Application of multiple combination retaining structures on high slope

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Abstract. With the increase of the height of the filled slope, the application of multiple combination retaining structures (MCRS) is becoming more and more popular. However, the traditional design methods seldom consider the coupling effects between the substructures. To investigate the interaction of MCRS, this paper takes the filled slope project of a middle school in Quanzhou City, Fujian Province, China as an example. The filled slope was supported by MCRS, including reinforced soil, double-row piles, anchors and counterfort retaining walls. The simulate procedure mainly included the following process: first, the MCRS model was established, then the mechanical response of the MCRS when replacing the fill materials and increasing the length of the rear row piles were obtained, and a comparative analysis was carried out. The following conclusions could be drawn: (1) The properties of backfill material have a significant impact on the displacement of backfill slope, and when the backfill is gravel soil, the displacement of slope can be controlled to a satisfactory degree. When the back-fill soil is replaced by silty clay, the shear strength and internal friction angle of soil become smaller, thus the displacement of slope increases significantly, which may lead to slope failure. (2) When the anchorage length is satisfied, increasing the length of the rear row pile has no significant effect on reducing the displacement of MCRS slope, but it can effectively reduce the axial force of anchor rod. (3) In MCRS, each substructure has complex interaction, and numerical simulation provides an effective means for accurate evaluation of MCRS.

Keywords: Dual-row retaining pile wall, Back-fill slope, Anchor, Counterfort retaining wall, Numerical simulation.

1. Introduction

With the development of economy, human beings utilized the natural environment more and more intensively. Many kinds of high slope projects appear in civil engineering such as water conservancy, hydropower station, highway, railway, etc. However, due to the complexity of geological conditions and the over-exploitation of natural resources, the landslide become prone to occur. High slope is a complex system, the high slope is affected by the, unloading-loading path [1], stress history [2, 3], soil...
property and so on. During site leveling in hilly areas, excavation and filling are inevitable, and higher filling slope is easy to be formed. However, due to construction quality, short filling time and other factors, the properties of filled material are poor, which may lead to failure of retaining structures. In addition, the forming process of fill slope is different from those of natural slope, and its property is different from that of natural slope, which further increases the design difficulty.

Traditional slope retaining structures include reinforced soil, anchor rod, double-row piles, counterfort retaining wall, etc. Many scholars have studied the above structures. However, most of the existing researches focus on the individual retaining structure, seldom considered their interaction, especially the combination of the above four retaining forms.

The application of dual-row piles is extremely wide, including side slope [4], foundation pit [5], cofferdam [6] and so on. Construction of the double row retaining piles first involves building two rows of parallel piles. The distance between the front and rear rows of piles is about 4-6d, and the distance between adjacent piles in each row is about 3-6d, where d is the pile diameter. And then the two rows of piles were connected by reinforced concrete cap beams. Wang et al. [4] conducted three-dimensional numerical simulation to investigate the spatial effects of dual-row piles in deep excavation. The force and earth pressure distribution of the dual-row piles were obtained. Hu et al. [5] presented a case of deep open cut excavation using dual-row piles to support. The shear strength reduction method based on finite element method (FEM) was adopted to study the behavior of the excavated slope. The results show that the excavated slope may collapse caused by surcharge loads. Zhou et al. [6] conducted FEM to simulate the multi-bench retaining structure. The retaining structure consists of a single row pile and a double row pile. However, the double row piles were simplified as single-row retaining pile wall. Ye et al. [7] adjusted the stiffness of front and back row piles to optimize the cantilever double-row anti-slide pile in slide.

In the study of reinforced soil, Mittal et al. [8] analysis the effect of reinforced backfill on the retaining wall, which was subjected to uniformly distributed surcharge load.

In the study of anchor, Yan et al. [9] considered dynamic changes in the axial force of the anchor cables using limit analysis and pseudo-dynamic methods to access the slope stability.

In the study of counterfort retaining wall, Hazra and Patra [10] conducted experiment to investigate the counterfort retaining wall with reinforced granular and fly ash backfill.

In the study of coupling effects, Shi et al. [11] proposed a coupled model to calculate the loss of anchoring force in slope, which is reinforced by frame beams and anchor cables.

However, most of the existing studies focus on the analysis of individual retaining structure, but few on their interaction, especially the combination of the four supporting forms mentioned above. In this paper, the mechanical responses of MCRS during construction are analyzed by means of numerical simulation method, and the coupled effect of the MCRS is determined.

