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Investigations on corrosion and mechanical properties of a 20-year-old ground anchor exhumed at a power station site

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ABSTRACT

This paper presents the observed findings and laboratory test results of an anchor exhumed from Manwan hydropower station, China which was installed 20 years ago. The prestressed cables are 25.6 m long with a working load of 1000 kN. It consists of eight strands, and each strand consists of seven wires. The anchor was installed using the 'single protection' technique (i.e., the steel strands without greased sheath and was backfilled directly with cement mortar). The anchor was unearthed by excavating a 1.5 m × 1.7 m tunnel. Visual inspection shows that the steel strands in the free and fixed lengths are basically stainless except for a few places where the grout failed to cover the anchor completely, thereby allowing direct contact of the strands with air. The magnitude of rebound of the tendon during the advancement of the tunnel face was simultaneously measured indicating a gradual release of bonding force, which was up to 62 % of the prestressed load. This shows that the existence of the bonding force is provided by the bonding between the strand and the grout, while this bonding does not exist in the 'double protection' system. The results of the mechanical test confirm that the tensile strengths in all the 33 steel wires exceed the requirement as specified by current Chinese Standard (NBS, 1985). The concentrations of various chemicals also satisfy the requirements as specified by CSBTS (1999). The results of the X-ray Diffraction test show that the stains taken from the surface of the strand are composed of FeO and FeOOH, both being oxide products of iron. This shows that exposure of the material to air is an important condition to initiate corrosion. By following ASTM test procedure (ASTM International 1999), the average corrosion rate is found to be between $3\text{--}6 \times 10^{-4}$ mm/year. This investigation generally supports the use of unprotected steel strands in rock anchor.

Keywords: Ground anchor, long term serviceability, prestressed tendon.

1. Introduction

While more and more ground anchors have been used in geotechnical engineering, the concerns over their long term reliability and durability have never been resolved. Based on a review of the literature reviews, it may be conclude that there is no certain way to identify the state of corrosion in the anchors and to predict the rate of corrosion with precision. It is believed that by improving the anchor structure to include more corrosion protection barriers is a positive way to ensure their long term serviceability (Barley 1997).

The ground anchor, traditionally, is installed with very simple technology. A rod or a strand tendon is first inserted into a borehole, which is then backfilled with cement grout over the fixed length. After the hardening of the cement grout, the tendon is stressed and fixed at the head. Subsequently, the free length of the tendon is normally backfilled with grout in order to provide insulation against ground water and air. A concern with this practice is whether the unprotected tendon could sufficiently maintain its integrity over its life span in a severe geo-environment which a rock cable would potentially encounter.

Modern anchor technology originated from Europe with the development of a 'double protection' technique (Barley 1997; Littlejohn and Mothersille 2007). The fixed length of the tendon, it is encased in a corrugated polyethylene sleeve which is then filled with cement grout. The individual strands in the free length are coated with corrosion resistant grease and placed in a plastic sleeve. This technique is used on the presumption that in the event of one barrier of the corrosion protection fails, the other corrosion protection barrier is still effective (Barley 1997).

Although this new technology has been widely applied throughout the world and has been incorporated into a number of standards (e.g., the British codes BS 8081:1989 and BS EN 1537:2000),

there is still a debate regarding its applicability and effectiveness. Nierlich and Bruce (1997) summarized the differences in opinions between the Europeans standards and the recommendations by the Post-Tensioning Institute (PTI). While the former considers the technology perfect and a reliable solution for maintaining long term durability of the tendons, 'Americans are more ready to look at the cost-effective ratio of this corrosion protection system'. They argued that there is no known rock failure due to insufficient corrosion barrier in rock anchoring. Hence, there is no need for the more sophisticated technology, such as the electric isolate testing which is too costly and impractical to use on a routine basis. On the other hand, the Chinese community relates to the advantages of having steel strands without protection of greased plastic sheath (Liu et al. 2005). They found that the direct contact of the strand with the surrounding cement mortar forms a very strong bond, especially when some additives that allow water reduction and grout expansion are added (Dai and Peng 2008). They further found that even when the anchor head or part of the free length is totally destroyed, the remaining part can still join on to the anchor group thereby stabilizing the rock mass. In fact, the stressing facilities of many prestressed concrete plates and beams are removed when they leave the factory for shipping and installation (Liu et al. 2005).

