Analysis of slope stability considering the mechanism of the bolt-beam-root pile composite retaining structure

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Abstract. This project focuses on the development of a new type of retaining structure, namely Bolt-Beam-Pile Composite Retaining Structure. The proposed structure is a technical and economically feasible method enhancing the slope stability. A parameter sensitivity analysis carried out to evaluate the behavior of the structure under different scenarios, and the variation of the soil parameters. Finite element method was utilized to stimulate the model and perform the analyses. The results demonstrated that, compared with other three typical retaining structures the new Composite Retaining Structure has larger safety factor and smaller displacement.

1. Introduction

A retaining structure is also known as a support or enclosure structure. The bolt-beam-pile composite retaining structure investigated in this paper is a new type of composite retaining structure formed by the combination of two rows in parallel vertical tree root piles, and anchor with the continuous beam at the top of the pile.

From the structural analysis, the double-row root piles are embedded in soil as portal frames explaining that the structure has greater lateral stiffness than conventional anti-slide piles. The tensile properties of the soil anchor bolts can efficiently limit lateral structural deformation [1]. Furthermore, the stress condition of the whole structure has a substantial spatial effect, which mobilizes the self-stabilization performance of soil [2]. Finite element methods (FEM) is used to study the composite retaining structure by utilizing the software package MIDAS [3].

The methodology used in this paper is PE is based Strength Reduction Method (SRM). It is a finite element method specifically developed to simulate the actual slope failure mechanism and determines both factors of safety and failure behavior. MIDAS is a FE-based software for the analysis of geotechnical projects. Accessing the failure zone of the element, the factor of safety can be consequently calculated. For this purpose, a detailed model can be established through numerical analysis, which can provide sufficiently reliable results [4]. Moreover, elastic-plastic finite elements method for slope stability analysis has the advantages of high accuracy, robustness, and simple calculation process over conventional analysis which are typically used by practicing engineers.
The high-pressure grouting technology during the construction of the root piles, and the composite soil around the piles formed by split grouting can make the piles work better. The body is reliably anchored in the soil leading to an increase in the strength of the soil.

2. Finite Element Method Analysis of the Bolt-beam-pile structure
In this study, the factors affecting the slope performance such as the shape of sliding surface, the distribution of foundation materials and the rigidity of sliding surface, are taken into account in the stability analysis of slope. Moreover, FEM analysis is carried out by modeling the structure and soil as whole to get better results. The analysis of CRS mechanism was developed in the FEM software. The appropriate model selected to simulate the soil behavior in MIDAS has confirmed the importance significance, and sensitivity of the soil material properties when compared with experimental data. The resulting data from this research was used to validate output mathematical models using a Mohr-Coulomb Plasticity model. The use of software is essential to perform nonlinear analyses by FEM. Furthermore, the software can model more general geometries and soil property variations. As such, such simulations can be applied to complex slope configurations and soil deposits in two or three dimensions to model virtually all types of mechanisms.

2.1 Definition of ground and structural materials
The constitutive soil model carried out in the present research is Mohr-Coulomb model because this research mainly focuses on the practical application.

Ground materials are defined as below:

| Name                  | Ground material 1 | Ground material 2 | Ground material 3 |
|-----------------------|-------------------|-------------------|-------------------|
| **Material**          | Mohr-Coulomb      | Mohr-Coulomb      | Mohr-Coulomb      |
| **Elastic modulus (E) (kN/m²)** | 10000             | 20000             | 30000             |
| **Poisson’s ratio (Nu)**   | 0.3               | 0.3               | 0.3               |
| **Unit weight (kN/m³)**   | 20                | 22.5              | 22.5              |
| **K0**                 | 0.5               | 0.5               | 0.5               |
| **Cohesion (c) (kN/m²)** | 18                | 22                | 25                |
| **Frictional angle (Phi)** | 17               | 21                | 22                |

The figure 1 represents an overall view of the two dimensional model of the current research.

![Figure 1. The two dimensional model](image)
2.2 Analysis of the bolt-beam-pile CRS with fixed constraints

Table 3. Total displacement CRS/ Fixed Constraints (m)

| Node location | Value (m) |
|---------------|-----------|
| 11075         | 0.06      |
| 6730          | 0.05      |
| 15815         | 0.05      |
| 13583         | 0.05      |
| 17776         | 0.05      |
| 11207         | 0.05      |

Figure 2. Total displacement CRS/ Fixed Constraints

Figure 2 shows that the presence of the structure changes the shape of the sliding arc failure. The increase of the safety factor and the decrease of the displacement demonstrate the technical feasibility of the CRS.

Figure 3. Anchor Axial Forces (kN) Figure 4. The axial force on the beam CRS/Fixed constraints (kN)

Figure 5. Constraints results

This comparison showed that the hinge constraint is the optimal choice, because it has smaller inner forces and bending moments, and reasonably reduce the displacement of the initial state of the slope. The appropriate constraint for the bolt-beam-pile CRS, and the pertinence of the implementation of the new CRS structure were in contrast with the typical retaining structure.

3. Conclusions

The research work presented in this paper analyzed the interaction between soil and the new composite retaining structure. after the simulation of the Bolt-Beam-Pile retaining structure by finite element software, the following conclusions and recommendations are obtained.

- The safety factors and displacement under the three types of constraints are significantly different. The hinge constraint is the optimal displacement constraint.
• The hinge constraints induce the minimum demand of axial and shearing force, bending moments, and deflections on the structural features. Hence, the hinge is the optimal constraint for the Bolt-Beam-Pile Composite Retaining Structure.
• The practical project is technically feasible because the finite element analysis confirmed the construction pertinence of the Composite Retaining Structure for slope stability.

References
[1] Liao, H.-J., Cheng, S.-H., & Chen, R.-D. (2019). Remedial Measures for Existing Anchored Slopes in Taiwan. ASCE, 1943-2000.
[2] Liu, H., Liant, R., Yang, K., & Nusairat, J. (2011). Slope Stability and Earth Retaining Walls. ASCE, 9-16.
[3] Shi, J., & Yonghui, C. (2015). Three-dimensional numerical parametric study of the influence of basement excavation on the existing tunnel. Journal of Computers and Geotechnics, 146-158.
[4] Cai, F., & Ugai, K. (2004). Numerical Analysis of Rainfall Effects on Slope Stability. ASCE, 68-78.
[5] Midas Elite Center. (2013). Slope Stability Design for Dams and Embankments. Geotechnics - Finite Element Analysis Training. London: Midas UK.
[6] Comodromos, E., Papadopoullou, M., & Laloui, L. (2016). Contribution to the design methodologies of piled raft foundations under combined loadings. Canadian Geotechnical Journal, 559-577.