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Analysis of the passive earth pressure on a gravity-type anchorage for a suspension bridge

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Abstract

In this study, numerical analyses have been performed for a reasonable gravity-type anchorage design. The emphasis is on evaluating the effect of the passive earth pressure for gravity-type anchorages under pullout loading. Three-dimensional FE analyses were performed for different types of bedrock and embedded depths. Based on this study, it is found that the displacement of the gravity-type anchorage decreased with increasing embedded depth due to the increase in the passive resistance in front of the anchorage. It is also found that the resistance due to passive earth pressure in front of the anchorage accounts for approximately 10–30% of the total resistance and thus represents a significant improvement in the prediction of the realistic resistance for gravity-type anchorages subjected to pullout loads.

Keywords: Suspension bridge, Gravity-type anchorage, Finite element analysis, Passive earth pressure, Embedded depth

Introduction

Suspension bridges are widely used as a type of bridge structure across long spans because they have significant advantages in their material properties and significant height-span ratios of the stiffening girders [2, 5]. An anchorage is a key structural component that is capable of withstanding the tension force due to the main cable in suspension bridge design [8]. Typical anchorage types are divided into two categories: tunnel-type and gravity-type anchorages. In most cases, a gravity-type anchorage, in which the horizontal loads from the main cables are resisted principally by friction between the underside of the foundation and the supporting strata, is widely used because it is less affected by soil conditions and has a well-known support mechanism. The passive resistance in front of the anchorage occurs, but it is ignored for conservative design and it has not been established yet. Therefore, it is necessary to analyze the effect of passive resistance in front of anchorage for reasonable design.

The objective of this study was to investigate the passive earth pressure in front of gravity-type anchorages by using 3D FE analyses. The effect of the passive earth pressure was investigated by changing the embedding depth and bearing layer. Additionally,

the passive earth pressure affecting the anchorage pullout capacity was quantitatively evaluated.

Finite element modeling

Numerical simulations were conducted based on the Paryoung Grand Bridge located in Korea. The dimensions, mechanical properties and loading conditions of the model used in this study can be referred to in the design and geotechnical investigation report [10, 11]. The FE package ABAQUS [1] was used. Figure 1 sho≤ws a typical 3D FE mesh used in this study. The gravity-type anchorage is modeled with 4-node tetrahedral elements, and the soil consists of 8-node hexahedral elements. A relatively fine mesh was used near the interface between the anchorage and the surrounding soil, and the mesh became coarser farther from the anchorage. The typical anchorage had a length L of 40.0 m, a width W of 32.0 m and a height H of 22.0 m. The anchorage extends through the layer of weathered soil, and the bearing end is located on weathered rock (or soft or hard rock). The mesh consists of a total of 70,156 elements. The vertical boundaries are allowed to move only in the vertical direction, and the bottom boundary is fixed in the horizontal and vertical directions.

The anchorage is modeled as a linear-elastic material, while a Mohr–Coulomb non-associated flow rule is adopted for the weathered soil and bearing layers. Mohr–Coulomb constitutive models of soils have commonly been used for FE modeling of

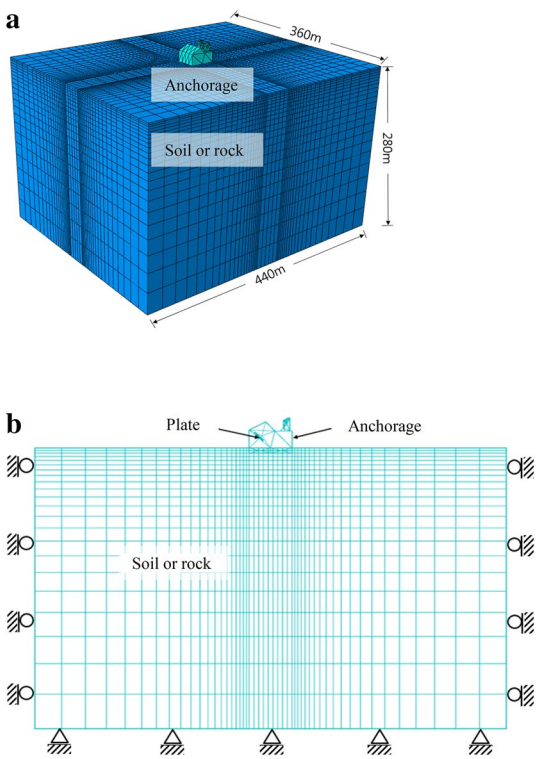

Fig. 1 Representative finite element mesh used in the analysis: **a** typical 3D FE mesh; and **b** cross-section view and boundary conditions