Clearly, this debate will not converge to a universal agreement unless there is evidence that is based on large scale field investigations. A well-known example of such a process is the working group under the FIP (FIP 1986), which collected 35 cases of anchor failures. Other similar efforts are described by Weerasinghe and Littlejohn (1997), Pells and Bertuzzi (1999), Hadjigeorgiou et al. (2008). It may be noted that most of the investigations are limited to the tendon components near the ground surface and the examinations normally employ nondestructive approaches. Positive chemical and mechanical tests that could quantitatively describe the serviceability of the tendon system are rarely reported.

One avenue of investigation into this problem is to exhume an installed anchor, which has been in service for a long time, and is available for visual and laboratory inspections. In view of the importance of this topic, it was decided to exhume a 25.6 m long 1000 kN prestressed anchor. It was installed as part of Manwan hydropower project in 1989 using the traditional 'single corrosion protection technique'. This project is jointly supported by China Ministry of Science and Technology, China Geology Survey and China Three Gorges Development Corporation.

The opportunity to exhume anchors is rare in practice (Weerasinghe and Littlejohn 1997), not only because of the objections from the owners, but also due to the difficulty of finding suitable technology of doing so. At the start of the project, it was considered to use a large diameter drilling machine to over core an existing anchor by destroying the surrounding rock so that the tendon could be pulled out by a hydraulic jacket. The idea was quickly abandoned because the tendon was unlikely to have been installed in a straight line due to the construction inaccuracy and its variance from the straight line is unknown. As such, the over core would most likely damage the anchor. It appeared that the only approach to exhume the anchor was to excavate a tunnel around the tendon. Blasting was not allowed at the site as it might jeopardize the nearby tendons and the concrete dam. Hence, the tunnel was excavated manually with limited machinery drilling. The exhumation operation lasted three months with a total expenditure almost one hundred times more than the cost used to install the anchor 20 years ago.

The excavation process was carefully monitored and the exhumed tendon was sent to laboratories for full mechanical and chemical examinations. The results obtained generally indicate minimal corrosion or loss of performance to the anchor. This paper presents the details of this investigation.

2. Field work

2.1 Background of the project

The exhumed anchor was located at the left abutment of Manwan dam, which is the main component of a hydropower development project in the middle reach of the Lanchangjiang River in Southwest China.

On January 8, 1989, during the excavation of the slope, a catastrophic landslide with a volume of 106,000 m³ occurred at the slope (Fig. 1a). As part of the emergency remedial work, nine prestressed 8-strand anchors, each with a capacity of 1000 kN, were installed to help stabilize the remaining part of the slope. Since the slope is now fully covered by a concrete gravity dam, the anchors are no longer serving any useful purpose. In view of the circumstances, they were allowed to be exhumed for research purposes. The anchor selected for exhumation was located at 1.5 m above the road on the left side of the dam crest, as shown in Fig. 1b. The exhumation was carried out in 2009.

2.2 Geology

The exhumed anchor was on the slope located on rhyolite formation. The rock quality ranges from heavily weathered near the surface to slightly weathered below the surface. The unconfined compressive strength of the rock mass ranges from 25-50 MPa. Groundwater was not observed during the exhumation.

2.3 Groundwater

Table 1 shows the test results of ions contained in the groundwater at the anchor service environment and the required standard in Chinese code GJB 3635-99 (GADPLA 1999). The pH value is in the neutral range, and the average concentration of corrosive ions is low. For the cement grout cover, residual Cl⁻ content is also very low. These results indicate that the groundwater did not contribute

significantly to the corrosion of the tendon.

2.4 Configuration of anchor

The anchor consists of eight strands with a design inclination of 18° to the horizontal in a 115 mm diameter drilling hole. Fig. 2 shows the layout of the typical 'single corrosion protection' anchor system. Each strand consists of seven wires. According to NBS (1985), the 8-strand tendon has a total cross-sectional area of $1.12 \times 10^{-3} \text{ m}^2$ with a nominal diameter of 15.2 cm and a strength of 1470 MPa. As shown in Fig. 2, the anchor has a fixed anchor length of 6.5 m and a free length of 18.5 m. For the fixed length, the cement mortar used had a water-cement ratio of 0.8 and a cement-sand ratio of 1:1. For the free length, the grout used was No.425 pure cement slurry, which had a water-cement ratio of 0.4.