The rest of the paper is organized as follows. Section 2 describes the general situation of the project, including the brief introduction of the project and the engineering geology. Section 3 describes research methods, numerical simulations, including construction of the model and the boundary conditions. Section 4 gives the numerical results and discusses them, and probes the effect of backfill material and rear-row length on the mechanical properties of MCRS. The last section summarizes this paper and gives relevant conclusions.

2. Project overview

2.1. Project background
The proposed high slope is located at the northwest side of the playground of No.12 Middle School in Anxi County, Quanzhou City, Fujian Province, China. The landform of the site is low mountain, and the terrain is generally high in the southeast and low in other directions. It is a filled slope formed by backfilling and leveling of the site, with the top of the slope being the school playground and buildings and the foot of the slope being the tea planting area. The length of the slope to be supported is about 384m, the design elevation of the slope top is 419.00-421.20m, the design elevation of the slope toe is
390.00-410.00m, and the slope height is between 9.0-32.0m. According to the planning, the slope is considered as a permanent structure. The slope is supported by multi-type of structures, including geotextile reinforcement, counterfort retaining wall, double row piles and anchor rod. And the substructures have complex interaction.

![Figure 1. The plane graph.](image1)

![Figure 2. Profile of 1-1.](image2)

Because the altitude difference at section 1-1 is the largest and it protrudes like a fish mouth, thus 1-1 section is selected as a typical section for analysis.
2.2. Geological conditions
According to the drilling test, the soil layer of the proposed site is distributed as follows:

(1) Miscellaneous fill: mainly grayish yellow and brownish yellow, slightly dense and wet. The filler is mainly fully and strongly weathered rock, and the soil quality is uneven. This layer has low mechanical strength and poor engineering performance.

(2) Silty clay: it is brown yellow, plastic to hard plastic, mainly composed of silt and clay, with sand content of about 10%.

(3) Sandy weathered rock: it is brownish yellow and scattered. The rock is severely weathered, and the core is sandy.

(4) Lumps of highly weathered granite: it is gray yellow to brown yellow. The rock weathering is strong weathered, with fractures. The rock samples are mostly in fragments, with dumb hammering sound, and fragile impact.

(5) Moderately weathered granite: The color is gray yellow, light gray to gray white. It is medium coarse-grained granite, with massive structure, developed rock joints and fissures. The core recovery rate is 75%-95% with RQD=70-90. The range of saturated uniaxial compressive strength is 42.1-64.8MPa, the average value is 54.2MPa, and the standard value is 51.3MPa. This layer is incompressible, with high strength and good engineering performance, which is used as an anchor layer.

3. Numerical simulation
Numerical modelling is a valid method to simulate the construction of fill slope. In order to further understand the mechanical characteristics of MCRS under the action of backfilling, FLAC3D (fast Lagrangian analysis of continua) is employed, which is widely used in geotechnical engineering analysis[12].

3.1. Construction of the model
For increasing the calculation accuracy, the mesh near to the MCRS was refined. The grid is shown in Figure 4. The stress-strain relationship of soil will greatly influence the numerical calculation results [13]. To model the behavior of the soil medium properly, the Mohr-Coulomb criteria was used in this study. The Mohr-Coulomb model requires only a few parameters [14]. The pile cap, the dual-row piles, the counterfort retaining wall, the backfill concrete, and the soil were modeled by solid elements. The bulk modulus \( K \) and shear modulus \( G \) are calculated as

\[
K = \frac{E}{3(1-2\mu)} \quad (1)
\]

\[
G = \frac{E}{2(1+\mu)} \quad (2)
\]

Where \( E \) and \( \mu \) are the modulus of elasticity and Poisson’s ratio, respectively.

Interfaces were adopted to model the pile-soil contacts. The normal rigidity of the interface was set \( k_n = 2.1 \times 10^9 \text{ Pa/m} \) and the shear stiffness \( k_s = k_n \) [12].

\[
k_n = k_s = 10 \max \left( \frac{K + \frac{4}{3} G}{\Delta z} \right) \quad (3)
\]

Where, \( K \) and \( G \) are bulk and shear modulus of the material connecting to the interfaces, \( \Delta z \) is the minimum unit size contacted to the interface.
3.2. Boundary conditions
The nodes on the vertical sides were restrained in horizontal direction and the nodes on the bottom surface were fixed in all the directions. The detailed simulation steps were as below: first, the initial stress field of soil medium under the action of gravity was generated. Then, the velocity field and displacement field are cleared. Next, the pile foundation was laid, the foam concrete was filled and the counterfort retaining wall was installed. After that, the soil was backfilled and the reinforced geotextile was installed, and the thickness of each filling is 2.5m. The backfill process is completed in 10 times. The following formula is adopted to generate the initial ground stress[14]:

\[
K_0 = 1 - \sin \varphi
\]
Figure 5. The back filling process.

