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Stability charts revisited using FEM

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STABILITY CHARTS REVISITED BY FINITE ELEMENT METHOD

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I have spent two more years in geotehnic master project. These two more years might be with the lowest emotions, but not the worst years in my life. I have experienced longtime depression, sad, loneliness and homesick all these bad emotions. But all these are become my fortune and precious. The finishing of thesis means not only a degree, but also I have won the challenge to myself. Thanks for the medic help from Eilisabeth Gusdal psykologspesialist in SIT Helse. Thanks for encourages and help from my homelike division every day, from every one. Professor Steinar Nordal , Professor Arnfinn Emdal , Ashenafi Lulseged Yifru , Marit Skjåk-Bræk and Lars Espen Bjørgum,

Also thanks for my friends and my parents' supports.

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Hao Jiang

ABSTRACT

The finite element method is a modern computer aided method developed in recent decades of years. While widely used Janbu stability charts theory is invented by hand calculation in 1954. The aim of this mater thesis is to revisit the Janbu stability chart by FEM Plaxis, especially is the basic parameters. After introducing limited method, especially Janbu stability charts theory, and Finite element method application in Plaxis, 1044 analysis units are designed to find proper simulation methods in Plaxis to achieve revisiting with single variation. A series of systematical tests are set up in stage of comparison on variation of slope angle β, variation depth D, comparison of different mesh size, evaluate effect of magnitude and length of distribution loading, partial submergence and drawdown condition and influence of tension cracks.

After analysis, the tendency of factor of safety varied by single factor is mostly same in Plaxis and Janbu stability chart analysis. The length upper surface and surcharge is unlimited in Janbu's assumption. But length of upper surface is better to bigger than 10 times as height of slope in Plaxis. And when length of surcharge is larger than 4, the factor of safety is tend to a stable value. The difference is mostly low than 8-10%. But with the influence of water, the difference will increase to 40-50%. It cites that water plays a key role in slope stability.

Contents

CHAPTER 1 INTROUDUCTION

This chapter introduces the background, aim of this master's thesis study. The aim is includes several objectives.

1.1. BACKGROUND

The theories were developed when only manual calculation methods were available. But nowadays slope stability analysis is relied on modern, computer aided method. Since the ordinary method introduced by Fellenius (1936), several limit equilibrium (LE) methods have been developed for slope stability analyses. Since then, the calculation methods have been refined and developed by modern modeling tools include the possibility of calculating the factor of safety, critical surface and so on. In 1954, Janbu stability charts theory is invented by hand calculation. But by the developing of computing and information technology, how can we determine whether this easily produced method is reliable or not as follow

A finite element method software PLAXIS develop by Plaxis Company (Plaxis bv) in cooperation with several universities word wide including Delft University of Technology in the Netherlands and Norges Teknisk-Naturvitenskapelige Universitet NTNU. It is geotechnical friendly and easily used software. The idea is use modern software revisit the Janbu stability chart.

1.2. AIM

The aim of this mater thesis is to revisit the Janbu stability chart by FEM Plaxis, especially is the basic parameters.

1.3. OBJECTIVES

Two main problems with the optimize function have been observed, and can be summarized as following:

- Finding proper simulation methods in Plaxis to achieve revisiting with single variation.
- Setup symmetrical tests with single variation in Plaxis
- Analyses and comparison the results between Janbu stability chart method and FEM Plaxis
- Propose the suggestion on in which aspects that FEM results can modified the Janbu stability chart theory.

1.4. LIMITATIONS

This master thesis is limited by author's knowledge background. The limitation may occur on the conclusion may be not highly abstractive and accurate which is based on the results analysis. And results analysis maybe limited by insufficient the mathematical and statistical knowledge. The natural slope cases are of complex condition which leads to insufficient real data to test and verify the conclusions obtained. Besides the function limitation of Plaxis or soil model cannot make up this problem.

CHAPTER 2 REVIEW OF STABILITY ANALYSIS METHODS

2.1. OVERVIEW

In this thesis, we will utilize two method for slope failure: the limit equilibrium method and the finite element method (FEM). Both analysis methods discussed aim on deriving a factor of safety, that is commonly defined as

$$F = \frac{shear\ strength\ available}{shear\ strength\ required\ for\ stability} \tag{2.1}$$

F is Safety factor, abbreviated as FOS. Safety factor shows the balance between the capacities of the soil body against to the failure trendy from the negative elements, as surcharge, tension cracks, water influence, and sudden-happen external environmental changings, including natural and human behaviors.

F equals 1 is the divider of safe and unsafe. For safety factor low than one, it means the shear strength of slope can no longer maintain a stable statue. Microscopically, soil grains lost combination. When the micro breaks connected, the soil body will move and collapse. The breaks connection is called break surface or mobilized surface. For safety factor higher than on, it means the soil body or slope can hold its own weight and external loads. Under civil construction or utilization stage, it is of necessity to ensure F bigger than one. The higher safety factor is, the safer slope is. In some project, there are some soil factors are unknown. So, an easy but uneconomical solution is to increase the design factor.

Aimed at soil slope, a lower design factor calculated by hand calculation or software simulation is of positive effect on the construction project. The capacity of soil is treated as a value to design the structure on the upper or lower surface of slope. So the lower safety factor gives a lower design value of slope, which leads to more caution on design.

In reality, slope is in three dimensions. A slope failure happens in 2D can be the projection from several 3D failure types. In the follows figure as follow, the cross section of plane failure, wedge failure and circular failure can be the same in 2D. Often slope stability is considered as a 2D problem since 3D failure surfaces higher factor of safety.

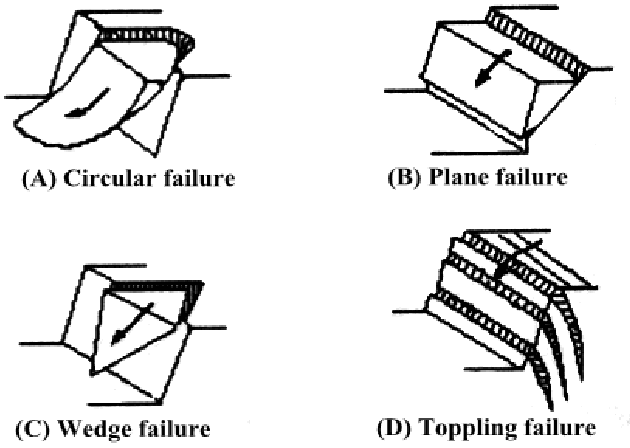

FIGURE 1 DIFFERENT TYPES OF SLOPE FAILURE

2.2. LIMIT EQUILIBRIUM PRINCIPLES

The basic assumption is that a soil mass is sliding on a failure surface when a slope fails. At the moment of soil, soil strength is fully mobilized along the failure surface. At the same time, the sliding mass is in static equilibrium.

The Mohr-Coulomb (MC) criterion is widely used in determination of shear strength along the sliding surface. The shear stress in shear is defined as the shear strength of the soil when failed. A state of limit equilibrium exists when the mobilized shear stress (τ) is expressed as a fraction of the shear strength. Janbu (1973)

The shear strength is usually expressed by the Mohr-Coulomb linear relationship, where the τ_f and τ are defined by:

Shear strength:

$$\tau_f = (a + \sigma')\tan\varphi \tag{2.2}$$

$$\text{or} \quad \tau_f = c + \sigma'\tan\varphi \tag{2.3}$$

Shear stress (mobilized):

$$\tau = \frac{\tau_f}{F} = \frac{(c + \sigma' \tan\varphi)}{F} \tag{2.4}$$

where,

a, = attraction in effective stress terms

c' = cohesion in effective stress terms

$F = \frac{S_a}{\text{Wsin}\alpha} = \frac{cL + N\tan\varphi}{W\sin\alpha}$ ' = friction angle respectively in effective stress terms

F = factor of safety (FOS).

According in equilibrium condition FOS can be expressed in three ways:

(A)Limit equilibrium, (B) Force equilibrium and (C) Moment equilibrium.

(A)Limit equilibrium is based on the shear strength. And there are two analysis: (a)s_u - analysis and(b) a - φ –analysis.

(a)Su analysis is a total stress approach. Total stress strength is used in clayey soils for short–term conditions. (b)a - φ –analysis is the effective stress strength which used in long-term conditions in any conditions where the pore pressure is known.

(B) and(C) equilibrium are based on the thought that safety factor is determined by resisting and driving sides. Each force or moment can separate into a neutral part and positive or negative components. The resisting side, no matter forces or moments, includes all components supported as positive contribution, since they increase resistance capacity. The driven parts give a negative contribution which leads a driven tendency

(A)Limit equilibrium

(a)Total stress

$$F = \frac{S_u}{\tau} \tag{2.5}$$

(b)Effective stress

$$F = \frac{c' + \sigma' \tan\varphi'}{\tau} \tag{2.6}$$

(B) Force equilibrium

$$F = \frac{\text{Sum of resisting forces}}{\text{Sum of driving forces}} \quad \text{and} \quad F = \frac{S_a}{\text{W}\sin\alpha} = \frac{cL + N\tan\varphi}{W\sin\alpha} \qquad (2.7)$$

Where L is total length of the sliding plane

(C)Moment equilibrium

$$F = \frac{\text{Sum of resisting moments}}{\text{Sum of driving moments}} \quad \text{and} \quad F = \frac{R\int_0^L s_u dl}{\text{Wx}} \qquad (2.8)$$

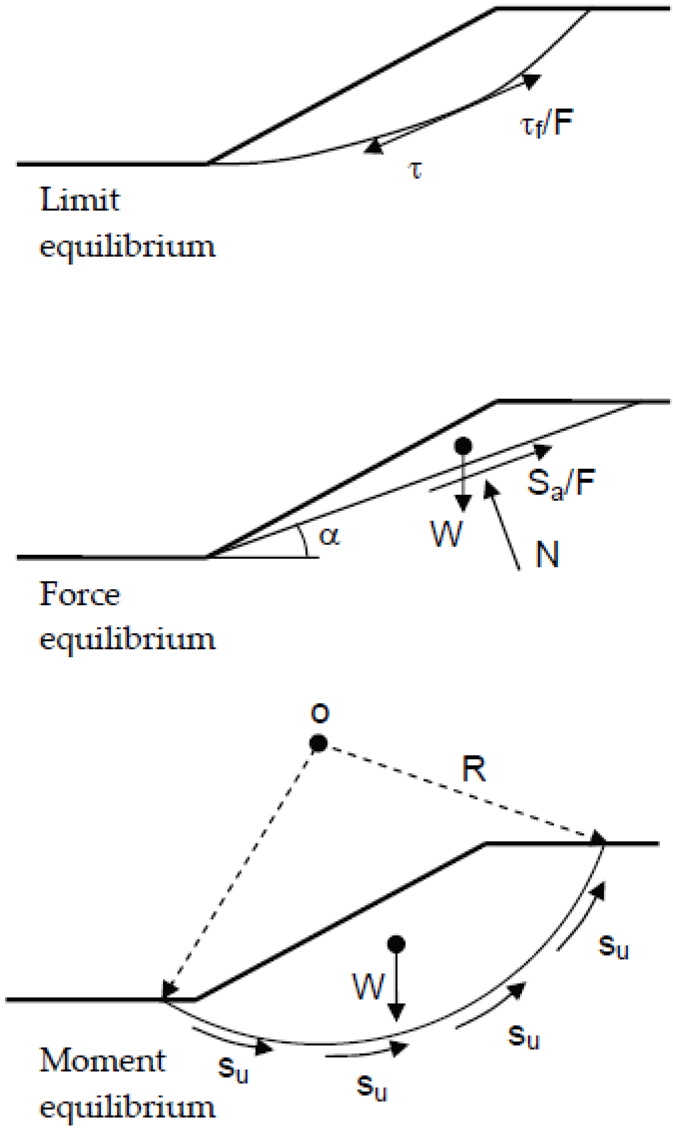

FIGURE 2 VARIOUS DEFINITIONS OF THE FACTOR OF SAFETY (FOS) (ABRAMSON ET AL. 2002)

2.3. LIMIT EQUILIBRIUM METHODS

Since the ordinary method introduced by Fellenius (1936), several limit equilibrium (LE) methods have been developed for slope stability analyses.