2.5 Excavation of tunnel

The tunnel used to exhume the tendon is of an inverted U shape. It is 1.5 m wide and 1.7 m high. Its inclination is parallel to the anchor (i.e., 18° to the horizontal). Figure 3 shows a schematic of the tunneling arrangement. The bench mark on ground surface is specified as 0+0.00 m. During the excavation, the anchor tendon and the surrounding grout cover to be exhumed were carefully fixed at the upper-left corner of the tunnel, as shown in Fig. 3a. The conventional drilling method was used to excavate the tunnel. As blasting may cause large vibrations in the surrounding rock mass, only slight explosion was used to loosen the rock. To avoid sudden rebound of the strand, the tendon was fixed at the tunnel. It was found that as soon as the grout cover was exposed, longitudinal cracks appeared at the surface of the grout. The excavation work started on November 17, 2011 and was completed on January 23, 2012. During the excavation, the tunnel walls were dry, indicating that the water table was

well below the anchor to be exhumed.

Fig. 4 shows a photograph of the exhumed anchor tendon with grout cover.

3. Results of visual observation

3.1 The anchor head

The excavated anchor head was covered by a concrete block which was used to resist corrosion. After the removal of the encasement and the protective epoxide mortar cap, the steel bearing plate and the protruding strands could be seen to be a brownish yellow color, a number of strands had yellow rust stains, as shown in Fig. 5a. There was no metallic brightness observed on the head. The wedges were firmly bonded with the strands. They could not be unlocked even after immersion in kerosene for 12 hours. The wedges were eventually unlocked using a jack with a pull-off force of about 20 kN. Irregular indentations and corrosion were clearly seen in the inner surface of the wedges and the outer surface of the strands, as shown in Fig. 5b. According to John and Littlejohn (2007), the anchor head is the most fragile part of the system to withstand corrosion.

3.2 The free anchor length

For the 18.5 m long free anchor length (from bench mark 0+0.00 m to 0+18.50 m), most of the strands were observed in good condition displaying metallic to brilliant black colors. There was no visible corrosion (as shown in Fig. 6), except at bench mark 0+6.50-0+9.00 where the strands were in direct contact with drilling hole wall. For this portion, the steel strands were yellow in color with bulging spots, as shown in Fig. 7. These findings clearly show that a proper and full grout protection is of prime importance to maintain the long-term serviceability and durability of a ground anchor further, similar to many relics found in archeological sites, the exhumed tendon corroded rapidly upon exposure to air, as

shown in Fig. 8. The corrosion initiated and developed rapidly within three days due to its exposure to air.

3.3 The fixed anchor length

The fixed anchor length is subject to the full tension load, and therefore its integrity is of critical importance. In contrast to the grout used in the free length which was only cement and water, the grout used in the fixed length was made of Portland cement, sand and water.

There were no longitudinal or transverse visible cracks within the cement mortar of the fixed end as shown in Fig. 9. Similar to what was observed in the free length of the tendon, the strands were found stainless with metal brightness (location B in Fig. 10). However, the steel strands near the bottom of the anchor, just a few centimeters from location B, were found brownish yellow in color and there was significant corrosion (location A in Fig. 10). The corrosion can be attributed to the incomplete grouting at this position, due to the retention of drilling debris during construction of the anchor. This finding further demonstrates that the grout cover plays an important role in preventing steel strands from corrosion.

4. Rebound of the cable during excavation

The 'single protection' technique provides direct contact of the strand with the grout, which thus enables a strong bond to be developed between them. This means that once the anchor head fails, the remaining part of the tendon could still join the anchor system to maintain the anchor stressed. In order to investigate this further, careful measurements of the magnitude of rebounds of the strand were undertaken when it was progressively dismantled from its surrounding rocks. Six measurement points (i.e., at benchmarks: 0+2.00 m, 0+2.50 m, 0+3.00 m, 0+3.50 m, 0+4.00 m, and 0+4.50 m) were set

immediately after their exhumations. Fig. 11 shows how the rebounds were measured. A base point was set on the tunnel wall with a red mark at the same position on the cable right after the strands were discovered. If this red mark does not move with reference to the base point as the excavation advances, it indicates that no bonding force exists between the strand and the grout. However, all the six red marks moved towards the tunnel portal as the excavation face advanced. The rebound magnitudes were measured by a vernier caliper. Table 2 contains the measured retractions at the six measurement points. Fig. 12 shows the measured retractions at the 0+2.50 m measurement point as a function of the bench mark of the tunnel face. Moreover, the surrounding grout cracked immediately after it was exposed, indicating the existence of bonding force.

