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DESIGN OF PILES BASED ON THE 3-D SLOPE STABILITY ANALYSIS(LEM)

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ABSTRACT: *This report explains the need for slope stability analysis using the 3-D limit equilibrium method, a 3-D extension of the 2-D slice method, rather than using the 2-D limit equilibrium method. Problems which need to be solved in order to perform the 3-D slope stability analysis are presented, and their solutions are discussed. Rational arrangement and design of piles through the 3-D slope stability analysis are also discussed.*

KEYWORDS: *3-D slope stability analysis;Limit equilibrium method;3-D simplified Janbu's method;Pile*

1. INTRODUCTION

In landslides observed in the 3-D form, prevention works designed based on the 2-D cross sections through the central section of the landslide can offer an appropriate amount of prevention works near the central section, while the design will be more uneconomical the closer the section is toward the edge. This is a huge concern when designing prevention works using the current 2-D limit equilibrium method. Although several 3-D analysis methods have been proposed, there have been few design methods for prevention works based on the 3-D slope stability analysis up to the present.

This report discusses the issues that need to be addressed regarding the design of prevention works based on the 3-D limit equilibrium method.

2. PROBLEMS TO BE SOLVED

Following issues should be solved:

1). Establishment of an appropriate 3-D stability analysis method.

2). Definition of an appropriate 3-D planning safety factor.

There may be also a following technical issue on the 3-D slope stability analysis:

3). Development of a preprocessor (program) which allows quick and easy reproduction (input) of the 3-D slope landform.

2.1. An appropriate 3-D slope stability analysis method

The 3-D slope stability analysis methods examined in this study include,(1) the Hovland method and (2) the 3-D simplified Janbu's method (Ugai et al,)[(1)(2)]. In this report, (3) the

Hovland (underwater effective weight) method, which considers the effective soil weight below the groundwater table, is excluded due to the lack of page space.

This report shows explicit solutions of a simple wedge landform shown in Figure 1(a), (b) and compares the results by both analytical methods. The landform is wedge-shaped, of 100m horizontal length and 100m width. Two cases, with and without a water table, are examined.