Bishop (1955) advanced the first method, Bishop's simplified methods (BSM).

Janbu (1954a) developed a simplified method for non - circular failure surfaces, dividing a potential sliding mass into several vertical slices.

The generalised procedure of slices (GPS) was developed at the same time as a further development of the simplified method (Janbu 1973)

These developments are reviewed in the follows section, which aims to find out the key differences in the various approaches for FOS determination. (K.Aryal 2006)

2.3.1. ORDINARY METHOD OF SLICES

The Ordinary method (OM) satisfies the moment equilibrium for a circular slip surface

Assumption: the interstices forces are oriented parallel to the baseline on the slice and that they have the same magnitude, left as right. It leads to no iteration process in the equation:

$$F = \frac{\sum_{i=1}^{n} C + N'\tan\varphi}{\sum_{i=1}^{n} W\sin\alpha} \qquad (2.9)$$

and $N' = (W\cos\alpha - ul)$

For mobilized shear strength S_m

$$S_m = \frac{C + N'\tan\varphi}{F} \qquad (2.10)$$

C and $N'\tan\varphi$ are the cohesive and frictional shear strength components of soil, C=cL

Where, u = pore pressure, l = slice base length and

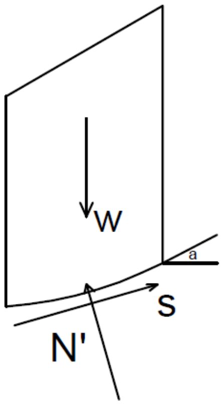

FIGURE 3 STRESS IN ORDINARY METHOD

It gives the most conservative FOS and s useful only for demonstrations the most conservative FOS, and is useful only for demonstrations.

Bishop's methods

Bishop's simplified method (BSM) is commonly used in CSS.It considers he interslice normal forces but not interslice shear forces.

Assumption: the interslice shear forces to be negligible; all interslice forces are oriented horizontally. It leads to BSM satisfies vertical force equilibrium for N

$$F = \frac{\sum_{i=1}^{n} C + N'\tan\varphi}{\sum_{i=1}^{n} W\sin\alpha} \tag{2.11}$$

$$N' = \frac{1}{m_\alpha}\sum\left(W - \frac{c'l\sin\alpha}{F} - ul\cos\alpha\right) \tag{2.12}$$

Where,

$$m_\alpha = \cos\alpha(1 + \tan\alpha\frac{\tan\varphi'}{F}) \tag{2.13}$$

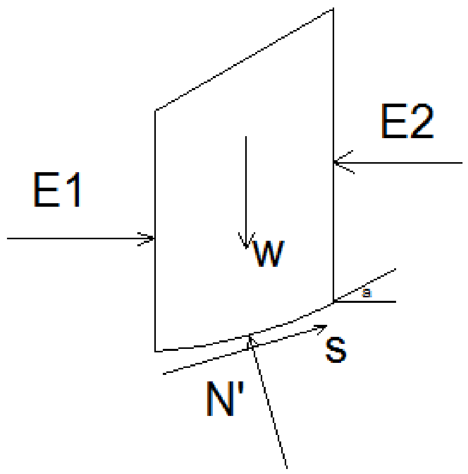

FIGURE 4 STRESS IN BISHOP'S SIMPLIFIED METHOD

It is more common in practice, and applies mostly for circular shear surfaces.

Furthermore, The Bishop rigorous method (BRM) considers the interslice shear forces and nomal forces. Hence the FOS are determined by an iteration procedure.

2.3.2. SIMPLIFIED JANBU METHOD

Janbu's simplified method (JSM) is not based on a CSS, but noncircular. And this method is based on the horizontal force equilibrium instead of moment equilibrium.

Assumption: vanishing shear force between slices.

$$F_f = \frac{\sum (c'l + (N - ul)\tan\varphi')\sec\alpha}{\sum W \tan\alpha + \sum \Delta E} \qquad (2.14)$$

Where, $\sum \Delta E = E_2 - E_1$ (net interslice normal forces)

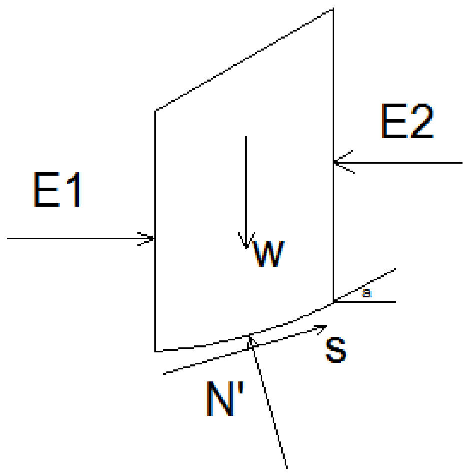

FIGURE 5 STRESS IN JANBU'S SIMPLIFIED METHOD

Janbu modified by introduced a correction factor (f_0) to accommodate the effects of interslice shear force. It's called Janbu's corrected method (JCM) or Janbu's modified method. The correction factor related to the depth to length ratio (d/L) .

$$F_f = f_0 F_0 \tag{2.15}$$

Where,

$$f_0 = 1 + b_1 \left[\frac{d}{L} - 1.4 \left(\frac{d}{L} \right)^2 \right] \tag{2.16}$$

Where b_1 is determined by the soil type found along the assumed failure surface

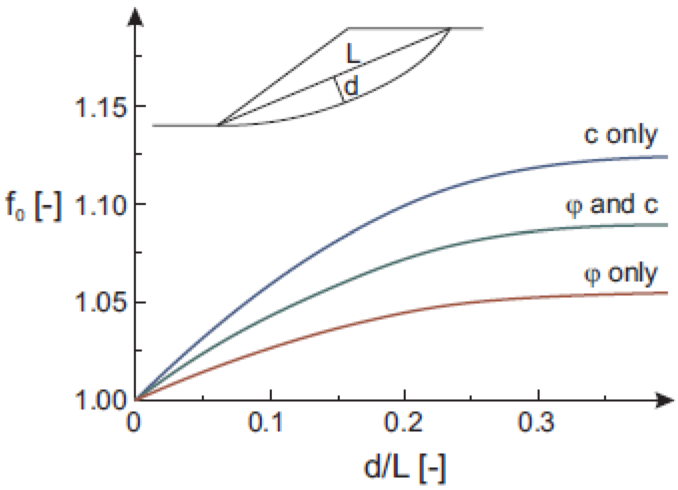

FIGURE 6 CORRECTION FACTOR F0 IN THE SIMPLIFIED JANBU METHOD

2.3.3. JANBU'S RIGOROUS METHOD

Janbu's rigorous method, Janbu's generalized method (JGM), known as the generalized procedure of slices (GPS),

Janbu's generalized method (JGM) or Janbu's generalized procedure of slices (GPS) (Janbu 1973)considers both interslice forces and assumes a line of thrust to determine a relationship for interslice forces. As a result, the FOS becomes a complex function with both interslice forces (Nash 1987):

$$F_f = \frac{\sum\left[\left(c'l + \left(N - ul\right)\tan\varphi'\right)\sec\alpha\right]}{\sum\left[W - \left(T_2 - T_1\right)\right]\tan\alpha + \sum\left(E_2 - E_1\right)} \quad (2.17)$$

$$N = \frac{1}{m_\alpha}\left[W - \left(T_2 - T_1\right) - \frac{1}{F}(c'l - ul\tan\varphi')\sin\alpha\right] \quad (2.18)$$

This method satisfies both force and moment equilibrium. The moment equilibrium for the total sliding mass is explicitly satisfied by considering an infinitesimal slice width (dx) and taking moments about the midpoint of the slice base (Janbu 1957, 1973).

Horizontal and vertical interslice force used in GPS

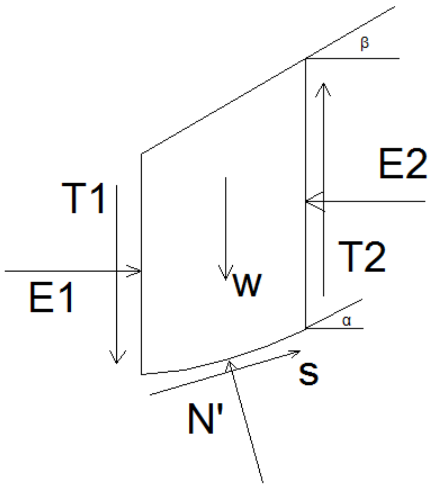

FIGURE 7 STRESS IN JANBU'S RIGOROUS METHOD

JGM considers both vertical and normal forces and satisfies both force and moment equilibriums. Hence this method can be used in more complex condition and failure surfaces.