As shown in Table 2 and Fig. 12, the maximum and average retractions of the six measurement points are 30.40 mm and 30.90 mm respectively, when 18.50 m of the anchor tendon was exhumed. The bonding force, F_r , can be evaluated based on the elastic modulus using the following equation.

$$F_r = E \frac{\Delta l}{l} A \quad (1)$$

where E is the elastic modulus, Δl is the rebound length of the anchor tendon; l is the length of the anchor tendon, A is the nominal sectional area of the anchor tendon. For this case, substituting $E = 198.00$ GPa, $\Delta l = 30.38$ mm, $l = 11.5$ m, and $A = 1.12 \times 10^{-3} \text{ m}^2$ into Equation (1) gives $F_r = 586$ kN. According to the construction specification for the tendon, it was required to be tensioned to a prestressed load of 943 kN. This result shows that at least 62% ($= 586/943$) of the prestressing force still maintained in the anchor, which can be attributed to the bonding between the strand and the grout after the anchor head was removed.

5. Tension testing of strand

A total of 33 strand specimens were prepared for tension testing. They were from three locations: (1)

near the anchor head at 2.00 m, 2.20 m, 3.20 m, 4.20 m; (2) in the free length at 8.20 m, 9.20 m and 10.20 m; and (3) in the fixed length at 18.20 m, 19.20 m and 20.20 m. Each strand consists of eight steel wires which are designated as J1 to J8 according to their spatial positions, as shown in Fig. 13. Table 3 contains the tensile strength, modulus of elasticity, and yield strength measured in the tests. Fig. 14 shows the tensile force and deformation curves of the 33 strand specimens. Figures 15 and 16 show the relationship between the elastic modulus and tensile strength for strands J1, J6 and J8 and the distance from the anchor head. Based on the test results, the following conclusions can be drawn:

- (1) The measured yield strength, elastic modulus and tensile strength of the 33 strand specimens all satisfy the requirements as specified in the Chinese standard (NBS, 1985), which respectively are 174.93 kN, 195 ± 10 GPa and 1470 MPa. For the measured tensile strength, they are between 1570 and 1590 N/mm² with an average of 1580 N/mm². That is, there is no practical variation in the property of strand, and all strands exceed the requirement of 1470 MPa as specified by NBS (1985).
- (2) The stress-strain curves show good ductility for the metal. The strands yielded at a strain of about 15-20%, beyond which the material hardened until at 60% strain at which the strand broke.
- (3) There is no substantial difference in tensile strength of the individual wires located at different benchmarks.

6. Results of chemical tests

6.1 Chemical composition

The chemical composition of the exhumed steel strand was evaluated using the procedures specified for #80 steel in the Chinese standard (CSBTS 1999). Table 4 lists the test results and the requirements of the standard. It is apparent that the chemical composition of the strand, after 20 years' service, still

satisfying the requirements of the standards.

To identify the chemical compositions of the corroded material, the strand wires which had brown and gray colors on the wire surface were subjected to the X-ray powder diffraction (XRD) testing. The XRD test is a rapid analytical technique primarily used for phase identification of a crystalline material and can provide information on unit cell dimensions (Smith et al. 2015). The material to be analyzed was finely ground into a homogeneous material. The average bulk composition was then determined (Dong and Zhao 2008; Smith et al. 2015). As shown in Fig. 17, the test results indicate that the principal components of the gray color corroded material are FeO and FeOOH, with a small amount of $\text{Fe}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$. The brown color corroded material mainly comprised Fe_3O_4 and Fe_2O_3 with a minor amount of FeOOH. Both color materials display iron oxides, indicating that the exposure of the material to air is an important condition to initiate corrosion.

6.2 Corrosion Rates of Strands at Different Depths

If a uniform or an uneven corrosion layer is removed from the strand surface, both the mass and diameter of the strand are reduced. Hence, by means of the traditional weight method and the thickness loss method, an estimate of both the extent and the rate of the corrosion can be evaluated. In the standard ASTM G1-03(1999), there are recommended methods and procedures for preparing the strand specimens, removing corrosion products and evaluating the extent of corrosion. The pickling method is used for corrosion cleaning, after which the extent of metal loss is corrected and converted following the testing procedures recommended by ASTM International (1999).

