Technical Challenges and Solutions for Super-Long Mountainous Tunnels at Great Depth

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ABSTRACT: There are various technical challenges faced by the construction of super-long mountainous tunnels at great depth, and also a series of new requirements for tunnelling arising from such aspects as geological investigation, construction duration, special geological conditions (high ground stress, high geothermal temperature and high-pressure groundwater), disaster prevention & evacuation and social development. Based on an analysis of the above-mentioned technical challenges, this paper presents technical views on solutions to those challenges and specifies the objectives of related technical development in the future. To improve the validity and accuracy of the geophysical prospecting, it is necessary to not only increase the accuracy of ground geophysical exploration at great depth, but also carry out research on the application of such techniques to tunnel investigation as airborne geophysical prospecting and HDD combined with borehole geophysical exploration. To maximize the benefits of tunnel projects, it is of importance that more attention should be paid to those issues relating to the tunnel design concept, such as the multiple functions of tunnel projects, energy saving and emission reduction, and environmental protection. As for tunnel support theories, in addition to optimizing the current theories, some unconventionally new lining theories need to be put forth to make the tunnel structure more durable and economical. It is also suggested that, in terms of construction, sustained efforts should be put into the development of innovative tunnelling techniques for a better, faster and more economical tunnelling, as well as the realization of intelligent mechanized tunnelling. When it comes to operation, it is obvious that there will be a trend towards intelligent maintenance in the future

KEYWORDS: Tunnels at great depth; Super-long tunnels; Mountainous tunnels; Technical challenges; Solutions; Development trend

1. INTRODUCTION

Nowadays, there are many countries all over the world that have accumulated considerable experience in building super-long mountainous tunnels at great depth, such as Switzerland, Austria, Italy, France, China, Japan, Spain and Norway. For instance, in Switzerland, the completion and opening to traffic of the 57km Gotthard Rail Base Tunnel is acclaimed as a new world record in the development of construction technology for super-long mountainous tunnels at great depth. In China, there are also a lot of super-long tunnels at great depth that have been successfully completed. Among them, the typical projects include the 32km New Guanjiao Railway Tunnel, the 28km West Qinling Railway Tunnel, the 28km Ping'an Railway Tunnel, the 18km Zhongnan Mountain Highway Tunnel at Qinling and a group of long tunnels at great depth built for the Jinping-II Hydropower Station. At present, a great number of tunnels of this kind are under construction or planned to be built worldwide, such as the 52km Brenner Rail Base Tunnel between Austria and Italy, the 32km Koralm Rail Tunnel in Austria and the 34km Gaoligong Mountain Rail Tunnel in China. In addition to the above, the 57km D'Ambin Rail Base Tunnel between France and Italy is already in the design stage and preliminary work has been carried out for the 52km Bioceanico Aconcagua Rail Tunnel which passes through the Andes between Argentina and Chile. Undoubtedly, there will be more technical challenges to be encountered in the construction of super-long tunnels at great depth in the future, and also more new requirements for tunnel engineering arising from social development.

2. TECHNICAL CHALLENGES

In terms of the project itself, the technical challenges facing a super-long mountainous tunnel at great depth are mainly caused by its great length and depth, the mountainous terrain and the new requirements for tunnels arising from social development in the future.

2.1 Technical challenges caused by great length

The three major challenges faced by super-long tunnels are huge investments, prolonged construction duration and difficulties in disaster prevention & evacuation during operation. In general, the investment in a super long tunnel is huge, so it is of great importance to either reduce the construction cost or improve the project benefits. As for the prolonged construction duration, the method widely used to solve this problem is to increase the number of working faces by setting up more adits. Although this kind of multiple-face tunnelling for short distances can speed up the construction progress, it will lead to some other problems consequently, such as an increased project investment and more severe impact on environment. With the strengthening of environmental protection policies in many countries, it will be unacceptable in the future to use such method like the one above that is environmentally unfriendly and the realization of rapid construction seems to mainly depend on mechanized tunnelling. Last but not least, super-long tunnels also face the difficulties in disaster prevention & evacuation during operation. Currently, the common practice is to set up a rescue station midway of the long tunnel for evacuation in case of fire in the tunnel. But such rescue station needs very high investment and also costly to maintain.

