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Conservation of Jiaohe ancient earthen site in China

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Abstract: Earthen sites, which are mainly made of earth, are cultural heritages with historical, artistic and scientific values. Many extremely valuable earthen sites have been preserved in the arid areas in China. The earthen site of Jiaohe Ancient City is one of the earliest National Protected Important Cultural Heritage Sites. The Jiaohe Ancient City site exhibits all kinds of deteriorations, which can be found in the earthen sites in arid environments in China. Through a case study of the Jiaohe ancient earthen site, we present in this paper the comprehensive conservation technologies, including the mud bricklaying and reparation, wooden rod anchorage, crack grouting, surface potassium silicate (PS) penetration consolidation, and suspended steel beam ceiling, etc. Results of this case study showed that better conservation effects could be achieved by selecting proper PS penetration and crack grouting processes based on the deterioration characteristics of the earthen sites. The technology of mud bricklaying and reparation was also an effective method for preventing the earthen body from collapsing. Compared with traditional conservation technologies, the suspended steel beam ceiling technology could effectively reduce the negative impacts to the original state of the earthen site. As for unstable cliffs, a new method using composite anchor rod of bamboo and steel with massive loose earth was applied. Deformation monitoring and temporary supports were critical and indispensable measures for the safe of site conservation projects. Through years of monitoring and practical operation at the Jiaohe ancient earthen site, deterioration at the site has been effectively controlled.

Key words: earthen site; conservation technology; Jiaohe Ancient City; arid areas

1 Introduction

Earthen sites, mainly made of earth (soils and clays), are cultural heritages with historical, artistic and scientific values. Earthen sites can be observed across China and most of them are located in arid Northwest China. For instance, the famous earthen sites include Jiaohe Ancient City, Gaochang, Loulan and Niya sites in Xinjiang Uygur Autonomous Region; the Great Wall remains and Beacon Towers in Gansu Province; the Royal Tombs of Western Xia in Ningxia Hui Autonomous Region; and the Lajia site and Liuwan site in Qinghai Province.

Since 2006, enormous investigations have been carried out at the Jiaohe ancient earthen site for conservation. The investigations covered deterioration conditions and their mechanisms [1–17], consolidation materials [18–26], conservation approaches and technologies [27–29], and consolidation mechanisms [29–34]. The conservation materials and techniques for the earthen sites in arid areas have been developed drastically through numerous researches. However, they have to be tested and verified at the sites. On the basis of these studies, certain research results have been successfully applied to conservation of the Jiaohe ancient earthen site. Furthermore, a comparative analysis of the effects of these conservation methods was made through relevant testing methods. Based on previous studies as well as conservation practices at the site of Jiaohe Ancient City, we summarized conservation theories, technologies and processes for the earthen sites in arid environments in this paper. The principles, methods and techniques of these technologies are also given. They can also serve as important guidelines for conservation of earthen sites in China.

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2 General description of the Jiaohe ancient earthen site

Jiaohe Ancient City is one of the national protected important cultural heritage sites announced by the State Council of China in 1961. The site is located at Yaernaizigou Village, 10 km west of Turpan City. The architectures of the site mainly consist of buildings and cave dwellings. The buildings are mainly composed of rammed earth building, dug from earth building, mud stack building, mud brick block building, and raw soil block building. The construction materials were basically locally acquired. The cave dwellings can be divided into mountain caves, ground caves, and tunnel caves. The ceilings of caves are mostly composed of irregular shaped arches, flat, and domes. Some of them have a truncated pyramidal ceiling. The dimensions of the site are roughly square, round or almost round.

The Jiaohe ancient earthen site is located on land terrace II, a tableland of a willow leaf shape between two rivers. The tableland is about 30 m high, trending in WN-ES direction. The direction of striking is 320° (Fig.1). The altitude of northwestern region is 80.64 m above the sea level. The southeast side is 42.95 m above the sea level. The longest length from north to south is 1 787 m, and the widest width from west to east is around 310 m. The cliff face with almost 90° steep slope borders the tableland.

Fig.1 Panorama of Jiaohe Ancient City.

The main building materials of the Jiaohe ancient earthen site are silty soil and silty clay with minor water content (usually 1%–3%, mostly 2%), and their physical properties are listed in Table 1. The building materials usually contain 80% of fine particles. The variation in particle constituents of mud stack is diversified and their grading is bad.