The mass loss due to corrosion can be calculated as follows:

$$\Delta W = \frac{w_0 - w_t}{A_0} + \Delta W_u \quad (2)$$

$$V_{\text{corr}} = \Delta W / t \quad (3)$$

In Eqs. (2) and (3), ΔW is the mass loss of corroded strand per unit area; w_0 is the mass of the non-corroded strand; w_1 is the mass of the corroded strand after removal of the corroded material; A_0 is the strand surface area; V_{corr} is the corrosion (weight loss) rate; t is the period of corrosion. Further, the mass loss of the non-corroded strand per unit area after pickling ΔW_u can be calculated as follows:

$$\Delta W_u = W_{u0} - W_{u1} \quad (4)$$

Where W_{u0} is the mass of the non-corroded strand per unit area before pickling; and W_{u1} is the mass of the non-corroded strand per unit area after pickling.

It should be noted that due to the inability of finding the initial mass when the cable was installed 20 years ago, it was taken as the required value specified in the Chinese code (NBS, 1985).

Table 5 summarizes the measured mass loss and average corrosion rate for the 20-year-old exhumed anchor at different zones. Figure 18 shows the relationship between the average corrosion rate with distance behind the anchor head. It should be noted that the corrosion rates of a cable are not constant. Only the average rate is investigated in this work.

As shown in Table 5 and Fig. 18, the average corrosion rate is about 0.005 mm/year, which is a very slow rate. Further, the corrosion rates appear independent of the distance behind the anchor head.

7. Conclusions

In an effort to assess the long term serviceability of ground anchors, a 20 years old anchor was exhumed at Manwan hydropower station site, allowing for visual inspection and mechanical and chemical tests. The main findings are:

(1) The anchor head along with its 1 m long cable beneath the bearing plate were found to be severely corroded. This can be attributed to the direct contact of the anchor head and cable with the

atmosphere and rainwater, even though they were enclosed by a concrete encasement. This observation is consistent with earlier research finding on ground anchorage corrosion.

(2) No tension cracks were found within the cement grout along the whole anchor. However, tension cracks gradually developed after the anchor was exhumed.

(3) With protection from 20 mm thickness of grout cement, the steel strands both in the free and the fixed lengths show virtually no corrosion. However, corrosion was found at some locations where there was inadequate grout cement cover allowing direct contact of the strand with air and water.

(4) The tension test results of 33 strands, which were extracted from the exhumed cable, show that the tensile strengths of the steel strands, after 20 years of service, still exceed 1500 MPa as required by relevant standards

(5) A total of 38 mm rebound was measured during exhumation of the tendon, indicating that at least 62% of the prestressed force had been provided by the bonding between the strand and the grout. This shows the effectiveness of the 'single protection' technique in providing tension to the tendon even after the anchor head was dismantled.

(6) The chemical tests of this 20 years old tendon indicated that the chemical elements of the steel material were still within the acceptable range as specified by relevant standards. The corroded materials mainly consist of FeO and FeOOH, and $\text{Fe}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$. Since they are all oxides, this shows that exposure of the material to air is an important condition to initiate corrosion. The average corrosion rate is found to be between $3\text{--}6 \times 10^{-4}$ mm/year.

The results of this research generally support the applicability of the conventional rock anchor technology that uses unprotected steel strands. However, this project was carried out in a less aggressive geo-environment where groundwater is not an effective factor. More work should be done in

order to improve our understanding of the long term serviceability of this type of anchor.

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Figure captions

Fig. 1. Illustration of site and the location of the anchor exhumed: (a) Manwan left-bank landslide occurred on January 8, 1989; (b) Location of the anchor exhumed.

Fig. 2. General arrangement of the exhumed anchor at the Manwan Power Station.

Fig. 3. Anchored cable excavated scheme: (a) Geometry of the inverted U shape tunnel; (b) The inverted U shape tunnel during construction.

Fig. 4. Photo of the exhumed anchor.

Fig. 5. Corrosion phenomenon found at the anchor head: (a) Bearing plate and strands; (b) Wedges.

Fig. 6. Initial state of the exhumed anchor at Benchmarks: (a) 0+2.40 m; (b) 0+4.00 m; (c) 0+10.00 m; (d) 0+12.00 m; (e) 0+15.50 m; (f) 0+17.50 m; (g) 0+19.50 m; (h) 0+20.00 m.

