Problems of durability and reinforcement measures for underground structures in China

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Abstract: In this paper, the bolt- and cable-supported structures mainly refer to anchored cables, anchored bolts, soil nails and other commonly used reinforcing and supporting structures in geotechnical engineering, as well as reinforced soil structures in permanent works. They are often used in combination, or formed into composite bolt- and cable-supported structures, with other traditional construction methods and relevant measures. Distinct characteristics of such structures are that they are most often invisible, exposed to more severe underground corrosive environments and with strict durability requirements. A number of serious durability problems of underground structures are discussed and major achievements and advances in China and abroad in terms of durability and reinforcement measures for underground structures are reviewed, followed by comprehensive analyses. Some suggestions for those problems are put forward.

Key words: underground structures; durability; service life; reinforcement measures

1 Introduction

Durability and service life of underground structures are significantly diversified at the varied material properties, construction qualities, corrosive environments, etc. All underground structures are associated with problems of durability and service life from the day when they are built. However, because of many complex factors involved and long testing cycles, no systematic study thereof has ever been reported in China. If the problems of durability and service life remain unsolved, serious accidents of unsafe operation may occur at unpredictable time to threaten safety.

In recent years, there have been enormous studies on durability and service life of above-ground concrete structures. Core issues of relative researches include multi-factor coupled corrosion, accuracy of accelerated test results, effective methods for degradation analysis, etc. However, relevant results are rarely reported in China with regard to durability and service life of underground structures. For this purpose, and systematic and in-depth studies of durability and service life of underground structures, under different operative conditions, corrosive environments and coupling conditions, should be conducted by combining accelerated corrosion test with theoretical analysis.

For traditional construction technology and method, underground structures basically involve bolt- and cable-supported structures for temporary support, and reinforced concrete structures of secondary lining for permanent support. The former is mainly considered to bear static and dynamic loads, while the latter is to provide necessary safety reserves. Two conditions can be presented as follows: (1) the bolt-supported structures are usually exposed to more severe corrosive environments, and (2) both bolt- and cable-supported structures are composed of the same or similar materials, i.e. underground shotcrete, reinforced concrete, bolt bars, inner surface bars or lining structure bars. Thus, research results of the two types of reinforcement structures can provide references for each other. If a
good solution is found for one, problems met by the other may also be solved. Therefore, in order to simplify relevant problems and to focus on the main problems, the durability problems of bolt- and cable-supported structures should be the research priorities.

The reinforcing effects and mechanism, relevant mathematical formulations for coupled corrosion, and the methods for degradation analysis of underground structures are the major technical bottlenecks. With the requirements of current design codes on anchored cables in China, if the problems of durability, service life and reinforcement measures of bolt- and cable-supported structures, which mainly serve as bearing structures, are rectified, corresponding problems for secondary permanent lining structures used for safety reserves will be solved readily. Thus, it would be possible to provide reliable predictions and suggestions for service life of underground structures in China.

2 Durability problems of underground structures

In China, numerous anchored bolts have been employed in geotechnical engineering since 1970s, and many types of anchored cables have been adopted since 1980s. Up to now, hundreds of millions of soil nails have also been used in civil engineering since 1990s. The technical advance and economical efficiency provided by the cables (bolts) and cable-supported structures are significant and obvious [1, 2]. However, the issues of life span of such a structure as a permanent support in engineering, and those of the service life and the possibility of unpredictable failure to endanger the whole project cannot be resolved accurately at present. The in-depth research on solving those problems should be continued.

In 1986, the International Federation for Prestressing (IFP) investigated 35 accidents of anchored cable fractures due to corrosion, among which 69% were permanent anchored cables and 31% were temporary ones. The results showed that most fracturing positions of anchored cable were close to the heads but within the free sections. The reason was that the free sections were not coated by mortar, and that anchorage device damaged the cable bodies close to the anchor heads during anchor tensioning. As for a Pakistan energy storage project, hydrogen brittle fracture in the free section of an anchored cable was found, which caused the outer anchor head to fly out and almost induced an accident.

In 1933–1934, A. Coyne adopted anti-corrosion measures for 34 prestressed anchored cables with a preload of 10 000 kN for the reinforcement of Cheurfa Dam. In 1965, a normal inspection for the dam found that the prestress loss of the anchored cables reached 9%, which was considered to be associated with loosing and corrosion of anchor head.

