Effect of in-situ stress on deformation of excavated slope with fold structure

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An analytical study was done to investigate the influence of in-situ stress on deformation of excavated slope composed by weathered mud stone. The objective slope was folded through collision of tuff breccia layer and mud stone layer. Considering that compressive stress by tectonic movement might still remain in objective slope, this study is to reveal effect of in-situ stress on deformation behavior of slope and preventive piles by numerical analysis, which is conducted under two-dimensional condition with finite difference method. Results show that both Poisson's ratio and additional horizontal in-situ stress could lead to obvious changes in deformation and shape of piles. The normalized pile displacement in the analysis is close to the measured, normalized displacements of the piles in the site.

Key Words : *numerical analysis, slope stability, in-situ stress, Poisson's ratio, excavation, geological structure*

1. Introduction

Ohishi and Terakawa[1] conducted research on an excavated slope composed of folded geological structure in Rajamandala, Indonesia, with large-scale deformation being observed during excavation. According to results of X-ray computed tomography scanning and XRD test, superficial layer of this slope was composed of weathered mudstone with several grades classified by scanning and consisted smectite components as well. With excavation beginning, cracks were observed on surface of slope, indicating that potential failure might occur inside slope. To enhance the slope, piles were inserted into stratum, with clinometers attached on piles to monitor deformation of slope. However, clinometers exhibited that unexpected large-scale deformation was still occurring inner slope, with maximum horizontal displacement of piles reaching more than 1.0 meters. Geological survey showed that initially tuff breccia and mudstone were located at same elevation, and furtherly objective slope was formed by tectonic moment from Pliocene to Pleistocene, as compressive tectonic stress acting at this area, making tuff breccia thrust up on mudstone and thusly forming a thrust fault structure as **Fig.1** shows. After that, wet and dry cycle occurred due to river and thusly mudstone turned to be weathered.

Up to now, lots of relative studies were trying to reproduce historically formed stress of slope and study deformation behavior of slope and structures. Potts[2] reproduced stress state of strongly over-consolidated clays by high coefficient of lateral earth pressure at rest K_0 over 1.5 and thusly observed a failure zone that similar to site results. Kamiya[3] studied consolidation anisotropy based on a fold structure composed of mudstone, condition of which is similar to this study. In Kamiya's study, coefficients of lateral earth pressure at rest K_0 in each direction were separately calculated by corresponding consolidation yield stress and result showed that K_0 in the direction that fold structure formed is larger, indicating that influence of tectonic moment could still remain in fold structure and larger horizontal in-situ stress need further discussion. Furtherly, give that K_0 could not be applied in all cases, especially

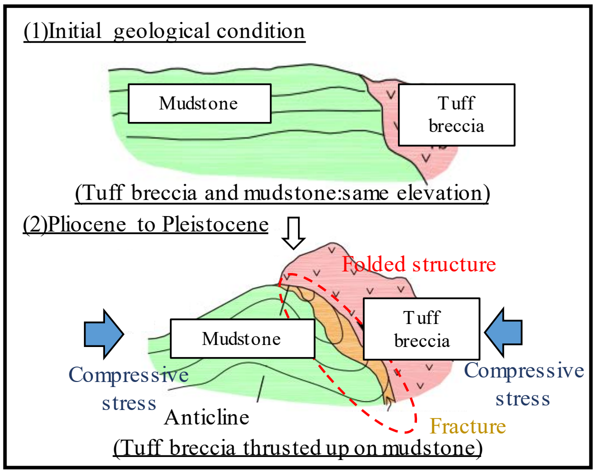


Fig.1 Formation of objective slope

cases with active earth pressure, Yang[4] put forward another approach to study influence of coefficient of lateral earth pressure, as directly change Poisson's ratio to reveal the deformation behavior in horizontal direction. When it comes to research about failure mechanism of excavated slope itself, Leroueil[5] studied failure mechanisms based on excavated slope and emphatically introduced stages of slope movements and behavior of stress path. In this study, stress paths of cases under several conditions based on critical state line were discussed, including normal consolidated case and over-consolidated case, which could be adopted as reference in discussion of stress path in this study.