4. Results analysis and discussions

4.1 Effect of backfill material

Table 1. Backfill material

| No.       | Type of backfill   | Model | Natural gravity | Elasticity modulus | Poisson's ratio | Cohesive strength | Internal friction angle |
|-----------|--------------------|-------|-----------------|--------------------|-----------------|-------------------|------------------------|
| Case 1    | reinforced gravel soil | M-C   | 23              | 100MPa             | 0.3             | 40kPa             | 40\(^\circ\)           |
|           | gravel soil        | M-C   | 23              | 100MPa             | 0.3             | 2kPa              | 40\(^\circ\)           |
| Case 2    | reinforced silty clay | M-C   | 18              | 50MPa              | 0.3             | 28kPa             | 38\(^\circ\)           |
|           | silty clay         | M-C   | 18              | 5.2MPa             | 0.35            | 25.8kPa           | 18.5\(^\circ\)         |

Figure 6. The horizontal displacement contour of Case 1.

The horizontal displacement contour of Case 1 after backfilling is shown in Figure 6. The maximum horizontal displacement is 43.6mm, and the maximum horizontal displacement is located near the pile caps of double-row piles.
Figure 7. The horizontal displacement contour of Case 2.

The horizontal displacement contour of Case 2 after backfilling is shown in Figure 7. The maximum horizontal displacement of soil is 119.1mm, which is located at the top of counterfort retaining wall, and the displacement at the top of slope is not obvious.

Horizontal displacement of retaining structure is the most important index for slope stability. In Case 2, gravel soil is replaced by cohesive soil. The horizontal displacement of retaining structure increases greatly, and the position of maximum displacement moves up from double-row pile caps to the top of retaining wall, which is extremely unfavorable to slope stability. Therefore, it is necessary to backfill gravel materials, instead of using silty clay.

Figure 8. The settlement contour of Case 1.

The settlement contour of Case 1 after backfilling is shown in figure 8. The maximum settlement is located at the joint between the backfill and the excavation face, which is 56.9mm.
The settlement contour of Case 2 after filling is shown in Figure 9. The maximum settlement is also located at the joint between the backfill and the excavation face, which is 214.5mm. When the backfill material was silty clay, the soil had a large settlement.

The horizontal displacement contour of MCRS in Case 1 is shown in Figure 10. The maximum horizontal displacement is 43.5mm and the minimum is 8.6mm.

The horizontal displacement contour of MCRS in Case 2 is shown in Figure 11.
Figure 11 shows the horizontal displacement contour of MCRS of Case 2. The maximum displacement at the top of the counterfort retaining wall is 119.1mm, and the displacement at the bottom of the pile is 6.7mm. There is large horizontal displacement at the pile cap, and the maximum displacement is 86.6 mm. The displacement of the counterfort retaining wall may be caused by the superposition of the pile cap and the counterfort retaining wall itself, resulting in the maximum displacement.

Figure 12. The settlement contour of MCRS in Case 1.

Figure 12 shows the settlement contour of MCRS in Case 1. The maximum settlement occurs at the front side of the rear row pile, and the maximum displacement is 8.4mm. Settlement of counterfort retaining wall is not obvious.

Figure 13. The settlement contour of MCRS in Case 2.

Figure 13 shows the settlement contour of Case 2 of the MCRS. When all the filling is completed, the maximum settlement occurs at the free surface of the pile cap, and the maximum displacement is 10.7 mm. Settlement of counterfort retaining wall is not obvious.
4.2 Effect of rear-row pile length
Keep the other parameter of Case 1 unchanged, the length of the rear row piles is increased from 10m to 12m. The deformation of the MCRS under different rear row pile length is compared.

Table 2. The pile parameter

| No. | Model  | Pile spacing in row/m | Row spacing/m | Length of front pile/m | Embed depth of front pile/m | Length of rear pile/m | Embed depth of rear pile/m | Elastic modulus/GPa |
|-----|--------|-----------------------|---------------|------------------------|-----------------------------|-----------------------|-----------------------------|---------------------|
| Case 1 | elastic | 3.5                   | 4.5           | 12                     | 3                           | 10                    | 3                           | 31.5                |
| Case 3 | elastic | 3.5                   | 4.5           | 12                     | 3                           | 12                    | 6                           | 31.5                |

Figure 14. The horizontal displacement contour of Case 3.