2.3.4. JANBU STABILITY CHARTS

Janbu's direct method known as Janbu stability charts

Janbu's direct method (JDM) is based on dimensionless parameters and series of stability charts(Janbu 1954a).It's an easy-used tool for fast slope analysis in both short term and long term condition. It is what we can

Parameters

N_0 : stability number for simple slopes (Figure A-1)

x_0 y_0: is unit coordinates are plotted versus the slope characteristics β and d.
$X_0 = x_0H$, $Y0 = y_0H$

μ_q : Effect of surcharge μ_q which is the dimensionless reduction factor that plotted versus the ration $q/\gamma H$ and the slope characteristics βand d (Figure A-2)

μ_w: Effect of partial submergence and drawdown conditions μw is the dimensionless reduction factor whose magnitude depends on the ration Hw/H and the slope characteristics βand d (FigureA-3)

μ_t : Effect of influence of tension cracks μ_t is a reduction factor which depends on the ratio Ht/H and the slope characteristics βand d (Figure A-4 A-5)

d: Dimensionless depth factor

$$d = \frac{D}{H} \tag{2.19}$$

β: slope angle,

$$\tan\beta = \frac{1}{b} \quad , \quad b = \cot\beta$$

c φ Su: these three parameters are average the value calculate from the central angles δ_i on each slice.

$$c_{avg} = \frac{\sum \delta_i c_i}{\sum \delta_i}$$

$$\varphi_{avg} = \frac{\sum \delta_i \varphi_i}{\sum \delta_i}$$

$$(Su)_{avg} = \frac{\sum \delta_i Su_i}{\sum \delta_i} \qquad (2.20)$$

γ_i is an average value calculate from all layers

$$\gamma_{avg} = \frac{\sum \gamma_i h_i}{\sum \gamma_i} \qquad (2.21)$$

Slope stability charts for $\phi = 0$ soils

Basic equation

$$Fs = N_0 \frac{c}{\gamma H} \qquad (2.22)$$

Where

c: shear strength of the soil. In stability charts, Su
γ : unit weight of the soil
H: height of the slope Where, Ns is the combination of surcharge submergence and tension cracks

$$Ns = \mu_q \mu_w \mu_t N_0 = \mu_d N_0 \qquad (2.23)$$

To calculate Fs, μ_q μ_w μ_t N_0 should be picked from charts. For surcharge (Figure A-2), submergence (Figure A-3) and tension cracks (Figure A-4 A-5),

$$P_d = \frac{\gamma H + q - \gamma_w H_w}{\mu_q \mu_w \mu_t} \qquad (2.24)$$

and $$F = \frac{N_0 c}{P_d} \qquad (2.25)$$

$$\text{or} \quad F = \frac{N_s c}{\gamma H + q - \gamma_w H_w} \qquad (2.26)$$

Slope stability charts for ϕ> 0 soils

The shear strength of soil s:

$$s = c + \sigma \tan\varphi$$

Stability number N_{cf} depends on defenseless parameter λ_{cf}

$$P_d = \frac{\gamma H + q - \gamma_w H_w}{\mu_q \mu_w \mu_t} \qquad (2.27)$$

μ_q μ_w μ_t are from surcharge (Figure A-2), submergence (Figure A-3) and tension cracks (Figure A-4 A-5),

And Calculate Pe

$$P_e = \frac{\gamma H + q - \gamma_w H'_w}{\mu_q \mu'_w} \qquad (2.28)$$

Where, $\mu_e = \mu_q \mu'_w$

Calculate the dimensionless parameter $\lambda_{c\phi}$:

$$\lambda_{c\varphi} = \frac{P_e \tan\varphi}{c} \qquad (2.29)$$

where ϕ and c are average values for cohesion and friction. For c = 0 use the charts for infinite slope analysis.

Determine the value of the stability number N_{cf}(Figure A-6) , which depends on the slope angle β and $\lambda_{c\phi}$.

Calculate the factor of safety:

$$F = N_{cf} \frac{c}{p_d}, \qquad (2.30)$$

[All figures and the using steps show in appendix A]

Methods	Circular	Non - cir.	Assumptions	Developed By:
Ordinary Method of Slices	√	-	$\Sigma M = 0$; Neglects both E and T	Fellenius (1927)
Bishop simplified	√	√	$\Sigma M = 0$; Considers E, but neglects T	Bishop (1955)
Janbu simplified	√	√	$\Sigma F = 0$ Considers E, but neglects T	Janbu (1954a, 1954b)
Janbu GPS	√	√	$\Sigma F = 0$ Considers both E and T,	Janbu (1954a, 1954b)
Lowe - Karafiath	-	√	$\Sigma F = 0$ interslice forces are inclined at an angle equal to the average of the ground surface and slice base angles	Lowe and Karafiath (1960)
Corps of Engineers Method	-	√	$\Sigma F = 0$ considers the inclination of the interslice force as both parallel to ground surface, and equal to the average slope angle between the left and right end-points of the failure surface.	Corps of Engineers (1970)
Sarma	√	√	$\Sigma M = 0$; $\Sigma F = 0$; uses the method of slices to calculate the magnitude of a horizontal seismic coefficient needed to bring the failure mass into a state of limiting equilibrium.	Sarma (1973)
Spencer	√	√	$\Sigma M = 0$' $\Sigma F = 0$; rigorously satisfies static equilibrium by assuming that the resultant interslice force has a constant, but unknown, inclination	Spencer (1967, 1973)
Morgenst. - Price	√	√	$\Sigma M = 0$; $\Sigma F = 0$; Similar to Spencer's method, except that the inclination of the interslice resultant force is assumed to vary according to a "portion" of an arbitrary function.	Morgenstern and Price (1965)

2.4. FINITE ELEMENTS ANALYSIS WITH PLAXIS 2D

Plaxis is a finite element analysis software develop by Plaxis Company (Plaxis bv) in cooperation with several universities word wide including Delft University of Technology in the Netherlands and Norges Teknisk-Naturvitenskapelige Universitet NTNU(PLAXIS (2004)). Compared with other Finite Element analysis software as ANSYS Abaqus etc, Plaxis is the one designed for Geotech problem, soil or rock slope. Plaxis set different soil models as Mohr-Coulomb, Advanced soil model, Hardening Soil model, Soft Soil Creep model and user-designed model. The soil test option is a convenient tool to study soil behavior.

Safety analysis in Plaxis

Safety analysis use a method called c-phi redaction. It's a method that strength of the soil material will be reduced with a factor ΣMsf until either failure is reached for a stable value of ΣMsf, or the maximum number of calculation steps is reached. c-phi reduction method is that tan(phi) and c are reduced according to the rule:

$\Sigma Msf = \tan(\varphi'_{input}) / \tan(\varphi'_{reduced}) = c'_{input} / c'_{reduced}$..

Basic, Plaxis will reduce the strength incrementally until reach the point when soil body collapse. Value of ΣMsf at failure gives the final factor of safety.

Mohr-Coulomb model Undrain type and effect on factor of safety

In Plaxis, there are three types of undrain analysis. Undrained (A) is undrained effective stress analysis with effective strength parameters. Undrained (B) is undrained effective stress analysis with undrained strength parameters. Undrained (C) is undrained total stress analysis with undrained parameters. Undrained B is the most suitable type for known Su and the case φ =0.

During case with *Undrained A* or *Undrained B* setting, c-phi reduction may lead to a change of excess pore pressures. The option "*Ignore undrained behavior*" can prevent for this change of excess pore pressures in the Safety analysis phase. For slope loading problems, allowing excess pore pressures to change often leads to an increase of excess pore pressures. This would lead to a lower safety factor compared to the case where no change of excess pore pressures. Therefore, the option "*Ignore undrained behavior*" is neglect in this thesis when using Plaxis to have a more conservation solution.

The slope analysis in follows chapters, were created by the input follows setting. A plain strain model of 15 node triangular elements was used to generate different element mesh types. Material properties including shear strength parameters were defined by each case. Moreover, a Mohr-Coulomb material model was selected for the stability analyses.

CHAPTER 3 ANALYSIS METHODS AND DATA COLLECTION

3.1. ANALYSIS METHODS

3.1.1. AIM

Aim of this thesis is to revisiting the stability chart by finite element method. The theory of stability chart is developed by Janbu in 1954 in which finite element method was not invented, neither the computer aid program Plaxis. The hand calculation must limit the theory of stability chart. So, it is of meaning to revisit the Janbu direct method by new method and new calculation tool nowadays.

3.1.2. METHOD

To revisit the theory, the cases shown in the original paper should be recalculated. The paper of Janbu 1954a separated slope stability problem in two main parts, classified them by whether the cohesion equal to zero. In the chapter as follow, introduction of Janbu direct method, the different between of cohesion equal to zero and cohesion lager than zero is that N_0 and N_{cf} ,additional P_e and λ_{cf} . But the effect factors of surcharge, partial submergence, and influence of tension cracks are the same. So solving the former part will be of larger percentage of thesis.

Basically, the method of revisit is building a same geometry model in Plaxis with the same material profile as the soil parameter of examples in the original paper. And each example shows the result of a specific application of design charts. For each example or each chart,

3.1.3. GENERAL PROCEDURE IN PLAXIS SIMULAITON

Finishing a safety analysis, the main result expected is a safety factor. A valid factor of safety need follows procedure and general setting:

1. Starting a new project.
   a) Project property

General options: Creating a plan strain

Elements choose 15-Node elements

   b) Acceleration: Earth gravity is 9.8m/s, x and y acceleration is 0
   c) Units should be in International System of Units. Janbu used imperial units in his paper.
   d) Geometry dimensions for x and y axis are from -20m to 40m

2. Basic geometry model and points

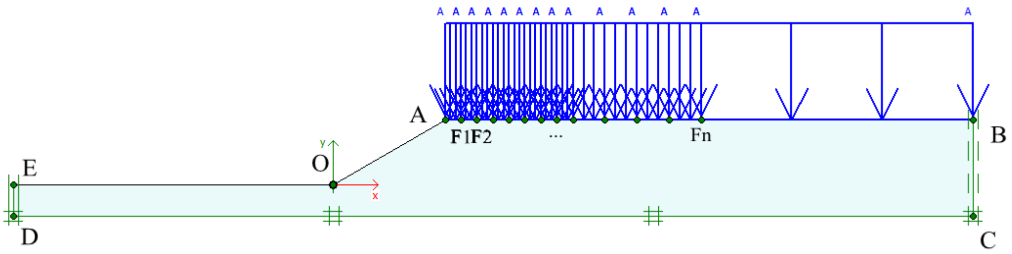

FIGURE 8 GENERAL GEOMETRY SIMULATION IN PLAXIS

Each case will follow this figure. O is the original point A to E follows the clock-wise sequence. F_1 to F_n is for analysis different length distribution loading under surcharge.

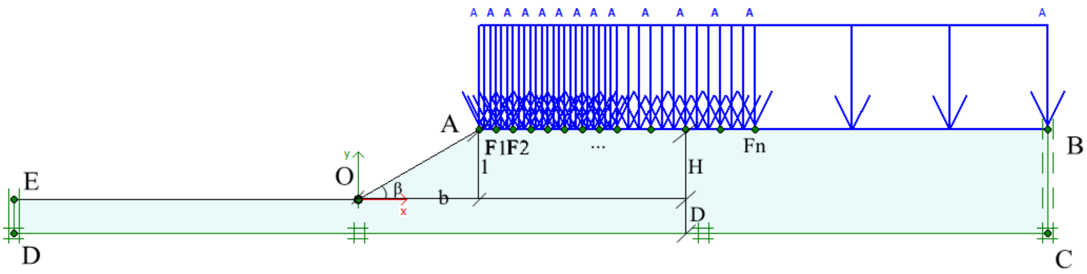

FIGURE 9 GENERAL GEOMETRY SIMULATION WITH PARAMETERS

β is slope angle and relative parameter b = cotβ.

D is the depth of slope.

H is the height of slope. And all the other length will be normalized by H.

3. Material profile

Mohr-coulomb model is the mainly research object. Parameters should be same with examples in Janbu paper. In the follows chapters, material profile will be given. The parameter which is not given uses the commonly empirical value.

4. Boundary fixity and loading

Boundary fixity and basic loading is also shown in the figure as follow.

