses [7,8]. The mechanism of rockburst and large deformation induced by high *in situ* stresses is complex, making it difficult to predict and forecast such events. Monitoring and early warning are effective means of guaranteeing safety. For early rockburst warning, Feng et al. [9,10] proposed the dynamic control theory of rockburst, which is based on the spatial–temporal evolution of microseismic information during excavation. During the construction process, early warning of rockburst grade is realized according to the evolution law of the measured microseismic information. Through feedback analysis and dynamic regulation, a real-time monitoring and interpretation analysis system for rockburst microseismicity is developed. This system has been successfully applied in the Jinping Hydropower Station, the diversion tunnel of the Neelum–Jhelum Hydropower Station, and the deep-buried tunnel of the Sichuan–Tibet Railway. By extracting the corresponding microseismic monitoring events from the characteristics of rock mass damage processes, Ma et al. [11] summarized the laws of microseismic monitoring indexes, such as the density nephogram of microseismic events, the magnitude and frequency relationship of such events, their magnitude, and the degree of energy concentration. Based on the "3S" principle of seismology (namely, stress buildup, stress shadow, and stress transference), four criteria for rockburst were proposed in order to reveal the relationship between the space–time evolution of microseismic events and rockburst. As a result of this research, remarkable rockburst prediction results have been obtained in the diversion tunnel of Jinping II Hydropower Station.

3.1.4. Large deformation monitoring of soft rock

During tunnel construction, systematic monitoring and measurement of vault sinking, surrounding convergence, bolt axial force, and surrounding rock pressure—and especially dynamic monitoring of the bulging deformation of the tunnel face—should be carried out. By analyzing the data trend, the deformation of surrounding rock at the initial stage of construction can be predicted and controlled scientifically; the construction scheme and parameters can then be adjusted dynamically in a timely manner in order to realize dynamic feedback design.

3.2. Design and construction

3.2.1. Design methods

Tunnel structures and hydrogeological conditions must be considered carefully in tunnel engineering design. However, exploration data for ultra-long and ultra-deep tunnels are usually quite limited. As the construction proceeding, geological conditions will change and may be far different from the initial understanding of engineers. Thus it is advisable to develop high-precision acquisition and analysis methods for dynamic design. [12,13].

The geological complexity encountered during ultra-long and ultra-deep tunnel construction makes it difficult to simultaneously meet safety and economic requirements for construction design, making a dynamic design system challenging. Limited by the organization form of current engineering construction, dynamic design in the construction process faces three major challenges:

(1) **There is a lack of a fast and accurate method to collect basic data.** The magnitude and distribution of *in situ* stress make it difficult to obtain data accurately. There is a lack of high-precision and automated means to obtain geometric and mechanical parameters of rock mass in construction. The accuracy of advanced geological prediction—which depends heavily on the operators' experience—and the monitoring data are susceptible to interference and lack of timely feedback.

(2) **Design parameters from field basic data are not reliable enough.** The design method, which is based on the classification of the surrounding rock, is not refined enough, and it is difficult to adjust the weight of each parameter under specific conditions. Furthermore, the system bolt support system lacks flexibility in dealing with anisotropic surrounding rock, obtaining certain basic onsite data is overly challenging, and it is difficult to apply numerical analysis and other methods to adapt the dynamic design process while satisfying the requirement for accuracy.

(3) **The designation of responsibility during the construction management process is unclear.** At present, it is often the construction or monitoring units that identify problems during construction and then report them to the owner or designer. After re-investigation and confirmation by the designer or a third party, a multi-party consultation decides on modifications to the design plan, and gives the modified plan to the construction unit for execution. Without clear designation of responsibility, this process is lengthy and inefficient; in such a process, a single problem often leads to chain reactions.

The rock mass characteristics and stress state of a deep-buried tunnel are quite different from those of a shallow-buried tunnel. In deep strata, the influence of tectonic stress is relatively small and that of 3D stress is large. Thus, it is necessary to use the true 3D strength criterion (i.e., the Zhang–Zhu strength criterion [14]) to consider the effect of intermediate principle stress. The geostress characteristics of deep strata make the circular cross-section of large-buried tunnels advantageous over a horseshoe shape in terms of structural stress. For a deep-buried tunnel, it is more difficult to assess the *in situ* stress and geological structure of the surrounding rock accurately and completely. The risk of rockburst and large deformation is relatively high. The selection of support forms and parameters is also quite different from that of a shallow-buried tunnel.

