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Reinforcement of renovated slope against additional steeper cutting at the lower part

Chan-Kee Jung^{1*} and Sang-Duk Lee²

*Correspondence:

chankee@kccworld.net

¹ Dept. of Civil & Trans.

Sys. Eng., Ajou Univ., 206

Woldcup-ro, Youngtong-gu,

Suwon-si, Gyeonggi-do

16499, South Korea

Full list of author information
is available at the end of the
article

Abstract

The behavior of a slope reinforced by passive piles 15 years ago was studied during removal of some passive piles, additional steeper slope cutting, and reinforcement by soil nails and anchors. Through a comparison of the measured value and numerical analysis results, it was found that the maximum lateral displacement developed at bench No. 4, which was the nearest bench to the additional steep slope cutting, and it could be correlated with the groundwater table. In particular, the relaxation of the ground from past failure sliding could affect the slope stability.

Keywords: Passive piles, Soil nails, Ground anchors, Behavior of renovated slopes, Ground water table, Numerical analysis

Introduction

For the development of urban areas and traffic solutions, more steep slopes and cuttings are being constructed, and significant land sliding and collapse of slopes has been reported recently during the widening of existing road sites [1, 2].

The slope in this study was cut for road construction, but, after the first construction, it experienced a large-scale landslide with tension cracks. It was reinforced by five rows of passive piles to halt the slope sliding. It has been maintained safely for 15 years [3].

However, additional steeper slope cutting was planned to widen the road, and the lower three rows out of the five rows of passive piles needed to be removed. Additional reinforcement with soil nails and concrete panel walls with ground anchors was planned [4].

To verify the reinforcement effect of the existing passive piles and additional soil-nails and concrete panels with ground anchors, the behavior of a new steeper slope was measured in site and analyzed numerically to determine the slope's behavior.

In this study, the stress and displacement of a slope at every construction stages (cutting and reinforcement) were verified by comparing the measured results at the existing passive piles with the results of numerical analyses [5].

Field status

Profile

Referring to Fig. 1a and b, the slope was located at the Singal-Suji road in Gyeonggi-do, South Korea. It had a height of 45 m height and longitudinal length of 380 m.

As shown in the figures, it experienced a wedge-shaped land sliding of the blocks with 40 m height and 380 m longitudinal length in August 2002. Vertical cracks of 18 m depth were measured at the slope crest.

In 2003, as shown in Fig. 1b, passive piles with 250 mm diameter casing and 150 × 150 × 7 × 10 mm H-shaped piles with cement mortar filling were installed on benches Nos. 1–5 (All piles were capped with concrete, and a double-row was installed on bench No. 5).

The slope needs to be cut at a steeper angle to widen the road. For this work, the lower three rows of passive piles should be removed, and the more steeply cut slope should be reinforced by soil-nails at the upper part and by a concrete panel wall with a ground anchor at the lower part (see Fig. 2).

During the steeper slope cut, the lower three rows of passive piles on bench No. 3 to No. 1 were removed, and four stories of concrete panel wall with a ground anchor were built as shown in Fig. 3a and b (the upper steeper slope was reinforced by the concrete panel wall, in which three layers of soil nails were installed).

Table 1 Summary of ground properties (ground investigation report) [4]

Layer	Unit weight (kN/m ³)	Cohesion (kPa)	Internal friction angle (°)	Deformation modulus (MPa)	Poisson's ratio
Deposit soil	19	–	30	33	0.35
Weathered soil	19	25	28	40	0.32
Weathered rocks	20	35	33	200	0.30
Bed rocks	20	200	35	1000	0.28

Geological history and underground condition

The ground in the site consists of deposit soil, weathered soil, weathered rocks, and bed rocks from the ground surface.