The grading of raw soils and rammed soils is comparatively good. The mineral content of earthen materials at the site mainly includes quartz, calcite and feldspar. Compared with fresh earth at depth, the weathered surface layer earth has lower calcite and higher feldspar in content. The chemical constituents are Si, O, Ca, Fe, Al, K, Mg, etc. The Na, S, and Cl of surface layer are relatively higher than those at depth. The cations are mainly Ca^{2+}, Na^+ and K^+ with fairly high content. Soluble salts in the building materials are mainly sulfate, chloride, and nitrate and there is almost no carbonate. The soluble salt content on the surface of wall is higher than that in the sample collected 10 cm deep inside the wall. The soluble salt content at the upper part of wall surface is lower than that at the lower part of wall surface. The raw soil has the highest concentration of soluble salts followed by the ramming soil and then the stack mud. The variation in mechanical indicators and strength of soils is fairly large. The cohesion of raw soil is 98–359 kPa and the friction angle is 28.9°–61.9°. The compressive strength is 1.49–4.25 MPa in the vertical direction and 1.05–3.76 MPa in the horizontal direction. The tensile strength is 0.42–0.76 MPa in the vertical direction and 0.34–0.68 MPa in the horizontal direction. The disintegration speed is 10–30 g/min. The wave speeds of different earth bodies are variable (Table 2). The velocity of Rayleigh wave (V_R) of silty clay is 300–350 m/s, and that of silty soil is 250–300 m/s. The stratum of fine silty sand is fairly loose, and its V_R is 150–200 m/s, lower than those of silty soil and silty clay, but that of sand-pebble layer is 350–500 m/s.

In this region, it is hot and dry in summer, dry and cold in winter. The highest temperature is 47.4 °C, the lowest is −28 °C, and the annual average temperature is about 35 °C. The high temperature can last for 99 days, where there can have 36 days with temperature over 40 °C, and the extreme ground surface temperature can reach 82.3 °C. Thus, the difference in temperatures is large. The maximum annual precipitation is 48.4 mm, and the minimum is 2.9 mm, with an annual average of 16.2 mm. The wind direction is mainly NW, and the maximum wind speed can be over 40 m/s.

Table 1 The physical properties of the soils from Jiaohe ancient earthen site.

Water content (%)	Specific gravity	Dry density (g/cm^3)	Void ratio	Liquid limit (%)	Plastic limit (%)	Plastic indicator	Crumbling speed (g/min)
1–3 (mostly 2)	2.7–2.72	1.42–1.72 (mostly around 1.6)	0.57–0.92 (mostly around 0.7)	23.5–31.65 (mostly 27–30)	15.05–21.56 (mostly 17–19)	≈ 10	10–30

Table 2 Wave speeds of different earth bodies.

Earthen body	Wave speed (m/s)	
	Horizontal	Vertical
Stack mud	992–1 494 (mostly 1 091–1 233)	1 191
Earthen body with fairly serious weathering condition	606–680	962
Fresh earthen body	1 102–1 113	1 134–1 146
Interbedding of silty sand and silty soil	966	511
Middle and fine sand	393–428 (average 417)	374–418 (average 391)
Ramming soil	—	688–774
Abode of Great Buddha Temple	1 103–1 403	—
Masonry mortar between abodes of Great Buddha Temple	628	854

3 Main deterioration mechanisms of Jiaohe ancient earthen site

3.1 Deterioration types at the site

According to site investigations, deteriorations at the Jiaohe ancient earthen site are caused by natural forces and human activities. The natural deterioration types consist of exfoliation, erosion, gulling, cracking and biological destruction. The exfoliation is caused by rain erosion and wind deflation. The erosion is caused by disruption and wind abrasion. The gulling is mainly of a runoff type. The cracking types consist of relief fissures, structure fissures, deformation fissures and building structure cracks. The biological destructions are mainly caused by animal and vegetation. The above mentioned mechanisms basically cover all 11 deterioration types found in the earthen sites. Among the 11 types, exfoliation, cracking and erosion are the major types of deterioration, where wind and severe rainfall are the main impact factors of deterioration.

3.2 Geological deterioration of the cliff (tableland) of Jiaohe Ancient City

The main deterioration mechanism of the cliff at Jiaohe Ancient City is collapsing, which mainly includes slumping, block sliding and toppling over. Three sets of joints can be observed in the whole area of cliff. The NE set has strike angles of 15°–35°, averaging 25°, and its inclination angle is nearly vertical. The NNW set has strike angles of 310°–330°, averaging 325°, and the inclination angle is also near vertical. The NWW set has a striking of 275°–295°, with an average of 285°, and the inclination angle is almost vertical. The two sets, defined with striking of 25° and 325°, are fully developed, followed by the set with a strike angle of 285°. A set of relief fissures parallel to the strike of the cliff can be observed. Its occurrence is NW with a mean strike angle of 328°, and the inclination angle is nearly vertical. These fissures are the main causes of cliff collapsing.

4 Stabilization techniques for the earthen sites

4.1 Reinforcement techniques for the main physical body of earthen sites

4.1.1 *Mud bricklaying and reparation techniques*

The mud bricklaying and reparation techniques are mainly employed to the earthen sites that have been subjected to severe undercutting but still have unstable suspended portions with space underneath for adding reinforcement supports. At this site, the areas were supported and filled by mud bricks made with the same material used at the site. Minimum intervention to the sites should be considered while implementing the reinforcement measures to prevent them from further erosion and collapsing.