Fig. 7. Corrosion found at free length where grout cover was thin: (a) Benchmark 0+6.50 m; (b) Benchmark 0+9.00 m.

Fig. 8. Development of tendon corrosion after exposure to air: (a) original state of benchmark 0+4.00 m; (b) three days later of benchmark 0+4.00 m; (c) original state of benchmark 0+17.50 m; (d) three days later of benchmark 0+17.50 m.

Fig. 9. No longitudinal or transverse visible cracks within the cement mortar of the fixed end: (a) 0+18.50 m; (b) 0+21.00 m; (c) 0+23.50 m.

Fig. 10. Corrosion occurred at the anchor end.

Fig. 11. Measuring rebounds of the cable when it is dismantled: (a) set a base point on the wall and a red mark on the cable; (b) the red mark moves towards to the fixed end as the front face of the tunnel advances with a magnitude measured by a vernier caliper.

Fig. 12. Rebound at benchmark 0+2.50 m as a function of excavation face advancement

Fig. 13. Naming convention for strands of the tendon.

Fig. 14. Tensile force and displacement curves of the strands tested.

Fig. 15. Relationship between tensile strength and distance away the anchor head.

Fig. 16. Relationship between elastic modulus and distance away the anchor head.

Fig. 17. XRD diffraction diagrams of the different colorful corrosion products: (a) Sample 1 (gray powder); (b) Sample 2 (brown powder).

Fig. 18. Relationship between the average corrosion rate and anchor depth for the 20-year-old exhumed anchor in Manwan Hydropower project.

(a)

(b)

Fig. 1. Illustration of site and the location of the anchor exhumed:
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(a)

(b)

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(a)

(b)

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(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

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(a)

(b)

Fig. 7. Corrosion found at free length where grout cover was thin:

(a) Benchmark 0+6.50 m; (b) Benchmark 0+9.00 m.

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(a)

(b)

(c)

(d)

Fig. 8. Development of tendon corrosion after exposure to air: (a) original state of benchmark 0+4.00 m; (b) three days later of benchmark 0+4.00 m; (c) original state of benchmark 0+17.50 m; (d) three days later of benchmark 0+17.50 m.

(a)

(b)

(c)

Fig. 9. No longitudinal or transverse visible cracks within the cement mortar of the fixed end: (a) 0+18.50 m; (b) 0+21.00 m; (c) 0+23.50 m.

Fig. 10. Corrosion occurred at the anchor end.

Fig. 11. Measuring rebounds of the cable when it is dismantled: (a) set a base point on the wall and a red mark on the cable; (b) the red mark moves towards to the fixed end as the front face of the tunnel advances with a magnitude measured by a vernier caliper.

Fig. 12. Rebound at benchmark 0+2.50 m as a function of excavation face advancement.

Fig. 13. Naming convention for strands of the tendon.

(a)

(b)

(c)

(d)

(e)

Fig. 14. Tensile force and displacement curves of the strands tested

Note: the nominal diameter and length of the strands tested are 12.50 mm and 1200 mm, respectively.

Fig. 15. Relationship between tensile strength and distance away the anchor head.

Fig. 16. Relationship between elastic modulus and distance away the anchor head.

(a)

(b)

Fig. 17. XRD diffraction diagrams of the different colorful corrosion products: (a) Sample 1 (gray powder); (b) Sample 2 (brown powder).

Fig. 18. Relationship between the average corrosion rate and anchor depth for the 20-year-old exhumed anchor in Manwan Hydropower project.

Table 1 Chemical analyses of ground water

Component	Sulfate ion (by SO_4^{2-} for unit)	Chloride ions (by Cl for unit)	pH	Detection units
mg/L	180	2.64	7.56	Pony Testing
m mol/L	1.875	7.44×10^{-2}		
mass fraction	0.0179951% (by SO_4^{2-} for unit)	0.0002639% ((by Cl for unit)	/	(conversion)
mass fraction	0.0266178% (by Na_2SO_4 for unit)	0.0004349% (by NaCl for unit)	/	(conversion)
Specification required	<0.1(weak)	<0.02(weak)	6.50-8.50(mid)	

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Table 2 Measured retractions

