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# Experimental research on the potential failure surface and stress of a reinforced earth wing wall of a water sluice

Liu, Z. & Han, H.
*Yangzhou Exploration Design and Research Institute, Yangzhou 225007, China*

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ABSTRACT: Generally, an empirical method is used to determine the potential failure surface of a reinforced earth wall less than 6 m high and using inextensible reinforcement. This experimental research is conducted through reconstruction of the wing wall of a water sluice, one of which using reinforced earth and the other using unreinforced earth to carry out the test and whole-process observation. In this paper, the results of the experiment to verify the applicability of the empirical method. It analyzes the stress and deformation of the soil and the strain of the reinforcement, discusses the arrangement of the reinforcement, and verifies the shape and location of the potential failure surface of this type of structure.

## 1 PREFACE

In the analysis of the internal stability of a reinforced earth retaining wall, the shape and location of the potential failure surface are involved. An empirical method is applied for this purpose.

The method comprises that the potential failure surface is assumed to coincide with the maximum tensile forces line. For inextensible reinforcement and height of the wall H < 6 m, the maximum tensile forces line is assumed to be approximately bilinear, one of which is an upper vertical line, 0.3H apart from and parallel to wall face, and the lower one is an active Rankine's rupture line passing through the toe of the wall, (in the following paragraphs, this method is called "Empirical method" in short).

This paper verifies that the Empirical method is applicable through the test. The Hekou Sluice, which needs to be reconstructed, is selected as the site of the test. The sluice is located on the channel leading to the Yangtze River, which was built in 1979. The wing wall is a gravity wall made of stone and the height is 5 m. This test is done to the wing wall on the east and west of the third section. The scheme of reconstruction of the wing wall is that the backfill behind the wall was excavated and then replaced by the reinforced earth. The geogrid used for the reinforcement is of wrapped type terminal and set against the face wall.

## 2 TEST PROCESS

### 2.1 *Purpose*

The purpose is to know the rule of magnitude and change of the force the reinforced earth bears through test of the case. It is expected to verify the shape and location of the potential failure surface of the reinforced earth through measuring the magnitude of strain with gages at the designated points on the selected reinforcement.

### 2.2 *Test method*

#### 2.2.1 *Place and time*

The test will be done on the east and west of the sluice. The wing wall on the west has reinforced earth, and earth pressure test and geogrid deformation test will be done to it. The wing wall on the east has unreinforced earth, and only the change of earth pressure will be observed. Comparative analysis can be conducted between them. The observation lasted from April 2002 to July 2002, for 109 days.

#### 2.2.2 *Selection of test instrument and materials*

(1) Earth pressure meter: resonate wire earth pressure meter, Model TYJ-20, product of Jintan City Civil Engineering Instrument Plant, range of 0.1 MPa.
(2) Metal-foil strain gage: Model BQ120-2AA, size 5.4 × 3.2 mm, strain limit 2%, and resistance 120 ± 0.1 Ω.

(3) Static resistance strain gage meter: Model YE2539, high speed/static strain fully automatic test system, max number of measurement points: 1000, product of Jiangsu Lianneng Electronics Co., Ltd.
(4) On-site filling index test equipment: ring cutter and supporting test equipment.
(5) Geogrid, polypropylene, Model TGDG50, ultimate tension strength T = 50 KN/m, peak strain = 10%, grid size 200 × 25 mm, product of Tai'an co., Ltd, Shandong, China.
(6) Light loam was adopted for backfill. Grain size distribution test and compaction test were made, see Table 1. The degree of the compaction = 0.90.

