Field test study on expansive soil canal of middle route of South to North Water Diversion Project

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ABSTRACT

The south to North Water Diversion Project is the most magnificent Chinese water diversion project, the project includes eastern, central and west routes, of which the total length of mid-route canal is about 1200 km. majority of the channel is the open canal, partly with the culvert, crossing river by the aqueduct or tunnel. The channel goes across China's Yangtze River, the Yellow River, Huaihe, Haihe River. There are expansive rock and soil, loess, easy-liquefied sand and other special soil (rock) area along the channel with complicated engineering geological condition. The accumulative total length involved the expansive soil (rock) area is about 340km. Due to the special engineering properties of the expansive soil (rock), it is very vulnerable to slope instability with a great impact on the safe operation of the project. Therefore, the treatment of the expansive soil (rock) is one of the main technical problems in the South to North Water Diversion project. To study the failure mode and stability mechanism of the expansive soil channel slope, typical channel slopes with the respective length of 2.05km and 1.5km were selected to conduct the field test studies for 3 years. The selected slope were preinstalled inclinometer, slope displacement meter, water content and suction probe, et al. To reveal the mechanism of instability of slope of expansive soil channel. Field experiment shows that: the expansive soil slope instability has two patterns of failure modes, one is the instability induced by the expansive deformation, and another is the instability controlled by fissure strength. In order to guarantee the stability of expansive soil slope, it is essential to identify the different failure modes in the design analysis.

Keywords: Mid-route of the South to North Water Diversion Project, expansive soil, failure mechanism, expansive deformation, strength of fissure plane

1 INTRODUCTION

The mid-route of the South to North Water Diversion Project goes across the Yangtze River, the Yellow River, Haihe River, involving Hubei, Henan, Hebei and Beijing with a total length of more than 1200 km. majority of the channel is the open canal, partly with the culvert, crossing river by the aqueduct or tunnel. The channel goes across China's Yangtze River, the Yellow River, Huaihe, Haihe River. There are expansive rock and soil, loess, easy-liquefied sand and other special soil (rock) area along the channel with complicated engineering geological condition. The accumulative total length involved the expansive soil (rock) area is about 340km, accounting for about 1/4 of the total length of the channel. Therefore, the treatment of the expansive soil (rock) is one of the main technical problems in the South to North Water Diversion project.

From 70's of last century, the Yangtze River Scientific Research Institute imitated the study on the expansive soil of Mid-route of the South to North Water Diversion Project. Laboratory test were conducted to investigate the test method for expansive soil, compiling test operation standards. Study on mineral composition, micro structure, the expansion and shrinkage mechanism analysis of the expansive soil and shear strength theory were carried out consequently. From the beginning of the 90's of last century, a number of small scale field tests were conducted to explain the phenomenon of damage of expansive soil slopes based on the unsaturated soil theory (Gong, et al., 1999, Zhan et al., 2003 and Gong, et al., 2006). In December, 2002, due to insufficient understanding of the failure mechanism of expansion soil channels slope, especially the lack of expansive soil channel treatment measures, the Ministry of Science and Technology of China and South to North Water Diversion Project Construction Committee Office jointly organized research, which is in charge by Yangtze River Scientific Research Institute. Two sections of the excavation channel slope located at Nanyang city and Xinxiang city were selected to carry out the laboratory and field test study to investigate the failure mechanism and the treatment technology of expansive soil channel slope.

This paper mainly discusses the field test research
work of Nanyang expansive soil test section, according to the test area with most serious landslide, the mechanism of landslide is analyzed based on the field observation data and laboratory test results.

2 OVERVIEW OF THE FIELD TEST

2.1 Basic characteristics of expansive soil

Geological survey shows that Nanyang test section is located in the intersection position of the northern Nanyang basin and Funiu Mountain Piedmont hillock edge. The ground elevation is 138.7m~153m, the terrain is relatively flat and open, the northeast high, southwest low in the region. The test involves the formation of Quaternary Pleistocene alluvial (al-plQ2) silty clay, clay, quaternary slope (dlQ) silty clay, with weak to middle expansion, strong expansion locally.