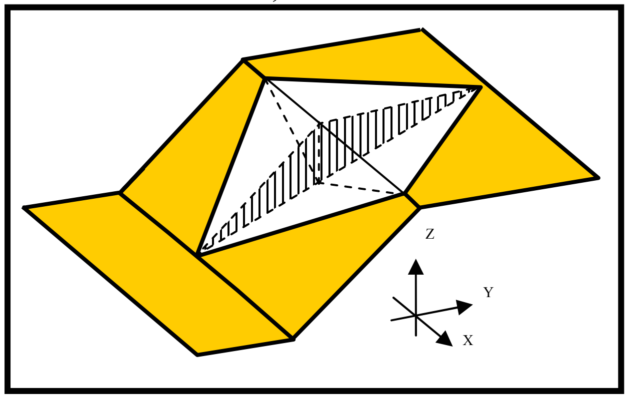

Figure 1. (a) 3-D view of the wedge-shaped landform

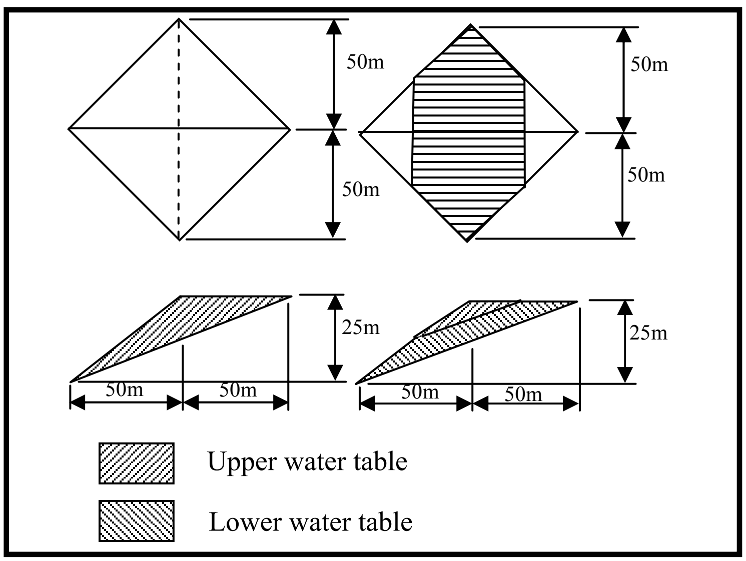

Figure 1. (b) Section and plan views of the wedge-shaped plain landform

Using the explicit solution, the value φ (φ0) is back-calculated, where the value c is 0 as well as the value c (Co), where the value φ is 0, using an initial safety factor of F0=1.00. With the combination of the back-calculated values (φ=φ0, c=0), (φ=0, c=C0) and the soil constants, the safety factor is then calculated using both analytical methods. The results are shown in Table 1 (a) and (b).

From these results, it is possible to conclude that the 3-D simplified Janbu's method is a more appropriate analytical method because the safety factor values by the method is nearer to the initial safety factor of 1.00 than those by the Hovland method, regardless of the existence of the water table.

Table 1. (a) Comparative results without water table

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Without water table (Fig1.b -Left)	Explicit value		Safety factor value(Fs)	
	Back-calculate value	Fo	Hovland	Janbu
φ(°)	13.65	1.000	0.944(0.972)	1.003(0.972)
c (kN/m2)	17.16	1.000	1.000	1.001

( ) : 2-D cross sectional safety factor(reference value)

Table 1. (b) Comparative results with water table

With water table (Fig1.b -Right)	Explicit value		Safety factor value (Fs)	
	Back-calculate value	Fo	Hovland	Janbu
φ(°)	18.52	1.000	0.924	1.001
c (kN/m2)	18.12	1.000	1.000	1.001

2.2. *Definition of an appropriate 3-D planning safety factor*

The amount of the prevension works is determined so that it satisfies the planning safety factor. Many design standards specify a planning safety factor (Fsp2) for the 2-D limit equilibrium method, but there are no specified planning safety factor (Fsp3) for the 3-D limit equilibrium method. Generally speaing, the 3-D planning safety factor value should be a little higher than the 2-D planning safety factor (Fsp3>Fsp2).

Using the 3-D simplified Janbu's method, a calculation procedure is proposed to determine a 3-D planning safety factor that is equivalent to the 2-D one. The conditions used in the calculation are:

1.The same initial safety factor value F0 is used for the 2-D and 3-D conditions.

2.The same required prevention force value is used for the 2-D and 3-D conditions, namely, Preq3 = L*Preq2(L: Total width of prevention works)

The following steps shall be taken to calculate the 3-D planning safety factor Fsp3 equivalent to the 2-D planning safety factor Fsp2:

1) Provide the initial safety factor F0

2) Back-calculate c or tanφ for F0 through the 2-D safety factor equation shown below:

$$F_{o2} = \frac{\sum \left[\dfrac{\left\{ c \cdot \Delta\ell \cos\alpha + \left(\Delta W2 - u \Delta\ell \cos\alpha \right) \tan\phi \right\}}{\cos\alpha \cdot m\alpha_2} \right]}{\sum \Delta W2 \cdot \tan\alpha} \tag{1}$$

$$m\alpha_2 = \cos\alpha + \frac{\sin\alpha \tan\phi}{F_{o2}}$$

$$\Delta W2 = \gamma_Z \Delta y$$

3) Provide the 2-D safety factor Fsp2 and calculate the required prevention force Preq2 from c or tan φ back-calculated by Eq(2).

$$P_{req2} = \sum \Delta W 2 \tan\alpha - \frac{1}{F_{sp2}} \sum \frac{\{c\Delta\ell\cos\alpha + (\Delta W2 - u\Delta\ell\cos\alpha)\tan\phi\}}{\left\{\cos\alpha\left(\cos\alpha + \frac{\sin\alpha\tan\phi}{F_{sp2}}\right)\right\}} \tag{2}$$