Table 1

| | | Grain Size Distributions (mm) | | | |
|---|---|---|---|---|---|
| Gravel | | Sand | | Silt | Clay |
| 2 | 2~0.5 | 0.5~0.05 | 0.05~0.075 | 0.075~0.005 | <0.005 |
| % | % | % | % | % | % |
| 0.1 | 0.5 | 0.3 | 53.0 | 33.1 | 13.0 |

| Compaction | |
|---|---|
| Max dry density | Optimum moisture content |
| $\rho_{dmax}$ mg/m$^3$ | $W_{op}$ % |
| 1.72 | 16.1 |

2.2.3 *Measurement point arrangement and installation*

Earth pressure meters are placed in both of west and east wing walls, each has a length of 6 m; there are two test sections is 2 m apart in the middle part of each wall, and total 8 meters are erected on each test section from the wall top to base. The first meter is fixed 40 cm below the filling surface, and the other 7 meters downward are fixed at an interval of 75 cm or 50 cm. Meters are embedded in the wall with cement mortar; the gap between the earth pressure meters and the filling is filled with coarse sand, so as to make the force evenly distributed.

Geogrid is used as reinforced material; its end are not connected to the face wall, wrapped type re-folding is adopted at the end, the geogrids and the earth pressure meters are erected at different heights in each layer; the first layer is 90 cm below the surface of the filling, and intervals between the lower 6 layers are 75 cm to 50 cm. 16~24 strain gages are distributed in the directions along the wall length or perpendicular to the wall length, and each point is numbered. The test gages are connected to computers for automatic return to zero and data recording. Measurement time and the intervals are controlled with software.

Strain gages are glued in the center of the geogrid with adhesive indoors. Pre-stretch is conducted, to make sure the strain gages bear the force closely with the geogrids. The geogrids are soft and easy to deform, so they are fixed after being stuck on. Certain initial pull is maintained, and return to zero is necessary.

2.2.4 *Construction and test process*

The backfill was placed and compacted in layers. Each layer was controlled in no more than 250 mm of thickness and samples were taken from each layer for test. As the compaction degree of a layer was up to the design standard, i.e. 0.90, then the next layer was placed. The rate of backfilling depends upon the quality of the filling. It took about one hour for each layer of filling and totally 7 days were needed to accomplish the whole construction.

It is hard to control the compaction of the filling above the geogrids. In order to avoid the interference with the operation of the strain gage on geogrids, a process of gently compacting with a heavy compacter was adopted and eventually the test results were satisfied. On west site, the average compaction of earth is 0.9, $W_o$ = 14.9%, $\rho_d$ = 1.46 Mg/m$^3$. On east site, the average compaction of earth is 0.91, $W_o$ = 11.3%, $\rho_d$ = 1.46 Mg/m$^3$. As the filling was completed, readings were recorded once every two hours in the first month, and 1~2 times every one hour afterwards, without any interruption.

The values of deformation of strain gages represent the deformation of geogrid at several points in each layer. These values are all lower than the peak value of the strain of geogrid, which is 10%. Accordingly, from these values we can understand the conditions of the tensile stress in geogrid. The test gages are connected to computers for automatic return to zero and data recording. Time for measurement and the time intervals are controlled by software. Data start to be read when filling is completed. It took about 40 days.

## 3 TEST RESULTS AND DISCUSSION

### 3.1 *Earth pressure analysis*

For comparison, the curves (P-T Curve) of the earth pressures of both reinforced earth group (a) and unreinforced earth group (b) are drawn as shown in Figure 1. It can be seen that the variation rules of the curve line of group (a) are different from that of group (b). Figure1 (a) shows the reinforced earth layers at different levels, and the earth pressure does not increase much as time goes. From the time of filling, the geogrids start to act, and the pressure rises slightly. As time goes, the geogrids and the earth mutually act, and the earth pressure drops slightly. For unreinforced earth, however, the earth pressure increases step by step as time goes, and it takes a long period of time to achieve a balance; as shown in Figure 1(b).