The mud bricks were fabricated by using soil with less than 0.5% soluble salt content that was similar to the soil used at the site. Local clay with soluble salt content lower than 0.5% was crushed, sifted (diameter less than 0.6 mm), and then mixed with molar ratio (SiO_2 to K_2O) of 3.7–3.8 and 3% concentration of PS to develop the stabilization mixture with water to ash ratio of 0.4. During reinforcement, small bamboo nails 5–10 mm wide and 100–200 mm long were used. The longitudinal and transversal spacings were both no less than 200 mm, and the depth of the hole was 40 mm. In order to improve the adhesive forces between main body and mud bricks for bricklaying and reparation, the areas with large openings were filled with certain types of structural materials, such as steel and wooden frames. Through detailed investigations on colors, shapes, structures and other surface appearances of the reinforced body, the final reparation measures were implemented (Fig.2) to be in harmony with the original appearances of the reinforced body.

(a) During reinforcement.

(b) After reinforcement.

Fig.2 Great Buddha Temple of EW4 during and after reinforcement.

4.1.2 *Anchoring techniques*

Generally, anchor bamboos or wooden rods with diameter ϕ 35–50 mm, wall thickness of 0.5–1.0 cm (Fig.3) and water content not greater than 3.0% were used at this site. The tensile strength of a single bamboo or wooden rod was not less than 10.0 kN. Holes of 50 mm in diameter were drilled with a helical auger and the inclination angle was no more than 5° (Fig.4). The mortar was prepared by mixing molar ratio of 3.7 and 10% concentration of PS, and fine particle soil. The water to ash ratio was 0.5–0.6. Upon the completion of drilling, 5% concentration of PS solution with molar ratio 3.8 was injected into the holes for consolidation. During construction, the mortar was poured into the holes firstly, and then the anchor rod was inserted to a proper position. After insertion of the rod, the holes were sealed with a mixture of PS (molar ration 3.7, 10% concentration) and silty soil. The water to ash ratio of the mixture was 0.3–0.4.

Fig.3 Wooden anchor employed for reinforcement of earthen site.

Fig.4 Pre-drilling anchor holes before sealing.

4.1.3 *Grouting techniques for cracks*

According to the characteristics of cracks at Jiaohe Ancient City, three types of consolidation procedures were implemented. They were microcrack and small cavity consolidation, small crack consolidation, and penetrated crack consolidation measures. The grouting materials for crack consolidation was prepared with silty soil and PS (molar ratio 3.7 and 3% concentration) solution, and at the same time, kept the soluble salt content less than 0.5%. According to the scale of the cracks, grouts with different water to ash ratios were developed, generally 0.3–0.6. During the consolidation process, cracks were sprayed with a PS solution (molar ratio 3.8 and 5% concentration) once or twice to reinforce its strength at both sides. The microcrack was filled with the prepared grout using a 5–10 mm size of restoration scalpel. As for small and penetrated cracks, firstly the injective catheter was inserted and the crack was sealed on surface, then the PS-C grout was injected through the injective catheter from bottom to top. If the crack was fairly narrow and small, the water to ash ratio was appropriately increased to reduce the viscosity of the grout, thus to ease the injection process. According to the actual condition, the quantity of the injected grouting material shall be properly controlled. Usually, the grout injection was selected at different spacings to prevent over-filling. Upon completion of injection, the injective catheter was pulled out. Then, a prepared mortar of PS solution (molar ratio 3.8 and 3% concentration) and silty soil with water to ash ratio of 0.3–0.4 was used to seal the injection holes. Figure 5 exhibits the south facade of northeastern temple S5 before and after consolidation.

(a) Before consolidation.

(b) After consolidation.

Fig.5 The south facade of northeastern temple S5 before and after consolidation.

4.1.4 *Surface weathering preventive consolidation*

The PS consolidation methods for the weathered surface layer at earthen site mainly consist of surface spraying and drip penetration. Depending on the site and its deteriorations, one or a combination of both methods can be applied. PS concentration was kept at 3%–7%. If the sprayed area is small, a manual atomizer can be used, or even intermittent spraying. If the sprayed area is large, it will be sprayed with an electrical atomizer.

(1) Surface spraying

Depending on the weathered condition of surface layer of physical body at the earthen site, 1–3 times of spraying PS consolidation may be needed. The second and third times spraying should be properly conducted after completely drying of the first sprayed PS solution. The spraying method should be exactly the same as that used in the first time spraying. The interval between spraying was about 2–3 days, and the appropriate air temperature for spraying should be kept at 25 °C.

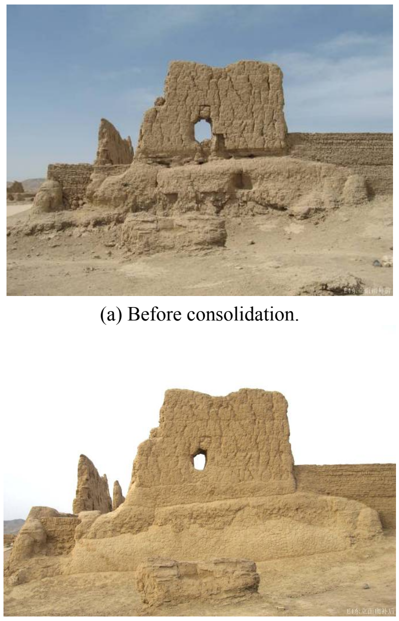
One time spraying with 5% PS solution was considered to consolidate a fairly compacted earthen body, which doesn't have serious weathering and has a fairly thin weathered layer (usually below 0.5 mm), some fine cracks on the surface, high internal wall strength, and good PS solution penetration.