Distance from the tunnel face (m)	Tendon exposure interval (hours)	Retraction measured at different points (mm)					
		0+2.00m	0+2.50m	0+3.00m	0+3.50m	0+4.00m	0+4.50m
7.2	0	0.00	0.00	0.00	0.00	0.00	0.00
7.2	54	3.00	3.00	3.00	3.48	3.30	2.38
8.2	94	5.20	6.80	5.50	6.10	5.90	4.00
8.2	118	7.86	8.14	7.70	6.84	8.28	6.44
9.3	143	11.42	12.00	11.00	12.50	12.10	10.00
9.3	175	13.80	13.60	12.20	13.40	13.80	11.10
10.5	191	15.60	15.58	14.14	15.96	15.90	13.50
10.5	209	16.14	16.78	15.58	16.48	16.28	13.90
11.7	231	17.80	17.56	16.90	17.38	18.86	16.50
11.7	258	18.58	19.50	17.80	18.10	19.26	16.90
12.8	275	19.20	20.00	18.44	18.90	19.60	17.30
12.8	297	21.40	21.50	20.50	21.26	22.60	19.70
14.0	328	21.28	22.62	21.62	22.20	23.00	20.10
14.0	347	23.86	24.60	23.20	24.30	24.56	21.70
14.9	396	25.14	25.36	24.00	24.90	25.00	22.10
14.9	421	26.60	26.80	26.90	26.38	26.86	23.60
15.7	445	27.00	27.90	27.40	26.70	27.90	24.50
16.3	468	27.90	28.40	27.80	27.80	28.50	25.10
17.4	515	29.10	29.10	29.10	29.12	29.20	25.80
17.4	539	29.50	29.70	29.60	29.60	29.70	26.20
19.0	588	30.40	30.28	30.00	30.30	30.90	27.30

Table 3 Results of tension tests of strands

Location	Specimen	Yield load(kN)[≥ 174.83]	Breaking load (kN)[≥ 219.52]	Tensile strength(N/m ²)[≥ 1470]	Extension (%) [≥ 3.5]	Elastic modulus(GPa)
Anchor head	J6-1-1.20	178.5	219.40	1570	7.00	195
	J1-1-1.20		213.06	1520	5.91	194
	J5-1-1.20	182.6	219.00	1560	7.00	202
	J8-1-1.20	181.2	220.90	1580	7.00	204
The free anchor length	J1-2-2.35		215.12	1540	7.29	183
	J1-3-3.50		215.51	1540	7.21	188
	J1-4-4.65		214.22	1530	6.69	191
	J1-5-5.80		215.97	1540	7.07	186
	J8-2-2.20	177.8	220.90	1580	7.50	204
	J8-3-3.20	178.5	219.40	1570	6.50	191
	J8-4-4.20	178.0	220.90	1580	7.50	201
	J6-2-2.20	180.5	215.80	1540	6.00	190
	J6-3-3.20	174.7	214.90	1535	6.50	185
	J6-4-4.20	180.2	216.30	1545	6.50	188
	J1-6-6.95		215.69	1540	7.00	174
	J1-B1-8.10		215.35	1540	7.03	192
	J1-B2-9.25		213.60	1530	6.19	187
	J1-B3-10.40		215.91	1540	7.62	189
Curved region in the free anchor length	J6-8-8.20.00	176.8	218.50	1560	7.00	194
	J6-9-9.20.00	178.5	218.50	1560	6.50	199
	J6-10-10.20	176.1	221.40	1580	7.00	192
	J8-7-7.20.00	179.5	221.40	1580	7.00	205
	J8-8-8.20.00	177.5	220.90	1580	7.50	199
	J8-9-9.20	180.4	221.40	1580	7.00	200
	J1-7-19.60		216.55	1550	7.20	195
	J1-8-20.75		215.75	1540	7.36	193
	J1-9-21.85		215.97	1540	7.47	191
	J6-19-19.20	186.3	221.90	1590	8.50	200
The fixed anchor length	J6-20-20.20	186.0	221.40	1580	8.00	203
	J6-21-21.20	183.6	219.40	1570	6.50	204
	J8-18-18.20	187.5	221.90	1590	7.00	195
	J8-19-19.20	187.9	220.90	1580	7.00	202
	J8-20-20.20	186.3	220.90	1580	7.00	196

Table 4 Chemical composition of the steel strand

Elements	Measured values(%)	Specified values for No. 80 steel ^a (%)
C	0.850	0.770-0.850
Si	0.250	0.170-0.370
Mn	0.680	0.500-0.800
P	0.014	≤0.035
S	0.034	≤0.035
Cr	0.024	≤0.250
Cu	0.058	≤0.250
Ni	0.022	≤0.300
N	0.005	≤0.080

^aIt refers to State Bureau of Quality Technical Supervision (1999).