The dynamic design of a mountain tunnel is a systematic process that includes information acquisition, data analysis, and application feedback. The speed and accuracy of the continuous acquisition and updating of basic information in the construction process lay the foundation for dynamic design. *In situ* stress information obtained during the pre-construction exploration stage cannot accurately reflect the changes of stress that occur during tunnel construction. The necessary information can be obtained through small-scale *in situ* stress tests conducted during tunnel construction [7,8]. Using binocular digital photography [15] and 3D laser-scanning technology [16], 3D point clouds of the rock mass surfaces exposed in the construction process can be quickly acquired; geometric information such as the occurrence and roughness of the rock mass surface structural plane can then be obtained by means of a spatial extraction algorithm [17]. The rebound stiffness of the rock mass can be obtained by a rapid impact test with a Schmidt hammer, and then converted into mechanical parameters such as rock strength and Poisson's ratio [18]. Using a remote wireless transmission system, real-time feedback of onsite forecasting and other monitoring information, computer-aided identification, and processing can be carried out offline in the background server.

It is necessary to connect field data with the server through a digital information platform in order to classify and store basic data and automatically extract indirect data such as the parameters needed to classify the surrounding rock in a dynamic design. Monitoring data of the rock mass and structures is incorporated into this platform in time for analysis, and dynamic support can be quickly evaluated. In addition to a refined surrounding rock classification system, numerical analysis results combined with fast numerical calculation can be used for support design in a short amount of time. The key block analysis and discontinuous deformation analysis [19] method can be used to consider the anisotropic characteristics of the rock mass, and to realize the design for the support through varying anchor distribution.

For dynamic tunnel design, it is advisable to designate a designer for the overall organization. The designer is directly responsible for the acquisition, transmission, analysis, application, and feedback of information communication. The owner and supervisor are mainly responsible for supervision, while the constructor is mainly responsible for the implementation of the design schemes. Such an organizational form can reduce unnecessary information copying and transmission, and hence improve the efficiency and accuracy of the project.

In addition, due to the special features of ultra-long and ultra-deep tunnels, a seismic design must address two major challenges: the spatial effect of non-uniform ground motions and stability under high geostress [20,21].

Large variance and complexity in the topographic and geological conditions are usually found along ultra-long tunnels. As a result, the vibration induced by seismic waves at various points along the longitudinal direction of a tunnel—that is, the spatial effect of inconsistent ground motions—differs from that of an ordinary tunnel. In the past, the seismic design of tunnels focused on uniform ground motion input, without considering the spatial variability of ground motion. Through experimental observation, Yu et al. [22] and Yuan et al. [23] found that non-uniform seismic input can significantly amplify the stress and deformation response of the tunnel structure, as compared with the results of uniform input. Based on this effect, a theoretical solution for the longitudinal seismic response of a long tunnel under the traveling wave effect was derived [21,24]. This solution can be used to evaluate the seismic safety of a long tunnel structure simply and quickly, thus providing a theoretical basis and simple method for the seismic design of a long tunnel in practical engineering.

The *in situ* stress of a tunnel increases with increasing embedded depth. An ultra-deep tunnel is subject to high *in situ* stress and is vulnerable to instability damage under the action of an earthquake. An investigation of tunnel damage at the epicenter of the Wenchuan earthquake showed that under high tectonic stress, the tunnel lining was more vulnerable to damage [3]. High tectonic stress in combination with strong earthquakes can trigger geological hazards such as rockburst. At present, there is a lack of a seismic design and analysis method for tunnel structures under high tectonic stress in areas with high seismic intensity. More research is required on catastrophic mechanisms and design countermeasures for ultra-long and ultra-deep tunnels under strong earthquakes. Research on anti-seismic technology and anti-seismic structural measures for tunnels is also required in order to establish a rational and unified concept design for the seismic performance of an ultra-long and ultra-deep tunnel.