2.2 Technical challenges caused by great depth

The technical challenges faced by tunnels at great depth include the impossibility of conducting ground surface investigation in no man's land, the inadequate accuracy of geophysical prospecting at great depth, the considerable cost of deep drilling and the "three highs" caused by great depth, i.e. high ground stress, high geothermal temperature and high-pressure groundwater. All these problems have made it very difficult and hazardous to carry out the construction of tunnel at great depth.

2.3 Technical challenges caused by mountainous terrain

The major challenges faced by mountainous tunnels at great depth are groundwater protection and the utilization and disposal of mucks. As the groundwater table is likely to be very high when tunnelling at great depth, to protect groundwater properly in such a condition can be regarded as a great technical challenge. If a full-sealing solution is adopted, the difficulty in high-pressure grouting has to be overcome so as to bring into full play the bearing ability of the ground for high water pressure. If a sealing & draining solution is taken into consideration, it is necessary to make good use of the drained water. In addition to the above, how to prudently utilize and dispose mucks during construction so as to minimize the impact on environment is also a big concern in mountainous tunnel project at great depth.

2.4 Technical challenges caused by new requirements arising from future social development

Due to the fact that investment in a super-long tunnel at great depth is very huge, it will be a new challenge to improve the investment benefits by way of innovations in design concept. Besides, for such kind of mega projects, how to satisfy the requirements of sustainable development is another major challenge for reason that in future, tunnels are expected to be safer, more comfortable and energy-efficient and more environmentally friendly.

3. COUNTERMEASURES AND DEVELOPMENT TREND OF TECHNOLOGY

To meet these technical challenges of super-long mountain tunnels at great depth, a series of countermeasures combined with innovative techniques need to be developed for such stages such as investigation, design, construction and operation.

3.1 Countermeasures in investigation - improving the validity and accuracy of tunnel investigation through innovations in technology

To effectively deal with such problems as the impossibility of conducting ground surface investigation caused by the inaccessibility to no man’s land, the inaccuracy of investigation at great depth, and the high cost of drilling at great depth, it is suggested that, while improving the accuracy of ground geophysical prospecting, the airborne geophysical prospecting technique such as Lidar (3D laser scanning) should be utilized to investigate the no man’s land and the combination of horizontal directional drilling with borehole geophysical prospecting should be regarded as an effective method to improve the efficiency, accuracy and validity of investigation for tunnels at great depth.

3.1.1 Airborne geophysical prospecting

Airborne geophysical prospecting refers to the method of utilizing a series of special prospecting instruments and equipment carried by aircraft to investigate the geological structure from the air by measuring and recording the changes in various physical fields (such as magnetic field, gravitational field, electrical conductivity, etc.) Compared with ground geophysical prospecting, it has the following main advantages: 1) it can overcome the limitations caused by unfavourable geographical, topographical and climatic conditions; 2) being faster and more efficient, it has a smaller demand of labour force and can collect the prospecting data of a large area in a short period of time. In fact, a number of technologies based on the high-resolution airborne geophysical prospecting methodology have been applied in petroleum and mining exploration, such as airborne magnetic surveying technology, airborne electromagnetic surveying technology, airborne radioactivity surveying technology and airborne gravity surveying technology, etc. (Yuan et al, 2011) Therefore, it is necessary to conduct extensive research on the application of high-resolution airborne geophysical prospecting methodology in tunnelling works so as to more efficiently collect and process weak geophysical signals and to overcome the challenge of carrying out investigation in no man’s land. Moreover, the use of drones will make airborne geophysical prospecting safer and more economical.