geotechnical structures [3, 4, 7, 9]. To simplify the analysis process, constant material parameters for the soil and anchorage were adopted with reference to literature [6, 10, 11]. Table 1 summarizes the material parameters used in the analyses.

Penalty-type interface elements were used to describe the anchorage–soil interface behavior. This model was selected from the contact model of ABAQUS [1] and an interface friction coefficient μ= 0.65. The anchorage–plate interface was considered as a frictionless model. The interface models prevent penetration between different materials at the contact surface.

Numerical analysis was performed with various bearing layers and depths of the weathered soil. The types of bearing layers were weathered rock, soft rock and hard rock. The embedded depth of the anchorage in the weathered soil was 0, 5, 10, 15 and 19.5 m. The pullout load was applied from the design load to twice the design load. A summary of the analysis is shown in Table 2. Figure 2 shows a cross-section of the model for the parametric studies.

Table 1 Material properties used in the analyses

Material	Model	E (MPa)	c (kPa)	φ (deg)	ν	γ (kN/m^3)
Anchorage	Elastic	24,000	–	–	0.15	25
Plate		210,000	–	–	0.3	78.5
Weathered soil	M-C	69	15	29	0.35	18.5
Weathered rock		98	39	30	0.3	20
Soft rock		2400	98	33	0.25	23
Hard rock		5300	255	38	0.22	26

M-C Mohr-Coulomb

Table 2 Summary of the soil conditions of the numerical analyses

Bearing layer	Embedded depth (m)	Friction coefficient
Weathered rock		
Soft rock	0, 5, 10, 15, 19.5	0.65
Hard rock		

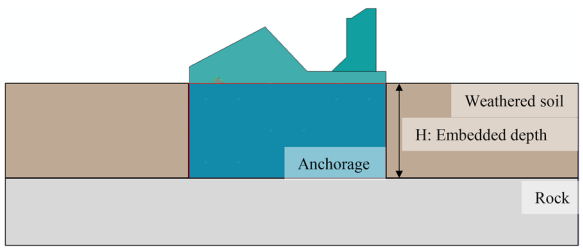

Fig. 2 Typical cross-section of the model for parametric studies

Results and discussion

To investigate the effect of the bearing layer, FE analyses were conducted under multilayered soil conditions. Figure 3 shows the load-displacement curves according to the embedded depth for different bearing layers when the design pullout load is applied to the anchorage. As expected, the results show that the deeper the embedded depth is, the smaller the displacement of the anchorage in every bearing layer. This is because a large passive resistance acts on the front of the anchorage as the embedded depth increases. In addition, when the weathering rock was a bearing layer, a displacement difference of up to 140 mm was significantly greater than that of the other bearing layers (i.e., soft rock and hard rock) depending on the embedded depth. This is because the anchorage is inclined toward the bearing layer when the pullout load acts on the anchorage, so the anchorage is less inclined as the strength of the bearing layer is stiffer. Therefore, it can be seen that not only the stiffness of the soil in which the anchorage is embedded, but also the stiffness of the bearing layer supporting the anchorage affects the pullout behavior of the gravity-type anchorage.

