DOI 10.15302/J-SSCAE-2017.06.007

Service Security of Underwater Tunnel Lining Structures and Corresponding Guarantee Countermeasures

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Abstract: This paper analyzes four aspects of the safety issues in tunnel lining structures: design and construction, environmental erosion, sudden natural disasters, and sudden accidents. A survey of underwater tunnels such as the Huangpu River Tunnel and the underground traffic tunnels in Shanghai was conducted, and the status quo of China's underwater tunnel lining structure was analyzed. Based on these analyses, countermeasures to guarantee the long-life security of underwater tunnel structures are being recommended considering tunnel construction, structural performance degradation, natural disasters, and accidents. These countermeasures are being proposed not only to effectively protect and ensure the service performance of the tunnel structures during their entire life cycle, but also can ensure the safe performance of the structure during its entire life cycle, even for long service times. This research can serve as a reference for enhancing the structural security of underwater tunnels and other major tunnels.

Keywords: underwater tunnels; service security; security guarantee countermeasures; long life; structural defects

1 Introduction

With the rapid development of the economy and society as well as the surge in demand for connectivity, the realistic demand of human beings to cross rivers, lakes, seas, and other water bodies is increasing gradually. Currently, three methods are used as the primary means to solve the problem of traffic barrier in a water area: ferry, bridge, and underwater tunnel [1–4]. The method that human beings cross a water barrier has gradually changed from the ferry mode to the land surface crossing of "crossing by water bridge" with the development of an underground connection mode, i.e., the "underwater tunnel." China will be in the period of high-speed development of the underwater tunnel construction in the near future and for a long time [5,6].

However, while building an underwater tunnel, the cracking and breakage of underwater tunnel structures occur occasionally during the construction and operation phase, thus causing significant challenges to the long-term safe service of underwater tunnels. Examples include the Sorrenberg gas tunnel in Switzerland during construction, the section of the Guangzhou Metro Line 1 and Line 2, the Shanghai Metro Line 7 and Line 9, and the Wuhan Yangtze River Tunnel [7]. Severe damages during construction and poor maintenance during the operation period can easily initiate further corrosion of reinforcement, corrosion of concrete, exfoliation, falling of blocks, etc., thus reducing the bearing safety of the structure and increasing the maintenance and maintenance cost. For example, the Shindagha cross harbor tunnel in Dubai was repaired 10 years after completion and the

Received date: November 17, 2017; **Revised date:** November 27, 2017

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Funding program: CAE Advisory Project "Strategic Studies on Safety of Major Structures of Transportation Infrastructure" (2015-XZ-28); National Key Research and Development Plan (2016YFC0802201); Project of National Natural Science Foundation of China (51578462)

Chinese version: Strategic Study of CAE 2017, 19 (6): 044–051

Cited item: He Chuan et al. Service Security of Underwater Tunnel Lining Structures and Corresponding Guarantee Countermeasures. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2017.06.007

cost of maintenance is twice the cost of its construction. Similar engineering cases include: Nearly 70% of the tunnels in Japan suffered from lining damage; cracking of shield tunnel segments of the Northern London underground tunnel after sulfuric acid erosion with insufficient operation; corrosion of reinforcing bars and joints in some sections of the Hong Kong subway and the cross-river tunnel of Dapu road, Shanghai after less than 20 years of operation; problems such as structural cracking, water leakage, and steel plate corrosion of the Kaohsiung harbor crossing, Taiwan after 20 years of operation; severe leakage and corrosion of the Ching Han subsea tunnel in Japan after 10 years of operation; reinforcement and initial support corrosion of the Xiamen subsea tunnel [8–10]. In general, various problems in underwater tunnels are closely related to the surrounding environment and the complex service environment of underwater tunnel engineering, as shown in Fig. 1, Fig. 2.

Currently, China is at the peak of underwater tunnel construction. In the context of such a large and rapid construction, it has become a severe challenge and a major task for the majority of scientific and technological workers approximately to ensure the safety of major underwater tunnel structures in the whole life cycle of design, construction, operation, maintenance, and even under the condition of long service life.

2 Safety problems of tunnel lining structure

During the tunnel construction and operation, because of poor design and construction, erosion of the environment, sudden natural disasters, and accidents, the emergence of different types and degrees of damages and problems have occurred in the tunnel lining structure.