Boundary fixity in all cases is selected as standard fixities. The surcharge and water condition can be treated as distribution loading or line loading in simulation,

5. Mesh size

Mesh geometry model into mesh unit. There are five types of mesh size, form very coarse, coarse, and medium, to fine and very fine. Different mesh size will be effect on the accuracy of simulation and calculated amount. The finer size will increase the total amount of finite element lead to a bigger calculated amount. Therefore, mesh size is a topic need to be discussed. The mesh should be regenerated when the geometry of the project is modified. So for each modifying the geometry conditions, additional points and mesh size, the mesh model should be regenerated. Besides, the follows analysis should recalculate as a new case. It will create a lot of case number.

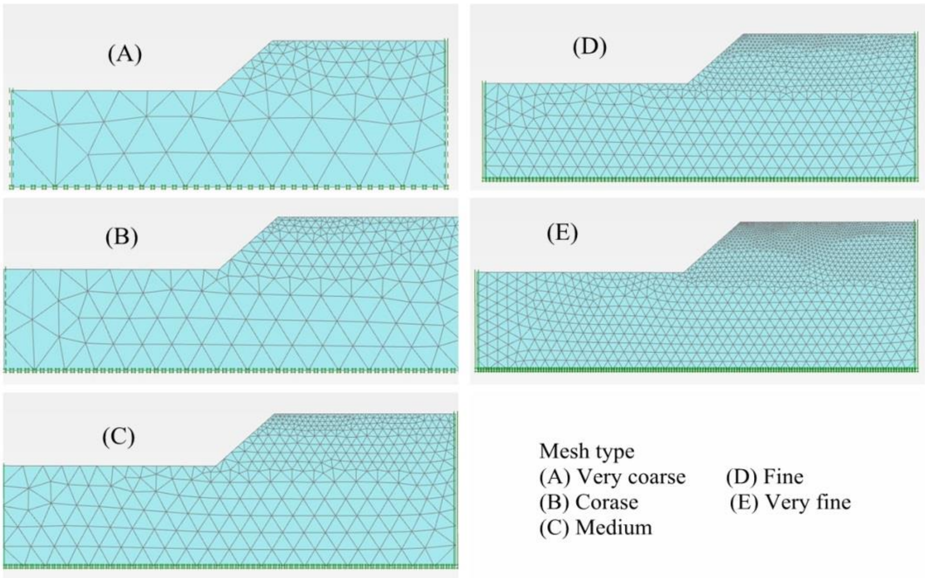

FIGURE 10 MESH TYPE

6. Phase arrangement

Phase arrangement is create an analysis procedure to get the result, safety factor.

The basic arrangement is consist of initial phrase, loading input and safety

Initial phrase: For reasons that many geotechnical engineering require of initial stresses, K0 procedure is used to generate the initial phrase.

Loading input: In this phrase, the objection is activation the distribution loading and flow options by plastic procedure.

Safety analysis: Run c-φ reduction for a stable safety factor.

This combination of three phrases is a basic analysis unit for one safety factor. Based on this, a requirement of a series of factor of safety will repeat this unit procedure with modifications.

7. Output

The mainly force output is safety factor and the critical surface.

3.2. FINITE ELEMENT METHOD REVISITING ON JANBU STABILITY CHART

3.2.1. FINITE ELEMENT METHOD REVISITING ON GEOMETRY FACTORS

For simple slopes in homogeneous and purely cohesive soil, the factor of safety is based on the formula (2.22)

$$Fs = N_0 \frac{c}{\gamma H}$$

The mainly difference of safety factor between Janbu chart and FEM is the stability number N_0 because of the c γ and H are the same in two methods.

N_0 is plotted versus the slope angle β and the depth factor d = D/H in (Figure A- 1)

This figure reveals several conclusions about the variation stability number:

- For slope steeper than 60°, N_0 depends only on the slope angle. The critical slip circle intersects the toe.
- For slopes flatter than 60°, N_0 depends on the value of slope angle β and d. The critical slip circle may intersect base, the toe or the slope above the toe.
- The flatter slope and the lower depth are safer.
- With the increasing of depth, the variation of slope angle has more effect on the flatter slope.

Geometry factors including two main factors slope angle β and depth factor d. The principle of revisiting is to compare the result from Janbu stability chart and Plaxis in the same conditions. Comparison use single variation method. The test will separate into two groups. In first group, the value of depth is fixed in both two methods. A series of slope angle is selected to set the geometry model in Plaxis. At mean time, N_0 can be read from the line in the same depth Janbu chart. So two group of safety factor can be obtained for further discussion.

3.2.1.1. CASE SELECTION AND EXPLANATION

Example case is named E01 and chosen from Janbu 1954a, P3. The original parameters are shown in the follows table 3-1

TABLE 1 PARAMETER OF EXAPLE E01

c	410	lb/ft2	19.63087	kN/m2
weight	120	lb/ft3	18.852	kN/m3
q	220	lb/ft2	10.53364	kN/m2
H	13	ft	3.9624	m
D	7	ft	2.1336	m
L	14.43796	ft	4.400691	m
beta	42			
b	0.900404			
d	0.538462			
Hw	0	ft		
Ht	0	ft		

This case is a slope with surcharge q=10.5kN/m^2. Dimensionless reduction factor μq=0.97.

For Plaxis model, material profile is showing the follows table

TABLE 2 MATERIAL PROFILE IN PLAXIS MODEL

Property	Unit	Value
Material set		
Identification		soil
Material model		Mohr-Coulomb
Drainage type		Undrained (B)
Colour		RGB 161, 226, 232
Comments		
General properties		
γ_{unsat}	kN/m ^{3}	19.00
γ_{sat}	kN/m ^{3}	19.00
Stiffness		
E'	kN/m ^{2}	8000
ν' (nu)		0.1500
Alternatives		
G	kN/m ^{2}	3478
E_{oed}	kN/m ^{2}	8447
Strength		
$s_{u,ref}$	kN/m ^{2}	19.60
φ_u (phi)	°	0.000
ψ (psi)	°	0.000

3.2.1.2. COMPARISON ON VARIATION OF SLOPE ANGLE B AND EFFECT OF SURCHARGE

Tests in is consist of three groups. All cases of these three groups are based on the Case E01. For each group, a given depth is fixed, but the slope angle is changing.

Group 1, d=0.5 (D=2m) and b= 0.94 – 6.67, with surcharge q=10.5kN/m². Janbu stability chart method 11 cases, Plaxis 11 cases. Totally, 22 cases are in this group.

Group 2, d=0.2 (D=2m) and b= 0.94 – 6.67, with surcharge q=10.5kN/m². Janbu stability chart method 9 cases, Plaxis 9 cases. Totally, 18 cases are in this group.

- **Group 1**, d=0.5 or D=2m
- Geometry simulation

Based on the case E01, the value of depth is fixed on 2m, d=0.5. And b is chosen in the range from about 45° to 0°. The range of b is from about 1 to +∞. The value of slope angle β and b is shown in the table3-3.

TABLE 3 SLOPE ANGLE IN E01B001- E01B011

Case No.	beta	b
E01B001	46.75	0.94
E01B002	40.63	1.17
E01B003	34.27	1.47
E01B004	28.21	1.86
E01B005	23.29	2.32
E01B006	19.17	2.88
E01B007	15.95	3.50
E01B008	13.64	4.12
E01B009	11.93	4.73
E01B010	10.22	5.55
E01B011	8.53	6.67

The coordinates of cases in Plaxis is shown in the table 3-4

TABLE 4 COORDINATES OF CASES IN PLAXIS GROUP 1

	b=	0.94	b=	1.17	b=	1.47	b=	1.86
	X	Y	X	Y	X	Y	X	Y
O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	3.76	4.00	4.66	4.00	5.87	4.00	7.46	4.00
B	23.76	4.00	24.66	4.00	25.87	4.00	27.46	4.00
C	23.76	-2.00	24.66	-2.00	25.87	-2.00	27.46	-2.00
D	-20.00	-2.00	-20.00	-2.00	-20.00	-2.00	-20.00	-2.00
E	-20.00	0.00	-20.00	0.00	-20.00	0.00	-20.00	0.00
	b=	2.32	b=	2.88	b=	3.50	b=	4.12
	X	Y	X	Y	X	Y	X	Y
O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	9.29	4.00	11.51	4.00	14.00	4.00	16.49	4.00
B	29.29	4.00	31.51	4.00	34.00	4.00	36.49	4.00
C	29.29	-2.00	31.51	-2.00	34.00	-2.00	36.49	-2.00
D	-20.00	-2.00	-20.00	-2.00	-20.00	-2.00	-20.00	-2.00
E	-20.00	0.00	-20.00	0.00	-20.00	0.00	-20.00	0.00
	b=	4.73	b=	5.55	b=	6.67		
	X	Y	X	Y	X	Y		
O	0.00	0.00	0.00	0.00	0.00	0.00		
A	18.94	4.00	22.18	4.00	26.66	4.00		
B	38.94	4.00	42.18	4.00	46.66	4.00		
C	38.94	-2.00	42.18	-2.00	46.66	-2.00		
D	-20.00	-2.00	-20.00	-2.00	-20.00	-2.00		
E	-20.00	0.00	-20.00	0.00	-20.00	0.00		

- Factor of safety Calculation

Janbu charts analysis

For the situation that slope only have effect of surcharge, the formula to calculate factor of safety is

$$F_s = \mu_q N_0 \frac{c}{\gamma H + q} \tag{3.1}$$

According to the figure A-1, A-2, dimensionless reduction factor μq=0.97. The results is shown in the table 3-5

TABLE 5 N_0 AND FOS BY JSC FOR E01B001 TO B011

Case No.	N_0	Fs J
E01B001	5.73	1.27
E01B002	5.81	1.29
E01B003	5.95	1.32
E01B004	6.17	1.37
E01B005	6.48	1.44
E01B006	6.92	1.53
E01B007	7.53	1.67
E01B008	8.26	1.83
E01B009	8.97	1.99
E01B010	9.84	2.18
E01B011	11.00	2.44

According to the coordinates in case E01B001 to E01B011 with the fine mesh, one groups of 11 factors of safety can be calculated follows the basic procedure introduced in before. The result of safety factor shown in the table 6

TABLE 6 FOS BY PLAXIS FOR E01B001 TO B011

Case N_0.	FS P
E01B001	1.418
E01B002	1.464
E01B003	1.519
E01B004	1.586
E01B005	1.679
E01B006	1.814
E01B007	1.975
E01B008	2.129
E01B009	2.286
E01B010	2.499
E01B011	2.785

- **Group 2**, d=0.2 or D=0.8m
- Geometry simulation

Based on the case E01, the value of depth is fixed on 0.8m, d=0.2. And b is chosen in the range from about 45° to 0°. The range of b is from about 1 to +∞. The value of slope angle β and b is shown in the table as follow

TABLE 7 SLOPE ANGLE IN E01B012- E01B020

Case No.	beta	b
E01B012	46.75	0.94
E01B013	40.63	1.17
E01B014	34.27	1.47
E01B015	28.21	1.86
E01B016	23.29	2.32
E01B017	19.17	2.88
E01B018	15.95	3.50
E01B019	13.64	4.12
E01B020	12.00	4.70

