Case study on slope stability of steep rock slope in colluvium using permanent anchor

Min Hye Ahn, Jeong Ku Kang & Eun Chul Shin
Incheon National University, Korea

ABSTRACT: Recently, heavy rainfall at local area intends to increase slope failure. Flow of water by rainfall between fractured rocks in a colluvium can cause rock slide failure. In this paper, the case of slope reinforcement on fractured rock was studied. The safety factor was analyzed by numerical method on the colluvium rock surface. Ground investigation, physical laboratory test, rock triaxial compression test, and field monitoring were performed. In order to prevent sliding failure or global shear failure by earth pressure, field pullout test was proceeded with the compression permanent anchor. Rock slope stability and design anchor force satisfied the standard specification. It was analyzed by stress reduction factor of Midas GTS NX program. In case of numerical analysis with seepage-stress coupled analysis, the stability and axial force are more critical in heavy rainfall condition. Therefore, it needs that groundwater flow in the bedrock should be controlled to prevent collapse of rock.

Keywords: Colluvium, Slope stability, Permanent anchor, Axial force, Local heavy rainfall

1 INTRODUCTION

A heavy rainfall intends to increase slop failure or ground subsidence. Because slope failure of colluvium or collapse of underground soil is due to the loss of fine materials. Retaining walls or temporary walls during an excavation work often collapse by local heavy rainfalls. Recently, temperatures in Korean Peninsula indicate often over 40 Celsius degrees because of recent global warming. Unstable temperature on the atmosphere sometimes causes serious local heavy rains. Sometimes, the local heavy rainfall can cause a number of human injury and damage of property. Therefore, it is very important issue that prevents the disasters like slope failure from heavy rainfalls.

It was reported that the ground anchor method has been spread rapidly every year since 1990s, it has been recognized as an effective slope stabilization method for rock sloping (Jang et al., 2016). Numerical analysis has been conducted on the stability of permanent anchors (Jang et al., 2016; Kang, 2011) and design criteria has been studied (Woo, 2010; Kang et al, 2015).

This research was focused on analyzing the axial force of permanent anchors for preventing collapse of exposed rock surface. The site of research is the hillside area that was excavated due to the development of the rocky mountain, and it is a place where the rocks collapse is progressive by weathering for a long time. Numerical analysis was carried out to analyze the change of axial force and slope behavior of the permanent anchor. It was discussed the differences of slope stability factor through the comparison of stress analysis method and seepage-stress coupled analysis method with the intensity of rainfalls.

Generally, slope stability analysis on the rock surface is used for geocell retaining wall, cutting soil, micro pile, soil nailing, and earth anchor method. The geocell retaining wall method is a method to reinforce incision slopes in the construction with the geocell retaining walls. Reinforced retaining walls with backfill materials are usually installed on the front the rock base. Backfill materials are effective to use good drainage aggregates. Rock anchors are often used to improve solidarity between geocell retaining walls and rock mass. When a rock is exposed to the slope of road during construction, cutting rock method is applied mainly. In case of the slope stability of the upper rock mass is insufficient, the method is effective to reduce the weight of upper rock mass. If there is a lot of cracks on the cut slope, micro piles or similar piles are useful method. When fractures and cracks are structurally strong on the rock base, micro pile is applied to protect the slope caused by heavy rainfall. To prevent the collapse of the slope of soil, nailing or rock-bolt is used to reinforce it. In addition, to prevent the surface scouring phenomenon, a seed spray method in which continuous filaments are mixed can be applied.

Nailing method is applied when a weathered rock layer on the upper part of incision slope is locally dropped off. Likewise, when pore water pressure increases in rock slope due to heavy rainfall, the anchor method is one of the methods for reinforcing incision slopes by pre-stressing. This paper describes the case of reinforcement of the exposed rock around Kyungin college area in Gyeonggi province, Korea. The cut-off site collapsed due to heavy rainfalls and ground subsidence. Therefore, in order to protect the slope stability of the front face and prevent the third collapse, a permanent anchor method is applied.