3.2.2. Construction method

The drilling and blasting method and the TBM method are the main construction methods for ultra-long and ultra-deep rock tunnels. The key idea behind the drilling and blasting method is the concept of the NATM, which takes full advantage of the self-stability of the surrounding rock to form an integral supporting system. The cost of the drilling and blasting method is relatively low. With this method, construction is flexible and adaptable, and it is easy to carry out a multi-face operation. However, the excavation speed is slow, especially in hard rock strata. Furthermore, the excavation process is complex and different stages interact with each other, making it impossible to realize continuous excavation. In addition, the impact produced by the drilling and blasting method can easily induce rockburst, water inrush, and other disasters. The TBM method is characterized by a high level of mechanization and automation, resulting in a fast construction speed. Generally speaking, the TBM method is 3–10 times faster than the conventional drilling and blasting method [25]. The construction quality of the TBM is reliable, and the tunnel wall is smoother, since only the issues of over-excavation or under-excavation require consideration. This method is safe and environmentally friendly, and can reduce or avoid the need for an auxiliary cavern to reduce subsurface damage. Furthermore, the high level of automation of the TBM method reduces the labor intensity of workers. When the ratio of the length to the diameter of the tunnel is greater than 600, TBM construction is economical [25]. However, the investment required for TBM equipment is high, and workers with a high technical level are required. The construction flexibility and adaptability of this method are limited (e.g., it is not possible to change the diameter of the tunnel, and there is limited adaptability to variance in stratum conditions). Especially in deep soft rock, TBMs are prone to getting stuck during construction.

Slag discharge during ultra-long tunnel construction should be speeded up by increasing the mechanization level. Continuity of the working procedure should be ensured when discharging slag during the drilling and blasting method. Slag accumulation may occupy a large amount of land, induce geological hazards and soil erosion, and seriously affect the environment. Therefore, slag should be reused as an engineering material in order to reduce its encroachment on land resources. Disposal or landfill of hazardous slag is also needed.

During the construction of ultra-long and ultra-deep tunnels, possible geological problems and measures to deal with them include the following:

(1) **Rockburst.** Pre-release stress and a combination of active and passive support and mechanized construction should be employed to reduce the risk of rockburst.

(2) **Large deformation.** The following measures can be used to address large deformation: ① Analysis of controlled deformation in rocks and soils (ADECO-RS) can temporarily protect the surrounding rock, and fully mobilize and give full play to the self-supporting ability of the advanced core surrounding rock. ② The negative Poisson's ratio (NPR) bolt/cable large deformation control technology developed by He et al. [26], which is based on the NPR of the material or structure in terms of impact resistance, shear resistance, and energy absorption, provides a new type of constant resistance and acts as a large deformation anchor/cable with the NPR structure. ③ The "D-Bolts" new energy-absorbing anchor developed by Li et al. [27] is anchored with cement mortar. The anchor head is firmly fixed, while the smooth steel bar can expand freely with the deformation of the rock mass; its extensibility can reach up to 15%. D-Bolts distribute the tension of rock mass deformation between each anchorage section, thus avoiding failure caused by stress concentration due to crack opening, which can reach the peak load prematurely. This measure provides better adaptation to rockburst and large deformation.

(3) **High ground temperature.** Measures should be taken for cooling and dehumidification, including: ① increasing the ventilation and placing ice cubes; ② installing a thermal insulation layer; ③ burying a cooling tube; and ④ strengthening crack resistance by improving the mix proportion and reinforcement of reinforced concrete.

(4) **High hydraulic pressure.** The principle of blocking and limiting the emission of water [28] should be adopted, given the important requirements of environmental protection and protection of the tunnel structure. Comprehensive advanced geological prediction should be employed to confirm the groundwater state in front of the tunnel face. A geographic information system (GIS) platform can be used for the analysis and management of hydrogeological data [27]. The treatment methods of drainage (e.g., for a high-pressure water-rich karst area), blocking (where bedrock

fissure water < 0.5 MPa, submarine tunnel), and a drainage-blocking combination (where > 5 MPa fissure water or karst water is treated by drainage) should be used according to the water situation and the mud inrush area [29]. Specific treatment methods for groundwater in the surrounding rock of a tunnel include the following: ① In high-pressure and water-rich karst areas, advance tunneling can be used to release the energy accumulated in karst water; however, this should not be done during the rainy season, because excessive water will damage the tunnel at this time [30]. ② Advanced grouting can be used to block cracks or karst caves and can act as a long-term reinforcement measure [31]. ③ Advanced jet grouting can be used for the rapid treatment of water and mud inrush [32].

(5) **High seismic intensity.** Important prevention ideas should include adapting the tunnel to shear displacement and facilitating post-earthquake repair. In addition to structural measures such as lining grouting and tunnel support, measures should be implemented to ensure the deformation coordination between the tunnel structure and stratum; that is, the tunnel structure and stratum should be closely connected in terms of geometry and should have a similar stiffness.