PS solution was sprayed twice to consolidate the surface of the earthen body having seriously weathered surface with fairly large pores. And the weathered loosened layer has uneven thickness (with the maximum thickness not exceeding 2 mm) and thick weathered surface areas exhibit exfoliation stripping. It was firstly sprayed with a 3% PS solution. After the first sprayed PS solution was completely dried and solidified, a 5% PS solution was sprayed.

If the surface weathering of the earthen body was extremely serious, and the pores in the surface layer were fairly large and loose, spraying 7% PS solution for the third time was needed. This final spraying treatment was to ensure a good protection against wind and rainfall erosions.

(2) Drip penetration

If the weathered surface layer of an earthen body was loose and thick, a large size of syringe needle was directly inserted into the loose strata to increase the height of PS solution. The drip penetration could be conducted via the pressure caused by different water levels. If the surface layer of an earthen body was compact but the inner layer was loose, small holes must be drilled on the surface of the earthen body with a small electrical drill. Then, a large size of syringe needle or a small size of catheter could be inserted into the earthen body for conducting drip penetration. Some surfaces have a great loose thickness and broken blocks due to weathering, and then it would be difficult to drill a complete hole for conducting drip injection. Sometimes the drilling process might cause damage to the surface layer. In these cases, the surface layer of the earthen body should be sprayed with PS solution once firstly to enhance the integrity of the loose surface. Then, holes were drilled and the drip penetration was carried out by using a 5% PS solution. When the integrity of the surface layer cannot be guaranteed, the surface of the earthen body was firstly sprayed with 5% PS, and then it was bored before drip penetration. After drip penetration, 5% PS solution can be sprayed one more time to improve the consolidation of local areas. Figure 6 shows the east facade at Great Buddha Temple E4 before and after consolidation.



(a) Before consolidation.

(b) After consolidation.

Fig.6 The east facade at Great Buddha Temple E4 before and after reinforcement.

4.1.5 *Reinforcement of a suspended ceiling with steel beam*

Cracks have been developed drastically in caves at Jiaohe Ancient City. Very often, cave top was split into several separated blocks by cracks. Gravity pull and/or other external forces caused caves to collapse (Fig.7). Aiming at the above mentioned situation, if a traditional method would be applied to support or jack and repair, it would cause a great negative impact on the original appearance of the cultural heritage sites.

(a) Before consolidation.

(b) After consolidation.

Fig.7 West cave opening of the official building before and after consolidation.

Utilizing the suspended steel beam ceiling method could effectively preserve the original appearance of the caves, in which the inner force would be transferred to the stable parts of the cave through steel beams. Therefore, anchor rods or other measures could be taken to improve the integrity and ensure the stability of the site (Fig.8).

(a) Before consolidation.

(b) After consolidation.

Fig.8 Doorway of the official building before and after consolidation.

4.2 Stabilization techniques for cliff face of Jiaohe Ancient City

4.2.1 *Establishing a deformation monitoring system*

Most of the cliff faces of Jiaohe Ancient City were in a critical status; even a small disturbance from reinforcement process may incur collapse of the site. A dynamic monitoring system for the cliff face stability should be considered throughout the entire process of slope reinforcement.

During implementation, the simple observation piles, dial indicator monitoring equipment, automatic crack extensometer, and automatic deformation monitoring equipment were employed to monitor the consolidated sections. They effectively protected the safety of the cultural heritage site and the operational staff. The data from the deformation monitoring system showed that the cliff faces appeared to have three different deformation characteristics as follows.

(1) Deformation stable for normal implementation

This type of deformation had the following characteristics: (i) Cliff face was stable and could withstand disturbance from normal implementation. Once deformation occurred, cliff face could self-recover to a stable status within a short period of time. (ii) The status of the cliff face and its surrounding conditions were suitable for implementing temporary support, and thus providing a great safety margin to prevent large deformation of the cliff face during implementation process. In fact, most of the consolidated areas belong to this type.

(2) Deformation leads to the stop of implementation and implementation can be continued after stable deformation

This type of cliff face had the following characteristics: (i) Deformation suddenly emerged at local section of a cliff face. (ii) Deformation occurred in areas with many cracks and the cliff face was fairly broken, but had certain resistance capacity. (iii) Surrounding the cliff faces, there was no place for setting up temporary support to ensure safety. (iv) It is mainly concentrated on the middle and upper parts of the cliff face. (v) Deformation occurred when implemented anchoring at the upper part of cliff face.

