Soil-water coupled analysis on an excavated large-scale slope composed of folded geological structure

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1. INTRODUCTION

Yuan et al. (2021) discussed a slope failure showing large-scale deformation, which Ohishi and Terakawa (2019) reported in Rajamandala, Indonesia. To be specific, a large deformation with the toppling phenomenon occurred in the objective slope during the excavation process. The geological survey indicates that the objective slope included fold structure formed by tectonic movement. The influence of the fold structure on the deformation mode of the excavated slope was discussed by Yuan et al. (2021). Furtherly, Yuan et al. (2022) discussed the effect of in-situ stress as a cause of the large slope deformation. In this report, the existence of groundwater due to heavy rainfall will be newly discussed during the excavation process. And the soil-water coupled analyses have been employed to the slope stability. The present analysis adopts the finite difference method operated by software FLAC2D. Then, it is discussed that the soil-water coupled analyses were influential on the stability of the slope.

2. METHOD AND PARAMETERS USED IN ANAYSIS

2.1 Analysis condition

Figs.1 exhibits the mesh used in this numerical analysis with the geological information and the boundary conditions of the soil-water coupled analysis. In the figure, mudstones are classified into three grades, as highly weathered D_L, moderately weathered D_H, and non-weathered C_L, described by Yuan et al. (2022) in detail.

Constitutive models of rock components are applied with elastic model and perfect elasto-plastic model, Mohr-Coulomb model respectively. The rigid rock such as Tuff breccia, Tuff breccia (C_L), and non-weathered mudstone C_L are modeled as elastic, and the other rocks are modeled as the Mohr-Coulomb model. The parameters of rock components are shown in **Table 1**, where σ_c is compressive strength, σ_t is tensile strength, and k indicates the coefficient of mobility used in the soil-water coupled analysis.

The groundwater level was confirmed through the boring test before Excavation 2. The excavation process was executed in the order of Excavation 1-1, 1-2, and 2. The field test revealed the groundwater level located around the boundary between the terrace deposit and the tuff breccia (**Fig.1(a)**). In other words, D_L mudstone should be fully saturated in the site before Excavation 2. From **Fig.1(b),** the left and right boundaries are set with the fixed head of water to consider the confirmed groundwater level. The surface of the slope is set to be permeable boundary, and the bottom of it is set to be impermeable boundary.

2.2 Analysis procedure

To clarify the deformation mode of the slope due to groundwater, both total stress analysis and soil-water coupled analysis were executed. The process of soil-water analysis is shown as follows:

Table 1 Parameters of rocks
(Parameters of tuff breccia from Osada,2005)

Parameters	D_L	D_H	C_L	TD	TB
ρ [g/cm^3]	1.855	1.834	2.014	1.684	2.100
ϕ [degree]	15.10	8.00	28.35	12.50	17.80
c [kPa]	31	99	830	83	100
ν	0.30-	0.30	0.30	0.30	0.34
E [MPa]	78.20	105.40	186.40	6.00	1900.0
σ_c [kPa]	57.30	39.90	2150	245.32	4500
σ_t [kPa]	7.16	4.98	268.75	0	562.50
e	0.476	0.475	0.398	0.337	0.375
k [10^{-5}cm/s]	4.43	4.43	4.43	10.69	3.68

I. Execute seepage flow analysis based on the head of water at the left and right boundaries (**Fig.1 (b)**) until the pressure equilibrium.
II. Conduct self-gravity analysis to reach at the primary stress field.
III. Start excavation analysis and set the piles before and during Excavation 2.

Here each excavation stage is divided into 200,000 steps analysis. In the case of total stress analysis, step I was skipped.

3. ANALYSIS RESULT AND DISCUSSION

3.1 Comparison of in-situ, analytical groundwater tables

Fig. 2 exhibits the heatmap of the saturation degree in the partial enlarged view at the same excavation stage as the boring test. The result shows that the unsaturated zone only appears in the terrace deposit area, especially the superficial part. During excavation analysis, drainage occurred at the surface of the terrace deposit, and the mudstone area is fully saturated. The analyzed saturation distribution could capture the groundwater level from the boring test.

The pore water distribution after all excavations is illustrated in **Fig. 3**. From the figure, the curved and layered distribution of the pore water pressure can be confirmed. This distribution seems to be determined by the drainage surface and the geometry of the slope.

In this way, the similarity of the in-situ groundwater level could be confirmed through the suggested soil-water coupled analysis. And then, furtherly, to clarify the deformation mode of the excavates slope due to the groundwater, the maximum shear strain increment after all excavation processes will be discussed.

Keywords: Slope stability, Numerical analysis, Excavation, Soil-water coupled analysis
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3.2 Maximum shear strain increment

Figs. 4 show the maximum shear strain increment of the slope from both total stress analysis and soil-water coupled analysis. From the figures, a relatively large maximum shear strain increment can be commonly confirmed in the two areas namely; the foot of the slope composed of Terrace Deposit (②) and the foot of the slope composed of D_L (①). However, the maximum shear strain increment at ① and ② was amplified in the soil-water coupled analysis. To be specific, the soil-water coupled analysis shows larger and wider shear strain distribution compared with the total stress analysis.