In 1962, M. Romanoff observed the corrosion of steel columns buried in soils. The major corroded part was found to be the section buried in backfill, and there was almost no corrosion in the undisturbed soil section. It may be explained that backfill soil was comparatively loose and contained plenty of oxygen. According to the observation, if clean carbon steel without any protection was placed in a humid tunnel for one day, there would be distinct rusty spots; if for three days, there would be continuous rusty scales.

Among the prestressed anchored cables used in Meishan reservoir, Anhui Province, China, steel strands of 3 cables were found ruptured (with hydrogen brittleness) due to stress corrosion after 6–8 years of operation. For anchored bolts used in Fengying coal mine of Jiaozuo City, Henan Province, China, after an 8-year service period, positions coated by mortar almost had no rust; but for positions not or not well coated by mortar, the greatest depth of corrosion pit was 0.65 mm, with a corrosion rate of 0.041 mm per year. With regard to anchored bolts in Jiaodong coal mine of Jiaozuo City, the minimum grip thickness was only 1–2 mm due to misalignment during installation. After a service period of 12 years, surface neutralization depth was about 0.8 mm and there was rust on the surface of bolts, but positions where grip thickness was greater than 3 mm had no rust.

For slit rod-and-wedge-type bolts in the Fourth Coal Mine of Hebi Coal Mining Bureau, China, after 28 years of service, the depths of corrosion pits were 0.4–1.5 mm for anchored bolts No.2 and 5 (with water leakage) and 0.05–0.10 mm for anchored bolts No.1, 3 and 4 (without water leakage).

In a copper mine in China, bolts coated with ordinary sulfate cement mortar were adopted. Two years later, due to the severe corrosive environments, the surface mortar became loose, like a soybean curb residue. Anchor-shotcrete lining was adopted for the
Yangyao River Tunnel No.1 of Chengdu-Kunming Railway Line. After 10 years of service, the surface was corroded into a white loose layer about 1 cm in thickness.

Preliminary study of Luoyang Institute of Hydraulic Engineering and Technology (LIHET), China, indicated that service life of high quality mortar bolts was 75–169 years. However, the service life of mortar bolts with poor construction quality was reduced to 50 years. Moreover, the service life of mortar bolts with poor construction quality in harsh environments was only 20–25 years.

In total, the issues about the safety and durability of bolt- and cable-supported structures are frequently encountered in engineering practice and should be given more attention. The solutions of durability problems, service life predications and reinforcing countermeasures of bolt- and cable-supported structures normally have two aspects of significance:

1. Quantitative control can be realized in both the design and the construction of currently dominant reinforcing and supporting.

2. Reliable predictions to the service life of relevant structures, corresponding reinforcing treatments and reinforcing countermeasures in major projects should be considered.

3 Issues of durability and reinforcement measures of underground structures in China

Since the New Austrian Tunneling Method (NATM) was proposed in 1963, it has been widely accepted in various engineering fields. At the same time, bolt- and cable-supported structures have been employed in numerous rail and road tunnels, underground powerhouses, high rock slopes, harbor bank slopes, bridge piers and culverts, etc. Since 1980, rail tunnels built with the NATM have accounted for about 10% of the total tunnel length in China [3]. In addition, these supporting structures in underground works (even in composite tunnel linings) were all designed as the major bearing structures. Bolt- and cable-supported structures are designed to bear dynamic and static loads during and after construction, while secondary permanent lining structures basically provide safety reserves. It is clear that the failure of a bolt- and cable-supported structures will induce the failure of the whole project.

At the end of the 1980s and the beginning of the 1990s, corrosion prevention for hydraulic steel gates and applications of epoxy coating for corrosion prevention in hydraulic engineering were employed. In recent years, Chinese scholars in the field of civil engineering gave great importance to the issues of safety and durability in engineering. Since the proportion of structural accidents caused by insufficient durability of civil structures was much higher than that due to insufficient safety in design, these predictions and warnings were urgently needed.

In order to improve basic research on durability of support structures, the State Science and Technology Commission of China (SSTCC) organized a National Program on Key Basic Research Projects (Climbing Program B) in 1995.

Liu [1] conducted a systematic study on safety and durability of structures with “three life stages” as the main route, based on several typical structures. Preliminary results, including the prediction model for concrete freeze-thaw damage and the prediction model for corrosion of reinforcement in concrete under atmospheric environment, were achieved. This study approximately represents the current research level in China.

Yao et al. [4] carried out an in-depth study on the resistance to alkali-aggregate reaction, durability and safety of concrete structures, which was mainly focused on alkali-aggregate reaction, corrosion, freezing and thawing, reinforcement corrosion and other factors affecting the durability of concrete structures.