The coordinates of cases in Plaxis is shown in the table 3-8

TABLE 8 COORDINATES OF CASES IN PLAXIS GROUP 2

	b=	0.94	b=	1.17	b=	1.47	b=	1.86
	X	Y	X	Y	X	Y	X	Y
O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	3.76	4.00	4.66	4.00	5.87	4.00	7.46	4.00
B	23.76	4.00	24.66	4.00	25.87	4.00	27.46	4.00
C	23.76	-0.80	24.66	-0.80	25.87	-0.80	27.46	-0.80
D	-20.00	-0.80	-20.00	-0.80	-20.00	-0.80	-20.00	-0.80
E	-20.00	0	-20.00	0	-20.00	0	-20.00	0
	b=	2.32	b=	2.88	b=	3.50	b=	4.12
	X	Y	X	Y	X	Y	X	Y
O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	9.29	4.00	11.51	4.00	14.00	4.00	16.49	4.00
B	29.29	4.00	31.51	4.00	34.00	4.00	36.49	4.00
C	29.29	-0.80	31.51	-0.80	34.00	-0.80	36.49	-0.80
D	-20.00	-0.80	-20.00	-0.80	-20.00	-0.80	-20.00	-0.80
E	-20.00	0.00	-20.00	0.00	-20.00	0.00	-20.00	0.00
	b=	4.70	b=	0.00	b=	0.00		
	X	Y	X	Y	X	Y		
O	0.00	0.00	0.00	0.00	0.00	0.00		
A	18.82	4.00	0.00	4.00	0.00	4.00		
B	38.82	4.00	20.00	4.00	20.00	4.00		
C	38.82	-0.80	20.00	-0.80	20.00	-0.80		
D	-20.00	-0.80	-20.00	-0.80	-20.00	-0.80		
E	-20.00	0.00	-20.00	0.00	-20.00	0.00		

- Factor of safety Calculation

Janbu charts analysis

For the situation that slope only have effect of surcharge, the formula (3.1) to calculate factor of safety is

$$F_s = \mu_q N_0 \frac{c}{\gamma H + q}$$

According to the figure A-1, A-2 , dimensionless reduction factor μq=0.97. The results is shown in the table 3-9

TABLE 9 N_0 AND FOS BY JSC FOR E01B012 TO B0020

Case No.	N_0	Fs J
E01B012	5.77	1.23
E01B013	5.93	1.28
E01B014	6.21	1.36
E01B015	6.75	1.48
E01B016	7.53	1.63
E01B017	8.42	1.81
E01B018	9.36	2.01
E01B019	10.26	2.20
E01B020	10.98	2.37

According to the coordinates in case E01B012 to E01B020 with the fine mesh, one groups of 11 factors of safety can be calculated follows the basic procedure introduced in as follow. The result of safety factor shown in the table as follow

TABLE 10 FOS BY PLAXIS FOR E01B012 TO B020

Case N_0.	FS P
E01B012	1.233
E01B013	1.277
E01B014	1.355
E01B015	1.482
E01B016	1.631
E01B017	1.814
E01B018	2.007
E01B019	2.196
E01B020	2.371

Tests in is consist of three groups. All cases of these three groups are based on the Case E01. For each group, a given slope angle is fixed, but the depth is changing.

Group 1, b=1.5 (β= 33.7°) and d= 0 - 3.0, with no surcharge. Janbu stability chart method 9 cases, Plaxis 9 cases. Totally, 18 cases are in this group.

Group 2, b=2.0 (β=26.5°) and d= 0 - 3.0, with no surcharge. Janbu stability chart method 9 cases, Plaxis 9 cases. Totally, 18 cases are in this group.

Group 3, b=2.5 (β=21.8°) and d= 0 - 3.0, with no surcharge. Janbu stability chart method 9 cases, Plaxis 9 cases. Totally, 18 cases are in this group.

- **Group 1**, b=1.5 (β= 33.7°)
- Geometry simulation

Based on the case E01, the value of slope angle is fixed on 33.7°, b=1.5. And d is 0 - 3. The range of D is from 0 m to 12m. The value of depth D and d is shown in the table 3-11

TABLE 11 DEPTH D IN GROUP 1

d	0	0.1	0.2	0.3	0.5	1	1.5	2	3
D (m)	0	0.4	0.8	1.2	2	4	6	8	12

The coordinates of cases in Plaxis is shown in the table 3-12

TABLE 12 COORDINATES OF CASES IN PLAXIS, GROUP 1

	d=	0	0.1	0.2	0.3	0.5	1	1.5	2	3
	X*	Y	Y	Y	Y	Y	Y	Y	Y	Y
O	0	0	0	0	0	0	0	0	0	0
A	6	4	4	4	4	4	4	4	4	4
B	26	4	4	4	4	4	4	4	4	4
C	26	0	0.4	0.8	1.2	2	4	6	8	12
E	-20	0	0	0	0	0	0	0	0	0
D	-20	0	0.4	0.8	1.2	2	4	6	8	12

*The x coordinates is the same in the case in different depths.

- Factor of safety Calculation

Janbu charts analysis

For the situation that slope only have effect of surcharge, the formula (2.22) to calculate factor of safety is

$$F_s = N_0 \frac{c}{\gamma H}$$

According to the table as follow , as follow The results is shown in the table 3-13

TABLE 13 N0 AND FOS BY JSC, GROUP 1

d	0.00	0.10	0.20	0.30	0.50	1.00	1.50	2.00	3.00
No	7.36	6.79	6.25	6.09	5.98	5.75	5.68	5.62	5.60
Fs J	1.92	1.77	1.63	1.59	1.56	1.50	1.48	1.46	1.46

According to the coordinates in case E01D001 to E01D009 with the fine mesh, one groups of 9 factors of safety can be calculated follows the basic procedure introduced in as follow. The result of safety factor shown in the table 3-14

TABLE 14 FOS BY PLAXIS FOR E01D001 TO D009

No.	E01D001	E01D002	E01D003	E01D004	E01D005	E01D006	E01D007	E01D008	E01D009
d	0.00	0.10	0.20	0.30	0.50	1.00	1.50	2.00	3.00
Fs P	1.832	1.705	1.617	1.575	1.524	1.457	1.427	1.407	1.388

- **Group 2**, b=2.0 (β=26.5°)
- Geometry simulation

Based on the case E01, the value of slope angle is fixed on 26.5°, b=2.0. And d is 0 - 3. The range of D is from 0 m to 12m. The value of depth D and d is the same as table 3-11

The coordinates of cases in Plaxis is shown in the table 3-15

TABLE 15 COORDINATES OF CASES IN PLAXIS, GROUP 2

	d=	0	0.1	0.2	0.3	0.5	1	1.5	2	3
	X	Y	Y	Y	Y	Y	Y	Y	Y	Y
O	0	0	0	0	0	0	0	0	0	0
A	8	4	4	4	4	4	4	4	4	4
B	28	4	4	4	4	4	4	4	4	4
C	28	0	0.4	0.8	1.2	2	4	6	8	12
E	-20	0	0	0	0	0	0	0	0	0
D	-20	0	0.4	0.8	1.2	2	4	6	8	12

*The x coordinates is the same in the case in different depths.

- Factor of safety Calculation

Janbu charts analysis

For the situation that slope only have effect of surcharge, the formula (2.22) to calculate factor of safety is

$$F_s = N_0 \frac{c}{\gamma H}$$

According to the table as follow , as follow The results is shown in the table 3-16

TABLE 16 N0 AND FOS BY JSC, GROUP 2

d	0.00	0.10	0.20	0.30	0.50	1.00	1.50	2.00	3.00
No	8.42	7.70	7.00	6.54	6.27	5.89	5.77	5.70	5.60
Fs	2.19	2.00	1.82	1.70	1.63	1.53	1.50	1.48	1.46

According to the coordinates in case E01D010 to E01D018 with the fine mesh, one groups of 9 factors of safety can be calculated follows the basic procedure introduced in as follow. The result of safety factor shown in the table 3-17

TABLE 17 FOS BY PLAXIS FOR E01D010 TO E01D018

No.	E01D010	E01D011	E01D012	E01D013	E01D014	E01D015	E01D016	E01D017	E01D018
d	0.00	0.10	0.20	0.30	0.50	1.00	1.50	2.00	3.00
Fs P	1.832	1.705	1.617	1.575	1.524	1.457	1.427	1.407	1.388

- **Group 3**, b=2.5 (β=21.8°)
- Geometry simulation

Based on the case E01, the value of slope angle is fixed on 21.8°, b=2.5. And d is 0 - 3. The range of D is from 0 m to 12m. The value of depth D and d is the same as table as follow

The coordinates of cases in Plaxis is shown in the table 3-18

TABLE 18 COORDINATES OF CASES IN PLAXIS, GROUP 3

	d=	0	0.1	0.2	0.3	0.5	1	1.5	2	3
	X	Y	Y	Y	Y	Y	Y	Y	Y	Y
O	0	0	0	0	0	0	0	0	0	0
A	10	4	4	4	4	4	4	4	4	4
B	30	4	4	4	4	4	4	4	4	4

C	30	0	0.4	0.8	1.2	2	4	6	8	12
E	-20	0	0	0	0	0	0	0	0	0
D	-20	0	0.4	0.8	1.2	2	4	6	8	12

*The x coordinates is the same in the case in different depths.

- Factor of safety Calculation

Janbu charts analysis

For the situation that slope only have effect of surcharge, the formula (2.22) to calculate factor of safety is

$$F_s = N_0 \frac{c}{\gamma H}$$

According to the table as follow , as follow The results is shown in the table 3-19

TABLE 19 N0 AND FOS BY JSC, GROUP 3

d	0.00	0.10	0.20	0.30	0.50	1.00	1.50	2.00	3.00
No	9.35	8.55	7.76	7.20	6.61	6.04	5.85	5.73	5.65
Fs	2.43	2.23	2.02	1.87	1.72	1.57	1.52	1.49	1.47

According to the coordinates in case E01D019 to E01D027 with the fine mesh, one groups of 9 factors of safety can be calculated follows the basic procedure introduced in as follow. The result of safety factor shown in the table 3-20

TABLE 20 FOS BY PLAXIS FOR E01D019 TO E01D027

No.	E01D019	E01D020	E01D021	E01D022	E01D023	E01D024	E01D025	E01D026	E01D027
d	0.00	0.10	0.20	0.30	0.50	1.00	1.50	2.00	3.00
Fs P	2.332	2.143	2.067	1.871	1.72	1.562	1.497	1.459	1.421

3.2.1.4. EFFECT OF MESH SIZE

To observe the influence of different mesh sizes, the follows paragraph is 4 groups, which are based on the case E01 and the E01D001 to E01D027.