3.1.2 The combination of horizontal directional drilling (HDD) with borehole geophysical prospecting

In general, the investigation results gained from the widely used vertical drilling are scope- limited, especially in super-long tunnel projects at great depth. For such projects, the vertical drilling operation often has a very high cost and is hardly conducive to accurately interpreting the geological conditions at tunnel sites. Therefore, it is suggested that horizontal directional drilling (HDD) at the tunnel axis be combined with borehole geophysical prospecting to investigate the geological conditions along the axis. On the one hand, the HDD has become a proven technology which can be easily used to drill several kilometers of horizontal boreholes. On the other hand, the borehole geophysical prospecting is featured by both a high resolution and a wide prospecting range as demonstrated in many application cases. Thus, the combination of these two technologies will make the drilling obtain comprehensive geological information along the tunnel axis. Currently, a number of methods based on borehole geophysical prospecting have been applied in mineral resources exploration including electromagnetic method, magnetometric resistivity method, and induced polarization method, etc. In this regard, detailed research should be conducted on the composite method of horizontal directional drilling (HDD) + borehole geophysical prospecting specifically developed for super-long tunnels at great depth, so as to improve the accuracy and efficiency of investigation under such circumstances.

3.1.3 Improving the accuracy of ground geophysical prospecting

Although ground geophysical prospecting has a high rate of usage nowadays, its accuracy is not very satisfying. To improve the accuracy, ground geophysical prospecting could be developed into a multi-functional and cross- discipline technology with a wide range of parameters. Such a more advanced technology can be used not only to detect electrical resistivity, magnetic susceptibility, intensification rate, density and longitudinal wave velocity, but also to improve the accuracy of prospecting by obtaining parameters that can reflect changes in the physical properties of geological bodies, such as shear wave velocity, amplitude attenuation degree and spectrum variation, etc. It is foreseeable that the development of geophysical prospecting technology for tunnels in the future will mainly focus on the application of comprehensive analysis supported by multiple parameters.

Similarly, a comprehensive analysis of geological investigation information is also very important for improving the accuracy of tunnel investigation. It is of necessity to comprehensively analyse all the information relating to geological investigation, geophysical prospecting, drilling, the physical and mechanical properties of rocks, etc.

3.2 Countermeasures in design - design concept innovation and technical innovation

3.2.1 Design concept

In terms of tunnel design concept, the first innovation to be taken into account is to transform a single function design into a multi-function design. More often than not, the investment is very substantial in a super-long tunnel project, so how to maximize the economic benefits of the tunnel has become a major concern. As a solution to this problem, the multi-function tunnel design can bring to the tunnel more functions, thus effectively improving its economic benefits. Around the world, there have been many successful project cases adopting this kind of design concept. Although the tunnels in such cases are not super-long and at great depth, the concept of comprehensive design involved in them is worth being taken into consideration. For instance, the British-French Channel Tunnel is capable for not only the transportation of passenger and freight trains, but also that of trucks and cars fixed on flat-panel trains. In Kuala Lumpur, Malaysia, the Smart Tunnel was originally planned to be a floodwater drainage tunnel in the city centre. However, considering that the annual number of days is very limited when it is used as a floodwater drainage tunnel and the traffic jams are serious along the line during rush hour, the planners decided to design it as a multi-purpose double-deck tunnel acting as both a floodwater drainage tunnel and a municipal road tunnel. As shown in Figure 1 (Operation Modes of SMART Tunnel, 2018) when there is no flood, this tunnel is used as a double-deck municipal road tunnel. Once its function of floodwater drainage is called for, this tunnel will be closed to traffic and used to divert floodwater. After the flood has ended, it will be opened to traffic again. In this way, the multi-function design has greatly increased the economic benefits of the SMART tunnel. The next innovation to be considered in tunnel design concept is related to energy-saving and emission reduction. Super-long tunnels at great depth often encounter the technical challenge of high geothermal temperature. Without exception, the 34km Gaoligong Mountain Rail Tunnel under construction is also facing this challenge. If the thermal energy can be used properly to serve the tunnels or other facilities, the harms caused by it will be turned into benefits, thus fulfilling the objectives of "energy-saving and emission reduction". In Europe, some researches and field tests have been carried out on the concept of untilizing thermal energy to heat surrounding buildings by embedding heat-absorbing pipes in the tunnel lining (Figure 2). Currently, this technology has been applied for trial in Austria's Jenbach High-speed Rail Tunnel (shield with segment lining) and in Germany's Fasanenhof Rail Tunnel (drill and blast with cast-in-place concrete lining) (Rehau, 2018).