According to previous study[6], excavation analysis under high K_0 condition was executed, with obvious curving shape shown in piles. However, maximum of pile displacement is still smaller than observed value. For further discussion, current study proposes a new method that conduct numerical analysis directly based on Poisson's ratio to reveal deformation behavior of slope and preventive piles,Meanwhile, horizontal stress is also enlarged based on vertical stress state to simulate a high horizontal in-situ stress state in fold structure. By these considerations, mechanic behavior of slope and piles could be studied based on horizontal displacement proportion Di/Dmax that could better describe deformation behavior and shape of piles. **Fig.2** shows geological structure and rock components of objective slope, with positions and displacement of preventive piles and groundwater locating at surface of slope after excavation. This mesh subdivides the excavation area based on actually excavation process in site in order to better describe process of stress release due to excavation in analysis. It should also be emphasized that preventive piles showed curving shape after excavation process, indicating that mechanic behavior of piles also needs further discussion.

2. Outline of numerical analysis

(1) Analysis method

In order to reproduce the large-scale deformation occurring in objective slope, finite difference method was chosen in this study, by conducting numerical analysis with software Flac2D. Flac2D is widely used in numerical analysis of slope, as it could evaluate stability of soil slope and show large-scale deformation behavior of slope by FDM[7]. Meanwhile, given that purpose of this study is to reveal influence of additional in-site stress on deformation behavior of slope in a saturated slope, water condition was not considered in this study and total stress analysis was conducted.

Besides, in order to study influence of in-situ stress, two different factors are taken into consideration: one is Poisson's ratio, as it could directly affect mechanic behavior of materials, and the other one is horizontal stress state because formation of slope by tectonic movement are always accompanied with high-level horizontal stress, which could still remain in stratum. **Table.1** shows analysis cases in this study based on Poisson's ratio and in-situ stress.

(2) Constitutive models for all material components and preventive piles

According to classification of mudstones by Ohishi and Terakawa[1] with XRD test and X-ray CT scanning, D_L is highly-weathered mudstone, D_H is moderately weathered mudstone and C_L is non-weathered mudstone. Meanwhile, some other rock components also existed in this slope, as rigid tuff breccia and sandy terrace deposit.

Following **Table 2** shows constitutive models for all rock and soil components. To be specific, rigid materials as C_L mudstone and tuff breccia adopts elastic model and sandy terrace deposit with no tension resistance is under Mohr-Coulomb model to describe its no-tension behavior. Additionally, weathered mudstones (D_L and D_H) with large-scale deformation occurring in site are under Modified Cam-Clay model, as this constitutive model could better describe deformation behavior of materials.

Table 3 shows parameters for each rock components. It should be mentioned that parameters of tuff breccia were data from other literature in similar condition[8) 9)]. Besides, excavated parts used parameters from surrounding rock components at same elevation.

Preventive piles in this analysis are under bilinear model, indicating that yielding behavior of piles is controlled by plastic bending moment M_p. Deformation behavior of piles could be divided into two stages in this model: one is elastic stage, as bending moment is smaller than given plastic bending moment M_p, and after bending moment reaches

Table 1 Analysis cases executed in this study

	Poisson's ratio	Is-situ stress level (time of vertical stress)
Case-1	0.3	normal
Case-2	0.3	1.4
Case-3	0.333	1.4
Case-4	0.499	1.4
Case-5	0.3	1.2
Case-6	0.3	1.8

Table 2 Constitutive model for rock components

	Elastic	Mohr-Coulomb	Modified Cam-Clay
Rock components	Tuff breccia Tuff breccia(C_L) Mudstone(C_L)	Terrace Deposit Excavation	Mudstone(D_L) Mudstone(D_H)