2.1 Structural safety problems caused by complex geological conditions

Along with the tunnel engineering came the planning and construction process one after another with longer length, greater water pressure, more complex geological conditions, and worse construction conditions. Tunnel construction in China would transform from the existing urban soft soil environment to the

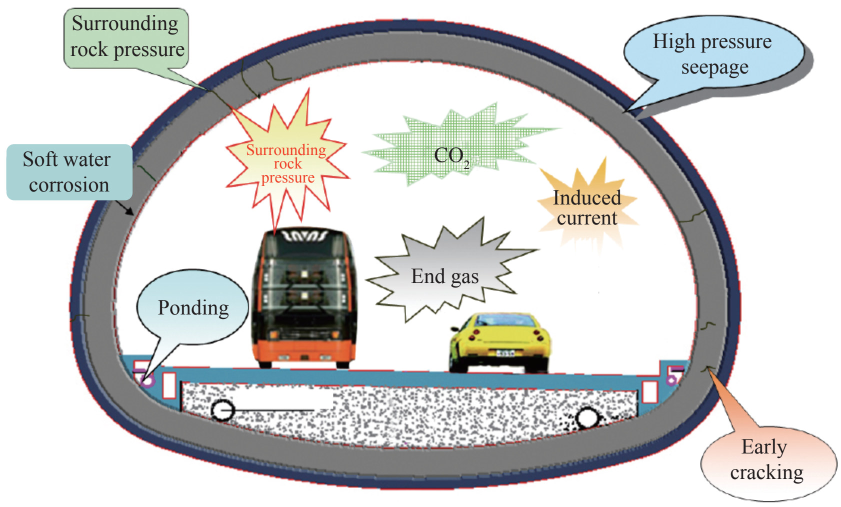


Fig. 1. Complex service environment for operating tunnels.

Fig. 2. Surrounding environment of underwater tunnel engineering.

complex geological environment of strong permeable formation, weak interlayer, weathering trough section, crossing the strata, solitary stone, and hard rock uplift, with uneven lithology between hard and soft strata. The physical and mechanical parameters of the surrounding rock are discrete, leading to the uneven distribution of load. Thus, the accurate evaluation and quantification of the envelope of the tunnel loads become more difficult. The safety design and construction of the tunnel structure are significantly affected. Examples include the following: the Xiamen West Passage Tunnel (6.33 km in length, passing through multiple weathering channels), the Xiamen South Passage Tunnel (13 km in length, local buried depth 100 m, through multiple strong weathering channels), the Zhoushan Continental Liandao Project Tunnel (17 km in length, deep sea water, long tunnel with presence of sensitive materials such as international waterways and optical cables), the Shantou Suai Bay Cross Harbor Tunnel (shield construction, 5.5 km in length, part of the section passes through the strata, and the design seismic intensity is up to eighth degree); the Qiongzhou Strait with a longer distance and worse construction conditions (the smallest sea area is 18.8 km in width, maximum water depth up to 100 m); Bohai Bay Strait (approximately 108 km); Taiwan Strait Passage Project (the shortest straight line distance is 120 km).

While the underwater tunnel passes through complex geological conditions and changeable environments, the long-term water pressure will be further increased. During the service period of the tunnel lining structure, it will bear higher water and soil loads. The characteristics of material nonlinearity and geometric nonlinearity are obvious. In addition, the natural scour of the river bed, the dynamic action of the sea water, and the accumulative actions of the traffic operation vibration can change the stress state of the tunnel structure with serious threats to the service safety of the tunnel. In a complex and changeable geological environment, owing to poor design and construction, improper selection of segments, poor posture control of shield machine, excessive grouting pressure, uneven jack thrust, inadequate consideration of soil and water load, etc., problems such as the staggering of segments, cracking of segments, dropping of segments, water leakage, and uneven settlement during the construction and operation period of the primary tunnel structure, as shown in Fig. 3.

2.2 Structural safety problems caused by environmental erosion

According to statistics, the number of subhealth tunnels in active service in China is approximately 20% to 30%. Similarly, according to statistics, more than 1600 highway tunnels exist in Japan, all of which suffer from material deterioration [8]. The long-term service safety of tunnels is seriously threatened by the continuous damage from the erosive environment.