On November 17 and 18, 2001, the Division of Civil Hydraulic and Architecture Engineering, Chinese Academy of Engineering (CAE) held an engineering technology forum on “safety and durability of civil structural engineering” in Beijing, which reflected the importance to the issue of engineering durability.

However, corrosive conditions involved in the above studies are different from those of bolt- and cable-supported structures. Service life of bolts and cables depends on their durability, and the largest threat to service life comes from corrosion. Environmental factors causing corrosion to bolts and cables basically include the properties of rocks and soils, groundwater, bimetallic action and stray current in strata. Under certain conditions, chloride and sulfate in rocks and soils may cause corrosion to bolts and cables. Currently, prestress of some anchored cables has exceeded 10 000 kN or more.
Studies showed that corrosion rate increased at time under stresses close to the yield limit of an anchored bolt. A tensile strength test was conducted for bolts in 90 days. The results show that the loss of bearing capacity is about 5%, which indicates that the stress corrosion problem cannot be ignored.

If a project is constructed without proper design and installation of bolt and cable supports, potential defects would be developed on them. After installation, anchored bolts and cables are normally grouted with cement mortar or pure cement paste. This kind of gel medium, with high cement content (especially high-early-strength cement or ultra high-early-strength cement) and low (or without) sand content, is less corrosion-resistant compared with concrete. Moreover, the coating is thin and the water-cement ratio is high (0.6–0.7). In some cases, arbitrary water-cement ratio is adopted for the convenience of grouting. Non-pressure (gravity) or low-pressure grouting leads to insufficient grouting of anchored cables and bolts and serious air shrinkage. Thus, the minimum cover thickness cannot be guaranteed, and some local positions cannot be coated perfectly by mortar.

For alignment supports of bolt- and cable-supported structures in China, steel bar supports (anchored bolts, soil nails) or support rings (anchored cables) have been used to solve the problem of bolt alignment to increase the grip force. Anchored cables and bolts outside the supports (or support rings) are possible to touch the wall of anchoring hole partially under gravity, indicating that after mortar is grouted, cover thickness of these positions may be greatly reduced, sometimes even to zero. Studies indicate that under such conditions, larger touching area of the hole wall will cause greater corrosion area and depth.

Another factor affecting the durability of anchored cables and bolts is the varied geological conditions. Bolt- and cable-supported structures may be adopted in a closed humid environment, or immersed permanently or in a wet/dry alternative environment. Preliminary studies suggest that: (1) average corrosion rate of anchored bolts soaked permanently in weak acid solutions is twice or more that in neutral solutions or weak alkaline solutions; (2) corrosion rate of anchored bolts in a closed environment with a relative air humidity of 100% is about 20% of those permanently soaked or those in a wet/dry alternative environments; and (3) regardless of testing environments, amount of corrosion of anchored bolts increases with time, but corrosion rate decreases with time. Since bolt- and cable-supported structures are buried works, accurate prediction for their lifetime is more difficult than that for concrete structures at surface.

Above analysis indicates that the issues of corrosion and durability of bolt- and cable-supported structures are complex and different from those of common concrete structures at surface.

At the present, the major achievements in service life and protective countermeasures of bolt- and cable-supported structures in China can be listed as follows:

(1) From July 1985 to July 1987, LIHET carried out a preliminary investigation on service life of anchored bolts and explored corrosion effects on mortared anchored bolts. Certain favorable results were achieved [5].

(2) In 1996–1997, a research on corrosion effects and mechanism of cement mortar in underground works was conducted by LIHET. A 720-day corrosion test was carried out with 516 test pieces. Based on the testing results, the development trend for strength loss rate of cement mortar in corrosive environments was predicted [6]. Given the concentrations of corrosive media in corrosive environments and limit values of strength loss rate, duration of cement mortar against corrosion in underground works can be calculated.

(3) Bolt- and cable-supported structures have been constructed in a variety of geological conditions in China for the last 20–40 years [7], with few technical standards on the durability, service life, design life and protective countermeasures. A national standard “Technical specification for design and construction of prestressed anchored cables in geotechnical engineering” (TSDCPACGE) was compiled by LIHET in 1999, based on long-term experiences in development, design and construction of prestressed anchored cables. In the TSDCPACGE, a chapter was especially prepared for the corrosion of prestressed anchored cables.

(4) During 2004–2006, LIHET conducted a study of durability, service life and protective countermeasures of anchored bolts and cables (a project supported by the National Natural Science Foundation of China), in which effects and mechanism of coupled corrosion were preliminarily explored. After that, another study on durability of bolt- and cable-supported structures was supported
by the National Natural Science Foundation of China. Details on its progress are not available at present.