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Table 5 The average corrosion rate for the 20-year-old exhumed anchor in manwan hydropower project

Serial number of the strand	Surface area of the strand A_0 [cm ²]	Mass of the strand after pickling w_t [g]	Original mass of the single strand w_0 [g]	Mass loss rate of the corroded strand [g/cm ² /y]	Thick loss rate of the corroded strand [mm/y]
1m-1	6.74	6.4669	7.0799	4.55E-03	5.83E-03
1m-2	6.69	6.1949	6.8502	4.90E-03	6.28E-03
1m-3	6.69	6.1787	6.8502	5.02E-03	6.44E-03
1m-4	6.52	6.1408	6.6831	4.16E-03	5.33E-03
2m-1	6.43	6.1607	6.7523	4.60E-03	5.90E-03
2m-2	6.21	5.8730	6.3656	3.97E-03	5.08E-03
2m-3	6.37	5.9487	6.5272	4.54E-03	5.82E-03
2m-4	6.45	6.0540	6.6051	4.27E-03	5.48E-03
6m-1	6.80	6.5673	7.1443	4.24E-03	5.44E-03
6m-2	6.58	6.2953	6.7388	3.37E-03	4.32E-03
6m-3	6.52	6.1888	6.6831	3.79E-03	4.86E-03
6m-4	6.54	6.2819	6.6998	3.20E-03	4.10E-03
7m-1	6.51	6.3329	6.8400	3.89E-03	4.99E-03
7m-2	6.36	5.9620	6.5160	4.36E-03	5.58E-03
7m-3	6.36	5.9385	6.5160	4.54E-03	5.82E-03
7m-4	6.35	5.9785	6.5104	4.19E-03	5.37E-03
11m-1	6.74	6.6766	7.0799	2.99E-03	3.84E-03
11m-2	6.69	6.3949	6.8502	3.41E-03	4.37E-03
11m-3	6.75	6.3502	6.9170	4.20E-03	5.38E-03
11m-4	6.69	6.4349	6.8502	3.11E-03	3.98E-03
12m-1	6.57	6.3767	6.9044	4.01E-03	5.15E-03
12m-2	6.52	6.2101	6.6831	3.63E-03	4.65E-03
12m-3	6.36	6.1283	6.5160	3.05E-03	3.91E-03
12m-4	6.46	6.1332	6.6218	3.78E-03	4.85E-03
13m-1	6.55	6.4310	6.8751	3.39E-03	4.35E-03
13m-2	6.49	6.1397	6.6552	3.97E-03	5.09E-03
13m-3	6.33	6.0843	6.4882	3.19E-03	4.09E-03
13m-4	6.44	6.0179	6.5996	4.52E-03	5.79E-03
14m-1	6.86	6.6820	7.2087	3.84E-03	4.92E-03
14m-2	6.70	6.2271	6.8613	4.74E-03	6.07E-03
14m-3	6.73	6.3593	6.8947	3.98E-03	5.10E-03
14m-4	6.72	6.2505	6.8836	4.71E-03	6.04E-03
15m-1	6.74	6.5640	7.0799	3.83E-03	4.91E-03
15m-2	6.63	6.1155	6.7889	5.08E-03	6.52E-03
15m-3	6.61	6.2080	6.7778	4.31E-03	5.52E-03
15m-4	6.61	6.2064	6.7722	4.28E-03	5.49E-03
16m-1	6.76	6.5793	7.0975	3.83E-03	4.92E-03
16m-2	6.69	6.3545	6.8557	3.75E-03	4.80E-03
16m-3	6.66	6.2334	6.8279	4.46E-03	5.72E-03
16m-4	6.69	6.2471	6.8502	4.51E-03	5.78E-03
18m-1	6.94	6.7425	7.2847	3.91E-03	5.01E-03
18m-2	6.77	6.4392	6.9337	3.65E-03	4.68E-03
18m-3	6.77	6.3883	6.9337	4.03E-03	5.17E-03
18m-4	6.79	6.4077	6.9560	4.04E-03	5.18E-03