2 THEORYTICAL BACKGROUND

2.1 *Composition of permanent earth anchor*

The performance and specification of the ground anchor are affected by the shear resistance and adhesion characteristics of the anchor, the type of anchor, the construction method, and the proficiency of the management technician. The ground anchor has a free length to transfer the stress exerted in the anchorage field and the bond length to exert the required stress through the adhesion resistance between the ground and the injection material, the injection material and the tensile material. It also has an anchorage to deliver stress to the bond length. The general structure of the ground anchor was shown in Figure 1.

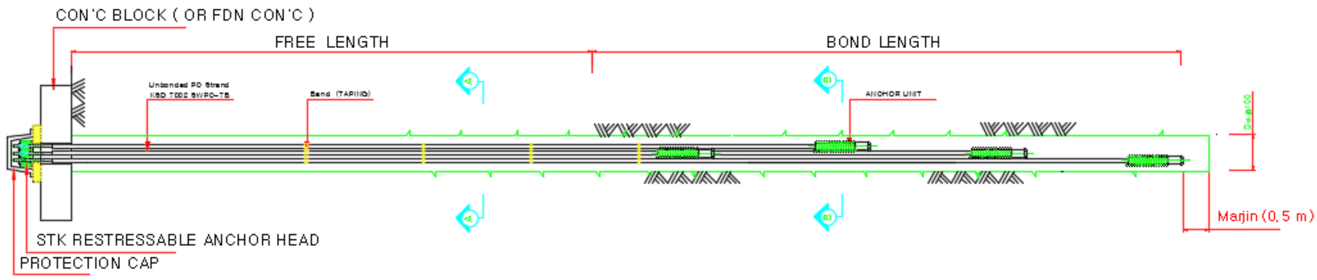


Figure 1. Structure of the ground anchor

2.2 *Classification of ground anchor*

Ground anchors are classified into earth anchors and rock anchors. The anchor method is a typical reinforcement method widely used for slope reinforcement, retaining material of retaining wall, and buoyancy prevention. The anchors are classified into friction type anchor, expansion type anchor, and multi-unit load transfer type anchor depending on the type of anchor. Friction type anchors are supported by frictional force between grout and ground. Filler type anchors are ground anchors that resist extrusion force by applying acupressure to the perforated walls by expanding the fuselage, and can be used effectively in the sections where the ground condition is good. On the other hand, the composite anchors are ground anchors that have the characteristics of the friction anchor and the anchor of the friction type at the same time. However, the design guideline is uncertain and rigorous construction management is required. In case of composite anchors, the length of the anchor fuselage should be calculated considering the frictional resistance of the main body of the fixture and the pressure resistance of the anchor. The pressure and frictional resistance should be checked by drawing test (Korea Infrastructure Safety and Technology Corporation, 2006)

2.3 *Concept of safety factor*

The safety factor of the ground anchor should be applied to each different characteristic in the tensile material, the ground condition, and the grout material. Considering the ground anchor tensile material with relatively reliable quality control, the ground which cannot characterize artificially, and the characteristics of grout with different behavior depending on the ground, each applied safety factor should be understood as a different concept. Table 1 shows the safety factor of the permanent anchor applied normal (Kang et al., 2015). On the other hand, Woo et al. (2010) estimated in the ground anchor failure investigation study that the safety factor for the wedge fracture was 1.5 for the critical activity surface in case of no sliding failure.

Table 1. Safety factor of permanent anchors.