Group 1 is based on E01 with a 7.5m depth. 3 cases are meshed in coarse, medium and fine size. E01M01- E01M05 (5 cases)

Group 2 is based on E01 with a 12m depth. 5 cases are meshed in very coarse, coarse, medium, fine and very fine size. E01M06- E01M19 (5 cases)

Group 3 is the coarse, medium and fine mesh for E01D001 to E01D009. E01M11-E01M28 (18 cases)

Group 4 is the coarse, medium and fine mesh for E01D010 to E01D017. E01M29-E01M46 (18 cases)

Group 5 is the coarse, medium and fine mesh for E01D018 to E01D027. E01M47-E01M64 (18 cases)

- **Group 1, D=7.5m, no surcharge loading**
  - Geometry simulation and Factor of safety Calculation

The coordinates of cases in Plaxis is shown in the table 3-21

TABLE 21 COORDINATES OF CASES IN PLAXIS, GROUP 1

	X	Y
O	0	0
A	4.4	4
B	18	4
C	18	-7.5
D	-20	-7.5
E	-20	0

  - Factor of safety Calculation in different mesh size

The result of safety factor shown in the table 3-22

TABLE 22 FOS BY PLAXIS FOR E01M01TO E01M05

No.	Fs P	
E01M01	1.426	very coarse
E01M02	1.426	coarse
E01M03	1.421	medium
E01M04	1.421	fine
E01M05	1.419	very fine

- **Group 2, D=12m, no surcharge loading**

The coordinates of cases in Plaxis is shown in the table 3-23

TABLE 23 COORDINATES OF CASES IN PLAXIS, GROUP 2

	X	Y

O	0	0
A	4.4	4
B	18	4
C	18	-12
D	-20	-12
E	-20	0

Factor of safety Calculation in different mesh size

The result of safety factor shown in the table 24

TABLE 24 FOS BY PLAXIS FOR E01M06TO E01M10

	Fs P	
E01M06	1.208	very coarse
E01M07	1.208	coarse
E01M08	1.207	medium
E01M09	1.207	fine
E01M10	1.207	very fine

- **Group 3, b=1.5, additional mesh for E01D001 to E01D009**

The geometry simulation and analysis procedure for E01M11-E01M19 are the same as E01D001 to E01D009 but in coarse mesh. E01M20-E01M28 are in the medium mesh.

Factor of safety Calculation in 3 different mesh size

The result of safety factor shown in the table 3-25

TABLE 25 FOS BY PLAXIS, GROUP 3

d	0	0.1	0.2	0.3	0.5	1	1.5	2	3
coarse	1.851	1.72	1.628	1.585	1.53	1.462	1.431	1.411	1.392
medium	1.844	1.714	1.627	1.578	1.525	1.46	1.424	1.41	1.386
fine	1.832	1.705	1.617	1.575	1.524	1.457	1.427	1.407	1.388

- **Group 4, b=2, additional mesh for E01D010 to E01D018**

The geometry simulation and analysis procedure for E01M29-E01M37 are the same as E01D010 to E01B018 but in coarse mesh. E01M38-E01M46 are in the medium mesh.

Factor of safety Calculation in 3 different mesh size

The result of safety factor shown in the table 3-26

TABLE 26 FOS BY PLAXIS, GROUP 4

d	0	0.1	0.2	0.3	0.5	1	1.5	2	3
coarse	2.109	1.952	1.875	1.74	1.613	1.512	1.466	1.437	1.409
medium	2.093	1.941	1.871	1.719	1.616	1.511	1.458	1.433	1.409
fine	2.082	1.928	1.86	1.708	1.613	1.508	1.459	1.432	1.403

- **Group 5, b=2.5, additional mesh for E01D019 to E01D027**

The geometry simulation and analysis procedure for E01M47-E01M55 are the same as E01D010 to E01D018 but in coarse mesh. E01M56-E01M64 are in the medium mesh.

Factor of safety Calculation in 3 different mesh size

The result of safety factor shown in the table 3-27

TABLE 27 FOS BY PLAXIS, GROUP 5

d	0	0.1	0.2	0.3	0.5	1	1.5	2	3
coarse	2.353	2.175	2.082	1.911	1.741	1.57	1.502	1.463	1.426
medium	2.341	2.153	2.072	1.883	1.728	1.565	1.5	1.461	1.423
fine	2.332	2.143	2.067	1.871	1.72	1.562	1.497	1.459	1.421

3.2.2. FEM REVISITING ON EFFECT OF SURCHARGE

3.2.2.1. EFFECT OF SURCHARGE

- **Group 1, d=0.5 (D=2m) and b= 0.94 - 6.67, with no surcharge.**

Janbu stability chart method has 11 cases, Plaxis has 11 cases. Totally, 22 cases are in this group.

The design purpose for this group factor of safety is to compare the effect of surcharge (result of Group 1 in Comparison on variation of slope angle β and effect of surcharge).

Geometry simulation

The geometry simulation condition is exactly same as the E01B001 to E01B011.

- Factor of safety Calculation

Janbu charts analysis

For the situation that slope only have effect of surcharge, the formula (2.22) to calculate factor of safety is

$$F_s = N_0 \frac{c}{\gamma H}$$

According to the table as follow , as follow The results of N_0 is shown in the table as follow

TABLE 28 SLOPE ANGLE IN E01B021- E01B031

Case No.	N_0	Fs J
E01B021	5.73	1.49
E01B022	5.81	1.51
E01B023	5.95	1.55
E01B024	6.17	1.61
E01B025	6.48	1.69
E01B026	6.92	1.80
E01B027	7.53	1.96
E01B028	8.26	2.15
E01B029	8.97	2.33
E01B030	9.84	2.56
E01B031	11.00	2.86

According to the coordinates in case E01B021 to E01B031 with the fine mesh, one groups of 11 factors of safety can be calculated follows the basic procedure introduced in as follow. But the difference in parameter stage is that the distribution loading is deactivated. The result of safety factor shown in the table as follow

TABLE 29 N0 AND FOS BY JSC FOR E01B021 TO B031

Case No.	FS P
E01B021	1.418
E01B022	1.464
E01B023	1.519
E01B024	1.586
E01B025	1.679
E01B026	1.814
E01B027	1.975
E01B028	2.129
E01B029	2.286
E01B030	2.499

E01B031	2.785

3.2.2.2. MAGNITUDE AND LENGTH OF DISTRIBUTION LOADING

Length of surcharge is unlimited in Janbu stability chart. But in Plaxis simulation, length of distribution loading is a necessary parameter. Besides, the slope angle and depth is also a factor which can influence the final result of safety factor. The basic idea to design the cases is that single factor variation.

Under this idea, a test case is shown in next paragraph.

This case is based on the case E01. The geometry simulation in Plaxis, a series of points A_n are inserted between A and B. The same loading needs to distribute from point A to point B as the same magnitude. By active the distribute loading between point A to point A_n. In the analysis phrases arrangement, each length of AA_1, AA_2, … ,AA_n will create a new analysis unit to obtain a factor of safety(figure 11). Since the geometry model without any change, these series calculations can be finish in one program sequence.

Identification	Phase no.	Start from	Calculation	Loading input	Pore pressure	Time	Stage	Water	First	Last	Design ...
Initial phase	0	N/A	K0 procedure	Unassigned	Phreatic	0.00 day	L 0	W 0	1	1	Refere...
L 0.25	1	0	Plastic	Staged construction	Phreatic	0.00 day	L 1	W 1	2	4	Refere...
Fs 0.25	28	1	Safety	Incremental multipli...	From previous ...	0.00 day	L 1	W 1	5	104	Refere...
L 0.5	2	1	Plastic	Staged construction	Phreatic	0.00 day	L 2	W 2	105	108	Refere...
Fs 0.5	16	2	Safety	Incremental multipli...	From previous ...	0.00 day	L 2	W 2	109	208	Refere...
L 0.75	3	2	Plastic	Staged construction	Phreatic	0.00 day	L 3	W 3	209	211	Refere...
Fs 0.75	17	3	Safety	Incremental multipli...	From previous ...	0.00 day	L 3	W 3	212	311	Refere...
L 1	4	3	Plastic	Staged construction	Phreatic	0.00 day	L 4	W 4	312	314	Refere...
Fs 1	18	4	Safety	Incremental multipli...	From previous ...	0.00 day	L 4	W 4	315	414	Refere...
L 1.25	5	4	Plastic	Staged construction	Phreatic	0.00 day	L 5	W 5	415	417	Refere...
Fs 1.25	29	5	Safety	Incremental multipli...	From previous ...	0.00 day	L 29	W 29	418	517	Refere...
L1.5	6	5	Plastic	Staged construction	Phreatic	0.00 day	L 6	W 6	518	520	Refere...
Fs 1.5	20	6	Safety	Incremental multipli...	From previous ...	0.00 day	L 6	W 6	521	620	Refere...
L1.75	7	6	Plastic	Staged construction	Phreatic	0.00 day	L 7	W 7	621	623	Refere...
Fs 1.75	21	7	Safety	Incremental multipli...	From previous ...	0.00 day	L 7	W 7	624	723	Refere...
L 2	8	7	Plastic	Staged construction	Phreatic	0.00 day	L 8	W 8	724	726	Refere...
Fs 2	22	8	Safety	Incremental multipli...	From previous ...	0.00 day	L 8	W 8	727	826	Refere...
L 2.5	9	8	Plastic	Staged construction	Phreatic	0.00 day	L 9	W 9	827	829	Refere...
Fs 2.5	23	9	Safety	Incremental multipli...	From previous ...	0.00 day	L 9	W 9	830	929	Refere...
L3	10	9	Plastic	Staged construction	Phreatic	0.00 day	L 10	W 10	930	932	Refere...
Fs 3	24	10	Safety	Incremental multipli...	From previous ...	0.00 day	L 10	W 10	933	1032	Refere...
L 3.5	11	10	Plastic	Staged construction	Phreatic	0.00 day	L 11	W 11	1033	1035	Refere...
Fs 3.5	25	11	Safety	Incremental multipli...	From previous ...	0.00 day	L 11	W 11	1036	1135	Refere...
L 4	12	11	Plastic	Staged construction	Phreatic	0.00 day	L 12	W 12	1136	1138	Refere...
Fs 4	26	12	Safety	Incremental multipli...	From previous ...	0.00 day	L 12	W 12	1139	1238	Refere...
L full	13	12	Plastic	Staged construction	Phreatic	0.00 day	L 13	W 13	1239	1241	Refere...
Fs full	27	13	Safety	Incremental multipli...	From previous ...	0.00 day	L 13	W 13	1242	1341	Refere...

FIGURE 11 ANALYSIS PHRASE

- **Experimental case with incremental length of loading and incremental depth**

Based on E01, the experimental case is with increasing length of loading and increasing the depth.