Table 1. Results of physical indexes of expansive soils in test area

<table>
<thead>
<tr>
<th>Test area soil</th>
<th>Moisture content w (%)</th>
<th>Dry density ρd (g/cm³)</th>
<th>Void ratio e</th>
<th>Sr &lt;0.005 mm %</th>
<th>αL17 %</th>
<th>αP %</th>
<th>IP17 %</th>
<th>δef %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2 silty clay</td>
<td>16.9~28.1</td>
<td>1.64(11)</td>
<td>0.650(11)</td>
<td>91.9(11)</td>
<td>27.1(12)</td>
<td>22.8(12)</td>
<td>28.6(12)</td>
<td>59(12)</td>
</tr>
<tr>
<td>Dlq silty clay</td>
<td>22.5~22.5</td>
<td>1.66(11)</td>
<td>0.639(11)</td>
<td>90.6(11)</td>
<td>27.8(2)</td>
<td>24.8(2)</td>
<td>28.8(2)</td>
<td>59(2)</td>
</tr>
<tr>
<td>Mid-expansive soil test area</td>
<td>22.5~22.5</td>
<td>1.67(11)</td>
<td>0.637(11)</td>
<td>90.6(11)</td>
<td>27.8(2)</td>
<td>24.8(2)</td>
<td>28.8(2)</td>
<td>59(2)</td>
</tr>
<tr>
<td>Q2 silty clay</td>
<td>14.7~24.3</td>
<td>1.65(18)</td>
<td>0.637(18)</td>
<td>86.5(18)</td>
<td>44.0(21)</td>
<td>29.6(21)</td>
<td>30.5(22)</td>
<td>73(20)</td>
</tr>
</tbody>
</table>

Note: minimum—Maximum

2.2 Layout of test section

The test section is 2.05km, the design depth of 7.5m, the channel bottom width 22m, height of slope is 5~17m, design ratio 1:2.0, slope height more than 6m with a level of ma. According to the expansion of the test section topography and the foundation soil, combined with experimental research objective, the test section is divided into fill test area, weak expansive soil area three regional test of expansive soil in the test area and. Among them, fill the test area and weak expansive soil test area away from the 810m, 100m apart from the expansive soil test area soil and weak expansion (Fig.1, Fig.2). Each test area according to different research programs, and is divided into several sub regions.

Fig. 1: Test zone illustration at Nanyang
Weak expansive soil test region is 450m long, which is divided into 4 sub-regions. Sub-region I ～Ⅲ is for the study on the treatment effect and construction technology of different treatment measures, that is non expansive soil replacement, cement modified soil, geomembrane covering treatment measures, respectively. Sub-region IV is the bare slope for the artificial rainfall test without any treatment measures. For sub-region I ～Ⅲ, the length of each sub-region is 110m, sub-region IV is 120m, of which separated from sub-region Ⅲ by the isolation dyke.

Mid-expansive soil test region is 600m long, which is divided into 7 sub-regions. Sub-region I ～Ⅵ is for the study on the treatment effect and construction technology of different treatment measures, that is non expansive soil replacement, cement modified soil, geotextile bag geogrid, geotextile membrane combined sand cushion treatment measures, respectively. Sub-region Ⅶ is the bare slope for the artificial rainfall test without any treatment measures. For sub-region I ～Ⅵ, the length of each sub-region is 80m, sub-region Ⅶ is 120m.

The fill test region is 240m long, which is divided into 2 sub-regions of 120m long. Two treatment measures, which are geogrid reinforcement in the inner slope and cement modified soil replacement in the inner slope are studied in 2 sub-regions, respectively.

3 INSTRUMENT LAYOUT AND INSTALLATION

3.1 Instruments layout

In order to investigate the slope failure process induced by water infiltration and atmospheric environmental change, the stress, strain and water content were observed in a comprehensive manner: the inclinometer tubes were installed at the channel slope top and first berm, settlement mark was placed in the slope surface. Earth pressure cell, water moisture sensor, the pore pressure sensor, tensiometer were instrumented at the different elevation of the canal bottom and slope. Meteorological observation station was established at the test area to monitor the rainfall and meteorological data. Take the mid-expansive soil as an example, observation instruments and arrangement are shown in Figure 3.

Fig. 2 Mid-expansive soils test area at Nanyang City

Fig. 3 Observation instruments and arrangement

(1) Weather monitoring: a small HOBO meteorological station, equipped with temperature, humidity, wind direction, wind speed, rainfall sensor, was employed for automatic monitoring and recording rainfall, wind, air temperature and relative humidity at the test area. The evaporation pan is employed to collect the local evaporation data.

(2) Slope deformation monitoring: the surface displacement identification point and preinstalled PVC inclinometer tube with inner diameter of 70mm. Surface displacement identification point is mainly located at the canal bottom and first berm; inclinometer tube mainly installed at the canal bottom, canal slope and the first berm. The inclinometer used in the test is the Canada RST digital inclinometer.

(3) Moisture content monitoring: using ML2X moisture content probe to monitor the water content. According to the geological excavation before the survey, install the moisture content probes in the canal bottom, canal slope foot and treatment layer and other parts, spacing is generally 0.5m, the maximum depth is more than 3m.