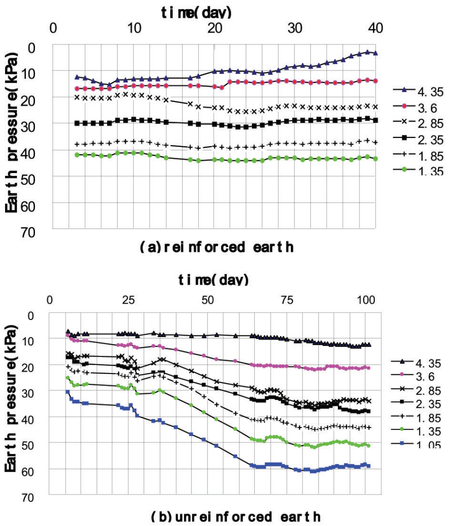

Figure 1. Comparison of earth pressure between reinforced earth and unreinforced earth.

The earth pressure of the reinforced earth is less than that of the unreinforced earth by 30~40%. Reinforced earth reaches earth stress balance shortly after the completion of construction.

### 3.2 *Determination of potential failure surface*

The investigation of the potential failure surface is conducted only in the reinforced earth of the west wing wall. Location of the failure surface is analyzed and determined according to the deformation of the soil. As the deformation of the geogrid &the earth mass coordinate with each other, the deformation of the latter can be determined through the measured the strain of the geogrid.

Table 2 gives the strain of the gages on geogrid at different points.

There is a tensile strain of max value in one of the gages on the geogrid in each layer. It indicate that the tensile deformation and also the tensile force of the earth mass at this point in each layer is also the maximum joining up all such points into a line, this line is the max tensile force line, with which the potential failure surface is assumed to coincide (Figure 2). Comparing this measured failure surface (curve 1) with that determined by Empirical method (curve 2), the curve 1 is very close to the curve 2.

Table 2. Strain of the gages on geogrid at different points (μ ε)

| Layer # | Elevation (m) | Point 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Layer # 1 | 4.6 | 950 | 1201 | 1237 | 950 | 507 | 489 |
| Layer # 2 | 3.85 | 938 | 896 | 967 | 666 | 804 | 528 |
| Layer # 3 | 3.1 | 618 | 637 | 620 | 496 | 790 | 652 |
| Layer # 4 | 2.6 | 486 | 567 | 494 | 674 | 878 | 503 |
| Layer # 5 | 2.1 | 531 | 632 | 679 | 665 | 508 | |
| Layer # 6 | 1.6 | 631 | 395 | 647 | 386 | | |

* The direction of Point 1 – Point 6 on this table equals the direction from left to right on Figure 2.

### 3.3 *Analysis of internal stress of reinforced earth*

During the construction of the reinforced earth wall, the lateral displacement of the wing wall were investigated. The measured value is very small and can be neglected.

The rigidity of the wall is high and the toe of it is deep-lying, while the base earth had been compacted for more than 20 years, therefore no new settlement being detected. There is a step at the elevation 3.5 m of the wing wall as shown in Figure 2. The rigidity of the wall above elevation 3.5 m is much lower than that below elevation 3.5 m, so that when comparing the measured earth pressure with that calculated by using the Rankine's formula, we can consider those values are all between the active & at rest earth pressure. The earth pressure on the wall above elevation 3.5 m is active pressure while that on the wall below elevation 3.5 m being approximately at rest pressure. Comparing the measured value of reinforced earth with that of unreinforced earth, the influence of the reinforcement is obvious as shown in Table 3.

Series of figure in the table show that from top of the wall downward the pressure exert by reinforced earth are all lower than that by the unreinforced one in every layer, while the differences (%) from wall top to base decline progressively. It is evident that the reinforcements control the deformation of the earth mass, thus causing the geogrids themselves to bear tensile force. However near the base of the wall, the effect of reinforcement is not noticeable.

To analyze the internal stable of the reinforced earth wall, the method and formulae recommended in the "Mechanically stabilized earth walls and reinforced soil slopes, design & construction guidelines" (Listed in References) is adopted. To

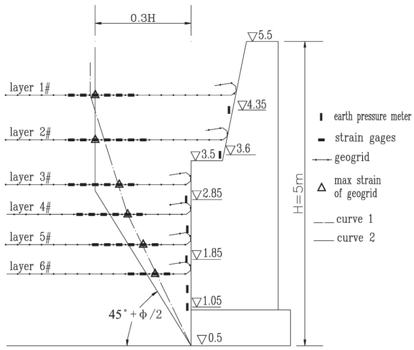

Figure 2. Shape and location of the failure surface of reinforced earth.