3.3. Operation and maintenance

3.3.1. Ventilation of ultra-long tunnels

(1) **Construction ventilation.** Common methods for tunnel construction ventilation include mechanical press-in ventilation, draw-out ventilation, hybrid ventilation, and auxiliary channels ventilation. An ultra-long and ultra-deep mountain tunnel combines the characteristics of a large construction scale, large excavation, and large number of support structures. As the length of the tunnel increases significantly, traditional tunnel construction ventilation methods are no longer applicable. Ultra-long and ultra-deep tunnel construction ventilation presents many problems. Common issues include a ventilation scheme that may not be properly designed, layout of the ventilation system being inappropriately arranged, and a selection of ventilation machinery and equipment that is not well suited to the conditions. When initial environmental-pressure monitoring is not in place, poor ventilation can result, leading to an unfavorable air environment inside the tunnel. Another common issue is that the construction ventilation method is often too simple, which makes it impossible to dynamically adapt to changes in the bored distance of the tunnel over the complete construction process.

Construction ventilation in China has gradually improved over the years, with the continuous development of highways, railways, and water diversion projects. Construction ventilation theory for ultra-long and ultra-deep tunnels has been continuously enriched and improved. The diffusion of toxic gas during construction must be carefully analyzed by computational fluid dynamics (CFD) software, especially in coal-bearing strata. It is necessary to combine tunnel construction ventilation safety measures with a management system in order to establish a ventilation scheme.

(2) **Operational ventilation.** In addition to meeting the requirements for pollutants dilution under normal operating conditions, tunnel ventilation must meet the requirements for smoke exhaustion in the case of a fire [33]. During the operation period of an ultra-long tunnel, traditional natural ventilation and mechanical ventilation methods are unable to meet the requirements of energy conservation and safety. With an increase in the length of the tunnel, the driving time of the vehicle in the tunnel increases, resulting in a significant increase in both the amount of pollutants discharged in the tunnel and the required air volume of the tunnel. Auxiliary tunnel ventilation such as shafts and inclined shafts are used to connect the closed environment of the tunnel to the atmospheric environment. The construction volume and operating energy consumption of the shaft and inclined shaft of an ultra-deep-buried tunnel are relatively large. Fire, high land temperatures, and gas pose significant challenges during the operation period of ultra-long tunnels.

In the 1970s to 1980s, a transition of road tunnel ventilation types occurred, from horizontal ventilation and semi-horizontal ventilation to longitudinal ventilation. With the promotion of the concept of green energy conservation and environmental protection, new methods such as double-hole complementary ventilation [34], single-channel blowing-in ventilation, and service tunnel ventilation continue to emerge. Forms of natural ventilation and various new ventilation methods for long tunnels are being developed.

The ventilation control technology of an ultra-long and ultra-deep tunnel must address many practical issues, including a high idle rate of ventilation equipment, inaccurate traffic volume with respect to the ventilation requirements, a high pollutant concentration, and a serious waste of electric energy. With the continuous development of modern control theory and intelligent control, intelligent ventilation control methods have gradually been applied in tunnels and have achieved good results [35].

3.3.2. Disaster prevention and traffic signs in ultra-long tunnels

(1) **Disaster prevention and rescue.** The toxic and harmful flue gas that is generated during a tunnel fire is the main cause of casualties in such an event [36]. In addition, due to the closed space, the heat generated by a fire in an extra-long tunnel cannot easily be evacuated; heat accumulation thus causes the tunnel temperature to rise rapidly, posing a serious threat to the stability and integrity of the tunnel structure.

During such a fire, human evacuation and rescue present an even more challenging task. However, digital dynamic evacuation and rescue technology and artificial intelligence (AI) can be used to achieve intelligent tunnel disaster prevention [37]. Real-time monitoring of the tunnel temperature and fire alarm system checks should be implemented during the normal operation period. In case of a fire, fire theory, data mining, and digitization techniques should be applied in order to reconstruct the tunnel fire in real time, provide key information and a real-time status for the tunnel, and efficiently guide fire rescue and personnel evacuation. The tunnel ventilation system must be ventilated and exhausted according to the conditions that occur during a fire, and a personnel evacuation rescue plan must be immediately provided in case of an emergency in order to mitigate the damage and losses caused by the tunnel fire.

In recent years, new ideas for tunnel fire prevention have emerged. For example, the tunnel lining structure can contain microencapsulated fireproof concrete materials [38], and a tunnel fire protection system can be provided that is shielded by a water curtain [39].