The above studies on the durability of bolt- and cable-supported structures have the following characteristics:

1. Observational check is not systematic or typical.
2. There were many tests considering only a single factor, but tests considering coupled corrosion factors were rarely reported.
3. Service life prediction can only be conducted under limited conditions.
4. Further studies on effects and mechanism of coupled corrosion are still needed.
5. Methodology for degradation analysis of accelerated tests needs to be established.
6. The study on reinforcement measures for underground structures in terms of durability is needed.

4 Issues of durability and reinforcement measures of underground structures abroad

In some countries or regions, especially those developed ones such as USA, UK, France and Australia, the studies of durability of bolt- and cable-supported structures are paid closer attention to, and relevant research started earlier than that in China. It can be explained in terms of their earlier large-scale infrastructure construction, earlier application of advanced technologies, and earlier exposure to relevant problems, as well as their economic strength and abundant input in scientific research [8–12].

Metal anchored bolts were first used in UK in 1872. From 1900 to the First World War, full-length wood anchored bolts were adopted in various types of mines. In 1973, some tunnels exploited before the First World War were discovered by chance in a coal mine in Berkeley County, West Virginia, USA. It was found that full-length wood anchored bolts were abundantly used in these old tunnels. Several decades later, both the anchored bolts and tunnel roofs were still in good conditions. The first recorded systematic adoption of metal anchored bolts as supporting structures was in St. Joseph Lead Ore in 1927. Valuable literatures about the use of anchored bolts for supporting systems were not reported in engineering field until 1945. Since then, anchored bolt support has been spread rapidly. During 1945–1957, a total of 500 000 anchored bolts were used each year in all mines of the National Coal Board (NCB), UK. In 1971, 55–65 million anchored bolts were adopted in UK.

USA started to use anchored bolt supports in the 1910s. In 1912, roof bolt supports were first adopted by Alfred Busch at Friedens Coal Mine in Pennsylvania. During 1915–1920, anchored bolt supports were applied to metal mines in USA, and were further developed and spread as well. After 1940, anchored bolt supports were extensively adopted in underground coal mines. According to the record, anchored bolt supports were comprehensively applied in USA during 1947–1949. In 1951, more than 500 construction sites used anchored bolt supports. At that time, around 2.6 million anchored bolts were used in each month.

In the latter half of the 1950s, the research and use of anchored bolt supports began in other countries or regions. About 5.7 million anchored bolts were used in France in 1969.

Anchoring technology was introduced to Japan in 1950. Because of the complex geological conditions and insufficient knowledge and experience, the anchoring technology was not popularized in Japan in the following 22 years. In 1971, metal anchored bolts were in use in 32 metal mines in Japan, and anchored bolt supports were adopted in 21 tunnels construction and other civil engineering works.

In 1966, Skozynski Mineral Exploration Institute of Former Soviet Union developed a new type of thread anchored bolt. Due to its outstanding performance, a thread rolling mill with an annual capacity of 180 000 threaded steel anchored bolts was installed in the machine repair shop of its associated enterprises. In 1970, anchored bolt supports were widely applied to the coal industry, and a tunnel with total length of 713 km was supported by anchored bolts in Kuhlbas Mining Area in the same year.

During 1960–1970, inspired by anchored bolt supports and reports of the United States Bureau of Mines, a local test in the New South Wales Coal Mine in Australia was conducted, which aroused wide interests. Thereafter, about 1.3 million anchored bolts were used annually in Australia.

8 210 anchored bolts were adopted in each month in Ziemowit Coal Mine, Poland.

The first record about anchored cables was in 1918 (Sylixian Mine), without prestress applied. In 1934,
prestressed anchored cables were used to increase the height of the Cheurfa Dam in Algeria, which was regarded as one of the earliest engineering cases of prestressed anchored cable. Prestressed anchored cables, which were developed following anchored bolts, were mainly used in important or major permanent projects, especially when conventional anchored bolts could not provide enough anchoring force for design, or when the space was strictly restricted in underground works. Huge quantity of anchored cables has been applied to various types of engineering fields at present, although the quantity may be smaller than that of anchored bolts.

Soil nailing technology was developed on the basis of anchoring technology. Soil nailing came into being in the 1970s, developed in the 1980s, and became popular in the 1990s, about 15 years earlier than that in China. The applied quantity of soil nailing was no less than that of anchored bolts.

Worldwide application of bolt- and cable-supported structures was closely related to the suspension theory proposed by Louis A. Panek et al. in 1952, the composite beam theory by Jacobi et al., and particularly, the new Austrian tunneling method by T. L. V. Rabcewicz in 1955. None of the three theories suggests using bolt- and cable-supported structures under unfavorable geological conditions.

