Study on a slope stability analysis expressed by the body force method considered unsaturated seepage

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ABSTRACT

Large numbers of researchers have proposed slope stability analysis methods to calculate the safety factor of slopes during rainfall. However, it seems that unsaturated seepage behaviors have not been considered in the conventional Limit Equilibrium Methods (LEM). The purpose of this study is to propose a slope stability analysis expressed by the body force method considered unsaturated seepage behaviors. Firstly, a seepage force and a body force by the difference of pressure head in unsaturated soil are introduced. An infinite slope method used the seepage force and the body force by the difference of pressure head in unsaturated soil are described. Finally, the necessity to consider the unsaturated seepage behavior in the slope stability analysis is discussed based on calculation results.

Keywords: slope stability analysis; unsaturated seepage behavior; body force

1 INTRODUCTION

Recently, the extreme weather events have been occasioned by the climate change all over the world. In Japan, the heavy rainfall events have increased, and a lot of slope failures have been occurred by heavy rainfall.

Large number of researchers have studied the slope stability analysis for the rainfall-induced slope failures (Duncan 1996, Kitamura and Sako 2010). For example, the estimation of the slope stability during rainfall have been simulated using the unsaturated seepage analysis and the LEM or the Finite Element Method (FEM) (e.g. Zhang et al. (2004), Collins and Znidarcic (2004), Travis (2010)). However, it seems that the unsaturated seepage behavior have not been considered in the conventional LEM. Hence, Sako et al. (2014) and Uto et al. (2017) tried to propose the seepage force and the body force by the difference of pressure head in unsaturated soil.

The purpose of this study is to propose a slope stability analysis expressed by the body force method considered unsaturated seepage behaviors. Firstly, a seepage force and a body force by the difference of pressure head in unsaturated soil are introduced. An infinite slope method used the seepage force and the body force by the difference of pressure head in unsaturated soil are described. Finally, the necessity to consider the unsaturated seepage behavior in the slope stability analysis is discussed based on calculation results.

2 BODY FORCES IN UNSATURATED SOIL

2.1 Seepage force in unsaturated soil

The seepage force is generated by the difference of total head in saturated soil and the seepage force per unit volume in saturated soil is expressed by the following equation.

$$j_{sat}=\gamma_w \cdot i \tag{1}$$

where, j_{sat}: seepage force per unit volume in saturated soil, γ_w: weight of water per unit volume, i: hydraulic gradient.

The seepage force acted on the saturated soil mass which has the volume of V (J_{sat}) is shown as Eq. (2).

$$J_{sat}=j_{sat} \cdot V=\gamma_w \cdot i \cdot V \tag{2}$$

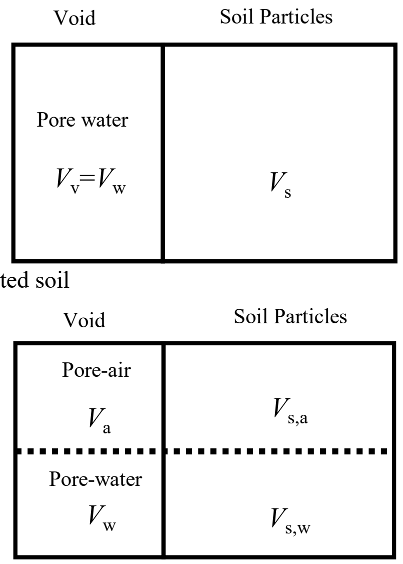
On the other hand, it seems that the seepage force can be generated in unsaturated soil because the seepage flow exists in unsaturated soil. Sako et al. (2014) have studied the seepage force acted on the unsaturated soil. As for the parts which the soil particles contact with the pore-water, the seepage force per unit volume in unsaturated soil can be expressed by Eq. (1). Fig. 1 shows the schema of the phase of the saturated soil and the unsaturated soil. In the case of saturated soil, all soil particles contact with the pore-water. But a part of the soil particles in unsaturated soil does not contact with the pore-water. Hence, the effective volume for seepage force acted on the unsaturated soil (V_j) is shown as Eq. (3).

$$V_j=V_w+V_{s,w}=S_r \cdot (V_V+V_s)=S_r \cdot V \tag{3}$$

where, S_r: degree of saturation, V_v: volume of void, V_s: volume of soil particles, V_w: volume of pore-water, $V_{s,w}$: volume of soil particles contact with pore-water.

