New system for investigating the corrosion of existing rock anchors

X S Sun1, Y J Wang1, T Yin1,2, H J Chen3, Y F Zhao1 and L P Liu1

1 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
2 College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, Jiangsu, China
3 Huaneng Lancang River Hydropower Inc., Kunming, Yunnan, 650206, China

Corresponding author: X S Sun, Email: sunxs@iwhr.com, ORCID: 0000-0003-4624-5364

Abstract: In this study, the characteristics of corrosion were described on the basis of previous findings on the corrosion of rock anchors, and various factors causing corrosion were explored. A corrosion investigation system of rock anchors was established by summarizing various methods for the detection of corrosion and influencing factors. In this system, corrosion was investigated by detecting and assessing the environmental influencing factors, analyzing the corrosion rate and morphological characteristics, testing the anchoring structure, and evaluating the causes, development, and prediction of corrosion. On-site corrosion cases were also examined. Results verified that this system is reasonable, effective, and practical.

1. Introduction

Rock anchors are widely used in coal mining, transportation, and hydraulic engineering because of their effectiveness and economic efficiency. With the wide application of rock anchorage technology, cases of anchoring instability and failure are common in engineering [1-3]. Another major factor influencing rock anchors is corrosion. As a high-stress structure buried underground, rock anchors have a complicated working environment. Long-term immersion in groundwater, humidity variation, temperature changes, corrosive ions in a rock mass and other variables may cause rock anchor corrosion, which adversely affects its long-term durability. The corrosion state and long-term durability of anchors has been extensively investigated because of the complexity of their working environment and the concealment of underground structures [4-5]. Therefore, the corrosion of rock anchorage structures should be evaluated.

The corrosion and durability of prestressed rock anchor structures are mainly explored through theoretical research, indoor and outdoor tests, and field investigations [6-12]. Theoretical and experimental studies are performed to investigate the underlying mechanisms and laws. However, the complexity and concealment of site conditions and the actual situation of anchor structures cannot be completely and accurately simulated in a particular test. Therefore, site investigations should be performed to study the corrosion and durability of anchor structures.
After decades of on-site investigations on rock anchor corrosion, we have accumulated relevant experiences and formed a relatively complete corrosion investigation system for rock anchor structures. We can use this system to accurately assess the corrosion of rock anchors in service and provide a reference for the engineering safety and durability evaluation of anchoring systems.

2. Corrosion investigation practice for rock anchors

According to China’s existing specifications [13, 14], the corrosion status of prestressed anchors in service, during their service life, or when their head concrete cracks, peels, or experiences other abnormal conditions should be inspected and analyzed. Inspection should focus on the corrosion of the anchor head and its adjacent free section. If necessary, the protective cover of the anchor head, the protective concrete, and the grout of the adjacent free section can be removed for visual inspection or sampling during physical and chemical analysis.

These specifications only describe the general rules and principles of corrosion testing of prestressed anchors and do not recommend particular investigation methods. Specific methods for inspecting the corrosion of prestressed anchors have yet to be developed. An actual investigation usually refers to metal corrosion theory and other similar corrosion detecting methods used in bridges, underground pipelines, and other structures.

The detailed practice of engineering investigation is summarized in the following sections.

2.1 Field Exhumation

Rock anchor exhumation is an effective and direct method for corrosion detection. During exhumation, the anchor can be taken out directly to detect its corrosion. At the same time, the location of corrosion, environmental conditions, and grouting quality can be easily determined. At different depths, the corrosion rate of the sample can be measured, the environmental parameters can be tested, and the anchor structure can be evaluated. Through exhumation, the corrosion of the anchor can be more comprehensively and accurately understood.

In the past decade, anchors were exhumed from several sites, including the longitudinal cofferdam of Shaping-II Hydropower Station, the tunnels of Qishan Coal Mine, the underground powerhouse of Jinping-I Hydropower Station, the left abutment slope of Manwan Hydropower Plant, and the old dam of Fengman Hydropower Station [15]. Figure 1 shows the exhumation of rock anchor at left abutment slope of Manwan Hydropower Plant. In Figure 1 (a), in exhumation, a small tunnel with a width of 1.5 m and a height of 1.7 m was excavated. In Figure 1 (b), the whole anchor was then taken out. The anchor cables and grout were revealed during exhumation (Figure 2).

