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Stress-Strain Behavior and Slope Stability of Cohesive Soils due to Excavation

粘性土斜面の掘削に伴う応力―ひずみ挙動と安定性評価について

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Abstract: It has been known that stress release produced by excavation in the ground causes reduction in confining pressure and swelling of soils, which in turn result in a loss of shear strength to be required for slope stability. In the ground composed of a sedimentary soft rock such as mudstone, which is expansive and/or ready to show slaking, change in soil properties due to stress release can be another influential factor for slope instability. This paper concerns behavior of cut slopes composed of expansive mudstone. FEM analysis was carried out to investigate deformation of slope surface due to swelling and stress redistribution (stress release) developed in the ground by excavation, by introducing actual swelling properties of mudstone obtained in the laboratory. Stability evaluation was then conducted by use of FEM and the Bishop's approach in order to discuss accuracy and reliability of the estimated behavior of clay slopes.

1. INTRODUCTION

Excavation and slope cutting performed in the construction of new residential areas, highways and bridges often deal with soft sedimentary rocks like mudstone. General characteristics of these rocks are easily affected by the natural conditions such as temperature change and rainfall. Mudstone is less durable with the change of these weather conditions, and it is easily weathered due to alternative wetting and drying.

Due to these reasons, the following problems are often encountered at the excavation and cut slope construction: that is, cracks easily appear on the cut surfaces under the change of temperature, which permits water to penetrate to the soil through the cracks. Cut slope excavation furthermore causes reduction in confining pressure and swelling of soils, which in turn result in a loss of shear strength to be required for slope stability. Slope surface and excavation base of cut slope is rapidly weathered due to alternative wetting and drying.

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From the above review of literatures, this study concerns the behavior of cut slopes composed of expansive mudstone. FEM analysis is conducted to investigate deformation of slope surface due to swelling and stress redistribution (stress release) developed in the ground by excavation, by introducing actual swelling properties of mudstone obtained in the laboratory. Also dealt with are problems that may happen, such as surface slides, instability and failure of slope during and after the construction period. The design method is finally proposed, on the basis of the minimum cost of construction, for preventing from slope instability by different solutions, such as anchors, tree cultivation on slope surface and using optimal slope inclination.

FEM analysis is done first to investigate the influence of FE mesh size and swelling properties of mudstone on the magnitude and distribution of deformation, and on the extent of stress release in the ground for different slope inclinations. Discussions are also made on the mechanism of deformation and sliding failure of slopes due to excavation and the proper method of evaluating stress-deformation and stability in cut slopes by using FEM analysis.

2. ANALYSIS PROCEDURE

2.1 Excavation Analysis

(1) Calculation of initial stress

The step-by-step procedures of the FE excavation analysis are described below together with Fig.1 through Fig.5. In the first step of calculation, Fig.1, the initial stresses $\{\sigma_0\}$ in the ground is determined by a simple FE gravity turn-on analysis with a constant linear elastic modulus (E, ν) of soils.

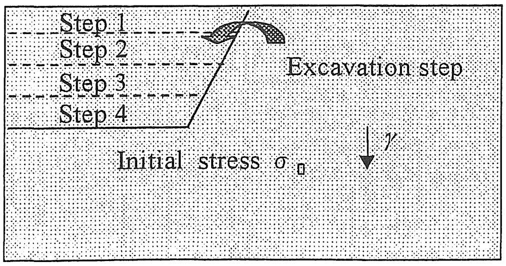

Fig.1 Calculation of Initial Stress

(2) Calculation of overburden load Δp_s in each step of excavation

During the excavation process, stresses in the ground decrease by $\Delta\sigma_s$, which is released from initial stress σ_0 due to excavation (or increased by a negative value of the stress $-\Delta\sigma_s$). In order to calculate stress release $\Delta\sigma_s$ in each step (step s) of excavation, the overburden load Δp_γ (s), which acts on the slope surface corresponding to the initial stress, should be obtained beforehand in Fig.2.