Table 3. The calculated value of earth pressure and the measured value.

| Depth from top of the wall Z (m) | | 1.15 | 1.90 | 2.65 | 3.15 | 3.65 | 4.45 |
|---|---|---|---|---|---|---|---|
| Elevation (m) | | 4.35 | 3.60 | 2.85 | 2.35 | 1.85 | 1.05 |
| Calculated value (kpa) | Active earth pressure $\sigma_a$ | 15.3 | 20.14 | 25.0 | 28.2 | 31.5 | 36.7 |
| | Earth pressure at rest $\sigma_o$ | 21.19 | 27.89 | 34.62 | 39.06 | 43.63 | 50.83 |
| Measured value (kpa) | Unreinforced earth pressure $\sigma_{h1}$ | 13.08 | 21.35 | 33.66 | 38.19 | 44.13 | 57.75 |
| | Reinforced earth pressure $\sigma_{h2}$ | 3.55 | 6.80 | 22.62 | 28.43 | 35.50 | 42.32 |
| $\Delta\sigma = \sigma_{h1}-\sigma_{h2}$ | | 9.35 | 14.55 | 11.04 | 9.74 | 8.63 | 7.93 |
| $\Delta\sigma/\sigma_{h1}$ (%) | | 71 | 68 | 33 | 26 | 20 | 14 |

calculate the tensile force T in the reinforcement of each layer, the extensibility of which is taken into account.

The results of calculation (T) are compared with the max strain of the geogrids in each layer as shown in Table 4. The latter values are excerpted from Table 2.

Table 4 shows that the max strain of the geogrid in the whole earth mass occurs in the layer at elevation 4.6 m. The strain of the geogrids in the following layers below drop progressively. Whereas, the calculated max tensile force occurs in the bottom layer, at elevation 1.6 m. It indicates that the stress-strain relations of the reinforcement are complicated. This is because the calculations of the tensile force in geogrid relate to many factors, such as the rigidity of the face wall, the extensibility & density of the material, the conditions of soil, etc. The wing wall, as in this case, the lower part of it possesses high rigidity. In accordance with this complicated conditions mentioned above, considering the strain near the top of the wall being maximum while the max T occurring near the wall base, reinforcements of constant strength are used from the top to the base of the wall.

Table 4. Measured max strain and calculated tensile force of the geogrid in each layer.

| Z(m) | Elevation (m) | Max strain (με) | T (kN) |
|---|---|---|---|
| 0.9 | 4.6 | 1237 | 24.77 |
| 1.65 | 3.85 | 967 | 18.89 |
| 2.4 | 3.1 | 790 | 18.99 |
| 2.9 | 2.6 | 878 | 16.66 |
| 3.4 | 2.1 | 679 | 18.17 |
| 3.9 | 1.6 | 647 | 33.08 |

## 4 CONCLUSIONS

(1) The shape and location of the potential failure surface of the reinforced earth retaining wall given in the current design manual are verified, and the relevant empirical formulae is applicable.

(2) For the reinforced earth retaining wall in this case, geogrid is used for reinforcement, wrapped type terminal is adopted for each earth layer and the face wall is a wing wall of higher rigidity. The earth pressure of which is less than that of unreinforced earth wall by approximately by 40%. The earth pressure varies stably and reaches the final value in a short period. It is suitable for hydraulic structure and the cost can be reduced.

(3) The force that each layer of reinforcement bears is known through the research, and consider the stress & strain of the reinforcements relate to many factors, such as the rigidity of the face wall etc, the mechanical conditions are much complicated, so that the reinforcements of constant strength from wall top to the base are adopted.

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