Although great success has been achieved by adopting the advanced support technologies, many problems have been found due to the failure to attain the designed life of bolt- and cable-supported structures, which have aroused great attention worldwide. At the end of the 1970s and the beginning of the 1980s, technical specifications for anchored bolts in various geological environments and technical regulations for anchored cables were issued consequently in France, Switzerland, Czech and Australia. In the 1990s, technical drafts for soil nails were formulated. In these technical standards, protections for bolt and cable-supported structures in corrosive environments were taken into full consideration, and strict requirements on relevant design and construction were specified. In 1975, R. Schach et al. published “Rock bolting: a practical handbook” (reprinted in 1979) and a series of books about soil anchors and rock anchors were published in Germany. For instance, “Foundation in tension ground anchors” edited by T. H. Hanna in 1982 and “Professional users handbook for rock bolting” edited by B. Stillborg gave clear requirements on comprehensive corrosion prevention for tension anchors (cables) and rock bolts in foundation works. During 1974–1981, the American Society for Testing and Materials (ASTM) published a book series, dealing specifically with the effects of various kinds of corrosions on metal materials, above-ground and underground, which covered natural environment corrosion, stress corrosion, corrosion prevention measures, etc. M. J. Turer conducted a systematic experimental investigation on permanent corrosion-resistant soil nailing wall, and developed a new type of material polyester mesh belt, which was economical, corrosion-resistant with high strength performance, to replace steel soil nails. But there was no detailed data about service life of this soil nail material, which was simply considered as a kind of “permanent” material. R. Eligshausen and H. Spieth studied the properties of connecting structures of inserted rebar, and pointed out that if the eyelet of this kind of steel bar was not clean, or if the bonding was not reliable, its service life would be reduced from 100 to 75 years. Their calculation basis and calculation details were not available.

During 1989–1996, the USA Federal Highway Administration (FHWA) published several handbooks, which introduced new technologies for design, construction and monitoring of anchored bolts and soil nailing walls in USA and Western Europe, and provided detailed provisions for permanent bolts and soil nails. It was stipulated that service life of a permanent soil nailing system was 75–100 years and that of a temporary soil nailing system was 1.5–3 years. The long-term work performance of soil nailing walls was confirmed in Europe and USA after a 20-year service period (1976–1996). In addition, it was pointed out that specific studies on corrosion prevention and testing methods should be emphasized:

(1) If soil nails were used in permanent road constructions, self-drilling soil nails were not applicable to corrosive media, and coatings including galvanization, epoxy and metal powder should be regarded as improper corrosion prevention measures.

(2) Corrosion prevention should be considered via reinforcement consumption, i.e. 125%–150% of the designed diameter of reinforcement.

(3) Some schemes are conflicted with popular views and practices in China and abroad, but are effective in practical engineering reinforcement, which are worthy of consideration and investigation.

In total, studies and applications of the safety, durability and reinforcement measures to underground structures abroad have the following features:
(1) Problems of durability and measures were considered earlier in other countries or regions than those in China. Studies were carried out immediately after relevant problems were found, including field investigations, indoor simulations, development of corrosion detection devices and investigation of preventive measures. Research findings were compiled into relevant technical standards ready for application.

(2) Studies of these problems were not individual behaviors of experts, or enterprise behaviors of financial groups, but were supported by various scientific foundations, under the guidance of relevant government bureaus.

(3) Some problems have not been completely solved, including the effects and mechanism of coupled corrosion and the methods for degradation analysis of accelerated tests, etc.

(4) There were few reports on reinforcement measures, functional parameters and testing and evaluation methods, etc., for durability problems of underground structures.

(5) With regard to the application of reinforcement measures for the durability problems of underground structures, no report has been found yet.

5 Analysis of durability problems of underground structures

Since there are still many problems to be addressed for the safety and durability of bolt- and cable-supported structures, scientific investigations and analysis should be carried out. Studies on service life and reinforcement measures of bolt- and cable-supported structures should be conducted on this basis to seek favorable solutions. The studies of safety and durability of bolt- and cable-supported structures in China are still in the initial stage, falling far behind other countries or regions. Main existing problems are listed as follows:

(1) There is lack of basic understanding on the impact of durability of underground structures on important and major projects in China. Therefore, it is difficult to make qualitative estimations for the rest of their service life, and more difficult to provide quantitative evaluations. In the past, more emphasis was laid on the strength and anchoring force of supporting structures. Analysis and estimation of internal, external and overall stability were also emphasized. But operative performance, status, failure mechanism and protective countermeasures of the structures in various corrosive environments were ignored to a large extent. In the recent 20 years, with increased international exchanges, corrosion prevention measures for bolt- and cable-supported structures have been improved and enhanced. However, it is still not easy to make a comprehensive and accurate estimation on the safety and durability of these supporting methods. Without advanced testing instruments for large-scale sample investigations, cross-department and cross-industry cooperation of various engineers and scholars, it is very difficult to accomplish this task.