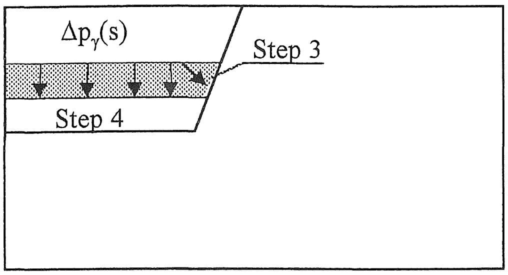

Fig.2 Calculation of Equivalent Load

(3) Calculation of Stress in each Step of Excavation

Stress free surfaces produced by excavation can be created by applying a set of load $-\Delta p_\gamma$(s) at nodes on the surface in the direction opposite to the direction of initial overburden loading as illustrated in Fig.3. The solution of stress in the ground at step s, can be evaluated as follows, $\sigma_s = \sigma_0 + \Delta\sigma_s$

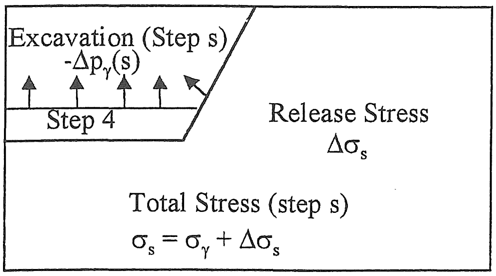

Fig.3 Calculation of Stress (step s)

(4) Calculation of Expansion

The problem of expansion due to swelling of soils is equivalent to that of the initial strain like as a thermal expansion, and such deformation can be represented by applying additional equivalent nodal forces to the medium, as shown in Fig.4.

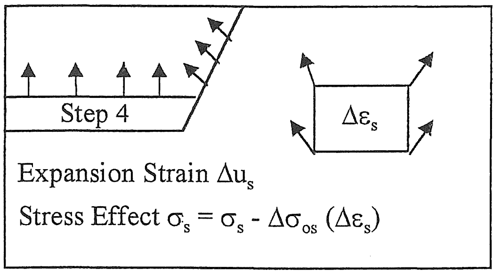

Fig.4 Calculation of Expansion

In this step-by-step calculation, the value of elastic modulus E is given from the relation between ε_v and σ_v, which is obtained in a one-dimensional compression test of mudstone, as follows:

$$E = \frac{(1-\nu-2\nu^2)}{(1-\nu)} Ec \qquad (1)$$

in which Ec stands for the elastic modulus of deformation of the material in the confined state, and it is determined by $Ec = \Delta\sigma_v / \Delta\varepsilon_v$ along the given ε_v - σ_v curve as shown in Fig.5.

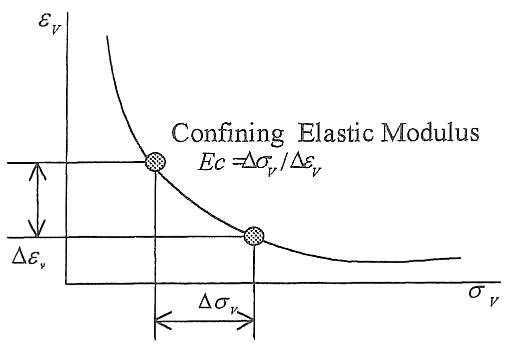

Fig.5 ε_v - σ_v Relation Curve

2.2 OC State in Excavation

Natural deposits in the ground more or less have some pre-compression effects on their deformation and strength when they become over-consolidated state due to excavation. Pre-compression effects on strength is illustrated in Fig.6, showing higher strength value in the low stress range ($\sigma < p_c$) of over-compression and a constant increase in strength in the high stress range ($\sigma > p_c$) of normally compression (NC). The relationship between the rates of strength increase in OC and NC states, $(s_u/\sigma)_{OC}$ and $(s_u/\sigma)_{NC}$, may be represented as a function of the over-compression ratio, $OCR = p_c/\sigma$, in a similar manner as proposed for undrained strength of saturated clay