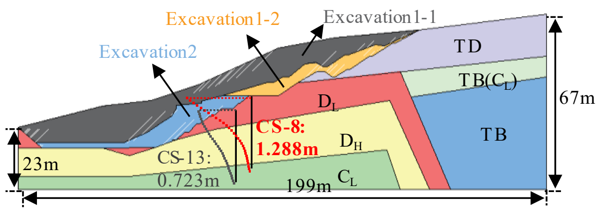


Fig.2 Structure and rock distribution of objective slope

M_p, pile turns to plastic stage. In plastic stage, bending moment would not increase anymore while curvature of pile would show rapid increase. This is to say that pile turns to yierld and show great plastic displacement under such condition and the value plastic bending moment acts as a role of critical point for pile yielding. In this study, plastic bending moment is calculated by the equation(1):

$$M_p = \sigma_y \times Z_{px} \tag{1}$$

Where σ_y is yield strength of steel and Z_{px} is plastic section modulus. **Table 4** shows parameters for preventive piles used in analysis. CS-8 is one preventive pile while CS-13 includes two preventive piles bounded by head. It should also be emphasized that while analysis in this study is 2-D analysis by x-axis and y-axis, characteristics of piles in z-axis are also considered in analysis, as piles are set in the slope with an interval of 1.5m along z-axis direction.

(3) Analysis mesh

Fig.3 shows the actual analysis mesh used in numerical analysis process. In order to avoid limitation of boundary on deformation of objective slope, mesh used in numerical analysis was expanded based on objective slope, for 100m in left and right directions and 20m in depth. Left and right boundary is fixed in vertical direction and bottom boundary is fixed in both horizontal and vertical direction. It should be mentioned that each excavation process was divided into several steps and executed one by one, as Ex.1-1 was divided into 10 steps, Ex.1-2 was divided into 5 steps and Ex-2 was divided into 7 steps.

(4) Procedure of numerical analysis

Procedures of numerical analysis follows:

I. In self-gravity analysis, all materials were set to be under Mohr-Coulomb model and Poisson's ratio was set according to schedules of analysis cases, thusly initial state of objective slope could be obtained and used later.

II. After self-gravity analysis, constitutive model for all materials were reset based on Table 2 and at the same time, horizontal in-situ stress state is redefined by following equation(2):

$$\sigma_x = k \times \sigma_y \tag{2}$$

Where σ_x is horizontal stress, σ_y is vertical stress and k is a coefficient used to control additional horizontal stress. Then self-gravity analysis was executed one more time because changes in constitutive model and stress state could lead to unbalanced state of slope.

III. Furtherly, after excavation 1 and 2 was removed, CS-8 was inserted into slope and area between scheduled position of CS-8 and CS-13 was excavated. And then, CS-13 was set and excavation was executed until the end.

Table 3 Parameters of rocks[8)9)]

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	0.34
E[MPa]	78.2	105.4	186.4	6.0	1900.0
λ	0.2	0.25	-	-	-
κ	0.085	0.04	-	-	-

Table 4 Parasmeters of piles

Parameters	CS-8	CS-13(Include 2piles)
Length [m]	30	30
E [Mpa]	2×10^8	2×10^8
Area [m^2]	0.608	0.608
I_x	2.94×10^{-2}	2.94×10^{-2}
Yielding strength [kPa]	2.05×10^5	2.05×10^5
Z_{px}	9.18×10^{-4}	9.18×10^{-4}
M_p [kN・m]	188.19	188.19
Interval	1.5m	1.5m