The effect of the internal friction angle of the soil was investigated. In the numerical analysis, the soil resistance was calculated by calculating the average horizontal stress of the soil during pullout loading and multiplying it by the cross-sectional area of the contact soil. In addition, the passive earth pressure was calculated using Rankine's theory for contact soil. α and β were defined as shown in Fig. 4a to quantitatively evaluate the passive resistance in front of the gravity-type anchorage. α is the ratio of the soil resistance(C) to the anchorage resistance(B) under the design pullout load. That is, it represents the ratio of the passive resistance to the total resistance of the anchorage. β is the ratio of the soil resistance(C) and passive earth pressure by Rankin's theory(A). In other words, it represents the ratio of the passive resistance to the theoretical passive earth pressure under the design pullout load. Figure 4b shows the α (%) value according to the embedded depth. It can be seen that for all the bearing layer conditions, the passive resistance of the entire anchorage resistance occupies a 10–30% distribution. This means that a reasonable design is possible when the passive resistance is considered in the anchorage design. Figure 4c shows the β (%) value according to the embedded depth. A similar behavior for all bearing layers shows the largest β (%) value at 5 (m) and the smallest β (%) value at 19.5 (m). In other words, it can be seen that the shallower the embedded depth of the anchorage is, the closer the value of the earth pressure is to the theoretical Rankine's passive earth pressure value. In addition, it can be confirmed that the deeper the embedded depth is, the greater the safety of the anchorage under pullout loading and the greater the anchorage pullout capacity.

Conclusions

A series of numerical analyses were conducted to investigate the behavior of a gravity-type anchorage subjected to pullout loads. The focus of this study is the effect of the passive earth pressure on the bedrock in front of the anchorage under pull-out loading. From the findings of this study, the following conclusions can be drawn:

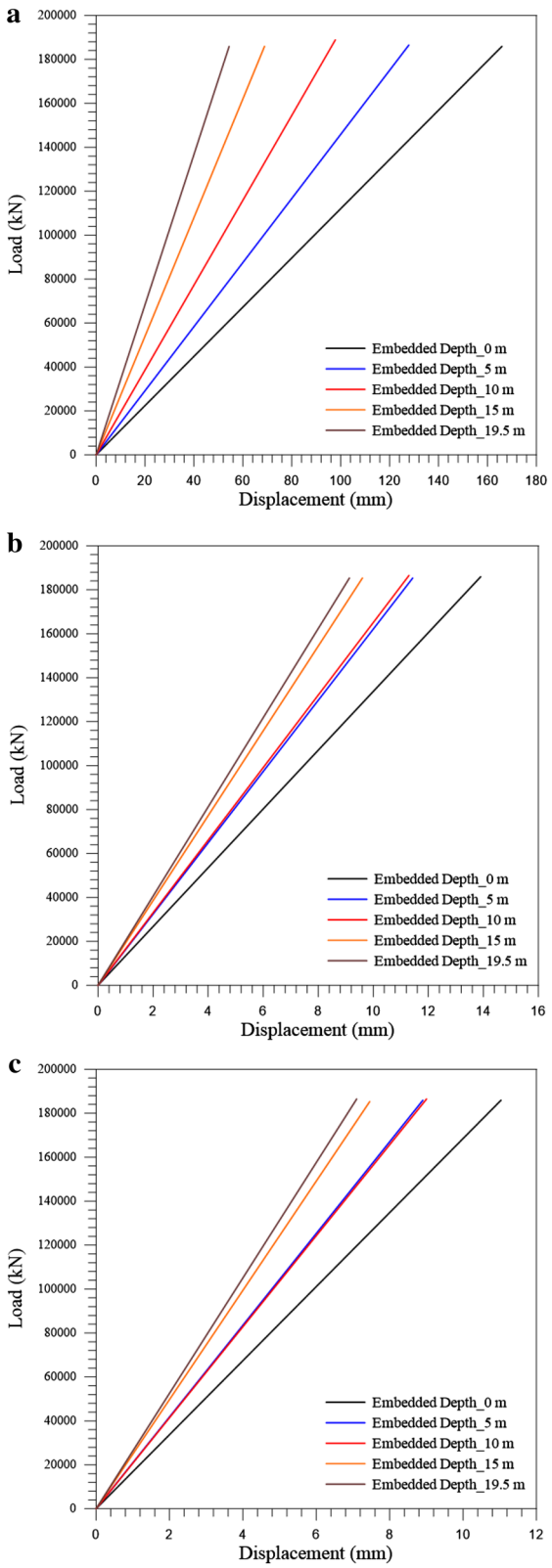

Fig. 3 Load-displacement curves with the embedded depth: **a** weathered rock; **b** soft rock; and **c** hard rock