In the normal service cycle, the tunnel lining structure often

(a) Stagger

(b) Water leakage

(c) Cracking near segment joint

(d) Joint failure

Fig. 3. Structural deteriorations caused by poor design and construction.

exists in a complex geotechnical environment. It will be subjected to the long-term interaction of both the loading environment (constant load of soil and water, fatigue load, instantaneous load) and the eroding environment (temperature and humidity of CO_2, chlorine salt, acid, alkali, etc.) with accelerated effects of combined loads, especially under a high water pressure, on the surrounding chloride erosion. Cumulative damages and the obvious deterioration of mechanical properties of the tunnel lining materials and members (Fig. 4) will not occur, such as concrete corrosion and steel bar corrosion that result in structural cracking, broken block, lining damage, etc. These can influence the bearing capacity of the lining structure and threaten the service safety of the structure [12].

2.3 Structural safety problems caused by sudden natural disasters

In general, because of the constraints of the surrounding strata, the vibration amplitude of underground structure is smaller than that of overground structure. Because the shield tunnel is a flexible multibody structure, it has a strong seismic performance [13]. However, under the condition of strong earthquakes, the earthquake damages of tunnel engineering is still prominent. For example, strong earthquakes such as the 1923 Kanto earthquake in Japan, the Kobe earthquake in 1995, and the Taiwan earthquake in 1999 have all caused serious earthquake damages to subway stations and interval tunnels [14]. On the May 12, 2008 Wenchuan earthquake, the earthquake damage characteristics of the shield section of some subways in Chengdu are obvious with damages to segments, spalling, slab staggering platforms, water leakage, etc. [15]. Although the earthquake damages above did not cause fatal damages to the primary structure of the tunnel, it will still affect the long-term durability of the tunnel structure.

2.4 Structural safety problems caused by sudden accidents and disasters

During the tunnel operation, owing to the influence of human factors and management, sudden accidents occur occasionally such as fire, train crash, truck collision, explosion, etc., coupled with the lack of operational health testing, monitoring, and structural maintenance, thus rendering it “ill in service,” with a reduced service length. Tunnel fire and explosions in expressways, train derailments, and impact problems in high-speed railway tunnels will inevitably lead to the deterioration of the tunnel lining structure, thereby affecting the stability and safety of the tunnel structure.

Currently, the number of underwater tunnel projects in China is the largest. The construction scale is the largest, the technical difficulty is the most complex, and the speed of development is the fastest, causing more problems in the structural design, construction and maintenance. The complexity of the problem is further increased. In addition, modern tunnel engineering is developing linearly, such as the super-large section, overburying depth, super-high water pressure, and super-long length. The major technical challenge is the method to ensure the system reliability and long-term safety of tunnel engineering in China.

3 Investigation on service status of underwater tunnel in a typical area

Based on underwater tunnel projects such as the Huangpu River Crossing Tunnel and the underground traffic tunnels in Shanghai (Fig. 5), a field research was conducted. The service status and primary problems of the existing underwater tunnel structures are analyzed.

From the results of the tunnel operation survey, owing to engineering geology, hydrogeology, surrounding environment and design, improper disposal during construction period, problems of varying degrees were found from the investigation of tunnels during service. This brings severe hidden danger to the tunnel during normal service, such as severe leakages in cross-river tunnels, obvious segment rupture and staggered table, side construction joint leakage, plugging hole leakage of incoming cable, breakage or leakage of segment joint, leakage of joint between

(a) Carbonation of concrete and corrosion of reinforcement (b) Concrete cracking and spalling

Fig. 4. Corrosion deterioration of tunnel lining structure.