![Figure 1](image_url)

Figure 1: Exhumation of rock anchor at the left abutment slope of Manwan Hydropower Plant: (a) tunnel and (b) anchor
For rock anchor exhumation, representative anchors, which can reflect the corrosion state of the overall anchors, should be carefully selected.

2.2 Morphological characterization of corrosion

Anchor corrosion is morphologically characterized to determine the corrosion degree, distribution, and appearance characteristics of the rock anchor. In an exhumation test, this process is relatively easy. However, for the rock anchor in service, morphological characterization usually focuses on the exposed parts only, especially the anchor head. This process is the most visual monitoring method of anchor corrosion. It helps determine the corrosion rate, type, and range.

Figure 2 shows a sample of the anchor cable from the tunnels of Qishan Coal Mine, the degree and characteristics of the anchor corrosion, and the fracture form of the anchor cable. The anchor cable breaks because of shear failure. Figure 4 illustrates the anchor head corrosion of anchors in the tailrace surge chamber of a hydropower station. It clearly displays the corrosion status of the anchor cable and the corrosive environment. The environment is quite humid, and the protective steel cap has rusted, forming a layered rust product, as shown in Figure 4 (a). The anchor head with a fallen protective steel cap corrodes quite seriously because of the wet environment, as presented in Figure 4 (b). These anchors have only been in service for about 15 years, and their corrosion is severe.
2.3 Guided wave nondestructive test
A guided wave method is widely used to inspect the quality of bolts and detect their density and anchoring length. It can also determine if an environment is corrosive by detecting grouting defects around the bolts. The basic principle of the guided stress method is based on one-dimensional wave theory. When a pulse echo is stimulated through the end of an anchor bolt, guided waves propagate through the bolt and become reflected at discontinuities in the bolt to form an echo, which is received by a probe.

When a guided wave propagates in an isotropic body, the propagation speed, amplitude, and type of the wave remain unchanged. However, when a guided wave propagates in an anisotropic body, it produces reflection, transmission, or scattering phenomena because of changes in wave impedance. Some of the energy propagates forward through the interface, i.e., the transmitted wave, and the remaining energy is reflected, i.e., the reflected wave. The anchoring quality of bolts can be analyzed with the reflected wave (Figure 5). The analysis of the wave information of a free-state bolt is relatively simple, but an actual anchored bolt on-site is affected by several factors, such as anchoring medium and surrounding rock. Its wave characteristics are also quite complicated.

2.4 Corrosion environment detection
2.4.1 Damaging ions and pH
For prestressed anchors in a rock, the most fundamental corrosion type is electrochemical corrosion [16]. Among environmental factors, the damaging ion concentration and pH of water are the most common. In the investigation, surface water and groundwater in the engineered region were sampled and tested in accordance with the Code for Hydropower Engineering Geological Investigation (GB 50287-2006) [17] and the Code for the Investigation of Geotechnical Engineering (GB 50021-2001) [18] for damaging ion and pH evaluation. The water sample could be collected from the drainage pipes in the slope and the underground surrounding rock (Figure 6).
Chloride ions are considered as one of the most harmful ions in the field. The passive layer breaks when a sufficient number of chlorides reach the surface of anchors; consequently, corrosion begins. Chloride ions can be found in the structure of an anchor because of the use of chloride-contaminated components in the grout or the diffusion of chloride from the external environment [19]. Free chlorides dissolved in a pore solution are responsible for initiating the corrosion process [20].

2.4.2 Temperature and humidity
For iron and steel, the corrosion rate increases approximately linearly with temperature [21]. The moisture of the anchorage structure, which is affected directly by atmospheric humidity, is an important factor that controls the corrosion speed of anchors. In this study, humidity was measured as relative humidity (Figure 7).

2.4.3 Underground stray current
Rock anchors are electrically conductive. Stray current exists widely in rock and soil mass. A corrosion cell is produced as stray currents flow in an anchor, thereby forming a potential difference. The current flows in a metallic part, which is defined as the cathode zone, and flows out of the other part, which is defined as the anode zone. Anchor corrosion caused by stray currents is called stray current corrosion.