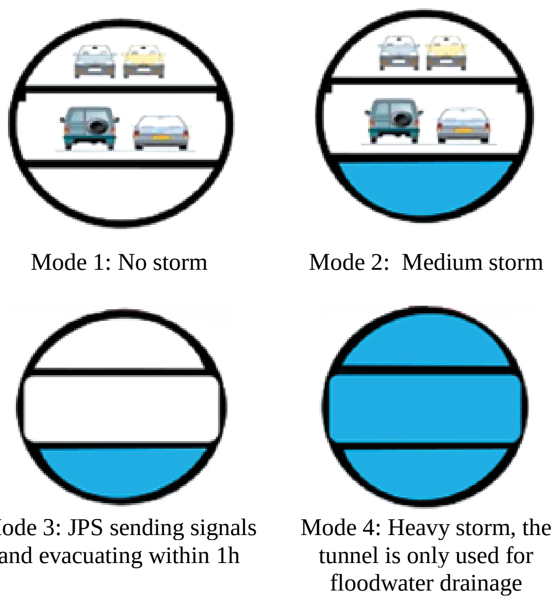

Figure 1 Operation Modes of SMART Tunnel, 2018

Besides the above, environmental issues during tunnel construction and operation also need to be taken into full consideration at the tunnel design phase, such as the utilization of mucks during construction, and the protection of groundwater during both construction and operation. Switzerland has gained some invaluable experience in dealing with these issues. For instance, the mucks coming from the 57km Gotthard Rail Base Tunnel were properly made use and disposed of, 33% being used as concrete aggregates, 66.3% being used in embankment, filling and re-cultivation, and only 0.7% being disposed in landfills as hazardous substances.

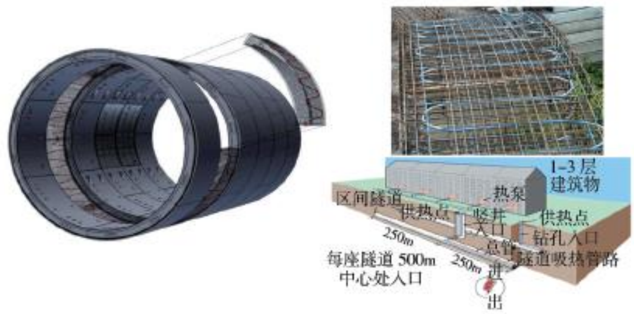

Figure 2 Layout of heat-absorbing pipes in segment lining (Alp Transit Gotthard AG, 2016)

3.2.2 The theory of tunnel support system

As for the tunnel support system, firstly, more researches should be conducted on the improvement of theory and design principle, so as to reduce the tunnel cost and ensure the tunnel safety at the same time. At present, China's support theory and design principle for hard rock tunnels are not without deficiencies. Especially in the application of shotcrete-bolt single-shell lining technology, there is a lack of complete and standardized guidelines for design, construction and quality acceptance. In fact, the overall stability of many hard rock tunnels is in a very good condition with only locally developed joints, and to use rock bolts and shotcrete for support will suffice under such circumstances. However, the support for these tunnels in China is always over-designed, thus resulting in unnecessary waste of money and time. Secondly, the researches on innovations in support materials are also of great importance. By means of adopting more efficient support materials, the tunnel support will be much easier and faster to build and made more durable. In recent years, structural fibres have been widely used in many countries to replace the traditional rebar in tunnel lining segments. At the early stage, steel fibres were the main support materials but nowadays polymer fibres are gaining a high rate of use. The application of these fibres in tunnel support markedly reduces the amount of high- strength rebar used, and the automated fibre adding devices make the lining segments more easier to produce and more quality-controllable. Although the R&D for tunnel support materials is not adequate at present, it is foreseeable that there will be more and better novel materials available before long. Last but not least, in addition to optimizing the current tunnel support theory, it is also practicable to develop some unprecedented new theories in the future. For instance, according to the laser-tunnelling method principle, the ground can be sintered by laser to form tunnel support. But, there is still a long way to go before these novel support theories are put into use.