During the installation of the first row of anchoring rods in area No.49, there was 4 mm displacement at the top of the cliff face detected by automatic crack deformation monitoring meter. The displacement could also be visually identified (Fig.9). The implementation was stopped immediately, and the staff and machinery were evacuated from the site. The consolidation work was arrested for a half day until the displacement of the monitored section gradually recovered to its original state. In the subsequent implementation, initial effective consolidation of the precarious cliff face was achieved, followed by the consolidation of the entire cliff.

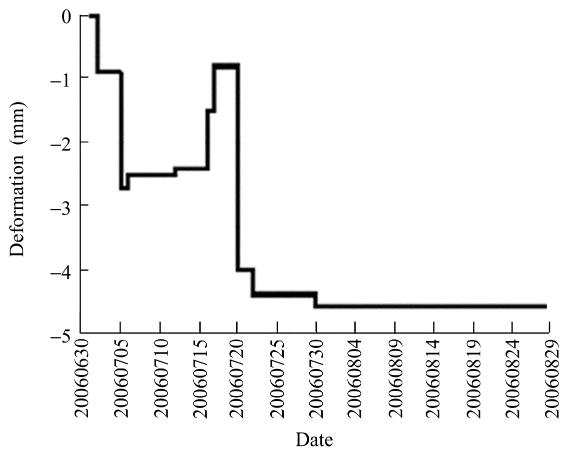


Fig.9 Continual monitoring deformation curve at time.

(3) Sudden changes in deformation surely arrest operation, and implementation can be continued only after further safety measures are taken

A cliff face of this type had the following characteristics: (i) Sudden deformation changes were concentrated on local section instead of a large area of the cliff face. (ii) The cliff face of this type was cross-cut by different types of cracks, and the width of crack opening was mostly above 10 cm. (iii) The cliff face itself was in a critical status. (iv) The temporary support could provide certain safety margin, but with a limited capability. (v) The anchorage was often to be carried out on the upper part of the cliff face.

The representative cliff face was in area 57-3. When the anchorage of the first row started, the displacement of 2 cm on the top of the cliff was detected immediately by the automatic deformation monitoring meter and it also could be observed visually (Fig.10).

The implementation was stopped immediately, and staff and machinery were evacuated. In order to prevent the tipping of scaffolding if the cliff collapsed,

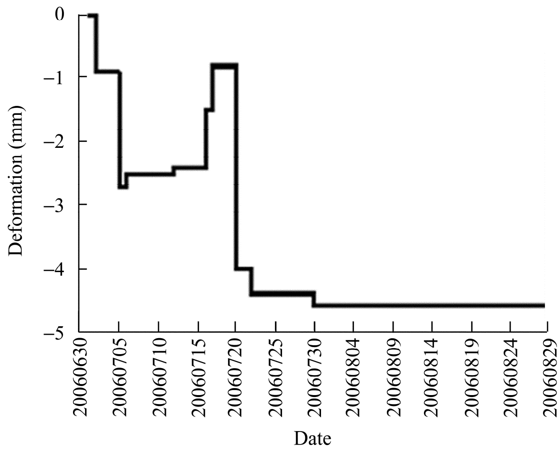


Fig.10 Deformation curve monitored by automatic deformation monitoring meter in the area 57-3.

model 14 channel steel was installed behind the scaffolding, which was connected to an existing anchor rod in the cliff face, to improve anti-tipping capability of the scaffolding. Cable ropes were added for temporary support in the local unstable cliff face, and the deformation monitoring frequency was increased. After 2 days of rest and the additional support measures, the deformation in the cliff face was reduced. In the subsequent construction, the reinforcement of the surrounding precarious cliff face was carried out firstly, and then the reinforcement of the other parts was followed.

4.2.2 *Temporary support*

According to site characteristics of Jiaohe Ancient City, the utilization of temporary supports effectively prevented failure or large deformation of the cliff face. With site-specific topographies, two measures were utilized, i.e. the unstable cliff face was temporarily supported by anchor rods, steel wires, ground anchor rods, and steel wires. After several years' experiences of conservation, a scheme of temporary support was gradually formulated as follows:

(1) According to the strike and appearance of the cliff face, the ground anchor was inserted in the cliff top. The ground anchors were then connected by a steel wire to enclose the upper part of the cliff face.

(2) For unstable cliff face, an additional method could be adopted, i.e. a special ground anchor was used to connect the steel wire rope and hold the upper part of the cliff face together.

(3) The middle and upper parts of the cliff face were drilled with temporary anchor holes, which were reinforced with steel anchor rods and connected with steel wire rope to protect unstable cliff face from collapsing.

(4) As for local part with severe recession, it was

supported and jacked by channel steel to ensure the stability of upper part of the cliff face during reinforcement.