In a stray current test, a CuSO₄ solution electrode was taken as the potential sensor. The potential between the electrode and the anchor was measured with a voltmeter (Figure 8).

2.4.4 Corrosion products and grout
During an investigation, corrosion products and grout exfoliation can be collected in some instances. The number and type of damaging ions in the environment can be assessed indirectly through tests such as microscopic morphology, energy dispersive spectrometry (EDS), and X-ray diffraction of corrosion products and grout.

2.5 Laboratory tests of the samples

2.5.1 Chemical composition analysis

The chemical properties of metals are mainly characterized by heat and corrosion resistance. The chemical composition of metals significantly affects the metallurgical structure and corrosion resistance, which play a prominent role in the performance of prestressed anchors in a complex rock environment. Chemical composition analysis on anchor samples should meet the requirements of No. 80 steel in the Quality Carbon Structural Steels (GB/T699-1999) [22] and prestressed steel strand stated in GB5224-85 [23].

2.5.2 Metallurgical structure analysis

A metallurgical structure is the internal structure of a metal, that is, the chemical composition of a given metal and the physical and chemical states of various components inside it. The metallurgical structure reflects the specific form of metal metallography, such as martensite, austenite, ferrite, pearlite. Although the metallurgical structure of steel strand is relatively stable after smelting and casting, it can be changed during thermal treatment and mechanical processing. This change affects the corrosion resistance and mechanical performance of materials. Anchor samples should be subjected to metallurgical analysis through morphological tests and EDS to determine the consistency of metals with the metallurgical structures of factory materials.

2.5.3 Electrochemical test

An electrochemical test is a widely accepted approach for studying metal corrosion. This method can indicate the corrosion sensitivity and rate by establishing a relationship between electrode potential and polarization current or polarization current density. Thus, it can provide a basis for evaluating the corrosion resistance of anchors.

Figure 9 presents the typical polarization curves of the steel anchor sample exhumed from Shaping-II Hydropower Station and placed in a neutral solution with different \( Cl^- \) concentrations. The test was conducted with an electrochemical workstation (Princeton, 273A). The corrosion resistance and corrosion rate of the steel in different environments can be analyzed by adjusting the pH and ion concentration of the solution to evaluate the corrosion initiation and propagation patterns of the anchor in a certain environment. Samples in a solution with a lower corrosion potential may have lower corrosion resistance, and samples with a higher corrosion current density may yield a higher corrosion rate. In Figure 9, the sample in 0.1% \( Cl^- \) concentration solution has the lowest corrosion potential and the highest corrosion current density. Therefore, this sample is susceptible to corrosion and has a high corrosion rate.
2.5.4 Mechanical test
As a reinforcement structure, a rock anchor stabilizes the rock mass by changing the stress state of the surrounding rock with tensile force. Therefore, its mechanical properties are relatively important. A microprocessor-controlled electrohydraulic servo all-purpose test system is usually used to examine various parameters, such as yield load, breaking load, tensile strength, elongation, and elasticity modulus, and evaluate the mechanical properties changes during the service.

3. Development of the corrosion investigation system for rock anchors
After years of corrosion investigation practice, a complete anchor corrosion investigation system has been developed. An investigation system involves several steps (Figure 10):

- Step 1. Determination of a corrosion investigation plan
- Step 2. On-site inspection of rock anchors
- Step 3. On-site environmental test
- Step 4. On-site sampling
- Step 5. Sample laboratory test
- Step 6. Summarization of the test results and drawing conclusions

Before Step 1 is even performed, relevant information should be obtained to establish a corrosion investigation plan. Therefore, a preliminary investigation is needed to determine the extent of the investigation. For example, if the degree of corrosion of the anchor is severe, exhumation should be considered to investigate the corrosion situation of rock anchors extensively. If corrosion is not particularly serious, or exhumation cannot be performed because of safety considerations, then investigations can be conducted under the existing conditions. The opening of the protective concrete and steel cap of the anchor head may be helpful for corrosion investigation and sampling.