3.2.3 High ground stress, high-pressure water and high geothermal temperature

Super-long tunnels at great depth are very likely to encounter the "three-high" challenges during construction. Although a lot of tunnels have been finally successfully completed despite such unfavourable conditions with some experiences worth learning, most of them were suffering from difficulties caused by the "three-highs" when they were being built. The most important thing for us to consider in depth is not whether tunnels can be completed under such conditions, but whether the design and construction methods adopted are the most appropriate ones that can keep the construction cost within a reasonable range. For instance, to deal with the large deformation in soft rock caused by high ground stress, the current support solution commonly used in China is a multi-layered support system by which almost all the deformations will be controlled to make the ground eventually stable. The disadvantages of this method are obvious. To construct such support structures is very inconvenient, time-consuming and costly. So, it is necessary to develop a more suitable control measure with only one working procedure to speed up the construction progress and reduce the cost. As for high-pressure water, the current solution is based on the principle of controlled drainage, that is, only a limited amount of high-pressure water will be drained, and the lining will partially bear the water pressure. Although this measure can reduce the water pressure on the lining, it will have some negative impact on the environment in the long run and cannot be implemented in sensitive areas. Therefore, a full-plugging solution for high-pressure water should be taken into consideration. According to this solution, the ground will be improved by grouting to bring into full play its capacity for bearing water pressure. The grouting technology under high- pressure water conditions is a key to the success of this solution, involving such aspects as grouting process, grouting materials, and the determination of an appropriate grouting scope for a certain water pressure through theoretical analysis and calculation. The last "high" refers to the high geothermal temperature and the principle to solve this problem is mainly to make a proper use of the geothermal temperature thus turning the harms caused by it into benefits. In Germany and Austria, there have been field tests of using the temperature difference between the inside and outside of the tunnel to provide heating or cooling. Adhering to this principle of turning harms into benefits, innovative solutions could also be developed in the future for super-long tunnels at great depth which are often subject to high geothermal temperature.

3.3 Countermeasures in construction - intelligent mechanized construction and innovative construction methods

A super-long tunnel project often has very long construction duration and involves a large amount of labour force. So, the development trend of tunnel construction should be directed to the intelligent mechanized tunnelling mainly represented by TBM, and efforts need to be made to improve both the mechanical performance of TBM and the intelligent system itself. As a rule, the intelligent system consists of the following three subsystems: 1) an intelligent geological prediction subsystem that can accurately make long-distance geological predictions in a short period of time so as to better deal with unfavourable geological conditions in advance; 2) an intelligent rapid construction subsystem that can not only automatically adjust tunnelling parameters on the basis of the geological conditions ahead to ensure a safe and rapid tunnelling, but also record and store various construction data (e.g. those for TBM tunnelling) to form construction big data; 3) an intelligent segment information subsystem that can detect the status of segments during construction and operation through sensors and test components embedded in them. While satisfying the needs of geological prediction, construction monitoring, and lining monitoring, these subsystems can also form big data and conduct analysis, thus continuously optimize the intelligent mechanical tunnelling system. Moreover, in the future, there might be more breakthroughs in the tunnelling methods, such as rock-breaking laser technology and rock-breaking high power waterjet technology among others. Currently, a great number of theoretical and experimental studies have been conducted on the use of laser for rock breaking. According to its theory, the laser can generate high temperature to melt and break rock, and the surrounding ground will be sintered into tunnel lining at the same time (Zhu etal, 2006, Dun *et al*, 2011). Theoretically, this laser method is feasible and has many advantages, such as only causing a small noise in static rock breaking and little disturbance to surrounding ground, etc. But there are still a lot of challenges to be overcome before it is put into practical use. In addition to the above, some scholars further proposed a composite rock-breaking laser method. By means of this method, the rock will be first heated by laser and then cooled by poured water, thus making the rock-breaking process faster and more economical. As for the rock-breaking waterjet technology (high power waterjet, 150MPa, 300kW), progress has been made in theoretical studies and experiments have been conducted in sandstone, schist, andesite, marble, granite with a good rock-breaking performance [JENG, 2004]. Together with blasting and mechanized methods, the application of these innovative tunnelling methods in the future will make the tunnel construction a more rapid, safe and economical process.