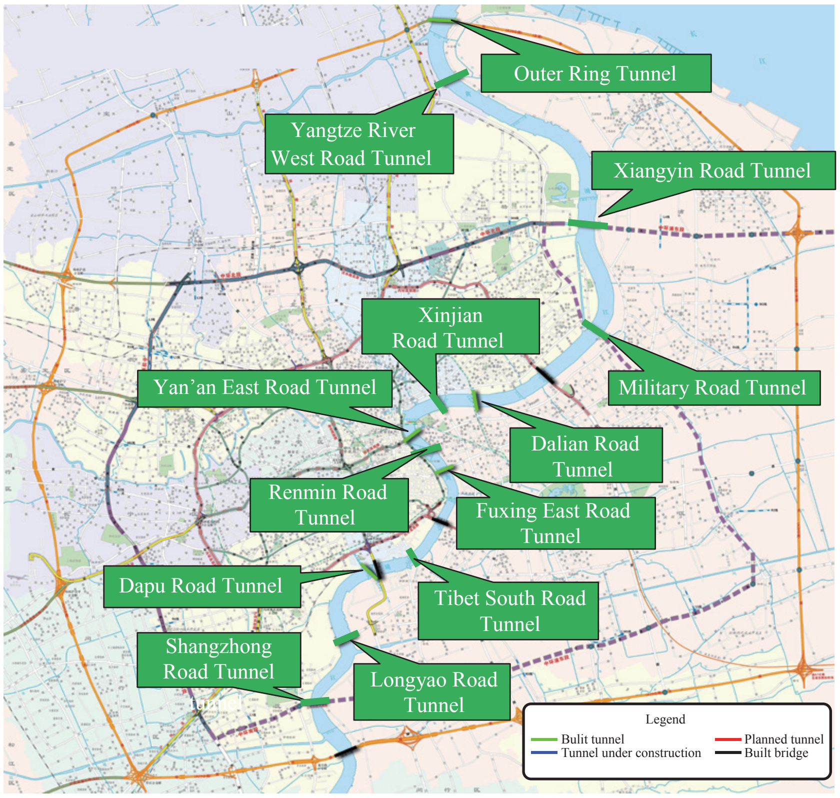


Fig. 5. Distribution map of underwater tunnel project in Shanghai area.
Completed tunnel: Outer Ring Tunnel, Xiangyin Road Tunnel, Dalian Road Tunnel, Bund Tourist Tunnel, Yan'an East Road Tunnel, Fuxing East Road Tunnel, Shangzhong Road Tunnel, Dapu Road Tunnel, Xinjian Road Tunnel, Renmin Road Tunnel, Military Road Tunnel, Longyao Road Tunnel, Dapu Road Tunnel (double line), Yangtze River West Road Tunnel, Tibet South Road Tunnel, Shanghai Yangtze River Tunnel; Planned tunnel: Yinxing Road Tunnel, Nenjiang Road Tunnel, Zhoujiazui Road Tunnel, Lujiabang Road Tunnel, Jiangpu Road Tunnel, Wanping Road Tunnel, Luoxiu Road Tunnel, Hongmei South Road Tunnel.

round tunnel and working well, circular tunnel lane plate crack, collision wall crack, oblique crack of post-cast slab, segment cracking, bituminous pavement, potholes, etc.

Among these, severe leakage, differential settlement increase in the tunnel structure, and sediment loss will cause structural load variations, thereby causing structural cracking or increase of original cracks that will accelerate structural damage and deterioration. Additionally, corrosive groundwater will aggravate the erosion of tunnel structure and internal facilities, increase durability damage of tunnel structure and cause the tunnel to be in service with a disease, reduce the reliability of the tunnel structure in service, and endanger the driving safety. Fig. 6 shows the uneven settlement and leakage of the tunnel structure.

4 Countermeasures and thoughts on long life safety guarantee of underwater tunnel structure

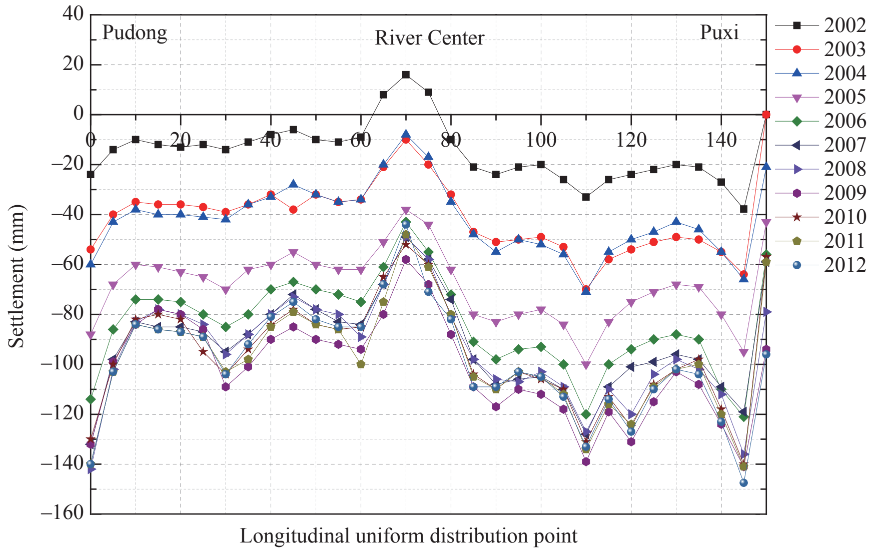
For the tunnel construction, the structure performance degradation, natural disasters, and sudden accident disaster are explored as safeguard countermeasures to ensure the service safety of the tunnel during the whole life cycle and for the requirement of long life.