TABLE 30 FOS OF EXPERIMENTAL CASES

No	XA	XA1	Lq	Lq/H	Depth	d	Fs P
*1	4.4	4.4	0	0.00	2.1	0.98	1.497
2	4.4	5	0.6	0.15	2.1	0.98	1.473
3	4.4	6	1.6	0.40	2.1	0.98	1.424
4	4.4	7	2.6	0.66	2.1	0.98	1.366
5	4.4	8	3.6	0.91	2.1	0.98	1.322
6	4.4	9	4.6	1.16	2.1	0.98	1.293
7	4.4	10	5.6	1.41	2.1	0.98	1.276
8	4.4	11	6.6	1.67	2.1	0.98	1.27
9	4.4	14	9.6	2.42	2.1	0.98	1.268
10	4.4	17	12.6	3.18	2.1	0.98	1.269
**11	4.4	18	13.6	3.43	2.1	0.98	1.269
12	4.4	18	13.6	3.43	2.7	1.27	1.262
13	4.4	18	13.6	3.43	3.3	1.55	1.253
14	4.4	18	13.6	3.43	3.9	1.83	1.248
15	4.4	18	13.6	3.43	4.5	2.11	1.244
16	4.4	18	13.6	3.43	5.1	2.39	1.241
17	4.4	18	13.6	3.43	6	2.81	1.236
18	4.4	18	13.6	3.43	7	3.28	1.232
19	4.4	18	13.6	3.43	8	3.75	1.229
20	4.4	18	13.6	3.43	10	4.69	1.224
21	4.4	18	13.6	3.43	11	5.16	1.222
22	4.4	18	13.6	3.43	12	5.62	1.221
23	4.4	18	13.6	3.43	13	6.09	1.221
24	4.4	18	13.6	3.43	14	6.56	1.221

*No. 1 to 11 are designed to reveal the influence of increasing length of loading to Fs.

**No.11 to 24 are designed to reveal the influence of increasing depth to Fs.

- **Systematical tests for surcharge effect**

From the previous tests, the safety factory stops changing in some point. Definitely, Factor of safety is influenced by slope angle, depth magnitude and length of surcharge. So a group of tests are designed to analysis the factors, as follows:

D=0, 0.5, 1, 2. For geometry simulation, Y coordinate for point D, E is 0, 2m, 4m, 8m

β=30°, 45°,60°,75°, 90°. For geometry simulation, X coordinate for point A is 6.9m, 4m, 2.3m, 1.07m, 0m.

q/rH=0.1, 0.2, 0.3, 0.4, 0.5. q=7.5 kn/m^2

The X coordinate increment is shown in the follows table 3-31

TABLE 31 X COORDINATE INCREMENT

No.	Point	Lq/H=	X increment (m)
1	F1	0.25	1
2	F2	0.5	2
3	F3	0.75	3
4	F4	1	4
5	F5	1.25	5
6	F6	1.5	6
7	F7	1.75	7
8	F8	2	8
9	F9	2.5	10
10	F10	3	12
11	F11	3.5	14
12	F12	4	16
13	F13	4.5	18
14	F14	5	20
15	F15	5.5	22
16	F16	6	24
17	F17	6.5	26
18	F18	7	28
19	F19	8	32

It is shown in the figure A-1 that slope angle is the mainly effect factor when β is lower than 45° and depth is the mainly effect factor when β is larger than 45°.

TABLE 32 DESIGNED PARAMETERS WHEN Β>45°

No.	d	beta	b	q/rH	q(kN/m^2)
1	2	30	1.73	0.1	7.54
2	2	30	1.73	0.2	15.08
3	2	30	1.73	0.3	22.62
4	2	30	1.73	0.4	30.16
5	2	30	1.73	0.5	37.70

6	1	30	1.73	0.1	7.54
7	1	30	1.73	0.2	15.08
8	1	30	1.73	0.3	22.62
9	1	30	1.73	0.4	30.16
10	1	30	1.73	0.5	37.70
11	0.5	30	1.73	0.1	7.54
12	0.5	30	1.73	0.2	15.08
13	0.5	30	1.73	0.3	22.62
14	0.5	30	1.73	0.4	30.16
15	0.5	30	1.73	0.5	37.70

TABLE 33 DESIGNED PARAMETERS WHEN B<45°

No.	d	beta	b	q/rH	q(kN/m^2)
16	0	45	1	0.1	7.54
17	0	45	1	0.2	15.08
18	0	45	1	0.3	22.62
19	0	45	1	0.4	30.16
20	0	45	1	0.5	37.70
21	0	60	0.57	0.1	7.54
22	0	60	0.57	0.2	15.08
23	0	60	0.57	0.3	22.62
24	0	60	0.57	0.4	30.16
25	0	60	0.57	0.5	37.7
26	0	75	0.26	0.1	7.54
27	0	75	0.26	0.2	15.0
28	0	75	0.26	0.3	22.6
29	0	75	0.26	0.4	30.1
30	0	75	0.26	0.5	37.7
31	0	90	0	0.1	7.54
32	0	90	6.13E-17	0.2	15.0816
33	0	90	6.13E-17	0.3	22.6224
34	0	90	6.13E-17	0.4	30.1632
35	0	90	6.13E-17	0.5	37.704

TABLE 34 FOS FOR CASE NO.1 TO NO.5 D=2, B=30°

	No1	No2	No3	No4	No5
1	1.417	1.407	1.397	1.387	1.374
2	1.405	1.385	1.352	1.291	1.212
3	1.393	1.352	1.264	1.174	1.086
4	1.373	1.316	1.199	1.102	1.024
5	1.358	1.297	1.171	1.073	\
6	1.344	1.26	1.145	1.054	\
7	1.332	1.24	1.131	1.042	\
8	1.321	1.224	1.119	1.041	\

9	1.304	1.2	1.102	1.031	\
10	1.291	1.184	1.086	1.017	\
11	1.285	1.175	1.078	1.001	\
12	1.282	1.171	1.078	\	\
13	1.282	1.171	1.077	\	\
14	1.282	1.171	1.076	\	\
15	1.282	1.171	1.077	\	\
16	1.282	1.171	1.077	\	\
17	1.282	1.171	1.077	\	\
18	1.282	1.171	1.077	\	\
19	1.282	1.171	1.087	\	\

TABLE 35 FOS FOR CASE NO.6 TO NO.10 D=1, B=30°

	No6	No7	No8	No9	No10
1	1.47	1.451	1.429	1.408	1.389
2	1.447	1.404	1.356	1.292	1.209
3	1.423	1.352	1.263	1.174	1.09
4	1.391	1.307	1.205	1.11	1.027
5	1.369	1.288	1.171	1.073	\
6	1.356	1.249	1.144	1.055	\
7	1.343	1.23	1.127	1.042	\
8	1.336	1.218	1.115	1.028	\
9	1.331	1.212	1.106	1.02	\
10	1.33	1.212	1.105	1.021	\
11	1.331	1.212	1.105	1.021	\
12	1.33	1.212	1.105	1.021	\
13	1.33	1.212	1.105	1.021	\
14	1.331	1.212	1.105	1.021	\
15	1.331	1.212	1.105	1.021	\
16	1.331	1.212	1.105	1.021	\
17	1.331	1.212	1.105	1.021	\
18	1.331	1.212	1.105	1.021	\
19	1.331	1.212	1.105	1.021	\

TABLE 36 3- 1 FOS FOR CASE NO.11 TO NO.15 D=0.5, B=30°

	No11	No12	No13	No14	No15
1	1.539	1.507	1.475	1.443	1.404
2	1.502	1.433	1.357	1.258	1.208
3	1.462	1.358	1.259	1.171	1.086
4	1.416	1.305	1.196	1.103	1.024
5	1.404	1.28	1.166	1.072	\
6	1.396	1.268	1.152	1.055	\

7	1.393	1.265	1.149	1.047	\
8	1.392	1.265	1.148	1.048	\
9	1.392	1.265	1.148	1.048	\
10	1.392	1.265	1.148	1.048	\
11	1.392	1.265	1.148	1.048	\
12	1.392	1.265	1.148	1.048	\
13	1.392	1.265	1.148	1.048	\
14	1.392	1.265	1.148	1.048	\
15	1.392	1.265	1.148	1.048	\
16	1.392	1.265	1.148	1.048	\
17	1.392	1.265	1.148	1.048	\
18	1.392	1.265	1.148	1.048	\
19	1.392	1.265	1.148	1.048	\

TABLE 37 FOS FOR CASE NO.1 TO NO.5 D=0, B=45°

	No16	No17	No18	No19	No20
1	1.546	1.457	1.407	1.374	1.34
2	1.46	1.326	1.215	1.212	1.113
3	1.413	1.254	1.128	1.086	1.023
4	1.383	1.231	1.101	1.024	\
5	1.383	1.232	1.098	\	\
6	1.383	1.232	1.097	\	\
7	1.383	1.232	1.096	\	\
8	1.383	1.232	1.096	\	\
9	1.383	1.232	1.096	\	\
10	1.383	1.232	1.096	\	\
11	1.383	1.232	1.096	\	\
12	1.383	1.232	1.096	\	\
13	1.383	1.232	1.096	\	\
14	1.383	1.232	1.096	\	\
15	1.383	1.232	1.096	\	\
16	1.383	1.232	1.096	\	\
17	1.383	1.232	1.096	\	\
18	1.383	1.232	1.096	\	\
19	1.383	1.232	1.096	\	\

TABLE 38 FOS FOR CASE NO.21 TO NO.25 D=0, B=60°

	No21	No22	No23	No24	No25
1	1.316	1.264	1.211	1.211	1.106
2	1.25	1.137	1.041	1.041	\
3	1.204	1.087	\	\	\
4	1.174	1.066	\	\	\

5	1.172	1.044	\	\	\
6	1.173	1.042	\	\	\
7	1.173	1.042	\	\	\
8	1.173	1.042	\	\	\
9	1.173	1.042	\	\	\
10	1.173	1.042	\	\	\
11	1.173	1.042	\	\	\
12	1.173	1.042	\	\	\
13	1.173	1.042	\	\	\
14	1.173	1.042	\	\	\
15	1.173	1.042	\	\	\
16	1.173	1.042	\	\	\
17	1.173	1.042	\	\	\
18	1.173	1.042	\	\	\
19	1.173	1.042	\	\	\

TABLE 39 FOS FOR CASE NO.1 TO NO.5 D=0, B=75°

	No26	No27	No28	No29	No30
1	1.115	1.107	1.058	1.012	\
2	1.098	\	\	\	\
3	1.051	\	\	\	\
4	1.023	\	\	\	\
5	1.023	\	\	\	\
6	1.023	\	\	\	\
7	1.023	\	\	\	\
8	1.023	\	\	\	\
9	1.023	\	\	\	\
10	1.023	\	\	\	\
11	1.023	\	\	\	\
12	1.023	\	\	\	\
13	1.023	\	\	\	\
14	1.023	\	\	\	\
15	1.023	\	\	\	\
16	1.023	\	\	\	\
17	1.023	\	\	\	\
18	1.023	\	\	\	\
19	1.023	\	\	\	\

TABLE 40 FOS FOR CASE NO.1 TO NO.5 D=2, B=90°

	No31	No32	No33	No34	No35
1	\	1.107	1.058	\	\
2	\	\	\	\	\

3	\	\	\	\	\
4	\	\	\	\	\
5	\	\	\	\	\
6	\	\	\	\	\
7	\	\	\	\	\
8	\	\	\	\	\
9	\	\	\	\	\
10	\	\	\	\	\
11	\	\	\	\	\
12	\	\	\	\	\
13	\	\	\	\	\
14	\	\	\	\	\
15	\	\	\	\	\
16	\	\	\	\	\
17	\	\	\	\	\
18	\	\	\	\	\
19	\	\	\	\	\

The stable factor of safety can be obtained in each case. Besides, the length of loading when Fs is stable is recorded in the follows table 3-41.