4.2.3 *Anchorage of a composite anchor rod (bamboo plus rod)*

The composite anchor rod anchorage (bamboo plus rod) was one of the essential engineering measures for reinforcement of cliff face at Jiaohe Ancient City. The effectiveness of reinforcement depended on the reinforcement qualities of the composite anchor rod and bamboo plus rod. The theory of anchorage with anchor rod was consistent with that of a slope anchorage, providing tensile force against outward-tipping of cliff faces and shear resistance against downward-slumping. Bamboo and rod were bound at a full length, and the strength of composite anchor rod was close to the strength of the surrounding earthen body. Thus, ideal deformation coordination could be anticipated. Furthermore, the strength between rod body and cement mortar met the requirements of anchorage force. Compared with other anchor rods, the composite anchor rod had the features of appropriate diameter, light weight, low cost and moderate strength, and it was appropriate for consolidating loose earthen body.

The bamboo, which was straight with a diameter of 90–100 mm, was selected and cut into two equivalent parts. It was opened to remove the film inside, and the inner surface was washed with epoxy resin. Then, it was cut to the required length of anchor rod. The inner surface of the bamboo was evenly coated with alcohol diluted epoxy resin with added curing agent. Epoxy resin, alcohol, curing agent, asbestos, coal ash, and pre-cut steel strand of d = 15 mm (7ϕ5 mm) were used to fill half of the bamboo. For anchor rod with length not greater than 5 m, one piece of steel strand was placed; for that with length over 5 m, two pieces of steel strands were employed. Then, the two halves of the bamboo were put back together. Every 20 cm, they were tied together with a gauge 10 iron wire. Finally, the rod was placed in a shade place for 6–7 days until the filling was completely solidified. After that, the anchor rod was wrapped with two layers of fiber glass, and each layer of glass fiber was coated with the epoxy resin, curing agent and alcohol mixture. After 24 hours, the composite anchor of bamboo plus rod was completed. As for the hole, a HQD110-type electrical down-hole drill was used, and the earth residue was discharged by Ingersoll-Rand 750 air compressor during borehole drilling. The diameter of final hole was 150 mm, and the inclined insert angle was 15°. The grouting equipment is Tongda JZB-2 extrusion grouting pump, whose maximum operating pressure was 3 MPa. The horizontal transportation and vertical conveyance distances of grouting pump of this type were 100 and 50 m, respectively. The mortar output capacity was 1.4–2 m^3 per hour. When it crossed a wide crack, a ϕ150 mm PVC sleeve was put on top of the crack to prevent mortar from leaking. The mortar was mixed with the cement, sand and water ratio of 1:1:0.43.

Before grouting, 5% PS solution was used to pre-reinforce the wall of the borehole. This also promoted the bonding of the anchorage and the loose and soft earthen bodies. Then, hoisting tools, such as pulley, were used to insert the anchor rod into the preset position. As for a long anchor rod (length over 10 m), it had a massive weight, thus installation should prevent any damage to the anchor rod.

Finally, the borehole was sealed with 3% PS solution mortar containing 10% hemp fiber, then the soil block was embedded in the mortar, and it was coated again with a layer of hemp fiber mortar for the second time to achieve the “appearing-old” purpose (Fig.11).

Fig.11 Anchor hole with completion of old treatment.

4.2.4 *Reinforcement of support by channel steel*

The composite anchor rod had good tensile strength but its shear resistance was slightly low for consolidation of slumping and heavily undermined cliffs. High shear resistance was required to prevent slumping and sliding deteriorations. Channel steel, which had large contact area and good mechanical performance, was effective for such reinforcement. Furthermore, it was invisible and met the guidelines of China’s principles. Supporting and jacking of channel steel in area 36-1 before and after reinforcement are shown in Fig.12.

(a) Before reinforcement. (b) After reinforcement.

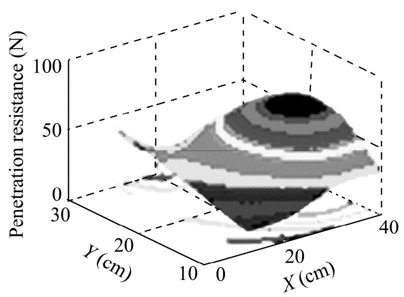
Fig.12 Supporting and jacking of channel steel in area 36-1 before and after reinforcement.

5 Inspection and assessment of consolidation effects

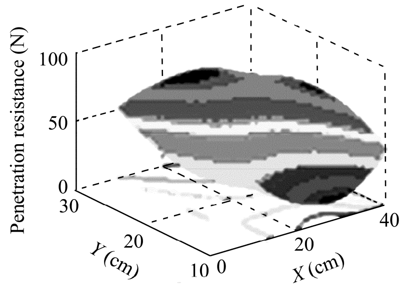
5.1 Assessment of effects of surface consolidation with PS solution

Effectiveness of surface consolidation measures was tested on site by touching, spraying water, and blowing the surface with an air compressor. Slightly shaking the small protruded block (or piece) by hand, there was no apparent loosening; slightly tapping the wall surface, there was an apparent increase in the strength of the wall. The water flow from the sprayed area was clean without the presence of mud, and when one touched the sprayed area, there was no mud clinging to hand. But the water flow from the untreated area was muddy and there was mud/sand clinging to hand upon touching. These indicated that resistance of the surface to rainfall erosion was increased. If air was blown to the surface of the wall with an air compressor, there was no shedding of residues, which indicated that the resistance to wind erosion was also increased.