$$(s_u/\sigma)_{OC} = (s_u/\sigma)_{NC} OCR^{\lambda} \tag{2}$$

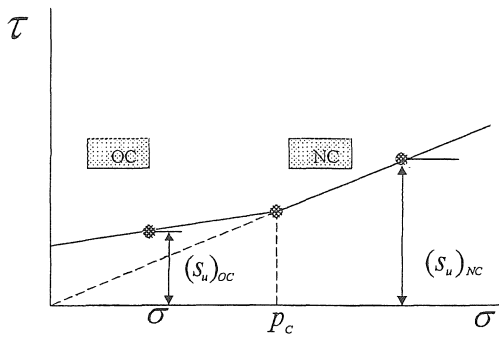

Fig.6 Pre-compression effects on strength

2.3 Excavation Analysis

FE calculation were carried out for simple cut slopes of a height H=20m, for cases of a 1:1.5 gentle slope and 1:1 steep slope without foundation layer, and cases of a 1:2 gentle slope and 1:0.5 steep slope with foundation layer. Although material non-linearity, together with step-by-step excavation process, can be taken into account in the analysis, a simple almost linear approach was adopted here to discuss principally on stress redistribution in slopes due to excavation. The values of strength parameters associated with Eq.(2) were assumed to be $(s_u/\sigma)_{NC}$ =1/3 and λ=0.8, by referring to experimental data for normally consolidated clay.

3. RESULTS AND DISCUSSIONS

3.1 Influence of Element Size

Because deformation modulus E changes sharply in the region of low confining pressure near the slope surface, the influence of element size in FE analysis is first examined by varying the thickness of soil layers in the ground. Fig.7 shows variations of the vertical displacement at two surface points 1 and 2 with the thickness of soil layer adopted in the analysis, in which the value on the abscissa stands for multiple number of the thickness of layer to the finest one. As can be seen in the figure, the vertical displacement increases as the element size becomes smaller, especially in the case of mudstone B by about 20% to 30%, but shows a tendency to converge at around 2 to 4 times of the finest mesh.

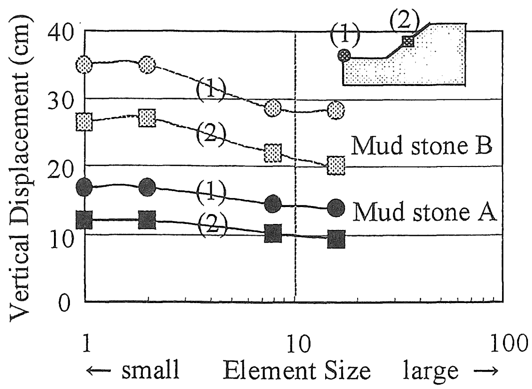

Fig.7 Influence of Element Size

3.2 One Step and Step-by-step Excavation

Comparison between one-step and step-by-step of excavation is done by FEM analysis. In step-by-step method of excavation, the soil layer to be excavated is divided into five layers, the thickness of layer is equal to 4m. Fig.8 shows the relation between the vertical strain and the depth along two representative lines 1 and 2. It is recognized that the value of the vertical strain in one-step is greater than that of step-by-step.