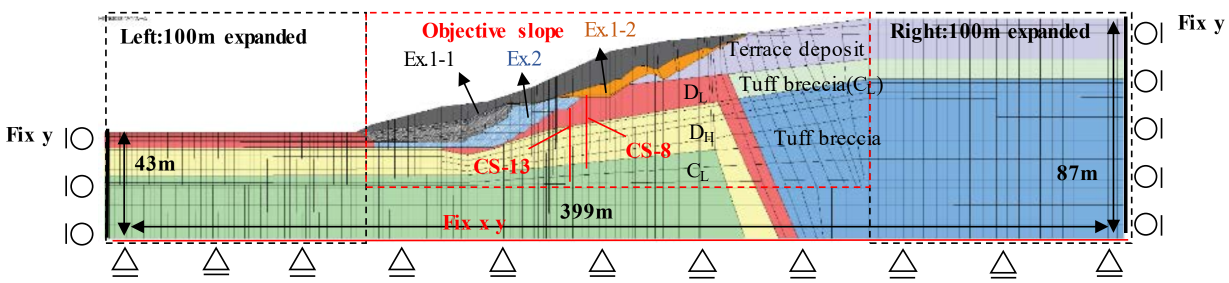


Fig.3 Expanded mesh for numerical analysis

3. Analysis results

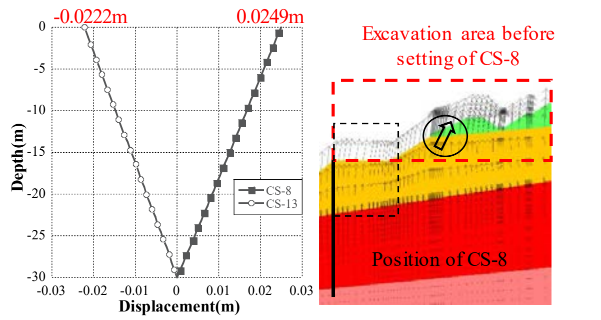
According to analysis results. deformation behaviors of preventive piles are playing an important role in this study. Given that previous study showed it's hard to obtain an analysis result of horizontal pile displacement that is close to observed value from site, shape of piles becomes a new focus in this study, which is describe by the proportion of horizontal displacement D_i to absolute value of maximum horizontal displacement D_{max} along piles. Negative value for D_i/D_{max} indicates that pile shows a leftward displacement. Meanwhile, in order to reveal reasons for curving shape showing in result of piles, bending moment of piles and stress path of surrounding earth are checked.

(1) Analysis with normal Poisson's ratio and in-situ stress: Case-1

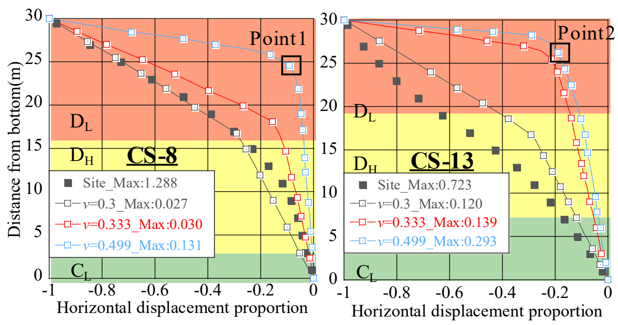
Figs.4 show horizontal displacement of piles after excavation analysis and displacement vector of slope before setting of CS-8 in Case-1, as Poisson's ratio was set to normal value 0.3 and additional horizontal in-situ stress was not considered. In this case, shape of two piles still tends to be linear and one interesting point is that CS-8 shows a leftward displacement, which is opposite to observation from site. Considering that higher in-situ stress state might have great influence on piles and thusly change deformation directions, analysis cases under different conditions are executed and compared with Case-1.

(2) Analysis with different Poisson's ratio and high in-situ stress: Case-2,3,4

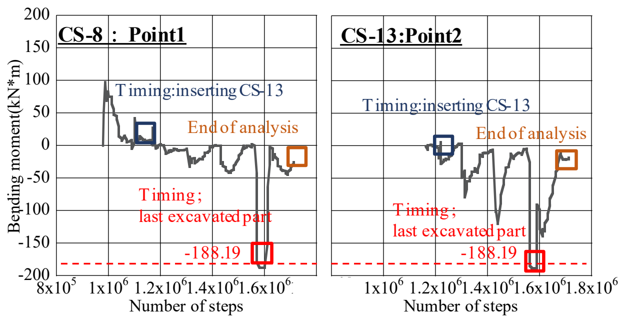
Figs.5 shows horizontal displacement proportion of each element along CS-8 and CS-13. Negative value of proportion means a leftward displacement in piles. It could be obtained from figures that with higher Poisson's ratio, pile tends to show a more obvious curving shape. At the same time, higher Poisson's ratio could also lead to curving points shown in position close to surface of slope, in the D_L area. In the case of CS-8, Case-2 with ν=0.3 shows a pile shape most close to result from site. Curving of piles shows that under high Poisson's ratio condition, yielding could potentially occur in piles and meanwhile, failure could also be probably to occur in slope. For further discussion, detailed deformation behavior of CS-8 with ν=0.499 is chosen to be a representative and introduced as following parts. **Figs.6** shows bending moment history of Point 1 and Point 2 during excavation process. It's apparently shown in the figure that both bending moments of Point 1 and Point 2 reached plastic bending moment M_p during analysis for a while. Moreover, **Figs.7** shows the bending moment distribution along piles CS-8 and CS-13 at this timing and end of excavation analysis, indicating that bending moment reached M_p at D_L area surrounding Point 1 and Point 2, corresponding to position of curving in CS-8 and CS-13.