(2) **Traffic signs in road tunnels.** The tunnel has a single profile/cross-section and there is no natural light, resulting in a blocked visibility. In this case, the judgment of drivers must rely entirely on traffic signs. If the signage is inadequate, it is very easy for drivers to miss important traffic information, which may lead to an increase in driver mental stress and fatigue. In the case of a traffic accident, a secondary accident can easily occur due to the poor visual field and narrow lateral width of the tunnel [40]. This problem is particularly serious in ultra-long tunnels.

At present, the main problems with traffic signs in road tunnels involve the signage at the entrance and exit, which may not be sufficiently conspicuous. In the vicinity of the entrance and exit of the tunnel, the significant contrast in the internal and external light intensity may result in "white hole adaptation" or "black hole adaptation" on the part of drivers, leading to a sharp drop in drivers' recognition of traffic signs; in severe cases, a traffic accident can even occur. Furthermore, the installation location of the tunnel sign is very high, making it difficult to clean. Tunnel signboards are commonly positioned in areas where dust can easily accumulate, making it difficult for drivers to perceive the signboard content. The entrance and exit tunnel sections—that is, the lighting of the approaching section, inlet section, transition section, tunnel section, and exit section—must be specially designed. In the future, the traffic sign of ultra-long road tunnels in China will focus on the development of new light sources, with a trend toward energy-saving green lighting and big data intelligent lighting control.

3.3.3. Operational tunnel performance

Tunnels commonly suffer a certain degree of deformation and deterioration during their operation period due to the effects of geological condition, the surrounding climate, construction quality, insufficient maintenance, and so forth. Longitudinal settlement, convergence deformation, water leakage, and cracks and spalling of structures are the main measurable defects in operational tunnels; these frequently induce tunnel deterioration, resulting in a decrease in tunnel safety, applicability, and durability. In addition, tunnels are characterized by complex function, monitoring difficulties, frequent disasters, and risk aggregation due to their complexity, concealment, and interactions with their surroundings [41]. A variety of intelligent detection systems and highway/freeway detection vehicle equipment have therefore been developed in order to compensate for subjective errors, low detection efficiency, and hidden hazards caused by traditional manual-inspection technology [42]. The construction of a wireless sensor network (WSN) [43–45] and the utilization of radar [46], unmanned aerial vehicles (UAVs) [47], and other advanced equipment can assist in tunnel health detection and assessment in order to bring tunnel maintenance into a new digital era.

We should now be aiming beyond timely countermeasures or repair after hazards, to focus on the realization of pre-disaster prediction. Nevertheless, quantitative analysis of tunnel serviceability is still in its infancy. Li et al. [48] have proposed the concept of the Tunnel Serviceability Index (TSI), which is a five-rank system for evaluating tunnel performance based on experts' judgment. Chen et al. [49] subsequently utilized the multiple indicators multiple causes (MIMIC) model to analyze the linear mapping relationship between the TSI and the measured distress/deformation.

3.4. Engineering investment and management

Ultra-long and ultra-deep tunnels are difficult to construct, invest, finance, and manage. Some of these problems are technical, while others are management issues. Standardized modes of management cooperation, effective ways of communication, and the training of personnel should be employed to solve non-technical problems.

Many past experiences in infrastructure construction can be referred to when solving problems related to extra-long and ultra-deep tunnels, such as investment problems. For example, build–operate–transfer (BOT) [50] and public–private–partnership (PPP) [51] are two of the most classic project-financing forms. During the construction process, it is difficult to coordinate the interests of each side. This difficulty should be improved through standardized management, communication methods, and changes in staff training [52].

4. Further development prospects

The construction of ultra-long and ultra-deep rock tunnels is becoming increasingly essential to social and economic development. The goals of safe, efficient, green, and intelligent tunnels lead future development directions.

First, safe and efficient construction, operation, and maintenance should be ensured. High-efficiency advance geological prediction methods should be developed. It is necessary to synthesize various advance prediction methods such as drilling and geophysical prediction. Furthermore, automatic extraction of geological information of the tunnel face can be realized by incorporating the digital rapid acquisition method. Based on big data of the surrounding rock mass, deep learning and machine learning can provide a sound foundation for safe construction. Meanwhile, mechanized construction equipment should be developed. It is necessary not only to promote mechanical construction using TBMs, but also to consider the mechanization of each construction procedure of the drilling and blasting method, and to combine TBMs with the drilling and blasting method in order to ensure safety and efficiency under various geological conditions. To conclude, improving the disaster prevention and resilience capability of tunnels by means of new materials, strengthening data monitoring and analysis to improve disaster resilience capability, improving the tunnel ventilation effects and construction environment with modern control technology, and adopting reasonable tunnel performance evaluation indicators can contribute to long-term, safe, and reliable operation.