(2) There are misunderstandings on tonnage design of prestressed anchored cables and bolts. Prestress is essential for minimizing deformations of dams, caverns, slopes, etc., to maintain their overall stabilities. Therefore, diameters of anchored cables and bolts in China increase and the tonnage of prestressed anchors became higher. In 1970s, prestress load of common tunnel anchored cables (such as expansion shell anchored cable) was only 200–300 kN and prestress load of secondary grouted anchored cables was merely 500, 600 or 900 kN (Table 1). Currently, the prestress loads of anchored cables reached or even exceeded 10 MN.
Higher prestress load does not always produce favorable results. Studies show that under the same conditions, greater prestress load will induce higher stress corrosion rate. Structural deformation should be restricted within a reasonable range, and stress corrosion rate should also be controlled within an acceptable range. Optimum points should be balanced in the ranges. It is difficult but not impossible to find these points. None should be overemphasized at the expense of others.

(3) Defects in bolts and cables have significant negative effects on their durability, which involve two aspects: material imperfections due to processing technology and poor construction quality due to relatively poor construction management. The latter may be more prominent at present in China. For example, the water-cement ratio (0.45–0.5) basically cannot meet the specified requirement, except for some major projects, in which strict requirements are enforced. The requirement of water-cement ratio in other countries or regions is relatively higher (Japanese specification: 0.38–0.44; the USA technical
standard: 0.4–0.5). According to the experiments, the lower limit value specified by Japanese standard is more reasonable. In practice, the adoption of water-cement ratio is somewhat arbitrary in China, sometimes reaches 0.6–0.7 or even greater due to jerry-building. This situation continues to worsen.

Furthermore, grouting pressure, anchor head protection, test and evaluation of underground corrosive environment and the minimum cover thickness are not explicitly stipulated in current standards, or not reasonably stipulated. For example, the minimum cover thickness in German and Chinese specifications is 5 mm, which may not be reasonable. But in most cases, this minimum cover thickness of 5 mm unfortunately is satisfied. If relevant studies fail to put forward effective predicting methods in terms of the major defects, it is difficult to evaluate the rest service life of the structures.

(4) Currently, serious potential dangers widely exist in constructions of bolt- and cable-supported structures, so their influences on safety and durability of the structures cannot be underestimated. Cement mortar or pure cement paste grouting is generally used. High sand and cement contents, cement mortar or pure cement paste are less corrosion-resistant, compared with ordinary concrete. In order to accelerate hardening, many secondary grouted anchored cables adopt high-and-early-strengthen cement or ultra high-and-early-strengthen cement in primary grouting. The content of mineral compositions, which makes great contributions to early strength in cement clinker, has increased greatly. It is favorable for the strength of solidified mortar but negative to its durability. From the 1970s to the 1980s, expansion shell anchored cables slit rod-and-wedge-type bolts and expansion shell anchored bolts were widely applied in China. Inner anchor head of such anchored cables and bolts might touch the wall of anchoring hole directly, and mortar grip thickness at some positions might even become zero, which was quite disadvantageous to the durability of anchored cables and bolts. Currently, in permanent projects abroad, such anchored cables and bolts are no longer in use or have been improved. Secondary grouted anchored cables also have drawbacks that are often neglected: there is always a part of inner anchoring section of a secondary grouted anchored cable with zero cover thickness. Due to the deviation of hole axis (even when the deviation rate requirement of 1/30 is reached), a section of the bolt in the middle of the hole may directly touch the hole wall and cause the mortar cover thickness to be zero. The reason is that: (i) In China, cables of inner anchoring sections are all made into jujube pit shapes in order to increase their grip force in solidified mortar without protection outside. After the cables are emplaced, the inner anchoring section will directly touch the hole wall under gravity. As a result, no mortar is grouted to the contact position and the relevant cover thickness is zero. (ii) The anchor holes excavated by drilling