- The deposit soil is composed of sandy gravel with silt for a depth of 1 m from the surface.
- The weathered soil is composed of silty sand (and a little bit of rock fragment) with a depth of 1.5–13.6 m under the bottom of the deposit soil.
- The weathered rocks are located at a 1.0–11.4 m depth under the bottom of the weathered soil. Rock fragment core can be found in it.
- The bed rocks seems to be highly or moderately weathered with lots of joints and fragments. Test core recovery of the bed rocks reaches 22–75%, and the rock quality designation reaches 0–12%.

Table 1 shows the physical properties of each soil and rock layer.

The ground water tables were observed at a depth of 8.8–15.5 m under the surface; however, they might be estimated higher. The permeability of the weathered soil and weathered rocks was evaluated as 7.48×10^{-4} cm/s and 9.02×10^{-5} cm/s, respectively, from the downfall test in the bore holes.

Measuring in site

Installation

To measure the behavior of the existing passive piles induced by additional slope cutting and the steeper slope reinforcement, four inclinometers and two ground water gauges were installed at the location of the passive piles [6].

As shown in Fig. 4, inclinometers were installed adjacent to the piles at benches No. 5 and No. 4, and the soil-nails were installed from the surface to 5 m under the bed rock along the typical section. A ground water gauge was installed adjacent to the piles at bench No. 4 along the typical section. Figure 5 shows a photograph of installation and measuring on site.

Results

The variation of the ground water table in the weathered rocks during the steeper slope cutting and the reinforcement is shown in Fig. 5, which is highly dependent on precipitation [7–9]. The maximum increase of the ground water table was 5.33 m.

No significant lateral displacement of the ground was observed at the crest of the slope. The maximum lateral displacements in weathered soil and rocks were 2.92 mm and 11.73 mm, respectively. The total lateral displacements at the inclinometers at benches No. 5 and No. 4 areas are shown in Fig. 6.

The maximum lateral displacements of bench No. 5 and the soil-nailed area were (–)3.03 mm and 0.80 mm, respectively, at depths of 8.0 m and 3.0 m from the surface.

However, the maximum lateral displacement of bench No. 4 was 11.73 mm at a depth of 0.5 m from the surface, which showed that passive piles at bench No. 4 deformed because of the steeper slope cutting.

Analysis of results

Lateral displacement at the ground surface and the maximum lateral displacement related to the ground water tables during the construction are shown in Fig. 7.

Figure 7a shows lateral displacement at the ground surface. As shown in the figure, no significant variation of lateral displacement at bench No. 5 (1HD_M) and the soil-nailing area (3HD_M) was observed during the slope cutting and rainfall. However, lateral displacement of the ground surface at the passive pile on bench No. 4 (2HD_M) increased gradually during the steeper slope cutting. Especially, the maximum lateral displacement of the passive piles of bench No. 4 (HD_M) and the ground water table near (UWL1) had a direct correlation.

All construction stages (steeper cutting and reinforcement in top-down method) can be designated as six stages as follows:

- Installing soil-nails for steeper cutting (SN).
- Installing ground anchor for fourth-story concrete panel wall (4LA).
- Installing ground anchor for third-story concrete panel wall (3LA).
- Installing ground anchor for second-story concrete panel wall (2LA).
- Installing ground anchor for first-story concrete panel wall (1LA).
- Final ground excavation for the new bridge foundation (FE).

At the construction of stage 4LA, 66% of the total displacement was developed as shown in Fig. 8a. Figure 8b shows the difference of lateral displacement between the passive piles at benches No. 5 and No. 4, which reached the maximum value at stage 1LA.

Numerical analysis

Modeling

As shown in Fig. 9, numerical analysis was performed using MIDAS GTS (Developer: Midas Information Technology Co., Ltd., South Korea [10]) under consideration of the construction stages to verify the variation of displacements and stresses of the ground and the reinforcement members on each stage.

Physical and mechanical properties of soil layers and bed rock are shown in Table 2. Locations of soil and rock layers from the ground surface are shown below:

- Weathered soil 1: 0–6.0 m.
- Weathered soil 2: 6.0–12.0 m.
- Weathered rocks: 12.0–15.0 m.
- Bed rocks: 15.0–20.0 m.