Second, the concept of the "green tunnel" should be taken seriously in order to enable the safe and efficient construction of tunnels. Tunnel construction projects should focus on the importance of environmental protection by embodying the following five aspects: ① energy conservation, which involves saving electric energy and fossil fuel, and developing geothermal resources; ② water conservation, which protects the groundwater balance; ③ material conservation, which involves the comprehensive processing and utilization of tunnel rock slag; ④ land conservation, which involves the ecological, economic, and reasonable reclamation of tunnel slag sites; and ⑤ environmental protection, which involves minimizing the disturbance of tunnel construction to the surrounding ecological environment.

Third, the integration of modern information technology and the construction of ultra-long and ultra-deep rock tunnels is a long-term task. Ultra-long and ultra-deep rock tunnels are characterized by their extreme length and depth, and by their location in trackless and dangerous areas. Therefore, humans must use modern equipment—such as intelligent equipment, digital information collection, new-generation communication networks (such as 5G networks, the Internet of Things (IoT), mobile communications, etc.), big data and AI analysis methods, cloud/material computing methods, and so forth—to carry out intelligent and even smart services for tunnel construction, operation, and maintenance. In remote areas where power supply and communications are severely deficient, it is necessary to use passively sensing components for sensing and transmitting. The premise of intelligentization is digitalization and informatization; it is imperative to collect information on the whole life-cycle of the tunnel, carry out dynamic information design and construction, highlight the integration of construction and maintenance, and establish an open and shared information service platform [12]. All aspects of the geological prediction, design, construction, operation, and maintenance can be intellectualized. We must conduct further research on and development of intelligent equipment and new materials, in order to eventually achieve completely intelligent tunnel construction.

Acknowledgements

Many thanks to graduate students of Tongji University, including Xi Wang, Ziyang Chen, Chao Guo, and Mengqi Zhu, and to associate professor Haitao Yu and assistant professor Wei Wu for their hard work. We are also grateful to CAE member Junzhi

Cui, senior engineer Hualao Wang, Prof. Lianyang Zhang, and Prof. Xiaoying Zhuang for their valuable comments, guidance and amendments. Thanks are also to the support of National Natural Science Foundation's Major Equipment (41827807).

References

[1] Xu Z, Huang R, Wang S. Tunnel classifying in light of depth (i.e thickness of overburden). Chin J Geol Hazard Control 2000;11(4):5–10. Chinese.

[2] Li SC, Xu ZH, Huang X, Lin P, Zhao XC, Zhang QS, et al. geological identification, hazard mode and typical case studies of hazard-causing structures for water and mud inrush in tunnels. Chin J Rock Mech Eng 2018;37:1041–69. Chinese.

[3] Yu H, Chen J, Yuan Y, Zhao X. Seismic damage of mountain tunnels during the 5.12 Wenchuan earthquake. J Mt Sci 2016;13(11):1958–72.

[4] Chen G, Wu Z, Wang F, Ma Y. Study on the application of a comprehensive technique for geological prediction in tunneling. Environ Earth Sci 2011;62(8):1667–71.

[5] Li SC, Liu B, Sun HF, Nie LC, Zhong SH, Su MX, et al. State of art and trends of advanced geological prediction in tunnel construction. Chinese J Rock. Mech Eng 2014;33:1090–113. Chinese.

[6] Li S, Liu B, Liu Z, Nie L, Song J, Sun H, et al., inventors; Shandong University, assignee. Advanced detection device, system and method using forward three-dimensional induced polarization for TBM construction tunnel. China Patent CN2013/000041; 2014 Jul 10.

[7] Haimson BC. Standard test method for determination of the *in-situ* stress in rock using the hydraulic fracturing method. Annu Book ASTM Stand 1989;4:851–6.

[8] Haimson BC, Cornet FH. ISRM suggested methods for rock stress estimation—part 3: hydraulic fracturing (HF) and/or hydraulic testing of pre-existing fractures (HTPF). Int J Rock Mech Min Sci 2003;40(7–8):1011–20.

[9] Feng X, Wu S, Li S, Qiu S, Xiao Y, Feng G, et al. Comprehensive field monitoring of deep tunnels at Jinping underground laboratory (CJPL-II) in China. Chin J Rock. Mech Eng 2016;35(4):649–57. Chinese.