4.1 Countermeasures of structural safety in tunnel construction

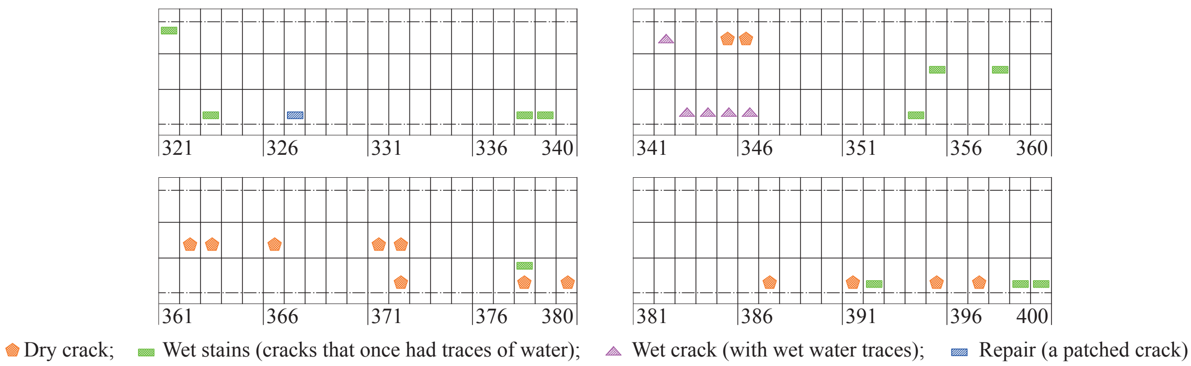
Currently, China is in the high-speed development stage of tunnel construction, where the number of underwater tunnels such as subway, high-speed railway, and power pipe corridor has increased sharply. The underwater survey, design load, mechanical construction, new materials, safety, and security are all facing major challenges.

(1) Promotion, application, and exploration of new survey methods. With the development of modern information technology and intelligence, the survey, testing and other methods combining macro control with micro tests are adopted in seismic reflection, transient electromagnetic method, logging, intra-hole TV, and other new surveying methods. Geological information are obtained, and formation parameters are modified to counter the limitation of traditional geological borehole exploration. Through the combination of geological analysis, engineering geophysical exploration, seismic methods, and geomagnetic methods, a joint solution is required for the advanced prediction of unfavorable geological structures in tunnels.

(2) The load theory of the tunnel structure is improved and



(a) Long-term uneven settlement of tunnel



(b) Longitudinal local expansion of tunnel leakage (number is for ring number)

Fig. 6. Uneven settlement and seepage of tunnel structure.

perfected. Currently, the analysis of common load calculation methods for the existing tunnel lining structures only considers the static constant load when they are designed with failure to carefully consider the load evolution during the entire construction process. For example, in a specific environment during the construction period, the structure may be in the most dangerous state. Its security risks are not fully and accurately controlled. The load theory of the existing tunnel should be perfected, and the load evolution in the whole process of construction should be emphasized, considering the load during the construction period, the special load in the operation period, and the influence of the "load reduction effect" after the structural damage.

(3) Development of integrated and full life design method for tunnel engineering. A comprehensive consideration of environmental conditions of tunnel construction, technical standards, use function, disaster prevention and rescue, construction technology and safety risks, etc. is required. The integrated design of a tunnel considering many types of factors is performed. Using the idea of "optimum system" and "full life cost" and the analysis method of lifetime variability for the full life design of the tunnel structure, the overall structural performance (safety, applicability, durability, economy, beauty, environmental protection, etc.) of the tunnel is optimized throughout its life cycle.