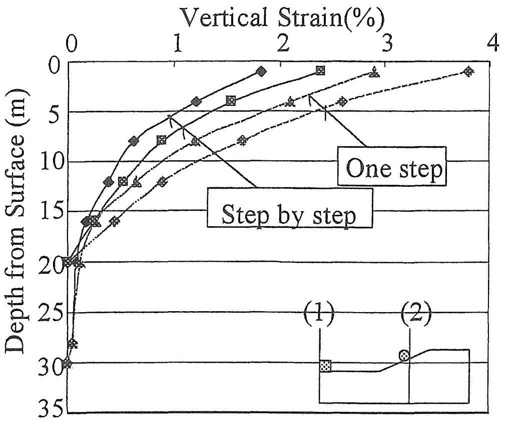

Fig.8 Distribution of Vertical Strain in Steps

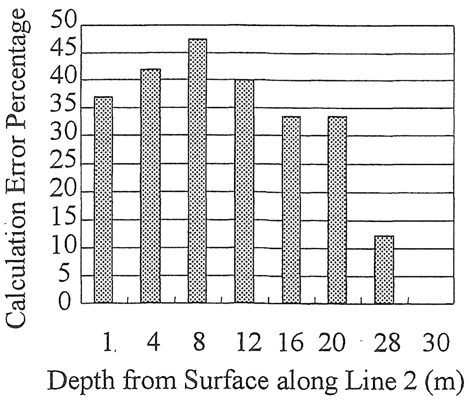

Fig.9 Calculation Error with ε_v~σ_v Curve

Fig.9 shows calculation error of the results obtained by one-step method relative to that obtained by step-by-step method. The value of calculation error is calculated by Equation as follows:

$$R = \frac{\varepsilon_{V1} - \varepsilon_{VS}}{\varepsilon_{V1}} x100 = \frac{\Delta\varepsilon_V}{\varepsilon_{V1}} x100 \tag{3}$$

in which R is calculation error, ε_{vl} is the vertical strain in the one-step excavation method, and ε_{vs} is the vertical strain in the step-by-step excavation method. It is seen that the relative calculation error initially increases with the increase in the excavation depth and it reaches to the maximum value of 45% at the depth of about 8m. Beyond the depth of 8m, the calculation error decreases and approaches to 10% at 28m.

3.3 Expansion Characteristics of Mudstone

Fig.10 shows the relationship between the vertical strain ε_v and the vertical confining pressure σ_V, which is obtained in the laboratory one-dimensional compression tests on two representative mudstone samples A and B. In these tests, several specimens were loaded simultaneously by applying different values of σ_v, and the expansion strain ε_v was measured as the final maximum value attained under the same vertical pressure. Deformation of cut slopes produced by the application of the equivalent expansion force is then calculated by using the modulus of deformation derived from Fig.10: i.e., the modulus value can be determined from Eq.(1) with $Ec = \Delta\sigma / \Delta\varepsilon$ along with the given $\varepsilon_v - \sigma_v$ curve in the figure

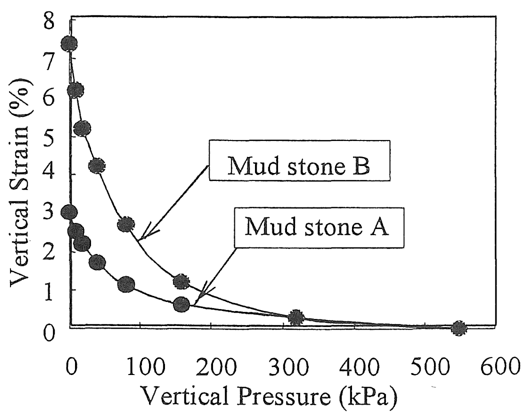

Fig.10 Expansion Characteristic of Mudstone

3.4 Deformation in Cut Slopes

Distributions of vertical expansion strain ε_v along two representative lines 1 and 2 are compared for mudstone A and B, as shown in Fig.11. It is seen that the value of ε_v increases sharply as approaching to the surface, beyond the depth of 5 m to 10m, where the overburden pressure corresponds to the vertical pressure σ_v at the point of sharp change in $\varepsilon_v - \sigma_v$ relation curves in Fig.10. It is then noticed that the upward deflection of cut slopes due to excavation may be governed by the large deformation in a relatively thin layer near the surface.