<table>
<thead>
<tr>
<th>No.</th>
<th>Project name</th>
<th>Reinforced rocks</th>
<th>Support position</th>
<th>Tonnage (kN/holed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Meishan reservoir</td>
<td>Bedrock</td>
<td>Right-bank dam foundation</td>
<td>4000 (or 3 240)</td>
</tr>
<tr>
<td>2</td>
<td>Mashii dam</td>
<td>Muscovite</td>
<td>Dam foundation</td>
<td>2000</td>
</tr>
<tr>
<td>3</td>
<td>Jingbo lake project 310</td>
<td>Diorite</td>
<td>Rock mass side slope</td>
<td>950</td>
</tr>
<tr>
<td>4</td>
<td>Fengman power plant project 250</td>
<td>Metamorphic conglomerate</td>
<td>Catch pit side wall</td>
<td>500</td>
</tr>
<tr>
<td>5</td>
<td>Bikou hydropower station</td>
<td>Sericite quartz phylite</td>
<td>Spillway tunnel</td>
<td>300 (or 2 200)</td>
</tr>
<tr>
<td>6</td>
<td>Bikou hydropower station</td>
<td></td>
<td>Left-bank water intake side slope</td>
<td>300 (or 2 200)</td>
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<tr>
<td>7</td>
<td>Overflow dam in Shuanggui reservoir</td>
<td>Interbeds of sandstone and slate</td>
<td>Dam foundation</td>
<td>1 500 (or 2 300)</td>
</tr>
<tr>
<td>8</td>
<td>An underground work</td>
<td>Mudstone or argillaceous limestone</td>
<td>T-shaped junction</td>
<td>500</td>
</tr>
<tr>
<td>9</td>
<td>Draft tube of Baishan power plant</td>
<td>Migmatite</td>
<td>Rock walls</td>
<td>600</td>
</tr>
<tr>
<td>10</td>
<td>Jilin City civil air-defense construction 801</td>
<td>Granite</td>
<td>Rock pillar</td>
<td>600</td>
</tr>
<tr>
<td>11</td>
<td>Dam in Baishan hydropower station</td>
<td>Concrete</td>
<td>Dam section No.15</td>
<td>300 (or 600)</td>
</tr>
<tr>
<td>12</td>
<td>Underground powerhouses of Baishan hydropower station</td>
<td>Migmatite</td>
<td>Downstream high side wall</td>
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<tr>
<td>13</td>
<td>Dams of Baishan hydropower station</td>
<td>Concrete</td>
<td>Sections No.17, 19</td>
<td>300 (or 600)</td>
</tr>
<tr>
<td>14</td>
<td>Fengman hydropower station</td>
<td>Concrete wall and bedrock</td>
<td>West training wall</td>
<td>400–600</td>
</tr>
<tr>
<td>15</td>
<td>Fengman hydropower station</td>
<td>Concrete and bedrock</td>
<td>Dam foundation</td>
<td>2 000</td>
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<tr>
<td>16</td>
<td>330 Project</td>
<td>Concrete</td>
<td>Large radial gate buttress</td>
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<tr>
<td>17</td>
<td>Nanhe River hydropower station</td>
<td>Concrete</td>
<td>Gate pier</td>
<td>600</td>
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<td>18</td>
<td>Xiaolangdi hydropower station</td>
<td>Polytic and calcareous siltstone</td>
<td>Dam foundation fault</td>
<td>300 (or 600)</td>
</tr>
<tr>
<td>19</td>
<td>Hongmen reservoir</td>
<td>Concrete and fine sandstone</td>
<td>Overflow weir</td>
<td>2 440</td>
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<tr>
<td>20</td>
<td>Sanxia water control project</td>
<td>Rock</td>
<td>Side slope</td>
<td>3 000</td>
</tr>
<tr>
<td>21</td>
<td>Lijiaxia hydropower station</td>
<td>Rock</td>
<td>Side slope</td>
<td>3 000</td>
</tr>
<tr>
<td>22</td>
<td>Lijiaxia hydropower station</td>
<td>Concrete and bedrock</td>
<td>Gravity dam</td>
<td>10 000</td>
</tr>
<tr>
<td>23</td>
<td>Qiantu hydropower station</td>
<td>Rock</td>
<td>Underground powerhouse</td>
<td>1 750</td>
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<tr>
<td>24</td>
<td>Shiwan hydropower station</td>
<td>Concrete and bedrock</td>
<td>Gravity dam</td>
<td>6 000–8 000</td>
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machine may not be perfectly straight. When a hole is tens of meters deep, significant deviations will occur. The specified deviation rate is restricted to be no more than 1/30 in China. However, the maximum hole depth in China has reached 80 m (Tongjiezi hydropower station), whose deviation is up to approximately 2.7 m, 10 times more than that of ordinary anchor holes in size. In fact, an axial line of anchor hole is more an irregular space curve. Therefore, when prestress load is applied, some sections of a cable will touch the hole wall inevitably, resulting in zero grip thickness of these sections. Moreover, the applied prestress load is uncertain due to the friction between the cable sections and the hole wall. In order to achieve permanent protection for the free section of an anchored cable, double-layer protection with a fiberglass-reinforced plastic (FRP) cover outside the coating, was adopted in Germany. But under such conditions, grip thickness of the cover was still zero. Similarly, almost all alignment supports for mortar bolts and full-length grouted permanent soil nails are welded into bolt bodies by means of metals in China, which is prohibited in USA and replaced by plastic products. Most of the alignment supports are in contact with the wall of anchor hole, thus the cover thickness is still zero as well.