(4) Mechanization, and information construction promotion. Currently, the tunnel construction methods in China have developed from the traditional drilling and blasting method, the open excavation method, and the shield tunneling method to the direction of combined drilling and blasting, and open excavation. With the continuous improvement in manufacturing in China, as well as the accumulation of construction experience and technology, such as subway shield, railway tunnel, etc., China already has the technical ability of using shield machines and roadheaders to build a complex tunnel project. With the continuous development of underground resources, the development of deep underground space in the city, the construction of underground city, and the underground integrated pipe gallery, the mechanization and information construction technology will certainly be developed in depth. Priority should be given to creating favorable conditions for the development of underground space.

(5) Breakthrough in the safety evaluation system method of

major tunnel structures. The evaluation method of tunnel structure safety state should be studied. A risk assessment model should be formed and risk levels should be classified. The tunnel structural safety evaluation system should be established with regional pertinence, geological condition pertinence, and structural pertinence.

(6) An intelligent evaluation and early-warning software system for developing the safety and health state of the tunnel structure. The intelligent evaluation and early-warning software system of the tunnel structure safety and health condition is researched and developed. The intelligent evaluation of safety and health of the tunnel structure can be realized. The structure safety can be predicted and forewarned.

4.2 Countermeasures of structural safety in structural performance degradation

To change the mindset of "attaching importance to construction rather than maintenance" in the engineering field, in which the deterioration of tunnel structure and the adverse effect of aging on the long-term safety and durability of the tunnel structure are neglected. Thus, the steps required are changing passive maintenance to active control and active prevention, and changing passive maintenance to active control and active prevention from the analysis of structure. The life safety and economic cost with the urgent need for a mindset change, proceeding from the aspects of reliability and durability design, quality control technology, comprehensive protection system, and whole life corrosion prevention, etc., is required for the prevention and control of major tunnel structure deterioration, aging, and other safety risks.

(1) The structural performance of a major tunnel during its initial and operation period is studied. In the whole process of tunnel construction and operation, the tunnel structure performance will have different types of response with different internal and external environments. In the early stages of construction, the quantification of load and structure is more accurate. It is more accurate to judge its structure and performance. However, because of the uncertainty of load, randomness, and the persistence of external action, it is a great challenge to evaluate the performance of the service tunnel structure accurately. Therefore, theoretical analyses, laboratory tests, and numerical simulations should be used, combined with the site test results of representative points, lines, and regional tunnels. A method and a theoretical system for evaluating the lifetime performance of major tunnel structures are established.

(2) Accelerate the revision of quantitative design, and the reliability metrics for the durability design specifications. Based on reliability theory, the characteristics of geotechnical environment, corrosion environment, and service operating environment of the tunnel structure are considered synthetically. A comprehensive quantitative design theory of the tunnel structure durability considering the influence of multifactor coupling is constructed to formulate the design code for the durability of the tunnel structure from the national and industry supervision level. From the pre-feasibility study and design stage, the long-term safety and durability of the tunnel structure should be focused more.

(3) Establish the quality control standard and protection system of the tunnel structure life cycle. The construction quality control standard and monitoring of tunnel structure during the construction period should be strengthened. The key parameters of durability of key structures, such as the water–cement ratio of concrete, thickness of concrete cover, and chloride diffusion coefficient of concrete, are primarily controlled for the preparation of high durability concrete; using the life cost analysis theory, the corrosion prevention scheme design of the tunnel structure is performed to increase the structural safety reserve.

(4) Strengthen the research of new materials, new anti-corrosion technology, and information durability monitoring technology. The research and development, and the application of new durability materials should be strengthened; perform new technology and its research on concrete anti-corrosion, reinforcement active anti-corrosion, etc.; the research and development of the whole life durability monitoring technology and monitoring system should be strengthened; the rapid application of new achievements should be promoted by combining production, education, and research.

4.3 Countermeasures of tunnel structure safety guarantee under the action of natural disaster

As an underground structure, the tunnel has good seismic performance. In general, the earthquake damage is not as serious as the ground structure damage. However, in terms of difficulty, economy, time limit, etc., the earthquake damage treatment of the ground buildings is at a disadvantage compared with that of the ground buildings, especially the repair and reconstruction after tunnel damage. Therefore, it is very important to guarantee the earthquake safety of tunnel engineering, especially that of the major tunnel.