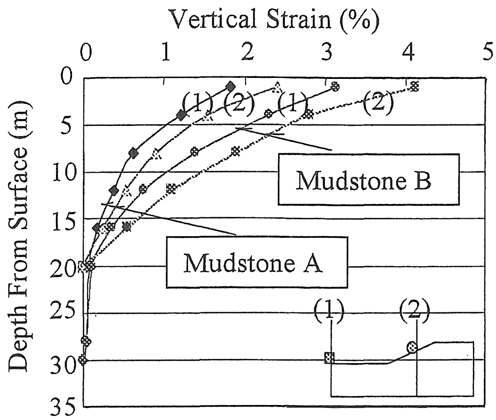

Fig.11 Distribution of Vertical Strain

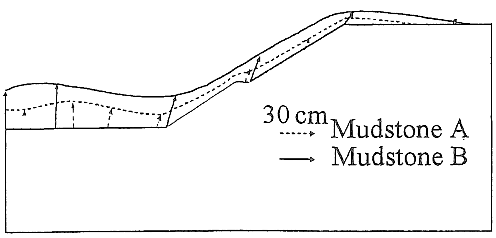

Fig.12 Surface Deformation of Cut Slope

Deformation pattern of the cut slope surface after excavation is compared in Fig.12 for two mudstone materials. It is recognized that the amount of expansion along the horizontal surface is not so large as compared to that of the slope surface, even though high stress release is anticipated in this zone, and that the relative amount of such deformation depends on the expansion characteristics of mud stone materials as presented in Fig.10.

3.5 Stress Release in Cut Slopes

The amount of stress release due to excavation can conveniently be expressed by using a parameter defined in the following equation:

$$Rsr = (1 - \sigma_1 / \sigma_0) \tag{4}$$

where σ_0 and σ_1 stand for stresses before and after excavation, respectively.

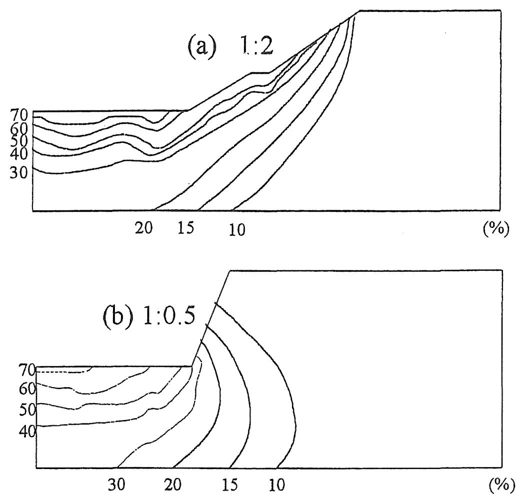

Fig.13 Release of Vertical Stress

Distributions of the value of stress release Rsr are presented in Fig.13 for the vertical stress, and in Fig.14 for the horizontal stress in two cases of slope inclination of 1:2 and 1:0.5. It is obviously seen in Fig.13 that high rate of vertical stress release comes out in case of gentle slope, high value of Rsr extending widely to the interior of the cut slope, and that stress release is concentrated near the horizontal excavated base in the case of steep slope. In the horizontal stress release in Fig.14, in contrast, higher value of Rsr extends to the interior of the steep cut slope, and stress release is on the whole not so large in case of gentle slope. Although strength reduction due to stress release in excavation cannot simply be estimated, a steep cut may be recommended for the stratified ground where the effect of vertical pre-compression is predominant.