Division	Safety factor of permanent anchor	
	Range	Korean Standard
Ultimate strength of tensile material	1.6-2.0	1.67
Adhesion resistance between grout and tensile material	2.0-3.0	2.5
Friction resistance between ground and grout	2.0-3.0	2.5

2.4 *Slope stability analysis*

The slope stability analysis by numerical method is similar to the Fellenius method, which takes the safety factor into the strength parameter in concept. If the shear strength is reduced to the shear stress level, the large deformation occurs at the weakest part, resulting in a state in which the convergence cannot be achieved numerically.
This condition corresponds to local failure, but at this time, the shape of the shear fracture of the slope is almost determined, and the shear plastic strain ratio reaches the fracture state along the fracture surface. This method is called the SRM (strength reduction method), which is the same as the safety factor. In the SRM, the safety factor was expressed as Eq. (1).

$$F_s = \frac{\int_l |\tau| dl}{\int_l |\tau_f| dl} \tag{1}$$

where τ is shear strength and τ_f is shear strength at failure which is expressed as the equation, $\tau_f = c_f + \sigma_n \tan \varphi_f$.

The strength reduction method is a nonlinear elasto-plastic analysis that deals with slope failure conditions. The minimum safety factor was obtained by reducing the physical properties and the nonlinear finite element equation was applied as shown in Eq. (2).

$$[K_G]\{\Delta u_G\} = \{\Delta R_G\} \tag{2}$$

where K_G is stiffness matrix, u_G is deformation and R_G is reaction force.

Physical properties affect the composition matrix, which is reflected in the stiffness matrix. The SRM reaches the fracture state trial and error to determine the strength parameter. The method can be approximated only when the strength parameter is used with a simple Mohr-Coulomb model. The non-convergence condition has the advantage of providing useful information for the measurement plan or calculation of theoretical safety factor because of confirming the failure mode (Shin & Midas IT, 2014).

3 EXPERIMENTAL TEST

3.1 *Condition of the test site*

The field test was applied to the site of rear rocky mountain of Gyeongin college, located at 00, Seoksu-dong, Anyang-si, Gyeonggi-do, Korea. The campus was established on a site of 450,000m^2, which was developed from aggregate site. Slope reinforcement work was carried out on the slope, slope failure prevention net and shotcrete, but locally collapse in the rock surface occurred two times recently. The first collapse occurred in the area of about 370m^2 of the rock cut area and the second collapse occurred in the area of the upper 307m^2 before the reinforcement. The reason of the collapse was estimated due to long weathering and heavy rainfalls. The anchor reinforcement was carried out because of the risk of subsidence and collapse of the ground when the heavy rain caused by the weather deteriorated. 35 permanent earth anchors with seed spray were applied in each collapsed area. Figure 2 shows the collapsed site.

(a) Site of Slope failure

(b) Collapsed rock

Figure 2. Collapsed site, 1st and 2nd area.

3.2 *Investigation and experiment*

The geomorphological survey was applied to the design by measuring the current status of the facility and the surrounding area based on the average coordinates and altitude of the previous survey points. The NX boring was conducted at a site. Ground water level, physical property of rock, uniaxial strength test, and triaxial compression strength were conducted at the same situation. Pullout test using hydraulic power was carried out on each anchor. Table 1 shows the list of field experimental test.

The colluvium layer is distributed 2.5 m thick at the top and consists of sandy gravels and alluvial deposits. Moderately soft rock layer exists as 4.0m thickness, 2.5 m below the surface. The bedrock shows normal strength and overall cracks. The total core recovery rate, TCR is 90% and RQD is 68%. Hard rock is distributed more than 13.5m from the lower part of 6.5m from the surface of the earth. Overall, the rock condition is moderately cracks and partially formed with iron oxide clay and clay fillings. TCR is 100% and RQD is 58-84%. Ground water level were measured below depth. Groundwater level changes due to seasonal changes, rainfall, construction work in the surrounding area. Table 2 shows drilling log data.

Table 2. Depth of each layer from the boring data.

Boring No.	Colluvium layer	Moderately soft rock	Hard rock	Total(m)	Ground water level(m)
BH-1	0.0-2.5 (2.5)	2.5-6.5 (4.0)	6.5-20.0 (13.5)	20.0	-

Rock tests were carried out on samples taken from depths 3.6-3.9m and 6.1-6.5m. As a result of the test, the unit weight is 25.56kN/m^3, the specific gravity is 2.616, the elastic modulus is 35.74GPa, and the Poisson ratio is 0.25. Uniaxial strength is 105.5MPa, cohesion 19.7MPa, and internal friction angle shows 54.9. Experimental test results show in Table 3.