(4) The suction monitoring: using Soilmoisture tensiometer for suction monitoring, maximum depth of the tensiometer is 2.0m.

(5) Earth pressure monitoring: soil pressure monitoring by earth pressure cells. Mainly installed in the interface between the treatment layer and the base layer.

(6) Pore water pressure monitoring: pore water pressure sensor installed below the canal slope toe surface 3~4m. All the above observation instruments and probes were calibrated before the test.

3.2 Instrument installation

The inclinometer tube, earth pressure cell and pore water pressure sensor were installed using the traditional borehole method. However, in order to avoid the groundwater influx induced by the borehole disturbance, the water moisture sensor and tensiometer have to use the single sensor single hole installation method (Gong, et al., 2006). The procedure of the single hole installation method are as follows: bore to depth little less than predetermined depth, then bore a hole the same size with sensor with special location, boring device, then static compact the probe to the predetermined position, guarantee the good contact of...
the probe and the surrounding soil. Then, fill the borehole using the original excavation soil and compacting layer by layer to prevent water infiltration.

4 FAILURE PATTERN AND MECHANISM

4.1 Failure process and morphological characteristics

In addition to the failure in the construction process, there were 5 large scale slope failures at Nanyang test section during the observation period, of which were located at the mid-expansive soil test region I ~ III, and IV left slope. Test zone 7 is the weak expansive soil test region I right slope. Site excavation shows most sliding surfaces are the gray white fissure, with a pan bottom shape, and steep facade.

Take the most serious failure in mid-expansive soil test region I, III and IV as an example. During the 2 years’ observation period, left slope failure constantly, however the right slope deformation with the same treatment measures is small, remaining stable. The mid-expansive soil test region I is the soil replacement test area, the thickness of clay replacement layer is 1m (vertical to the slope surface, later the same), the maximum deformation located about 4.5m below the slope surface, and the sliding surface is more than 3m deeper below the treatment layer. Mid-expansive soil III and IV regions were the geotextile bag (treatment layer thickness 1.5m) and geogrid treatment test area (treatment layer thickness 2.0m). Test regions III slope failed after the completion of the lining construction. Using anti-slide pile and other measures in the first berm, the slope tends to be stable. However in the second year, the failure depth and range enlarged and developed to the adjacent test region IV, forming the large failures connecting test region III and IV. The landslide is located on the top of the channel, the crack is more than 10m with 1m ground subsidence, causing 1m heave of the lining plate at the first berm. The failure continues to develop upstream, due to the isolation dyke between test region IV and V, only a crack was observed in the slope above the first berm. Fig.4 (a) shows lining plate heave induced by the landslide, Fig.4 (b) shows the excavated failure profile after the testing.

Table 2 shows failure pattern, deformation characteristics and inclinometer observation curve in the mid-expansive soil test region III. From the analysis of inclinometer observation data, the slope deformation exhibits obvious dislocation in a certain depth range, indicating the location of the sliding surface. The location of the deformation dislocation were deeper than treatment layer depth, illustrating the sliding is not along the interface between the treatment layer and the original soil layer. Revealed by the excavation of the slide surfaces, the failure is along the fracture surface, with little relationship with canal slope treatment measures. Further analysis of fracture distribution of expansive soil in the test region III shows, left slope fracture has advantage tendency to channel inside, while the right slope fissure to the channel outside. The mechanical properties of soil, the construction schedule and the weather condition were the same, the only difference is the relationship between the fracture and canal slope tendencies. Therefore the fissure is an important factor controlling the slope stability.

### Table 2 Failure characteristics at mid-expansive soil test regions

<table>
<thead>
<tr>
<th>Mid-expansive soil Test</th>
<th>Landslide form</th>
<th>Deformation characteristics</th>
<th>The observation section and the observation curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region I</td>
<td>first berm of The left slope surface heave</td>
<td>Larger dislocation deformation occurred at the opening line and the inclinometer at the certain depth of first berm, deformation increased sharply.</td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

(a) Lining plate heave induced by the landslide

(b) Excavated failure profile

Fig. 4 Slide and deformation of mid-expansive soil test zone
Two failure occurred successively in June 2009 and May 2010. Remove treatment layer, make slope gentle after the first failure. And drive anti-slide pile in a first berm to stabilize slope. But the depth and range of failure in second years expanded. Obvious dislocation deformation monitoring.

Excavation period failure occurred, with geogrid-reinforcement layer, in June 2009 deformation increases, May 2010 failed, obvious dislocation Deformation observed.