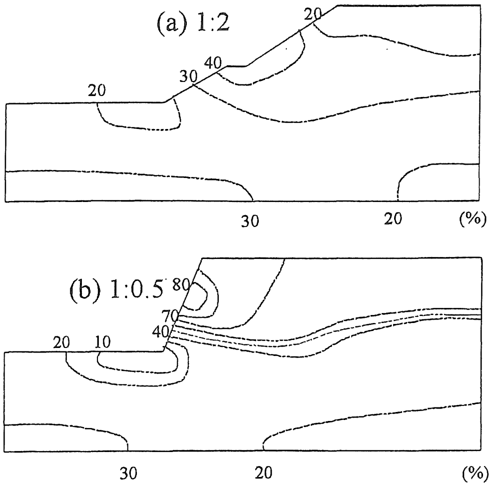

Fig.14 Release of Horizontal Stress

3.6 Evaluation of Slope Stability

(1) Definition of Factor of Safety

A finite element analysis utilizes the vertical stress and expansion strain (ε_v~σ_v) relationship curve, Poisson's ratio ν, and the unit weight γ, for the cohesive soils involved to calculate the stress strain in soil mass. The stresses together with coefficients (s_u/p) and exponent λ can subsequently be used to compute a factor of safety. The overall factor of safety is calculated by FEM and expressed as the ratio of the sum of resisting shear strengths, S_r, to the sum of mobilized shear forces, S_m, along the slip surface.

$$F_s = \frac{\Sigma S_r}{\Sigma S_m} \tag{5}$$

The resisting force for each slide is calculated in terms of the shear strength, s_{uni}, at the center of slide multiplied by base length of the slice l. The available resisting shear strength for a saturated and unsaturated layer can be written as:

$$S_r = s_{uni} l = \{(s_{ui} / p_i)(OCR)^{\lambda} p_{ni}\} l \tag{6}$$

The mobilized shear force, S_m, for each slide is calculated as mobilized shear strength, τ_i, at the center of a slide multiplied by base length l.

$$S_m = \tau_i l \tag{7}$$

The local factor of safety is defined as the ratio of resisting shear force, S_r, at a point along slip surface divided by the mobilized shear force, S_m, at the same point,

$$Fsl = \frac{S_r}{S_m} = \frac{s_{uni}}{\tau_i} \tag{8}$$

(2) Fsl and OCR Distribution

Fig.15 shows distribution of the local factor of safety *Fsl* and *OCR* in cut slopes of the height H=20m, and 1:2 and 1:0.5 slope. It is recognized as a matter of course that higher *OCR* values concentrate along the excavated base and normal consolidated state almost remains unchanged in the rest part of the original horizontal ground surface. Distribution of the local factor of safety shows, however, concentration of lower value of *Fsl* along the slope surface and that of high *Fsl* in the bottom of the excavated base. This is supposed to be caused by the fact that the increase in diving shear stress by excavation predominantly develops in the surface part of low confining pressure as compared with the strength increase due to over-consolidation.

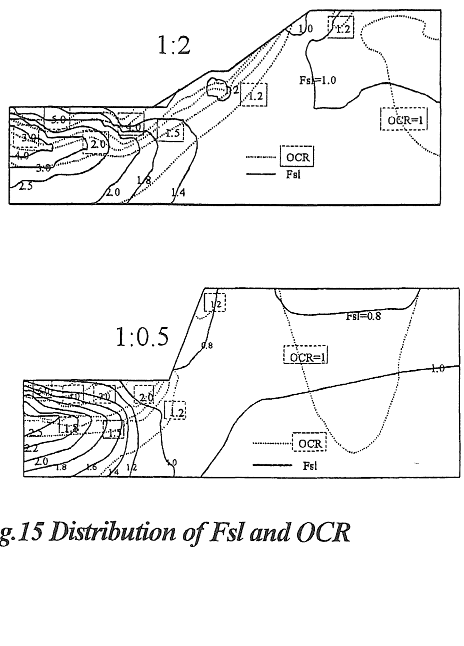

Fig.15 Distribution of Fsl and OCR

Distribution of *Fsl* is drawn in Fig.17 for the case where over-consolidation effects disappear through swelling and weathering processes. It is noticed that the value of *Fsl* becomes lower as approaching to the slope surface because the strength increase is not expected in a zone of low overburden compression stress. The effect of over-consolidation on the increase in shear strength and resulting recovery of safety along slope surface is then apparent as compared with Fig.16.