Table 3. Physical property of rock base.

No.	Depth (m)	Unit weight (kN/m^3)	Specific gravity	Elastic modulus (GPa)	Uniaxial strength (MPa)	Triaxial strength		Poisson's ratio
						Cohesion (MPa)	Internal friction (Φ)	
BH-1	3.6-3.9	25.56	2.616	35.74	105.5			0.25
	6.1-6.5					19.7	54.9	

3.3 *Anchor axial force test*

To evaluate the performance of an anchor, tensile tests were carried out on a total of 16 anchors. The specification of the test anchor is shown in Table 4.

Table 4. Specification of ground anchor at 1st and 2nd construction site

Section	Anchor type	Specification		No. of hole	PC strand	Design strength(ton)
		Free length	Bond length			
1st site	permanent	6	3	9	4	39.8
2nd site	permanent	6	3	7	4	39.8

Tensile tests were conducted to confirm whether the anchors were damaged or not. Margin of tension strength and secured tensile strength were also checked. The tensile test was carried out by loading and unloading 20%, 40%, 60%, 80%, and 100% step load cycles. Anchor axial force test shows in Figure 3.

Figure 3. Anchor axial force test

4 NUMERICAL ANALYSIS

4.1 *Rainfall intensity and modeling of rock slope*

The numerical modeling was performed by the Midas GTS NX and critical cross section of the site. The analysis was performed along to the following step: removing colluvium rock, analysis without anchor, anchor with pre-stressed condition, anchor with pretention condition, and seepage-stress coupled analysis. In this study, the behavior of anchor with pretension condition was analyzed and creep behavior with elapsed time was excluded. Figure 4 shows the cross section and modeling of rocky mountain.

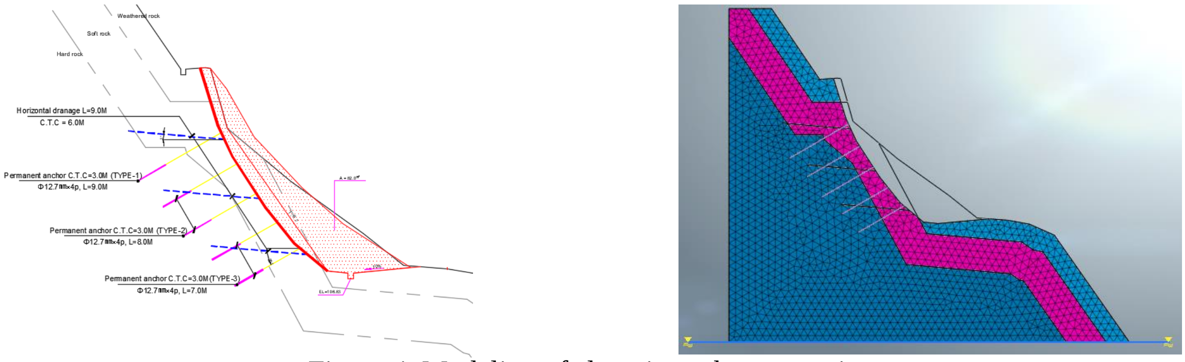


Figure 4. Modeling of slope in rocky mountain

The rainfall conditions applied rainfall intensity data supported by the Ministry of Land, Infrastructure and Transport. The site was located at longitude 126-55-14 latitude 37-26-7, and the rainfall was applied based on the recurrence period of 500 years and the rainfall duration of 5 hours in Table 5.