4.2 Failure geological description

Fig. 5 is the fissure tendency rose diagram at weak and mid expansive soil test regions. The fissure tendency for the weak expansive soil is generally NW, NNW, and almost orthogonal to channel (as shown). The fissure tendency for the mid-expansive soil is generally NEE, NE, SEE with 2 kinds of advantageous fissure trend, one is the long the channel, another is orthogonal to channel. In the mid-expansive soil test regions, for the left channel slope, the crack with tendency of SEE is the slide surface with slow-inclination, while in the weak expansive soil test region, for the right channel slope, the crack with tendency of NW, NNW is also consistent with the slope inclination, as the main cause of failure. It accounts for the failure occurrence at the left slope at mid-expansive soil test region and the right slope at weak expansive soil test region. In addition, the geological survey shows in the mid-expansive soil test region, from the surface down, crack distribution exhibits obvious zoning characteristics. The crack length more than 2.0m is mainly located 3~10m below the slope surface.

In order to investigate the moisture content and density at the fissure surface. In the excavation process, the gray fissure fillings and adjacent expansive soil were sampled to conduct tests, it is found that the moisture content of the filling is 5%~7% higher than that of the adjacent soil, the dry density is 0.1~0.2g/cm3 lower than that of the adjacent soil, Degree of saturation for the filling material is generally above 90%.

4.3 Failure mechanism analysis

Most of previous theory explaining the sliding mechanism of expansive soil slope: rainfall causes water content increased with the suction decrease, consequently strength sliding surface reduces, then slope failure occurs. Fig. 6 is the observation data of water content, boxed numbers represent the times significant rainfall in a year. The rainfall has significant impact on the water content of the slope soil within the depth of 1.5m, while little effect for the deeper soil. According to the geological survey, most of the cracks and fissures exist in the 3m below the surface. Combined with the deformation observation data, the initiation time for the failure is around 2009 May (as shown in the figure of Table 2). In June and July, 2009, water moisture probe installed at 2.5m and 3.5m below the slope surface broken due to slope soil slide. Until September, 2009, the slope slide has destroyed all the water moisture sensors installed in the channel slope. In the observation period the water moisture sensors are located within 1.5m was obviously affected by rainfall, moisture content fluctuated. The moisture content located near the sliding surface showed no obvious change, indicating little effect by rainfall.
Combined with the geological investigation results, it is believed that the main control conditions for the slope failure are soil strength at sliding surface. Therefore, direct shear tests, triaxial tests and CT triaxial test on undisturbed soil sample containing inherent fissure surface were conducted, respectively. In order to compare the strength with and without fissure plane, two groups of specimens with and without the fracture surface were selected to conduct the test. For the specimens with fissure surface, attempt to make fissure surface locate at the middle part of sample (direct shear test) or 45 degree to the axial force direction. The CT triaxial test methods can refer to literature (Cheng, et al., 2011 and Hu, et al., 2012). Strength indexes obtained by three test method are shown in Table 3, respectively.

According to the test results, fissure surface strength is obviously lower than that without fracture surface. Comparing different test methods, the strength obtained using CT triaxial test is minimum. It is because the shearing surface and fissure surfaces cannot be controlled to coincide completely for direct shear and conventional triaxial test, whereas for CT triaxial test can. Therefore, only the CT triaxial test can reflect the strength characteristics of fissure surface.

Based on the fissure survey results, the variation principle of the moisture content and deformation and shear strength test results, the failure mechanism of Nanyang mid-expansive soil in the test region is: due to the existence of advantage fissure with certain tendency, low strength of the surface and the lateral restraint release induced by the excavation, dozens or even hundreds meters of sliding crack forms gradually under the action of soil mass gravitation. In the field test, although rainfall caused the significant increase of the soil water content in the shallow layer, but the water content on the fracture surface varies little. Rainfall is an important factor which increases the slope soil weight, eventually lead to the slope failure due to the insufficient strength of the fissure surface. Field test found that the small scale slope failure still occurred even the fissure is not very developed. There are repetitive failures in some slope even though the slope is very small. Therefore, through a series of laboratory model tests, another failure pattern of expansion soil slope sliding is revealed, expansive deformation induced by the change of soil moisture content (Cheng, et al., 2011).

5 CONCLUSION

Field test results reveal a failure mechanism of Nanyang expansive soil canal slope. It is found that the fissure surfaces with advantage tendency are existed in the expansive soil slope. The strength of the surface is very low. After the channel slope excavation, fissures gradually go through, finally yield the overall instability. The test results play an important role for the design and construction of expansive soil channel in the Middle Route of the South to North Water Diversion Project. According to the test results, the anti-sliding measures with combined anti-slope pile and the frame beam on the slope surface are suggested to deal with the failure pattern proposed by this paper.

REFERENCES