[10] Feng X, Zhang Z, Chen B, Feng G, Zhao Z, Ming H, et al. Dynamical control of rockburst evolution process. Chin J Rock Mech Eng 2012;31(10):1983–97. Chinese.

[11] Ma T, Tang C, Tang L, Zhang W, Wang L. Mechanism of rock burst forcasting based on micro-seismic monitoring technology. Chin J Rock Mech Eng 2016;35(3):470–557. Chinese.

[12] Zhu H, Li X, Lin X. Infrastructure Smart Service System (iS3) and its application. China Civ Eng J 2018;51:1–12.

[13] Zhu H, Wu W, Li X, Chen J, Huang X. High-precision acquisition, analysis and service of rock tunnel information based on iS3 platform. Chin J Rock Mech Eng 2017;36(10):2350–9. Chinese.

[14] Zhang L, Zhu H. Three-dimensional Hoek-Brown strength criterion for rocks. J Geotech Geoenviron Eng 2007;133(9):1128–35.

[15] Zhu H, Wu W, Chen J, Ma G, Liu X, Zhuang X. Integration of three dimensional discontinuous deformation analysis (DDA) with binocular photogrammetry for stability analysis of tunnels in blocky rockmass. Tunn Undergr Space Technol 2016;51:30–40.

[16] Gigli G, Casagli N. Semi-automatic extraction of rock mass structural data from high resolution LIDAR point clouds. Int J Rock Mech Min Sci 2011;48(2):187–98.

[17] Chen J, Zhu H, Li X. Automatic extraction of discontinuity orientation from rock mass surface 3D point cloud. Comput Geosci 2016;95:18–31.

[18] Aydin A. ISRM Suggested method for determination of the Schmidt hammer rebound hardness: Revised version. Int J Rock Mech Min Sci 2009;46(3):627–34.

[19] Wu W, Zhu H, Lin JS, Zhuang X, Ma G. Tunnel stability assessment by 3D DDA-key block analysis. Tunn Undergr Space Technol 2018;71:210–4.

[20] He C, Geng P, Yan Q, Feng K. Status of seismic analysis methods for traffic tunnel and their applicability suggestions in China. J Earthq Tsunami 2013;7(3):1350026.

[21] Yu H, Yuan Y, Bobet A. Seismic analysis of long tunnels: a review of simplified and unified methods. Undergr Sp 2017;2(2):73–87.

[22] Yu H, Yong Y, Xu G, Su Q, Xiao Y, Chong L. Multi-point shaking table test for long tunnels subjected to non-uniform seismic loadings—part II: application to the HZM immersed tunnel. Soil Dyn Earthq Eng 2016;108:187–95.

[23] Yuan Y, Yu H, Li C, Xiao Y, Yuan J. Multi-point shaking table test for long tunnels subjected to non-uniform seismic loadings—part I: theory and validation. Soil Dyn Earthq Eng 2016;108:177–86.

[24] Yu H, Zhang Z, Chen J, Bobet A, Mi Z, Yong Y. Analytical solution for longitudinal seismic response of tunnel liners with sharp stiffness transition. Tunn Undergr Space Technol 2018;77:103–14.

[25] Zhou J, Yang Z. Discussion on key issues of TBM construction for long and deep tunnels. Rock Soil Mech 2014;35:299–305. Chinese.

[26] He MC, Li C, Gong WL, Wang J, Tao ZG. Support principles of NPR bolts/cables and control techniques of large deformation. Chin J Rock Mech Eng 2016;35:1513–29.

[27] Li X, Li Y, Zhou S. Study and application of forecasting system for water inrush under high pressure in Xiamen submarine tunnel construction based on GIS. Proc Environ Sci 2011;10(Pt B):999–1005.

[28] Wang X, Tan Z, Wang M, Zhang M. Analysis of interaction between surrounding rock and lining in high water-level tunnels with controlled drainage. Rock Soil Mech 2008;29(6):1623–8.

[29] Zhao Y, Li P, Tian S. Prevention and treatment technologies of railway tunnel water inrush and mud gushing in China. J Rock Mech Geotech Eng 2013;5(6):468–77.

[30] Zhang M. Yichang–Wanzhou Railway tunnel construction technology of karst fault. Beijing: Science Press; 2010. Chinese.