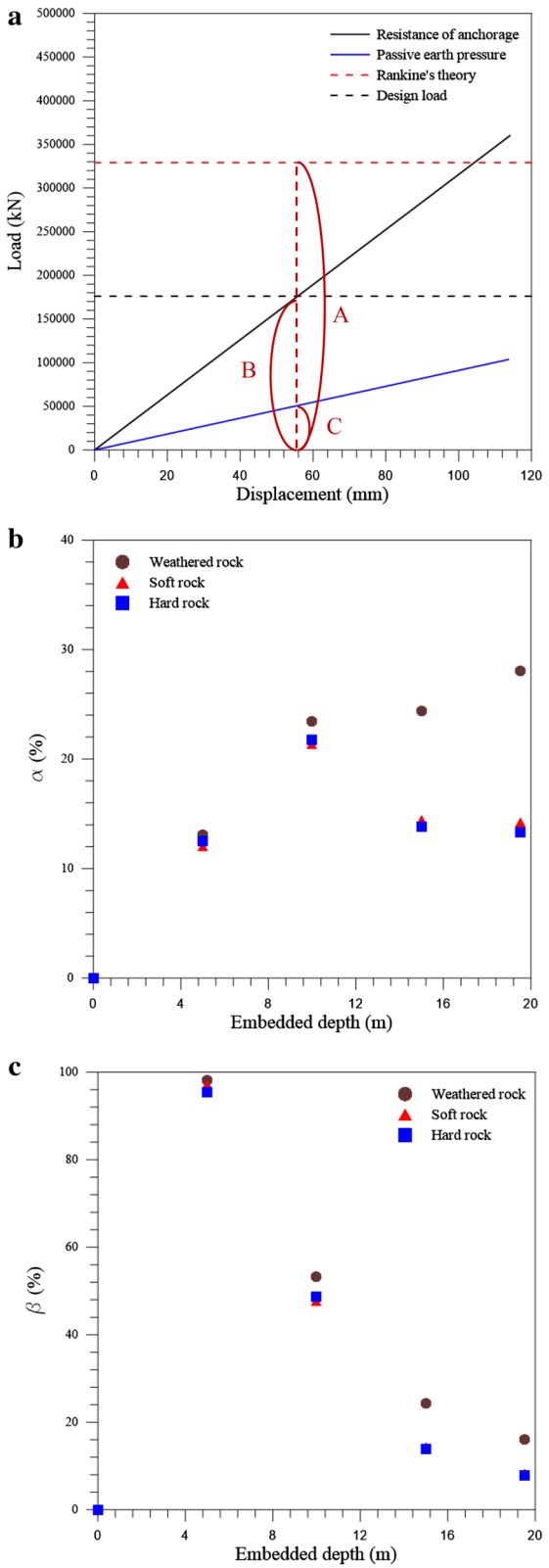

Fig. 4 Evaluation of the passive resistance in front of the anchorage: **a** definition of α and β; **b** α (%) value according to the embedded depth; and **c** β (%) value according to the embedded depth

- The stiffness of the bearing layer and the embedded depth of the anchorage have shown a significant influence on the pull-out capacity of the anchorage. It can be seen that the stiffer the stiffness and the deeper the embedded depth, the better the anchorage's pullout capacity is.
- It was confirmed that the passive resistance in front of the anchorage accounts for approximately 10–30% of the total resistance of the anchorage. In addition, it can be seen that the shallower the embedded depth of the anchorage is, the closer the earth pressure is to the value of the theoretical Rankine's passive earth pressure.
- In conclusion, the effect of the passive earth pressure presented in this study can be used to reasonably predict the pullout behavior of gravity-type anchorages for suspension bridges.

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Authors' contributions
MC has supervised the project and conceived of the presented idea. SL performed the numerical analysis. HL and SS analyzed the results and took the lead in writing the manuscript. All authors contributed to the final version of the manuscript. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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