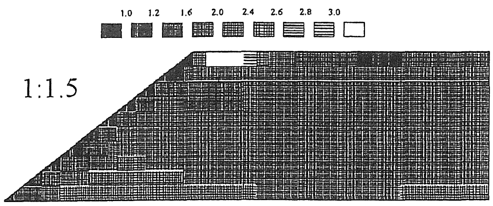

Fig.16 Distribution of Fsl

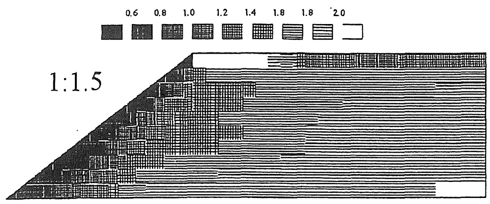

Fig.17 Distribution of Fsl in NC

(3) Overall Factor of Safety

In order to discuss overall safety of cut slope along potential sliding surfaces, the factor of safety *Fs* is calculated by FEM with selected slip circles passing the toe of the slope, *A* to *D* as shows in Fig.18.

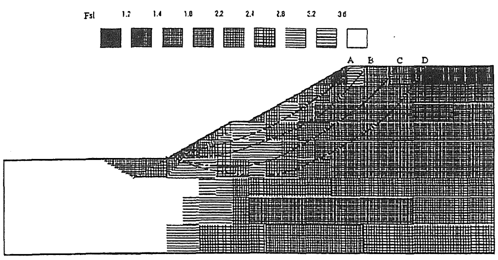

Fig.18 Selected Circle for Calculation

The results are summarized for various cases of excavation in Table 1, denoted by (F), together with the safety factor obtained by the Bishop's simplified method, denoted by (B). Focus is placed in this study on how the distribution of the local safety obtained by FEM affects on the overall safety of excavation and how its value changes with the variation of the influential factors listed before in conjunction with the Bishop's conventional approach employed in the design.

Table 1: Factor of Safety

Case No, inclination & height of slope	Slip circle				
	Fs	A	B	C	D
① 1:0.5,10m	F	0.88	0.81	0.86	0.91
② 1:1.5,10m	F	1.77	1.79	1.80	1.83
③ 1:1,10m	F	1.45	1.49	1.52	1.56
④ 1:1.5, 10m	F	1.69	1.72	1.75	1.80
⑤ 1:0.5, 20m	F	0.94	1.05	1.36	1.46
	B	1.23	1.29	1.46	1.82
⑥ 1:2, 20m	F	1.20	1.23	1.26	1.27
	B	1.69	1.72	1.78	1.89

Note. Case④: the soil is summed to be in a NC state.
(F): FEM, (B): Bishop

The value of (F) gradually increases as the slip circle passes deeply and it gives the minimum critical value for a circle passing through the boundary portion of OC and NC states.

4. CONCLUSIONS

1) Deformation of cut slopes of expansive soils is largely influenced by the size of FE mesh in calculation. Development of expansion strain concentrates in a thin layer near the ground surface, which is correspondent to the swelling properties of materials.
2) The value of vertical strain in one-step calculation is greater than of the step-by-step calculation. So that the result is calculated by step-by-step, which can be used in design because it corresponds in practicality for cut slope.
3) Behavior of stress release in cut slopes depends much on the inclination of slope and the stress component under consideration. Strength reduction

in cut slopes due to excavation is then not so simple and considered difficult to be estimated.

4) Distribution of the local factor of safety *Fsl* and OCR value demonstrates different manner in stress transmission and pre-compression and the usual over-consolidation effect on the stability of cut slopes.

5) In cut slopes, concentration of lower value of *Fsl* along the surface is predominant, because driving shear stresses due to excavation develops much more in the surface part of low confining pressure as compared with the strength increase due to over-consolidation. The loss of pre-compression and over –consolidation effects caused by swelling and weathering after excavation in cut slopes gives a significant influence on the slope stability.

6) FEM analysis can be a practically useful tool for evaluating stability in layer mudstone deposit due to excavation.

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