4) Back-calculate c or tan φ for F0 from the 3-D simplified Janbu's method.

$$F_{o3} = \frac{\sum\sum\left[\frac{\{(c - u\tan\phi)\Delta A + \Delta W\tan\phi\}}{\cos\alpha_{yz}\cdot m\alpha}\right]}{\sum\sum\Delta W\cdot\tan\alpha_{yz}} \tag{3}$$

$$m\alpha = \frac{1}{J} + \sin\alpha_{yz}\frac{\tan\phi}{F_{o3}}$$

5) Calculate the 3-D planning safety factor Fsp3 equivalent Fsp2 using Eq(4), where Preq3=L*Preq2.

$$F_{sp3} = \frac{\sum\sum\left[\frac{\{(c - u\tan\phi)\Delta A + \Delta W\tan\phi\}}{\cos\alpha_{yz}\cdot m\alpha_3}\right]}{\sum\sum\Delta W\cdot\tan\alpha_{yz} - P_{req3}} \tag{4}$$

$$m\alpha_3 = \frac{1}{J} + \sin\alpha_{yz}\frac{\tan\phi}{F_{sp3}}$$

Recurrent calculations must be performed repeatedly to obtain Fsp3 from Eq(4).
From these steps, the 3-D planning safety factor equivalent to the current 2-D planning safety factor can be determined.

2.3. Reproduction of 3-D landslide forms

A relatively easy reproduction method for 3-D landslide forms is proposed by inputting a number of cross-sectional forms in 2-D style operational steps.

Specifically, this method inputs multiple 2-D cross-sectional forms, as shown in Figure 2, and connects the nodal points between each cross section via a specific rule before covering the intervals with triangular planes. Therefore, if multiple landslide lateral line data are available, 3-D landforms can be reproduced easily with a conventional 2-D style input method.

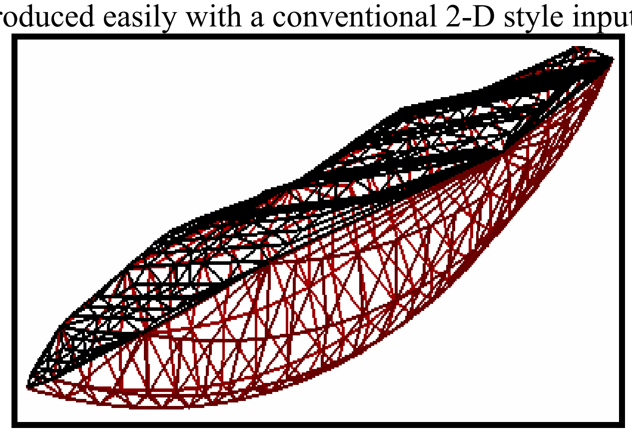

Figure 2. 3-D reproduction using multiple 2-D cross section forms

3. BENEFIT OF THE 3-D ANALYSIS IN TERMS OF PILE DESIGN

Once the 3-D analysis is done, and the crosswise prevention force distribution is made clear, appropriate locations of piles, can be determined, considering the whole landslide block.

3.1. Sideways distribution method of the prevention force

As a way of distributing (by columns) the required prevention force (Preq3) sideways for the whole landslide, the sliding force ratio of each column shuld be detemined. The equation for the prevention force at each column is shown as follows:

$$P_{req}(n) = P_{req3} \times \frac{s(n)}{\sum s} \qquad (5)$$

where,
Σs: total sliding force
S(n): sliding force at each column

The meshes in Figure 3 show each column (soil block segment) in the landslide plain chart. In this case, the landslide occurs downward from the upper side as shown by the thick arrow. The thin arrows show the size of sliding force at each column.