3.4 Intelligent operation, maintenance and disaster prevention

Generally, super-long mountainous tunnels at great depth are located far away from cities and, consequently their operation and maintenance require additional manpower. But the poor working conditions can hardly attract enough skilled operation and maintenance personnel to work there. So, at the design stage, more efforts need to be made to reduce the maintenance work for the tunnel with some parts being of zero maintenance design. Another concept that needs to be changed is related to the service life. Super-long mountainous tunnels at great depth should extend the service life from the current 100 or 120 years to 200 years (or even longer), for in fact, many tunnels built in the 19th century in Switzerland are still in use today. Besides the above, sensors or test components can be installed during construction to realize intelligent operation and maintenance with such functions as automatic diagnosis, automatic maintenance, and automatic alarm, etc. As for disaster prevention in super-long mountainous tunnels at great depth, countries around the world at present basically adopt the method of setting up a rescue station midway of the long tunnel to solve the problem of evacuation during fire hazards. From the author's point of view, investment for the rescue station is too high and not proportional to such a small probability event of fire hazards. So, it is necessary to develop some innovative concepts for disaster prevention and solve the problem by completely preventing the occurrence of fire hazards in advance rather than only focusing on evacuation and rescue after the fire hazards have occurred. In this way, it is probable that a more economical and efficient disaster prevention solution could be developed for super-long mountainous tunnels at great depth.

4. CONCLUSIONS

With the development of society, there will be more super-long mountainous tunnels at great depth to be built in the future, and the challenges confronted will concern not only technical problems, but also social, economic and environmental issues. In order to cope with these challenges, it is necessary to make corresponding measures in such aspects as investigation, design, construction and operation as follows:

(1) To greatly improve the accuracy and validity of tunnel investigation by updating investigation techniques and methods;
(2) To bring into full play the composite functions of tunnels and improve the project benefits by changing design concepts;
(3) To optimize tunnel support systems and reduce project cost on the basis of safety by improving the studies on tunnel support theory;
(4) To achieve the sustainable development objectives for tunnel projects by focusing on energy-saving and environmental protection in the design;
(5) To speed up the construction process, shorten construction duration and reduce labour intensity by implementing intelligent mechanized construction;
(6) To make the tunnel construction better, faster and more economical by applying innovative technologies in tunnel construction;
(7) To solve fire hazard problems in tunnel completely by developing innovative disaster prevention technology;

(8) To deal with maintenance challenges during operation by reducing maintenance needs and promoting intelligent maintenance.

5. REFERENCES

Alp Transit Gotthard AG. Project Data-Raw Construction Gotthard Base Tunnel [EB/OL]. [2016-06-01]. https://www.alptransit.ch/ fileadmin/dateien/media/zahlen_und_fakten/gbt_e.pdf.

Dun Miaomiao, Song Hongwei, Wang Chunmiao. Discussion on Tunnel Boring by Laser Beam[J]. Journal of China Three Gorges University (Natural Science Edition), 2011, 3(6):55-58.

JENG Fushu, HUANG Tsanghwei, STEFAN HILMERSSON. New Development of Waterjet Technology for Tunnel Excavation Purposes [J].Tunnelling and Underground Space Technology, 2004, (19): 438-439.

Operational Modes of the Smart Tunnel [EB/OL]. [2018-06-01].http://smarttunnel.com.my/opei,ational-modes.

Rehau. Geothermal Tunnel Lining [EB/OL]. [2018-06-01].http:"www.rehau.com/tunnelling.

Yuan Guiqin, Xiong Shengqing, Meng Qingmin, *et al*. Geophysical Prospecting Technique and Application Research [J]. Acta Geologica Sinica, 2011,11(11): 1744-1805.

Zhu Fengpan, Song Jianan, Li Yan. Techniques and Challenges of Excavating Rock Tunnels with Laser [J]. Construction Mechanization, 2006, (4):42-45.