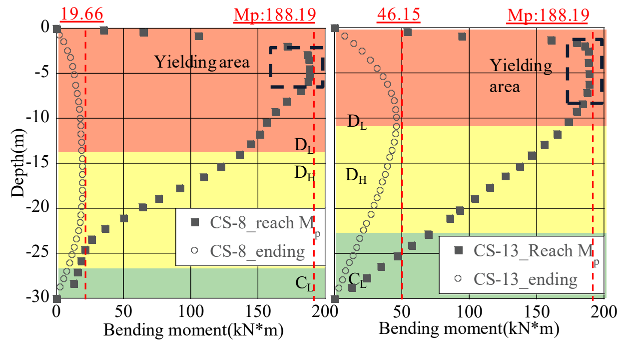
Figs.4 Case-1: Horiozontal displacement of piles after excavation and displacement vector before setting CS-8



Figs.5 Horizontal displacement proportion with different Poisson's ratio (D_i/D_{max})



Figs.6 Bending moment history of Points



Figs.7 Bending moment distribution along CS-8 and CS-13 at timing for yielding and end of analysis

At the end of analysis, with unbalanced force generated by stress release turning to equilibrium state, bending moment along pile also shows a comparatively small value. **Figs.8** shows stress path of soil element surrounding Point 1 and Point 2 during excavation analysis. Compared with critical state line CSL, stress path of Point 1 shows obvious changes due to stress release, while it is still located below CSL and it indicates that soil element at Point 1 didn't fail during excavation process. However, different result could be observed from the figure for Point 2 at CS-13, as end of stress path is nearly touching the critical state line, suggesting that soil element around Point 2 could yield and fail during excavation, thusly leading to obvious curving shape of CS-13.

(3) Analysis with normal Poisson's ratio and different in-situ stress coefficient:Case-2,5,6

Figs.9 shows horizontal displacement proportion of each element along CS-8 and CS-13. Influence of additional in-situ stress is similar to that of Poisson's ratio, as higher additional in-situ stress could lead to curving point moving to superficial layers.Meanwhile, An obvious change is shown when coefficient of in-situ stress changes from 1.2 to 1.4, as deformation direction of CS-8 changes from rightward to leftward, meaning that in-situ stress level could show great influence in this slope

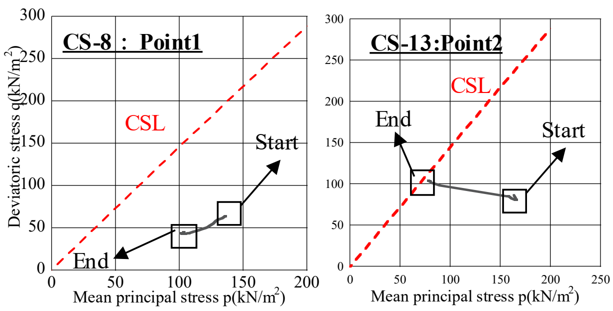
4. Discussion

Case-1 with normal Poisson's ratio and in-situ stress state shows that CS-8 kept a linear shape until end of analysis, different from observation from site with curving shape. Reason for such phenomenon is considered to be that horizontal in-situ stress is not fully described in this case, as potential horizontal stress due to tectonic moment was not included. Meanwhile, CS-8 tended to deform in right direction, opposite to observation result from site. Reason for this phenomenon is considered to stress release process for excavated earth before setting of CS-8, as earth locating at right-upward area of CS-8 position was excavated before setting of CS-8 and furtherly led to a right-upward direction rebound inner the region surrounding CS-8.