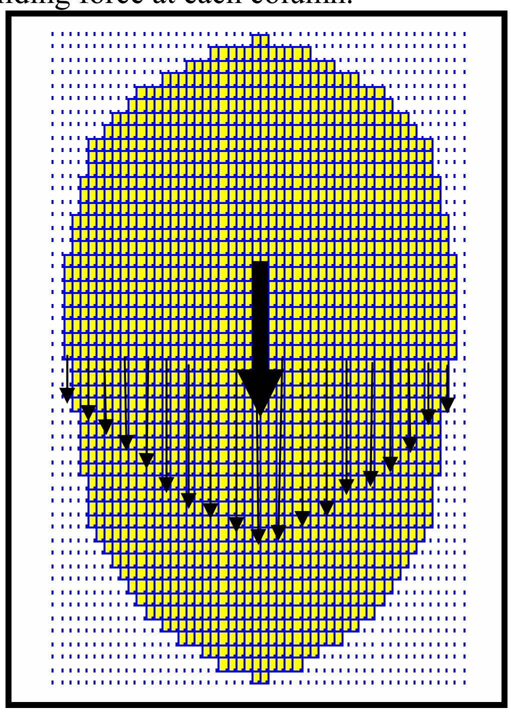

Figure 3. Meshed landslide plain diagram

While the 3-D stability analysis sums the sliding force and resisting force of a meshes' entire array of rows and columns, the 2-D stability analysis adds them up, column by column.

Figure 4 and Figure 5 show sideways distribution diagrams of the prevention force. The bar graph of Figure 4 shows the prevention force distribution chart by column where the required prevention force in Eq(5) is distributed sideways by the sliding force ratio. The line graph shows the 3-D prevention force distribution per unit width.

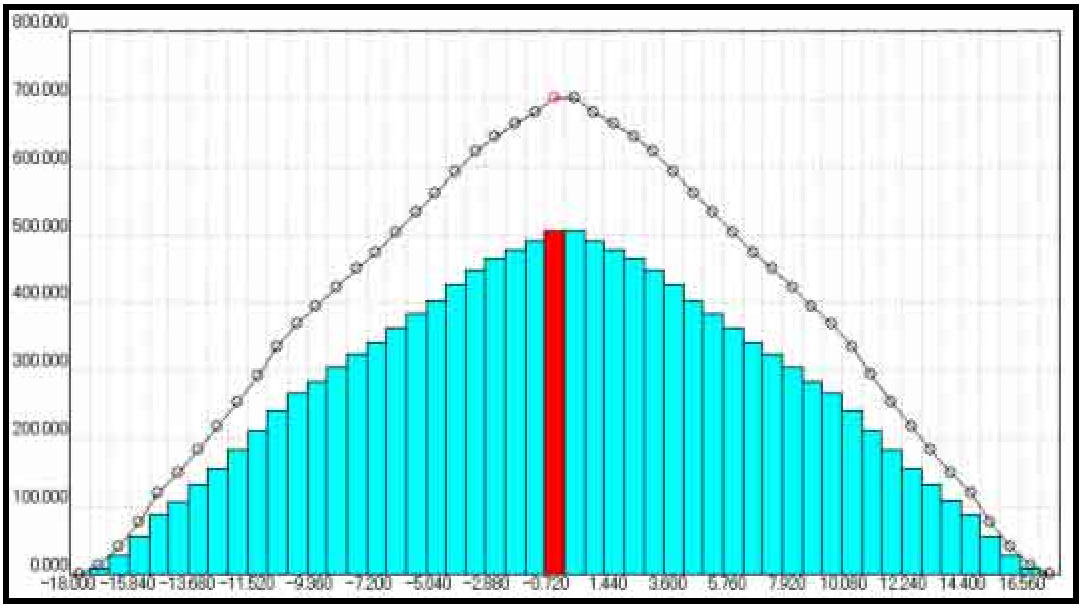

Figure 4. 3-D prevention force distribution chart
(Vertical axis = prevention force [kN]; Horizontal axis = landslide width [m])

Figure 5 shows required prevention force calculated individually. In short, this is the result of a 2-D analysis. The bar graph shows the required prevention force per column width and the line graph shows the 2-D prevention force distribution chart per unit width.