Using Eq. (3), the seepage force acted on the unsaturated soil mass which has the volume of V (J_{unsat}) can be expressed by Eq. (4).

$$J_{unsat}=j_{sat}\cdot V_j=\gamma_w\cdot i\cdot S_r\cdot V \tag{4}$$



(a) Saturated soil

(b) Unsaturated soil

Fig. 1. Schema of the phase of soil

2.2 Body force by the difference of the pressure head in unsaturated soil

Body force by the difference of the pressure head in saturated soil is called the buoyancy. The buoyancy ($P_{v,sat}$) is shown as:

$$P_{v,sat}=\gamma_w\cdot V=\gamma_w\cdot(V_w+V_s) \tag{5}$$

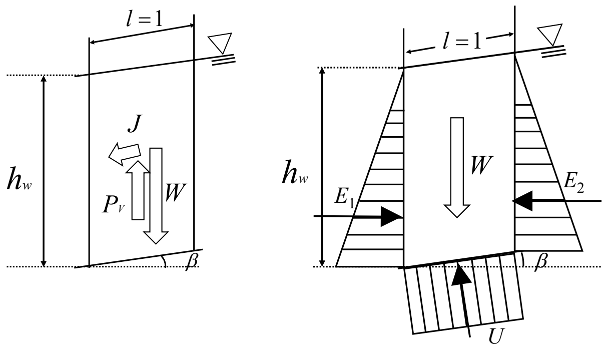
where, V: volume of soil mass, V_w: volume of pore-water, V_s: volume of soil particles.

It seems that the difference of the pressure head also is generated in unsaturated soil. Because the area on that pore-water pressure acts depends on the degree of saturation of the soil, the body force by the difference of the pressure head in unsaturated soil ($P_{v,unsat}$) can be expressed by Eq. (6).

$$P_{v,unsat}=\gamma_w\cdot(V_w+V_{s,w})=\gamma_w\cdot S_r\cdot V \tag{6}$$

3 SLOPE STABILITY ANALYSIS CONSIDERED UNSATURATED SEEPAGE BEHAVIOR

In this paper, the infinite slope stability analysis method is employed as the slope stability analysis. The infinite slope stability analysis can be written by the two methods. One is the water pressure method, and the other is the body force method as shown in Fig. 2. These methods considered unsaturated seepage behavior are described in this chapter, respectively.



(a) Body force method (b) Water pressure method

Fig. 2. Expressions of body force/water pressure in the infinite slope stability.

3.1 Infinite slope stability equation expressed by the water pressure method

The conventional infinite slope stability equation are expressed as follows.

$$F_I=\frac{c+(W\cdot\cos\beta-U)\cdot\tan\phi}{W\cdot\sin\beta} \tag{7}$$

$$E_1=E_2=\frac{1}{2}\cdot\gamma_w\cdot\cos^2\beta\cdot h_w^2 \tag{8}$$

$$U=\gamma_w\cdot\cos^2\beta\cdot h_w \tag{9}$$

where, F_I: safety factor, E_1, E_2: horizontal resultant force of water pressure, U: resultant force of water pressure acted on the slip plane, β: angle of slope, W: weight of soil mass on the slip plane, c: apparent cohesion, ϕ: inter particle force, h_w: height of ground water level from the slip plane.

In this equation, the water pressure is considered only below the ground water level.

The resultant force of water pressure acted on the slip plane are improved to consider the seepage behavior in unsaturated soil. Fig. 3 shows the water pressure acted on the upper part and lower part of the slice of the soil mass.

$$U_{sat}=u_{sat}\cdot A \tag{10}$$

$$U_{unsat}=U_{unsat2}-U_{unsat1} \tag{11}$$

$$U_{unsat1}=u_{unsat1}\cdot S_{r1}\cdot A \tag{12}$$

$$U_{unsat2}=u_{unsat2}\cdot S_{r2}\cdot A \tag{13}$$

where, U_{sat}: resultant force of water pressure acted on the slip plane below the ground water level (=Eq.(9)), u_{sat}: water pressure at the bottom of the slice of the soil mass, A: area of the upper part and lower part of the slice of the soil mass, U_{unsat1}: resultant force of water pressure acted on the lower part of the slice of the soil mass, U_{unsat2}: resultant force of water pressure acted on the upper part of the slice of the soil mass, u_{unsat1}: water pressure at the lower part of the slice of the soil mass, u_{unsat2}: water pressure at the upper part of the slice of the soil mass, S_{r1}: degree of saturation at the lower part of the slice of the soil mass, S_{r2}: degree of saturation at the upper part of the slice of the soil mass.