It indicates that shear failure could potentially occur at the boundary of highly weathered D_L and moderately weathered D_H. At the middle part of the slope with an earth mound (Area②), both two analysis cases show noticeable shear strain increment. The reason for the significant shear strain increment is the weak mechanical properties of terrace deposits acting as sandy materials. To reveal the reason for the significant shear strain, the stress paths of soil elements in the two areas are necessary.

4. CONCLUSION

This paper discusses the study of an excavated slope with unexpected large deformation by total stress analysis and soil-water coupled analysis. According to the analysis results, the groundwater level after the excavation process in the soil-water coupled analysis could capture the measured groundwater level by the boring test before Excavation 2. Furtherly, compared with the result of total stress analysis, the max shear strain increment of the soil-water coupled analysis showed more significant values and a concentration at the foot of the slope and the middle earth mound. It indicates that potential shear failure could occur.

To reveal the reason for large shear strain in soil-water coupled analysis, the stress path of soil elements needs further discussion, which is scheduled as future work. Besides, the current study also shows a lack, as the constitutive model used in this analysis is the Mohr-Coulomb model. The Modified Cam-Clay model could be a better choice to describe the deformation behavior of the highly weathered mudstone, which is similar to clay. Furtherly, strain-softening due to swelling could also lead to a decrease in strength, which should be included in further study.

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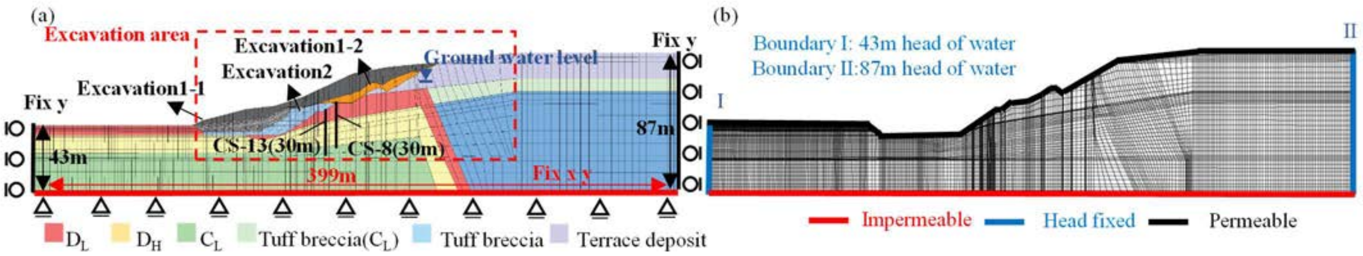


Figs. 1 Mesh used in numerical analysis and pile displacement accompanied with rainfall

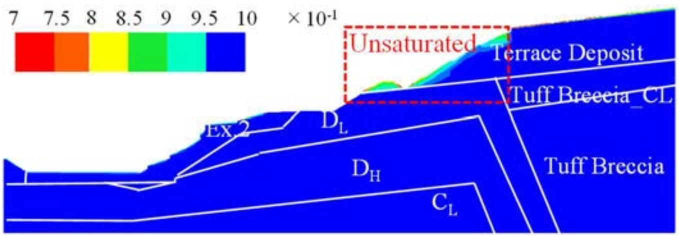


Fig. 2 Heatmap of saturation degree in enlarged partial view named "Excavation area" in **Fig. 1 (a)**

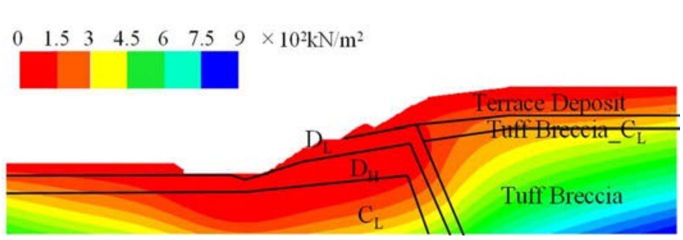
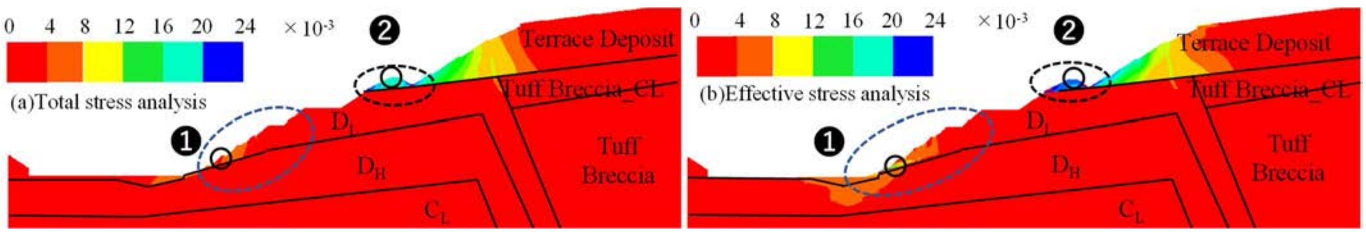


Fig. 3 Heat map of porewater pressure after all excavation stages



Figs. 4 Heatmap of maximum shear strain increment from (a) total stress analysis and (b) soil-water coupled analysis in enlarged partial view named "Excavation area" in **Fig. 1 (a)**