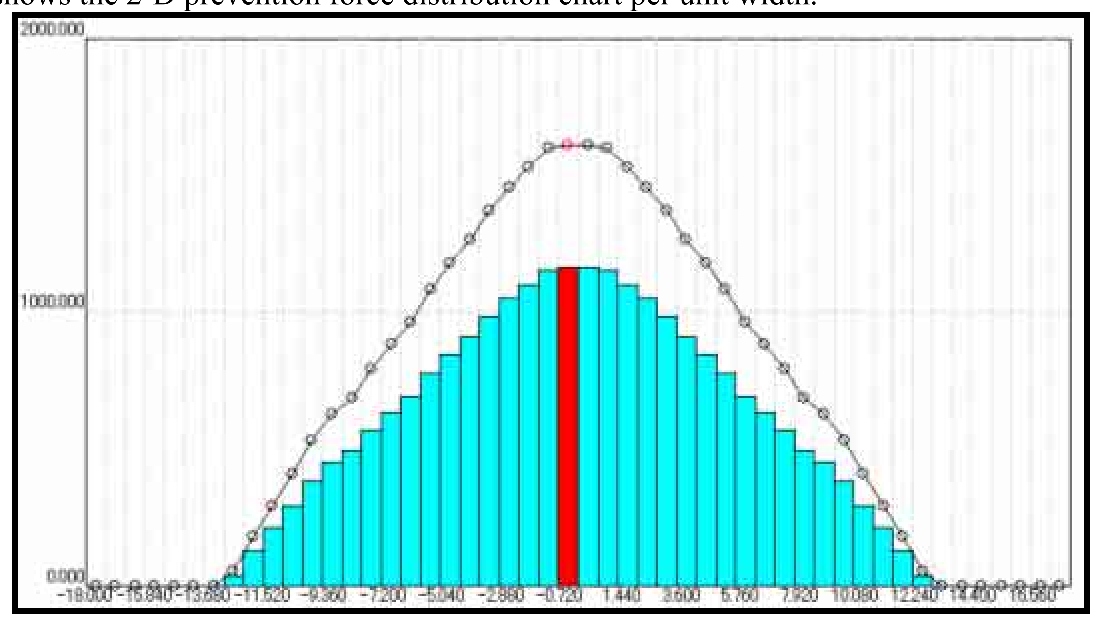

Figure 5. 2-D prevention force distribution chart
(Vertical axis = prevention force [kN]; Horizontal axis = landslide width [m])

3.2. Considerations of pile arrangement

Figure 5 is a prevention force distribution chart derived from the current 2-D design methods. Briefly, the 2-D prevention force calculated per cross section offers greater value near the center of the landslide, while no prevention force occurs in the cross sections near the edges where the stability is maintained. In practical design, almost no stability analysis of the cross sections of the edge areas is conducted. Generally, a pile arrangement designed for the center area, where the most dangerous cross sections exist, is applied over the entire landslide block.

On the other hand, Figure 4, the 3-D prevention force distribution chart, provides a visible distribution status of the entire landslide block. This allows a determination of appropriate pile arrangement for the entire landslide block -- a dense arrangement near the center and a light arrangement near the edges.

4. CONCLUSIONS

Advantages of the 3-D slope stability analysis are as follows:

(1) 3-D effect is clearly existing

It is quite possible for the 3-D safety factor to be 1.2-1.3 times higher than the 2-D in actual slopes.

(2) Overestimation of back-calculated strength constants

There is a risk of overestimating c and φ in a 2-D assumption when back-calculating a soil strength constants c and φ.

These are advantages of the 3-D limit equilibrium methods. There are other optimizations available, such as concentrating piles around the most dangerous cross sections and sparsely locating them around the edge areas of the landslide.

With programmed 3-D limit equilibrium slope analysis (LEM) that includes the features discussed in the report, the 3-D slope stability analysis is easier now.

The next step is to develop a program that will support the processes of calculating the arrangement of prevention works using the 3-D limit equilibrium slope analysis (LEM) and then examining their effects using the 3-D finite element method (FEM analysis).

The program "3-D landslide slope stability analysis(LEM)"(co-produced by Gunma University and Forum 8) was used for all calculations and validations in this report.

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