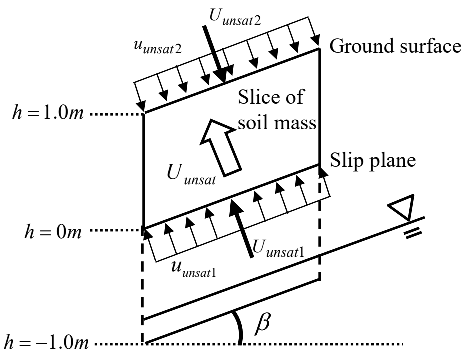
U_{sat} and U_{unsat} are used as resultant force in the equation of slope stability (Eq. (7)). The weight of soil mass (W) in Eq. (7) is derived based on the distribution of degree of saturation in the soil mass.

3.2 Infinite slope stability equation expressed by the body force method

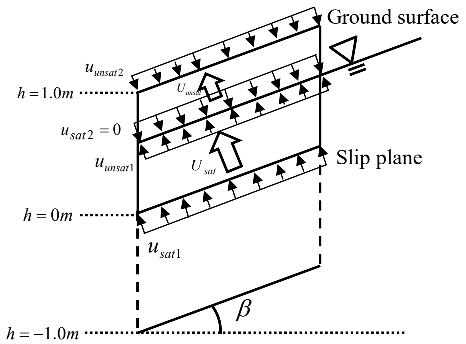
The conventional equation of the infinite slope stability expressed by the body force method is shown as Eq. (14).

$$F_1 = \frac{c + (W - P_v)\cdot\cos\beta\cdot\tan\phi}{J + (W - P_v)\cdot\sin\beta} \tag{14}$$

When the ground water level is below the slip plane as shown in Fig.3(a), Eqs. (4) and (6) are used instead of J and P_v in Eq. (14). Then, the Eqs. (2), (4), (5) and (6) are used instead of J and P_v in Eq. (14) when the ground water level is above the slip plane as shown in Fig. 3(b). The weight of soil mass (W) in Eq. (7) is derived based on the distribution of degree of saturation in the soil mass.



(a) Case that the ground water lever is below the slip plane



(b) Case that the ground water lever is above the slip plane

Fig. 3. Treatment of water pressure acted on the ground surface and the slip plane.

4 CALCULATION RESULTS

In this chapter, the calculations are conducted to get to know the effect of the consideration of unsaturated seepage behavior for the infinite slope analysis equation. The first calculation has the condition that the degree of saturation of the slope is uniformly changed. The second calculation has the condition that the ground water lever is changed in the slope. The water pressure method and the body force method are calculated for each calculation condition, respectively. Each calculation is conducted for 4 cases. Case 1 and Case 3 are the results obtained from the conventional body force method and the water pressure method, respectively. Case 2 is the body force method considered the unsaturated seepage behavior, and Case 4 is the water pressure method considered the unsaturated seepage behavior.

The geometry and the soil properties of the slope used in these calculations shown in Fig. 4 and Table 1. The distribution of the pore-water pressure and the degree of saturation in the unsaturated area of the slope are estimated by the soil-water characteristic curve as shown in Fig. 5. The soil-water characteristic curve was derived from the concept model for the water retention property of the unsaturated soil (Sako and Kitamura 2006) using the soil properties of Shiras which is defined as one of

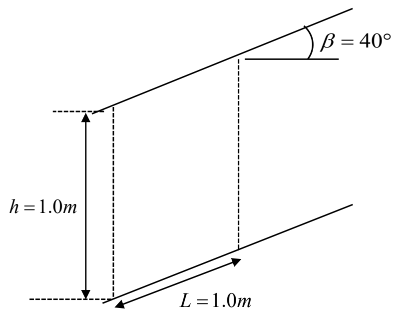


Fig. 4. Geometry of the slope.