[31] Zhuang H, Mu J. The prevention and treatment of large cross section tunnel mud gushing in karst areas. Railw Eng 2009;6:49–51.

[32] Yang D, Zhang P. Study on the rapid treatment method of mud gushing and land-slide at shallowly covered karst section in Yunwu Mountain Tunnel. West-China Explor Eng 2008;10:192–4.

[33] Yan ZG, Zhu HH, Yang QX. Large-scaled fire testing for long-sized road tunnel. Tunn Undergr Sp Technol 2006;21(3–4):282.

[34] Berner MA, Day JR. A new concept for ventilating long twin-tube tunnels. Aerodyn Vent Veh Tunnels 1991:811–20.

[35] Huang Y, Fang G, Li X. An optimal control method of long tunnel ventilation based on variable domain fuzzy control. In: Proceedings of the 2018 Chinese Automation Congress; 2018 Nov 30–Dec 2; Xi'an, China. New York: IEEE; 2018. p. 2626–30.

[36] Hu LH. Studies on thermal physics of smoke movement in tunnel fires [dissertation]. Hefei: University of Science and Technology of China; 2006. Chinese.

[37] Yan Z, Tian Y, Zhu H, Yu L. Tunnel fire dynamic early-warning, evacuation and rescue system and its application. Mod Tunn Technol 2016;53(6):31–5.

[38] Zhang Y, Ju JW, Zhu H, Guo Q, Yan Z. Micromechanics based multi-level model for predicting the coefficients of thermal expansion of hybrid fiber reinforced concrete. Constr Build Mater 2018;190:948–63.

[39] Yang P, Shi C, Gong Z, Tan X. Numerical study on water curtain system for fire evacuation in a long and narrow tunnel under construction. Tunn Undergr Space Technol 2019;83:195–219.

[40] Yeung JS, Wong YD. Road traffic accidents in Singapore expressway tunnels. Tunn Undergr Space Technol 2013;38:534–41.

[41] Shi P, Li P. Mechanism of soft ground tunnel defect generation and functional degradation. Tunn Undergr Sp Technol 2015;50:334–44.

[42] Shen ZY, Tan Z. Application research on GRP5000 tunnel inspection car in Shanghai subway. Shanxi Archit 2013;39(27):158–9.

[43] Hada A, Soga K, Liu R, Wassell IJ. Lagrangian heuristic method for the wireless sensor network design problem in railway structural health monitoring. Mech Syst Signal Process 2012;28:20–35.

[44] Schwamb T, Soga K, Mair RJ, Elshafie MZ, Sutherden R, Boquet C, et al. Fibre optic monitoring of a deep circular excavation. Geotech Eng 2014;167(2):144–54.

[45] Hoult NA, Soga K. Sensing solutions for assessing and monitoring tunnels. In: Wang ML, Lynch JP, Sohn H, editors. Sensor technologies for civil infrastructures. Cambridge: Woodhead Publishing; 2014. p. 309–46.

[46] Huang H, Liu T, Xie X. Application of GPR to grouting distribution behind segment in shield tunnel. Rock Soil Mech 2003;24:353–6.

[47] Lyu X, Gu H, Wang Y, Li Z, Shen S, Zhang F. Design and implementation of a quadrotor tail-sitter VTOL UAV. In: Proceedings of the 2017 IEEE International Conference on Robotics and Automation; 2017 May 29–Jun 3; Singapore, Singapore. New York: IEEE; 2017. p. 3924–30.

[48] Li X, Lin X, Zhu H, Wang X, Liu Z. Condition assessment of shield tunnel using a new indicator: the tunnel serviceability index. Tunn Undergr Space Technol 2017;67:98–106.

[49] Chen X, Li X, Zhu H. Condition evaluation of urban metro shield tunnels in Shanghai through multiple indicators multiple causes model combined with multiple regression method. Tunn Undergr Space Technol 2019;85:170–81.

[50] Yu C, Lam KC, Yung P. Factors that influence the concession period length for tunnel projects under bot contracts. J Manage Eng 2014;30(1):108–21.

[51] Zhou X, Pan H, Shen Y. China's underground comprehensive utility tunnel project of PPP mode risk identification. In: Proceedings of the International Conference on Construction and Real Estate Management 2017; 2017 Nov 10–12; Guangzhou, China. Reston: American Society of Civil Engineers; 2017. p. 318–27.

[52] Ma JQ. Influence of non-technical factors on the construction of tunnels. Adv Mater Res 2011;201–203:1300–7.