In addition, a micro penetration meter was used to check the effectiveness of consolidation of PS material (Fig.13). From Fig.13, it was observed that the penetration value of wall body was increased after consolidation, which illustrated that the consolidation was effective.



(a) Before consolidation.



(b) After consolidation.

Fig.13 Test results of micro penetration meter.

5.2 Assessment of grouting effect on cracks controlling in the main body of the earthen site

The direct wave method was employed to carry out the comparison test of a wall body before and after reinforcement. The results are listed in Table 3. The wave speed V_P reflects the strength of a wall body to some extent. It can be seen that the wall body after reinforcement has been improved.

Table 3 Wave speed test result before and after reinforcement of wall body of the earthen site.

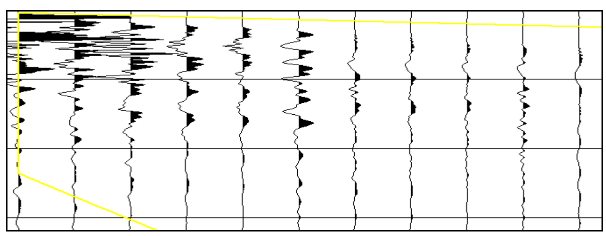
No.	V_P (m/s)	
	Before reinforcement	After reinforcement
1	352	532
2	296	516
3	314	501
4	303	485
Average	316	509

5.3 Grouting effect on the main body at earthen sites

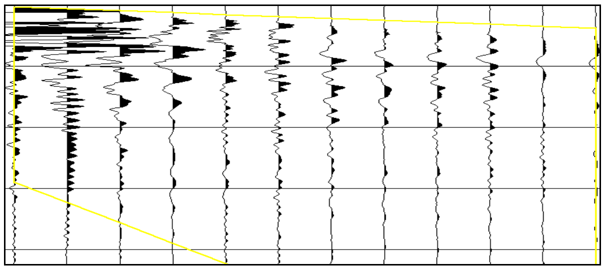
The Rayleigh surface wave prospecting technology, artificial seismic inspection, electrical prospecting, etc., were used to examine and assess the grouting quality at Jiaohe Ancient City.

5.3.1 *Rayleigh surface wave prospecting technology*

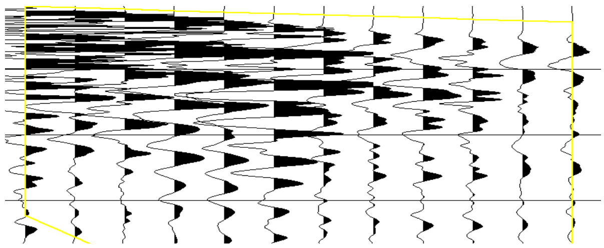
Figure 14 shows that before grouting, surface wave energies were attenuated during passage through the cracks. Only very low wave intensity was recorded.



(a) Before grouting.



(b) 6 hours after grouting.



(c) 30 hours after grouting.

Fig.14 Wave forms of grouting inspection of cliff top at various times.

Six hours after the completion of grouting, the wave form exhibited little variation. This insignificant change might result from that the mortar grouting was not totally cured yet. However, 30 days after the completion of grouting, intense continuous waves were recorded during inspection. This meant that the grouting material had successfully sealed the cracks.

5.3.2 *Artificial seismic wave test*

On the upper part of cliff face, a large number of cracks parallel to the surface of the cliff were observed. In order to evaluate the reinforcement effect of grouting, an artificial seismic wave test 4 m away from the site was carried out, and the test results were listed in Table 4.

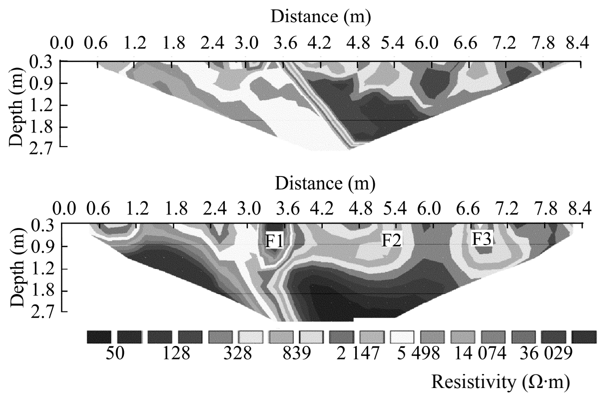
Table 4 Test results of grouting effects on cliff face with an artificial seismic load.