(1) The core goal of the tunnel structure safety guarantee system under an earthquake is established. The tunnel structure must be ensured to not be damaged, even slightly, under the earthquake intensity, and can be continued to use with a little repair; after the earthquake, the key line tunnel can restore the function of the original design by means of repair. The mechanisms are to be established and improved for the identification, assessment, and emergency response of post-earthquake tunnel damages, such that the seismic response and damage characteristics of the tunnel can be quickly fed back, evaluated, and implemented in the rescue and disaster relief and post-disaster reconstruction work. A complete system of evaluation standards, technical measures, and schemes for post-earthquake tunnel

repair and reconstruction should be formed. It will provide a reference for the repair or reconstruction of the tunnel structure after an earthquake, as well as the scheme and technology for repairing or reconstructing the tunnel structure after an earthquake.

(2) Seismic planning, design, and construction of tunnels. For the tunnel structure in the planning and construction phases, the anti-seismic design of the tunnel structure should be performed according to the specifications from the planning, from the design to the construction stage. The earthquake disaster feedback and emergency plan of the tunnel after the earthquake are fully considered. In the planning and design stages, China's geological and topographic conditions should be fully considered to avoid the constructing the tunnel in a high-intensity seismic area, active fault zone, unstable slope, and other locations. From the site, the seismic intensity and other aspects of the program comparison should be obtained. The research on special seismic designs should be performed for high-intensity seismic areas, where important tunnel engineering through the special geological conditions of the tunnel is to be utilized.

(3) Seismic fortification technology. In the area of seismic fortification technology, great efforts have been conducted to develop the measures, materials, and technologies suitable for earthquake resistance and the damping of tunnel structures; the anti-seismic technology of underground structures is extended from the theoretical stage to the stage of extensive application, and gradually forms the tunnel seismic absorption technology system for shallow buried, partial pressure, fault, and other seismic-vulnerable geological sections.

4.4 Safety guarantee countermeasures of tunnel structure under the action of sudden accidents and disasters

The tunnel is faced with explosions, fires, vehicle impacts, and other disasters, which affect the structure safety.

(1) Accelerate the establishment and improvement of the safety and security system for the major tunnel structures. Based on the risk theory, considering the tunnel operating environment, regional economy, national strategy and other factors, the public safety, transportation, construction, and other industries are to be coordinated to extensively absorb the opinions in design, construction, operation, scientific research, equipment, materials, and other institutions and units. The improvement in the system safety and the security standards and norms for tunnel structures should be accelerated.

(2) Prevention of major hazard sources, such as dangerous chemicals, vehicles, etc. During the tunnel operation, liquefied petroleum gas vehicles, heavy trucks, and other major risk sources are important risk sources that may cause the tunnel damages. We should strengthen the use of new technologies, laws, regulations, and other measures to prohibit dangerous chemical transporting vehicles from entering the major tunnel structure.

(3) Strengthen the damage mechanism of the tunnel, protection technology, equipment, facilities, and scientific research of new materials. The damage mechanism and mechanical behavior of major tunnel structures under the action of heavy fires, explosions, and train impacts are studied. The structural safety guarantee technology of the existing deterioration and aging structures under sudden disasters (explosion, fire, etc.) is studied. To strengthen the research and development of early warning, detection, protection technology, and equipment for major disasters, the development of new fire-proof coatings, fire-proof panels, and other tunnel structure safety protection materials are to be performed.

5 Conclusions

Currently, China is the country with the largest construction scale, the most complicated technology, and the fastest development rate of underwater tunnel projects. The problems in engineering construction, operation, and maintenance are increasing. In addition, the complexity of the problem is gradually expanding along with the development of modern tunnel engineering in the direction of super-large sections, super-buried depths, ultra-high water pressures, and super-long distances. The method to ensure the system reliability and long-term safety of a large number of underwater tunnel projects built in China is a severe challenge to the majority of scientific and technological workers.

In its entire life cycle, the underwater tunnel is under the complex soil and water load environment, the internal operation environment, and the internal and external changeable erosion environment under the long-term interaction coupling action. The performance of the tunnel structures is continuously and progressively damaged and degraded. Hence, for a large number of underwater tunnel projects built in the short term, the emphasis of the current scientific research mission is to establish a plan to maintain the performance of the tunnel structure in the whole life cycle to ensure the structural safety of the underwater tunnel accurately, reasonably, and controllably. Based on the safety guarantee of the whole life cycle, scientific planning and a step-by-step implementation are performed to realize the "life extension project" of the underwater tunnel structure to extend the service life of the important underwater tunnel structure that are already built and those that are to be built, in order to implement the long life security strategy of the underwater tunnel structure.

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