Figure 14 shows the horizontal displacement contour of Case 3 after filling. The maximum horizontal displacement decreased from 43.6mm in Case 1 to 40.1mm in Case 3.

Figure 15. The settlement contour of Case 3.

Figure 15 shows the settlement contour of Case 3 after filling. The maximum settlement decreased from 56.9mm in Case 1 to 54.2mm in Case 3. It can be seen that increasing the length of the rear row piles is effective in reducing settlement, but the effect is not significant.
The horizontal displacement contour of retaining structure after filling of Case 3 is shown in Figure 16. The maximum horizontal displacement decreased from 43.5mm in Case 1 to 40.1mm in Case 3. Increasing the pile length of the rear row piles has a significant effect on reducing the displacement of the double row piles.

The settlement contour of retaining structure after filling of Case 3 is shown in Figure 17. The maximum settlement is reduced from 8.4mm in Case 1 to 6.3mm in Case 3.

### 4.3 Comparison of the three cases

| No. | Total displacement/mm | Increase amplitude | Lateral displacement/mm | Increase amplitude | Settlement/mm | Increase amplitude |
|-----|-----------------------|--------------------|-------------------------|--------------------|--------------|-------------------|
| Case 1 | 60.5 | 1 | 43.6 | 1 | 56.9 | 1 |
| Case 2 | 220.1 | 263.8% | 119.1 | 173.2% | 214.5 | 277.0% |
| Case 3 | 57.4 | -5.1% | 40.1 | -8.0% | 54.2 | -4.7% |
Table 4. Comparison of the total displacement of MCRS.

| No. | Total displacement / mm | Increase amplitude | Lateral displacement / mm | Increase amplitude | Settlement / mm | Increase amplitude | Axial force of anchor / kN | Increase amplitude |
|-----|-------------------------|--------------------|---------------------------|--------------------|------------------|--------------------|--------------------------|--------------------|
| Case 1 | 44.1 | 1 | 43.5 | 1 | 8.4 | 1 | 166.6 | 1 |
| Case 2 | 119.2 | 170.3% | 119.1 | 173.8% | 12.4 | 47.6% | 267 | 60.3% |
| Case 3 | 40.4 | -8.4% | 40.1 | -7.8% | 6.3 | -25.0% | 144 | -13.6% |

Based on Case 1, Case 2 changed the backfill material, and Case 3 increased the length of the back pile. Compared with Case 1, the total displacement of soil and the displacement of retaining structure in Case 2 and 3 have changed obviously.

Under Case 2, the total displacement of soil increased by 263.8%, the total displacement of retaining structure increased by 170.3%, and the axial force of anchor also increased significantly. It can be seen that during the construction of backfill slope, the filling materials cannot be changed at will, otherwise the slope will be unstable.

In case 3, the length of the back-row piles is increased, and the anchoring depth is greatly increased. However, the total displacement of the soil decreases by only -5.1%. The total displacement of retaining structure decreases by -8.4%, but the axial force of anchorage decreases by -13.6%. It can be seen that increasing the pile length in the back row can effectively reduce the axial force of anchor rod, but it has limited effect on reducing the overall displacement of slope. When the anchorage depth is satisfied, simply increasing the pile length has no significant effect on reducing the slope displacement.

5. Conclusions

In order to investigate the mechanical characteristics of MCRS, this paper took a backfill slope project for example. The numerical MCRS model was established, the responses of MCRS when replacing backfilled material and increasing the length of back pile were obtained, a comparative analysis was made. The following conclusions could be drawn:

1. Backfill material has significant influence on the displacement of backfill slope. When the backfill material is gravel soil, the slope displacement can be controlled to a satisfactory degree. When the back-fill material is replaced by silty clay, the shear strength and internal friction angle of soil become smaller, and the displacement of slope increases significantly, which may lead to slope failure.

2. When the anchorage length is satisfied, increasing the length of the back row pile has no significant effect on reducing the displacement of MCRS slope, but it can effectively reduce the axial force of anchor rod.

3. MCRS is composed of various retaining substructures, and its mechanical mechanism is complex, which is considered separately in the existing literatures. In MCRS, there are complex interactions among various substructures, including double-row piles, anchor rods, counterfort retaining walls, reinforced soil and backfill concrete. The existing design methods are difficult to consider their interaction, and numerical simulation provides an effective method for MCRS design.

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