Table 1. Soil properties of the slope.

sample	Shirasu (None-welded pyroclastic flow deposits)
soil particle density [g/cm^3]	2.58
void ratio	1.395
apparent cohesion [kPa]	4.2
Inter particle force [deg.]	35.0

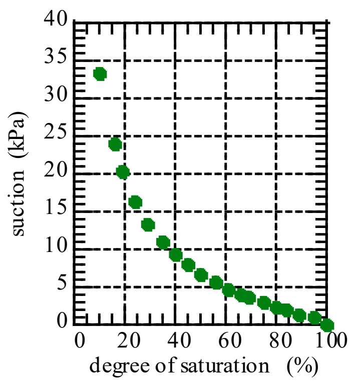


Fig. 5. Soil-water characteristic curve of Shiras (Sako and Kitamura 2006)

the non-welded pyroclastic flow deposits. It is assumed that the distribution of the pore-water pressure depends linearly on the depth to the ground water level.

4.1 The calculation condition that the degree of saturation of the slope is uniformly changed

Fig. 6 shows the relationship between the degree of saturation and the safety factor. It can be seen from Fig.6 that the safety factors derived from the proposed body force method (Case 2) are lower than the results obtained from the other methods. The safety factors of Case 4 are same value to the Case 1 and Case 3 in spite of consideration of the unsaturated seepage behavior. It seems that U_{unsat} gets balanced out because the U_{unsat1} and U_{unsat2} get the same value in this calculation condition.

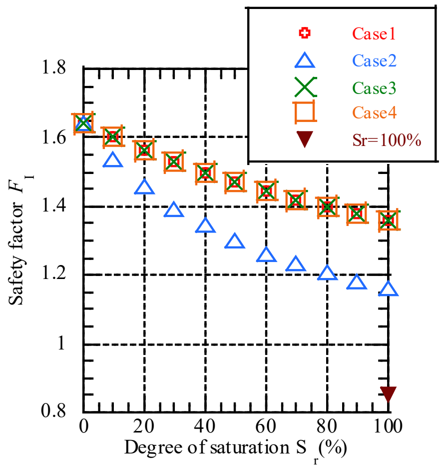


Fig. 6. Relationship between degree of saturation and safety factor.

4.2 The calculation condition that the ground water level is changed in the slope

Fig. 7 shows the relationship between the ground water lever and the safety factor. The positon of the ground water level is defined to the slip plane as shown in Fig.3. The safety factors of Case 2 are lower than that of the other cases. The results of Case 4 are also lower than the results of the Case 1 and Case 3. And it seems that the changes in the safety factors of the Case 2 and Case 4 with the change in the ground water level are more natural than that of Case 1 and Case3. However, the results of Case 2 and Case 4 are not same. It is necessary to check the validity of the definition of the seepage force and body force by the difference of pressure head for each slope stability method.

5 CONCLUSIONS

The slope stability analysis expressed by the body force method considered unsaturated seepage behavior was introduced, and the calculation were conducted. Then the availability of the proposed method is discussed comparing with the results obtained from the conventional methods and the water presser method considered unsaturated seepage behavior. It can be seen from Fig. 6 and Fig. 7 that the safety factor derived from

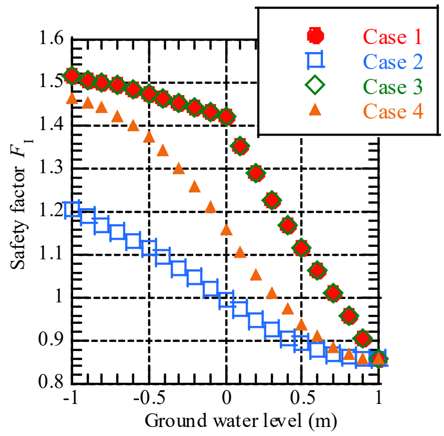


Fig. 7. Relationship between ground water level and safety factor.

the equations considered unsaturated seepage behavior showed lower values than the conventional slope stability analysis. It seems that the results in this study show the importance to consider the unsaturated seepage behavior for the slope stability analysis. In future, it is necessary to experimentally check the validity of the proposed seepage force and the body force by the difference of pressure head.

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