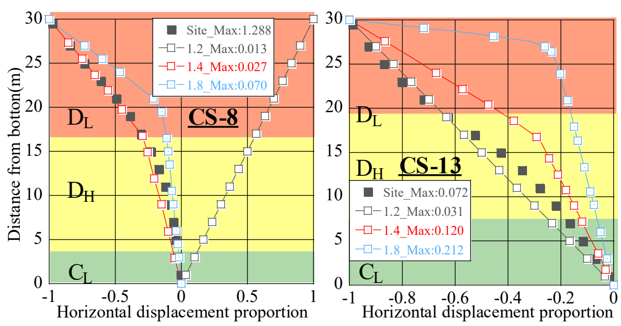
Compared with Case-1 and 5 with comparatively low Poisson's ratio and in-situ stress state, other cases show difference in shape of piles, as obvious curving shape could be seen in these cases. This is to say that both Poisson's ratio and high in-situ stress could have great influence on deformation behavior of piles, especially in the , cases with higher obviously show a curving shape, with curving point locating at positions close to surface. However, it could be obtained that Case-2 with Poisson's ratio equals to 0.3 shows a shape most close to that observed from site. It suggests that excessively high Poisson's ratio is not suitable for further study because it could lead to unexpected large curvature occurring in piles.

Meanwhile, from analysis of bending moment of piles, such conclusion could be made that yielding occurred in piles under condition with high in-situ stress and Poisson's ratio during analysis. From stress path of Point 1 and Point 2, mechanic behavior of soil elements surrounding top parts of CS-8 and CS-13 could be revealed. Stress path of Point 1 shows that large deformation could occur during analysis but soil element didn't reach yielding state, while result of Point 2 shows that at the end of analysis, stress path of Point 2 is nearly touching the critical state line and failure occurs in the surrounding soil elements. This is to say that, yielding of piles CS-13 could be a result of comprehensive influential factors, as both yielding of piles and surrounding soil element could be reason for such phenomenon.

Results of analysis with different additional in-situ stress coefficient show that such a critical value exists between 1.2 and 1.4 for k that makes deformation direction of CS-8 correspond to that from site. Reason for such phenomenon is considered to be the comparatively weak properties of weathered mudstone area D_L and D_H, as most part of CS-8 located at this area and such areas could be under great influence of in-situ stress level . Moreover, shapes of piles from site show curving in positions with lower elevation compared with Case-2(k=1.4), while Case-5(k=1.2) show that piles were not yet reaching yielding state and kept linear until the end. It suggests that a suitable value of *k* for further study



Figs.8 Stress path of soil element surrounding Point 1 and Point 2



Figs.9 Horizontal displacement proportion with different in-situ stress level(D_i/D_{max})

could vary from 1.2 to 1.4, not excessively large such as 1.8 or 2.0.

5. Conclusion

This paper reports the study of numerical analysis based on an excavated slope with fold structure formed by tectonic movement. In this study, remaining influence of tectonic movement is considered by two factors as Poisson's ratio and additional horizontal in-situ stress set based on vertical stress. According to analysis result, both increase of Poisson's ratio and in-situ stress could lead to curving shape of preventive piles inserted in slope, while case with normal Poisson's ratio and in-situ stress showed linear shape of piles until end of analysis. Based on further discussion by bending moment and stress path, it's revealed that curving shape of preventive piles resulted from both yielding of piles and soil element surrounding piles. Combing influence of Poisson's ratio and in-situ stress, the most proper condition for further study is that Poisson's ratio ν=0.3 and horizontal stress set to be 1.4times of vertical stress.

However, there are still several parts that need further discussion. For example, this study is based on total stress analysis, while in actual case influence of water could be rather obvious, especially in such case that slope is fully saturated. Meanwhile, stress path of other positions such as middle and bottom of piles also need further study because behavior of soil element is rather important to evaluate the effect of preventive piles. In further study, all these factors that are not fully discussed should be included in order to reach a comprehensive achievement.

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