Table 5. Relation of Rainfall intensity-duration-recurrence interval

Duration(m) / Recurrence (y)	Rainfall intensity							
	5	10	15	20	30	40	50	60
500	295.8	224.7	196.9	180	158.3	143.7	132.7	123.9

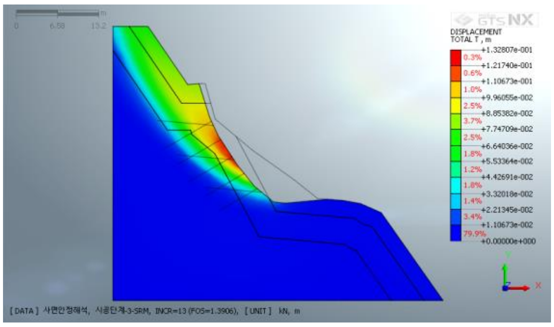
The bond length is 3.0m and the free length is 6.0m. The design bonding load is 39.8ton. The specifications of the applied anchor are shown in Table 6.

Table 6. Specification of ground anchor

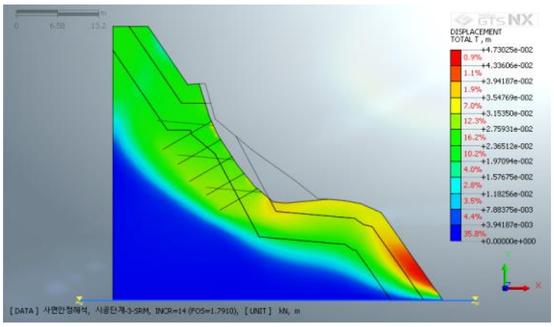
Type	Bond length (m)	Free length (m)	Total length (m)	Design loading (ton)
T-1	3.0	6.0	9.0	39.8

4.2 *The result of seepage-stress coupled analysis*

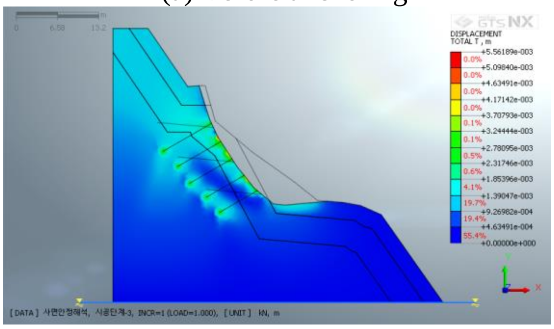
Slope stability analysis with different condition was shown in Figure 5. In case of Figure 5(a) Before anchoring case was failed at a safety rate 1.39. The situation of slope failure was located in the center of anchor part. The anchor with pre-stress condition shows stable at safety rate 1.79. The maximum displacement is 4.7 cm. In case of pretension anchor, it was converged at 1.25. The maximum displacement was 7.0 cm, and the failure type shows punching failure type due to anchor tensile force. In the case of seepage-stress coupled analysis shows general failure type. Displacement around the anchor construction part was 0.9 ~ 1.3cm, it is stable but the shear failure occurred at the lower level of the anchor part.