Step 2 mainly involves the on-site anchor bolt inspection methods, such as guided wave testing and corrosion morphological inspection. A certain number of tests should be performed to reveal the overall corrosion situation.

In Step 3, an environmental test includes pH, damaging ion, temperature, humidity, stray current, corrosion product, and grout tests. Some tests, such as temperature, humidity, and stray current tests, can be carried out in the field. Other tests require sampling in the field and testing in a laboratory.

In Step 4 or on-site sampling, surface water and groundwater samples should be collected for pH and damaging ion tests. Corrosion products and grout should be obtained for damaging ion tests. Anchor
samples should be collected for chemical composition, metallurgical structure, and electrochemical and mechanical tests if a rock anchor is exhumed. In this investigation, some corrosion-related materials should be collected to help examine anchor corrosion. The obtained samples should be protected and kept intact as much as possible.

In Step 5, different tests are performed on various samples obtained on site. The retrieved samples should be tested as soon as possible to obtain reliable data. If necessary, a sample should be sent to a qualified special testing agency.

In Step 6, the measured results in the field and the test data acquired in laboratories, combined with the morphological inspection results, are compiled for reporting.

4. Discussion
For anchor corrosion investigation, exhumation is relatively reliable and in depth. During exhumation, the corrosion of anchors and the quality of grouting can be directly observed. Samples at different depths can be obtained to acquire the complete environmental and corrosion information of anchors. However, bolt exhumation has disadvantages. First, excavating an anchor is costly. Exhuming a rock anchor is more expensive than building one. Second, safety issues related to the exhumation of an anchor as a reinforcement structure should be considered, but current specifications and manuals have not provided related measures. Therefore, anchor exhumation is quite difficult. Furthermore, this test method cannot be readily promoted to others. In our practice, only the anchors of the Manwan Hydropower Station and Qishan Coal Mine were excavated. The rest of the exhumation process was carried out simultaneously with the demolition project. Therefore, further studies should focus on conventional corrosion investigation methods.

In addition to guided wave and stray current tests as methods for detecting on-site metal corrosion, resistivity, electric potential, and ultrasonic methods are used. These methods have achieved good results in the corrosion detection of other metal structures. However, they cannot be used to detect rock anchor corrosion because of its depth and structural complexity. Similarly, many advanced geophysical techniques are difficult to use in the corrosion investigation of anchors because of their particularity, that is, the depth of an anchor is often relatively large, and its internal structure is difficult to detect. For other parts, such as an anchor cable, each steel strand is composed of seven steel wires, each anchor cable is made of multiple steel strands, and a grout exists between the surrounding rock and the anchor cables. Anchor cables are special components because of the depth and complexity of their cross-section, but these factors exacerbate the difficulty of detection. Consequently, inspecting anchor corrosion, especially in deep parts, remains a difficult problem.

In many tests, the results of different projects, chemical composition tests, metallurgical structure tests, and electrochemical tests meet the design requirements or specifications. Furthermore, almost all results are qualified mainly because the objects of these tests are the materials of the anchor itself. In the service life of an anchor, although it has corroded, its base material remains unchanged. Therefore, the inspection of its base material has not changed. From another perspective, although the anchor has corroded and experienced high stress during its service, its base material has remained the same. Therefore, corrosion and stress have not altered the anchor material itself. Such tests can be reduced or even cancelled in subsequent investigations.

5. Conclusion
On the basis of the common practice of corrosion investigations of rock anchors, relevant investigation methods were described, the performed tests were summarized, and the test content and requirements were explained. The characteristics of corrosion were described on the basis of the investigation results, and various factors causing corrosion were examined. A corrosion investigation system of rock anchors was established by summarizing the methods for detecting anchor corrosion, influencing factors, and investigation content. In this system, corrosion was investigated by developing an
investigation plan, conducting an on-site inspection of rock anchors, detecting and assessing the environmental influencing factors, obtaining field samples, performing laboratory tests of the anchor samples, and analyzing the investigation and testing results. Our investigation on on-site corrosion cases verified that this system is reasonable, effective, and practical.

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