Crack No.	Distance from hammer blow point to measuring point (m)	Pulse amplitude ratio		Evaluation of grouting effect
		Before grouting	After grouting	
F1	1	0.05	0.76	Good
	2	0.03	0.74	
	3	—	0.61	
	4	—	0.58	
F5	1	0.03	0.78	Good
	2	0.09	0.70	
	3	—	0.65	
	4	—	0.61	
F9	1	0.02	0.88	Good
	2	0.02	0.83	
	3	—	0.75	
	4	—	0.70	

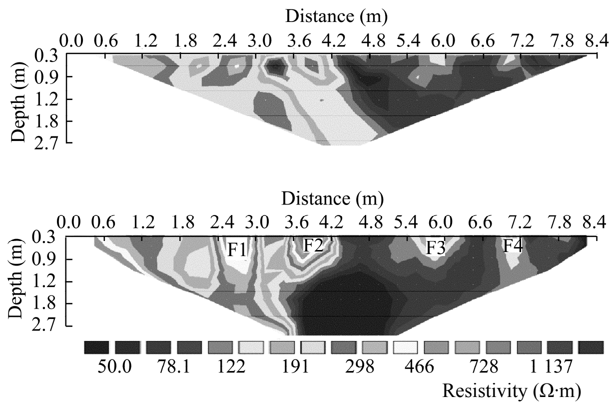
The test results showed that after grouting with PS-(F+C) (where PS is the PS solution, F for coal ash, and C for clay), the pulse amplitude ratios at test points on both sides of a crack were increased, which meant that grouting was effective and the cracked cliff face was consolidated.

5.3.3 *Electrical resistance detection*

High-density resistivity method was used to measure the changes in stratum resistivity (Fig.15). From Fig.15, it was observed that the resistivity forms of cracks and sand layer before and after grouting were exceptional. Before grouting, the crack F1 was wide, and its vertical depth was great. The value of resistivity was as high as (3–6) × 10^4 Ω·m. The resistivity of other small cracks was also very high. After grouting, the resistivity of separated blocks at the edge of the cliff and the shallow stratum was lowered to some extent, and the resistivity along the cracks had also been changed. The resistivity of crack F1 was lowered to several hundred Ω·m and that of F2 was lowered to approximately 1 000 Ω·m, while those of cracks F3 and F4 were only 200 Ω·m. Since the size of the crack was smaller than electrode distance, the resistivity of the cracked area was in fact the composite resistivity of crack and the surrounding stratum. The actual crack resistivity was less than the resistivity of consolidated mortar. According to test results, it can be seen that the grouting was effective.



(a) Before grouting.



(b) After grouting.

Fig.15 Distribution and comparison of apparent resistivity (upper) and inversion resistivity (low) before and after grouting.

5.4 Evaluation of anchor rod quality

Through the anchor pullout tests, the *Q*-*S* curves of composite anchor rods, with lengths of 5, 10 and 15 m, respectively, were analyzed. Under the test loads of 90, 120 and 150 kN, the deformation of anchor head and the pulling displacements of composite anchor rods with various lengths tended to be stable. Based on calculation and the stable performance of the rods under heavy loads, it was believed that there was no slipping (1) between anchor rod and composite material, (2) between composite material and bamboo, (3) between bamboo and cement mortar, and (4) between cement mortar and earthen body. Fifteen 5 m-long composite anchor rods, fourteen 10 m-long composite anchor rods and thirteen 15 m-long composite anchor rods were tested and all of them were validated.

5.5 Comparison of case report

On March 21, 2008, an earthquake with magnitude of $M_s = 7.3$ occurred at 6:33 AM in Khotan of Xinjiang Uygur Autonomous Region. As a result, the cliff section in the east of northern tableland, which was not consolidated, collapsed with about 200 m^3 debris (Fig.16). While the originally unstable cliff face was kept intact due to the effective consolidation. According to the analyses of long-term deformation monitoring data and operative conditions, the site has been effectively protected after consolidation.

Fig.16 Collapse of cliff face in the east of northern tableland due to impact of seismic load (without conservation).

6 Conclusions

Focused on the deteriorations of ancient earthen sites, various techniques have been employed for the consolidation of Jiaohe ancient earthen site. By summarizing these engineering measures, this paper presents the comprehensive conservation techniques for the Chinese earthen sites in arid environments. After years of experiments and practices, the deterioration of this site has been controlled effectively.

(1) The consolidation techniques for earthen sites include mud bricklaying and reparation, wooden anchor rod anchorage, crack grouting, surface PS penetration consolidation, and suspended steel beam ceiling, etc.

(2) The technique of mud bricklaying and reparation is an effective method for preventing collapse of the main earthen body. Appropriate dimensions, proper replica-making treatment, reinforcement rods and compact connection of sites are very essential for effective reinforcement.

(3) It is necessary to consolidate different types of cracks with different grouting methods.

(4) The penetration process of PS must be controlled according to deterioration characteristics of the earthen sites to achieve effective consolidation.

(5) Unlike traditional processes, the techniques of suspended steel beam ceiling can effectively reduce the negative impacts to the original appearance of the earthen sites.

(6) Deformation monitoring and temporary support measures play an important role in conservation earthen sites safely. A composite anchor rod of bamboo plus rod is a new method for the consolidation of earthen sites with massive loose earth.

In all, the practices have shown that these conservation techniques are effective and can be applied to conservation of most Chinese earthen sites in arid environments.

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