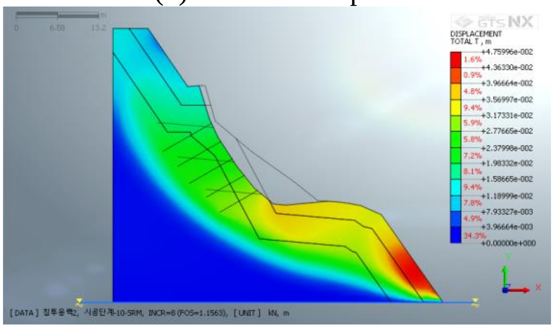
(a) Before anchoring



(b) Anchor with prestress



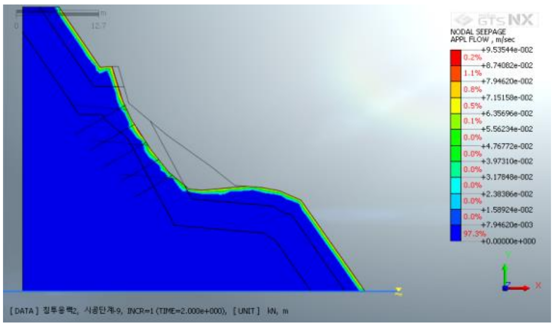
(c) Anchor with pretension



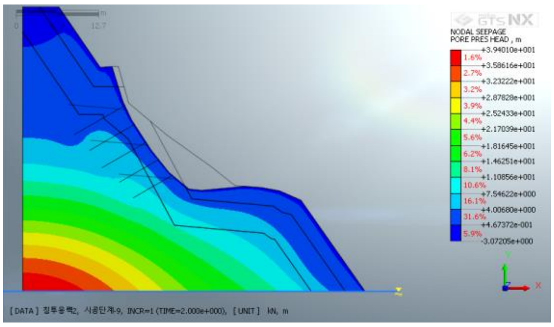
(d) Anchor with seepage-stress coupled analysis

Figure 5. Slope stability analysis with different condition

In the case of the seepage-stress coupled analysis, the pore water pressure rises as the rainfall flows into the ground surface. The most vulnerable point of the slope after anchor reinforcement was found to move from the center of the anchor part to the lower level. Figure 6 shows the distribution of surface water and pore water pressure according to rainfall.