The land sliding plane in 2002 was regarded as the interface between weathered soil layers 1 and 2.

Table 2 Summary of input properties of soil and rock layers

Layer	Unit weight (kN/m ³)	Cohesion (kPa)	Internal friction angle (°)	Deformation modulus (MPa)	Poisson's ratio
Weathered soil 1	19	15	30	14	0.35
Weathered soil 2	19	25	28	40	0.32
Weathered rock	20	35	33	200	0.30
Bed rock	20	200	35	1000	0.28

Results of numerical analysis

Figures 10 and 11 show the displacements and stresses during the construction in the whole slope. The maximum displacement and the maximum stress are observed at the top of the passive piles on bench No. 4 as shown in Fig. 12.

Comparative analysis with measured value

Comparative analysis of the numerical analysis results and measured values at the site are described below:

- No significant displacement was developed at the depth of the bed rocks and weathered rocks in the numerical analysis results and measured values at the site.
- The displacement of weathered soil layer 1 estimated numerically coincided with the measured value.
- The lateral displacement of weathered soil layer 2 estimated numerically was larger than the measured value at the site.

- The lateral displacement on stages SN and 4LA estimated numerically coincided with the measured value at the site.

The numerically estimated lateral displacement at the ground surface of bench No. 4 was larger at anchor stages (4LA–2LA) and smaller at the SN and FE stages—see

Fig. 13a. The lateral displacements estimated by the numerical analysis during the construction stages compared with the in-site measured value were as follows [5, 11, 12].

- Larger than actual measured value at SN stage.
- Smaller than actual measured value since 2LA stage.
- Larger again after 1LA stage.

This seems to have happened because the numerical analysis model was varied more sensitively than the real ground by tensioning the ground anchors.

Conclusion

This study was performed to verify the effect of the reinforcement method for aslope renovated by five rows of passive piles 15 years ago. This slope had to be steepened for wider road construction. For steepening the slope, the lower three rows of the passive piles were

removed, and the steepened slope was reinforced by soil-nails and four stories of concrete panel walls.

- The maximum lateral displacement was observed at the passive pile on bench No. 4, which reached 11.73 mm at the final steepening stage.
- The maximum increase of the ground water table in the weathered rocks during the steepening and reinforcement of the slope was 5.33 m. The variation of the ground water table had a great effect on the displacement of the slope.
- The maximum lateral displacement developed in the slope-steepening stage for the fourth-story concrete panel wall (the first concrete panel wall from top–down cutting). There was 66% of total displacement in this stage, and, after this stage, the tension forces of the ground anchors could restrain the displacement.
- No significant displacement developed in the bed rocks and weathered rocks. However, in the weathered soil layer, a sharp increase of lateral displacement was observed during the construction stages, which shows that the past land sliding or failure plane could be redeemable and affect the stability of a slope.
- The lateral displacement by numerical analysis was estimated smaller than the actual value in the ground-anchoring stages. This means that the numerical analysis model reacts more sensitively than the real soil by tensioning ground anchors.
- The failure plane of a slope renovated by passive piles could be redeemed through steeper slope cutting. However, it could be stopped by soil-nails.

Authors' contributions

C-KJ carried out studies regarding the reinforcement of renovated slope, participated in the sequence alignment and drafted the manuscript. S-DL reviewed the draft prepared, presented directions and participated in final preparation. Both authors read and approved the final manuscript.

Author details

¹ Dept. of Civil & Trans. Sys. Eng., Ajou Univ., 206 Woldcup-ro, Youngtong-gu, Suwon-si, Gyeonggi-do 16499, South Korea. ² Dept. of Civil Sys. Eng., Ajou Univ., Suwon, South Korea.

Competing interests

The authors declare that they have no competing interests.

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