(5) Severe underground corrosive environments and influences of various factors are the basic issues for the study of safety and durability of underground structures. Alternative dry/wet environment, permanent immersion and closed humid environment, as well as medium resistivity, pH value, chloride and sulfate under certain conditions will cause corrosion to bolts and cables to a certain degree, but corrosion rate varies. Corrosion rate of anchored bolts in a closed environment with a relative air humidity of 100% is about 1/5 of that of test pieces permanently immersed or in an alternative dry/wet environment. Studies indicate that medium resistivity, pH value, chloride and sulfate will cause corrosion or severe corrosion to bolts and cables only under certain conditions, and will not induce corrosion under other conditions. Critical points exist, which are necessary to be explored and determined. The coupling effect of multiple adverse factors is not always simple superposition of individual factors. If all the above factors such as material defects, stress corrosion and construction factors are considered, the issue will become a complex problem.

(6) Close attention has been paid to corrosion prevention of bolts and cables in the engineering field. It is imperative to clarify the misunderstandings of corrosion prevention and to carry out effective protective countermeasures. The main measures include galvanization epoxy and metal powder coating for bolts. However, according to relevant studies in USA, these anti-corrosion measures were not appreciable or adoptable, which were explicitly stipulated in relevant technical standards. Therefore, our confirmation on corrosion-resistant materials and evaluation of their anti-corrosion effects should be estimated based on rigorous scientific research. Meanwhile, the American opinion of “Only if corrosion prevention is achieved through steel bar consumption, namely, using oversized steel bars to guarantee corrosion resistance, will the soil nail walls be used in permanent reinforcement projects” should not be taken for granted. No matter what kind of stress a bolt bears, the bolt will be unable to bear stress and inevitably lose its function when a certain thickness of the surface is corroded.

6 Conclusions

(1) The application of bolt- and cable-supported structures to underground works has a history of several decades in China. The structures have been extensively used and mainly designed as major bearing structures. Currently, the study of service life, rest life and design life of these structures is still insufficient. Many questions cannot be answered clearly, or have not received enough attention, in which potential dangers may be encountered for various types of engineering projects. When the supporting structures reach the end of their life, they will bring unexpected disasters.

(2) The study of safety and durability of underground structures in China is still at a starting stage. Research on the effectiveness of protective countermeasures and reinforcement measures is still on its way. There is a lack of original standards for corrosion prevention countermeasures in China. Compared with other developed countries or regions, China still has a long way to go.

(3) The research on durability of underground structures in China is needed to provide comprehensive, systematic and reliable predications.
(4) Carrying out simulation tests in different operative conditions, corrosive environments and coupling corrosion factors are essential. Considering severe underground corrosive environments and different degrees of defects on supporting structures, understanding of the service life of supporting structures may be improved significantly.

(5) Studies on the effects and mechanisms of coupled corrosion and the methods for degradation analysis of accelerated tests are the keys to durability of underground structures.

(6) The studies of safety and durability of underground structures from worldwide communities, which started relatively earlier than that in China, will be helpful but should not be blindly copied in China.

(7) The study on service life of underground structures must be given top priorities, so as to provide reliable predictions for rest life of the structures constructed under various operative conditions, and to take corresponding countermeasures for reinforcing treatment before the end of their lifespan. If necessary, effective measures should be taken to strengthen the structures and to solve the problems of unpredictable failures that are major technical difficulties.

(8) In accordance to current technical specifications and construction methods, major bearing structures (dynamic and static loads) in underground works are supported by bolts and cables as temporary supports, while secondary concrete lining structures function as safety reserves. If effective solutions are presented for durability problems of the former, problems of the latter will be solved readily.

References