(a) Distribution of Rainfall

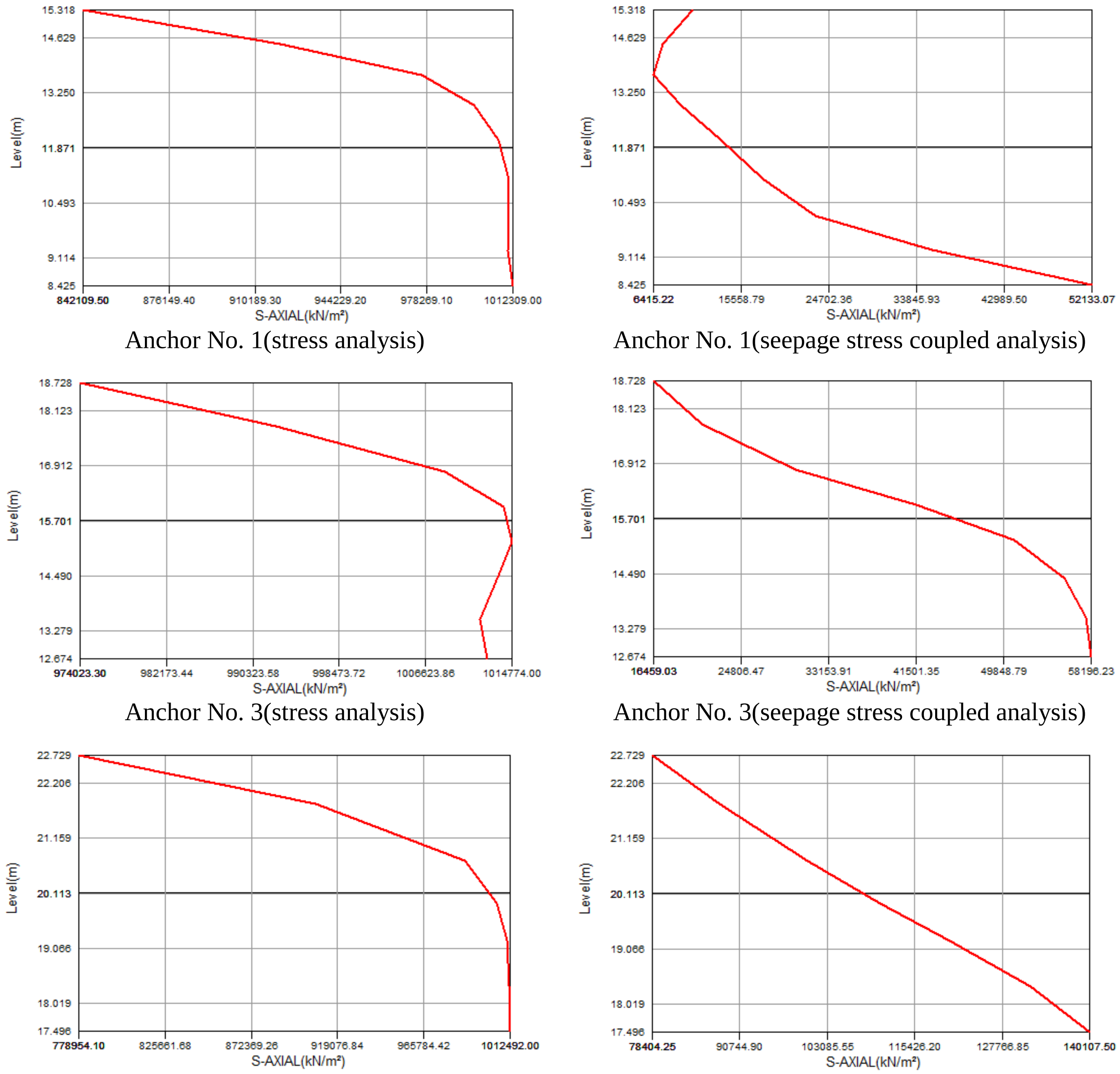


(b) Distribution of pore water pressure

Figure 6. Seepage behavior with rainfall condition

4.3 *Variation behavior of Axial stress*

The numerical modeling was performed. The loss of anchor force due to initial tension loss of anchor is reported to be reduced by 20% (Kang, 2011). In this study, the influence of axial stress on the change of stress is analyzed through stress analysis and penetration stress connection analysis. Figure 5 compares the axial force variation of the anchor body with the stress analysis and the penetration-linkage analysis. In the stress analysis, the magnitude of the fusing stress is distributed around the maximum value. The seepage-stress coupled analysis showed that the axial force gradually decreased and the stress reduction rate was higher at the upper side anchor than the lower side anchor. This is similar to other research results. Detail analysis is needed in the seepage-stress coupled method with long term elapsed time.



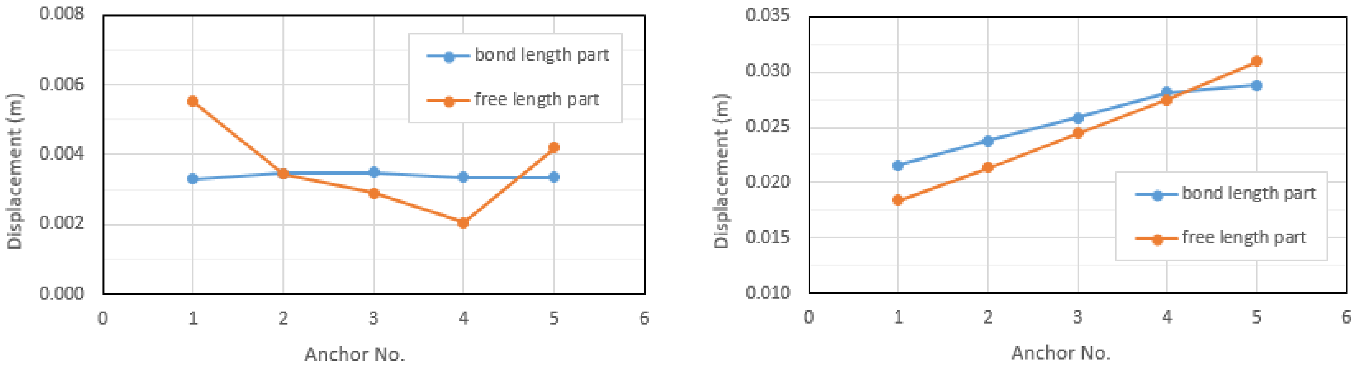
Anchor No. 1(stress analysis) Anchor No. 1(seepage stress coupled analysis)

Anchor No. 3(stress analysis) Anchor No. 3(seepage stress coupled analysis)

Anchor No. 5(stress analysis) Anchor No. 5(seepage stress coupled analysis)

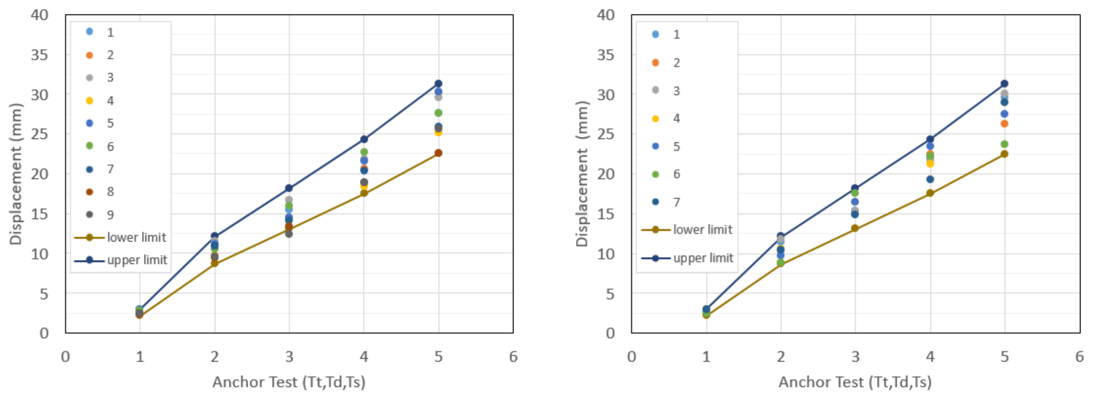
Figure 7. Anchor force at stress analysis and seepage-stress coupled analysis

Tests were conducted on 16 anchors which each length was 9 m in the first and second area. The minimum displacement limit was 2.2mm and the maximum limit is 31.3mm. All 16 anchor upper limit displacements were satisfied and 15 anchor lower limit values were satisfied. Comparing with displacements in numerical analysis, the behavior of displacement shows similar value under 30mm. Figure 8 shows displacement of anchor length by numerical analysis and Figure 9 shows the results of field tension test



(a) Stress analysis (b) Seepage-stress coupled analysis

Figure 8. Displacement of anchor length by numerical analysis



(a) 1st area (b) 2nd area

Figure 9. Displacement of anchor length with pullout test

5 CONCLUSION

In this study, slope stability analysis on the rock base was carried out using field tension test and numerical method. The exposed rock slope was reinforced by permanent anchor after the collapse of rock surface. Pullout tests on the anchor were carried out and safety rate was calculated by SRM method.
Overall, the safety factors were not decreased at the anchor installation area. In the case of seepage-stress coupled analysis, the safety factor was lowered to 1.1 or less value. It was studied that the most weakness point moved to the lower part of the slope through the seepage-stress coupled analysis.
As a result, the seepage-stress coupled analysis show that the slope failure can be caused by heavy rainfall. It was confirmed that the rainfall intensity significantly affects a variation of axial force of anchor.
The decrease of axial force was not considered in this study. It need to be studied more as regards reduction of initial tension or creep behavior by seepage-stress coupled method using analytical tool.

REFERENCES

Jang, H. I., Kim K. S., Lee S. L., Park Y. S. 2016. Investigation of application condition and making the performance improvement technique of permanent ground anchor, Korea Expressway Corporation. Report No. 2016-59-534.9607, pp. 97-99.

Kang I. K. 2011. Case study on slope stability of retaining wall supported by permanent anchor, Geoenvironmental Engineering, Vol. 12(4), pp. 9-18.

Kang I. K., Kim J. H., Kim J. M., Son M. R. 2015. Problems and technical direction for ground anchors, KSCE, pp. 57-58.

Korea Infrastructure Safety and Technology Corporation 2006. Slope design specification for construction work, Gumibook, pp.148-152.

Shin J. H. & Midas IT 2014. Computational geotechnics, CIR, pp. 207-231.

Woo S. B., Lee J. D. Jung H. S., Choi Y. K. 2010, Collapsed slope and reinforcing design in weathered zone, KGES-KGS Geo-environmental and slope stability conference, pp. 386-397.