TABLE 41 FOS SUMMERY BY PLAXIS ANALYSIS

No.	d	beta	b	q/γH	q	Lq/H (stb)	Fs stb
1	2	30	1.73	0.1	7.54	4	1.28
2	2	30	1.73	0.2	15.08	4	1.171
3	2	30	1.73	0.3	22.62	3.5	1.077
4	2	30	1.73	0.4	30.16	\	\
5	2	30	1.73	0.5	37.70	\	\
6	1	30	1.73	0.1	7.54	2.5	1.33
7	1	30	1.73	0.2	15.08	2.5	1.212
8	1	30	1.73	0.3	22.62	2.5	1.106
9	1	30	1.73	0.4	30.16	2.5	1.021
10	1	30	1.73	0.5	37.70	\	\
11	0.5	30	1.73	0.1	7.54	1.5	1.392
12	0.5	30	1.73	0.2	15.08	1.5	1.265
13	0.5	30	1.73	0.3	22.62	1.5	1.149
14	0.5	30	1.73	0.4	30.16	1.5	1.055
15	0.5	30	1.73	0.5	37.70	\	\
16	0	45	1.00	0.1	7.54	1	1.38
17	0	45	1.00	0.2	15.08	1	1.232
18	0	45	1.00	0.3	22.62	1.25	1.098

19	0	45	1.00	0.4	30.16	\	\
20	0	45	1.00	0.5	37.70	\	\
21	0	60	0.58	0.1	7.54	1	1.174
22	0	60	0.58	0.2	15.08	1.25	1.044
23	0	60	0.58	0.3	22.62	\	\
24	0	60	0.58	0.4	30.16	\	\
25	0	60	0.58	0.5	37.70	\	\
26	0	75	0.27	0.1	7.54	1	1.023
27	0	75	0.27	0.2	15.08	\	\
28	0	75	0.27	0.3	22.62	\	\
29	0	75	0.27	0.4	30.16	\	\
30	0	75	0.27	0.5	37.70	\	\
31	0	90	0.00	0.1	7.54	\	\
32	0	90	0.00	0.2	15.08	\	\
33	0	90	0.00	0.3	22.62	\	\
34	0	90	0.00	0.4	30.16	\	\
35	0	90	0.00	0.5	37.70	\	\

The factors of safety calculated in Janbu stability chart are shown in the next table as follow

TABLE 42 FOS SUMMERY BY JANBU STABILITY CHART ANALYSIS

No.	d	beta	b	q/γH	q	uq	No	Fs J
1	2	30	1.73	0.1	7.54	0.965	5.636	1.384
2	2	30	1.73	0.2	15.08	0.945	5.636	1.355
3	2	30	1.73	0.3	22.62	0.928	5.636	1.331
4	2	30	1.73	0.4	30.16	0.915	5.636	1.312
5	2	30	1.73	0.5	37.70	0.898	5.636	1.288
6	1	30	1.73	0.1	7.54	0.954	5.816	1.412
7	1	30	1.73	0.2	15.08	0.917	5.816	1.357
8	1	30	1.73	0.3	22.62	0.877	5.816	1.298
9	1	30	1.73	0.4	30.16	0.839	5.816	1.242
10	1	30	1.73	0.5	37.70	0.798	5.816	1.181
11	0.5	30	1.73	0.1	7.54	0.902	6.087	1.397
12	0.5	30	1.73	0.2	15.08	0.824	6.087	1.276
13	0.5	30	1.73	0.3	22.62	0.758	6.087	1.174
14	0.5	30	1.73	0.4	30.16	0.7	6.087	1.084
15	0.5	30	1.73	0.5	37.70	0.646	6.087	1.001
16	0	45	1.00	0.1	7.54	0.843	5.767	1.249
17	0	45	1.00	0.2	15.08	0.715	5.767	1.059
18	0	45	1.00	0.3	22.62	0.611	5.767	0.905

19	0	45	1.00	0.4	30.16	0.523	5.767	0.775
20	0	45	1.00	0.5	37.70	0.441	5.767	0.653
21	0	60	0.58	0.1	7.54	0.789	5.25	1.070
22	0	60	0.58	0.2	15.08	0.639	5.25	0.867
23	0	60	0.58	0.3	22.62	0.513	5.25	0.696
24	0	60	0.58	0.4	30.16	0.402	5.25	0.545
25	0	60	0.58	0.5	37.70	0.332	5.25	0.450
26	0	75	0.27	0.1	7.54	0.742	4.522	0.870
27	0	75	0.27	0.2	15.08	0.563	4.522	0.660
28	0	75	0.27	0.3	22.62	0.416	4.522	0.488
29	0	75	0.27	0.4	30.16	0.297	4.522	0.348
30	0	75	0.27	0.5	37.70	0.197	4.522	0.231
31	0	90	0.00	0.1	7.54	0.671	3.83	0.669
32	0	90	0.00	0.2	15.08	0.475	3.83	0.474
33	0	90	0.00	0.3	22.62	0.308	3.83	0.307
34	0	90	0.00	0.4	30.16	0.178	3.83	0.177
35	0	90	0.00	0.5	37.70	0.071	3.83	0.071

3.2.3. FEM REVISITING ON PARTIAL SUBMERGENCE AND DRAWDOWN CONDITION

Under partial submergence and drawdown condition, a reduction factor μ_w is introduced in JSC. And the Fs is calculated by

$$F_s = \mu_w N_0 \frac{c}{\gamma H - \gamma_w H_w} \tag{3.2}$$

First, a example in Janbu original paper is revisited by Plaxis

- **Example revisiting and method introduce**

Example case is named E02 and chosen from Janbu 1954a, P4. The original parameters are shown in the follows table 3-43

TABLE 43 PARAMETERS OF E02

C	540	lb/ft2	25.85529	kN/m2
weight	125	lb/ft3	19.6375	kN/m3
q	0	lb/ft2	0	kN/m2
H	24.5	ft	7.4676	m
D	21	ft	6.4008	m
L	46.0778	ft	14.04451	m
beta	28			
b	0.531709			
d	0.857143			
*Hwa	11	ft	3.3528	m
Hwb	20.5	ft	6.2484	m

*a,b represent two case with different Hw.

μ_{wa}=0.97 and μ_{wb}=0.96 is from figure A-3

The Plaxis geometry simulation and phreatic level are shown in the next figure

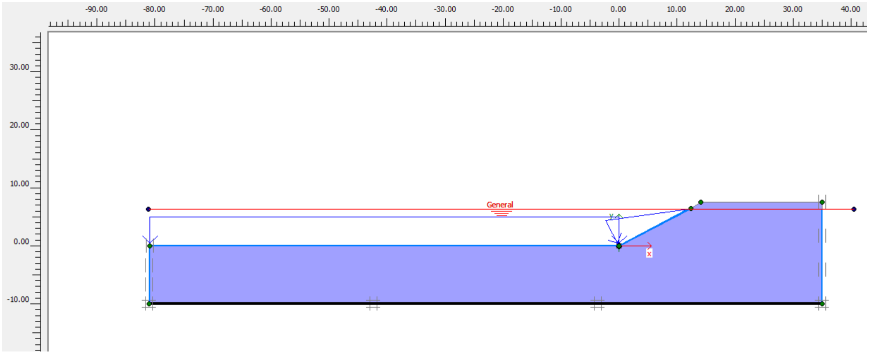

FIGURE 12 GEOMETRY SIMULATION AND PHREATIC LEVEL

The phrase procedure is

Identification	Phase no.	Start from	Calculation	Loading input	Pore pressure
Initial phase	0	N/A	K0 procedure	Unassigned	Phreatic
Method 1	3	0	Plastic	Staged construction	Phreatic
Msf	4	3	Safety	Incremental multipli...	From previous ...
Method 2	1	0	Plastic	Staged construction	Phreatic
Msf	2	1	Safety	Incremental multipli...	From previous ...

FIGURE 13 PHRASE PROCEDURE

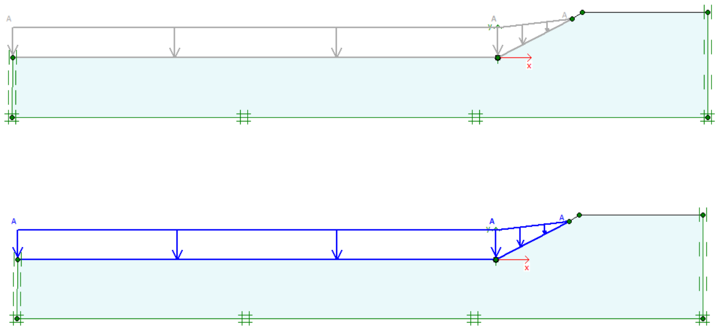

FIGURE 14 “METHOD 1” (UP) “METHOD 2” (DOWN)

The distribution loading in the model is simulated the effect of water weight. “Method 1” phrase defined without loading and show in the figure 14 . “Method 2” phrase defined with loading and show in the figure14 .

Result of F_S is

The results are of little difference between Plaxis and JSC.

TABLE 44 FOS OF E02 FROM PLAXIS AND JSC

Hw	Fs P M1	Fs P M2	Fs JSC

6.24	1.737	1.736	1.73
3.352	1.246	1.466	1.29

- **Systematical tests for submergence and drawdown conditions**

From the previous tests and Janbu theory, factor of safety is influenced by slope angle, depth, and water level. So a group of tests are designed to analysis the factors, as follows:

D=0, 0.5, 1, 2. For geometry simulation, Y coordinate for point D, E is 0, 2m, 4m, 8m

β=30°, 45°,60°, 90°. Hw /H=0.1, 0.2, 0.4, 0.5, 0.7, .09. and Hw=0.4m, 0.8m, 1.6m 2.0m, 2.8m, 3.6m

The cases defined and factor of safety by two methods in Plaxis and Janbu stability chart is shown in the next table3-45

TABLE 45 FOS FROM PLAXIS AND JSC. HW/H

No.	d	beta	b	Hw/H	Hw (m)	Fs P M1	Fs P M2	μw	No	Fs J
1	2	30	1.73	0.1	0.4	1.488	1.557	0.97	5.636	1.500
2	2	30	1.73	0.2	0.8	1.563	1.714	0.94	5.636	1.538
3	2	30	1.73	0.4	1.6	1.757	1.970	0.90	5.636	1.675
4	2	30	1.73	0.5	2	1.881	2.253	0.89	5.636	1.785
5	2	30	1.73	0.7	2.8	2.207	1.666	0.91	5.636	2.132
6	2	30	1.73	0.9	3.6	2.685	1.309	0.96	5.636	2.707
7	1	30	1.73	0.1	0.4	1.544	1.596	0.95	5.816	1.515
8	1	30	1.73	0.2	0.8	1.611	1.726	0.90	5.816	1.525
9	1	30	1.73	0.4	1.6	1.796	1.971	0.84	5.816	1.609
10	1	30	1.73	0.5	2	1.922	2.267	0.83	5.816	1.703
11	1	30	1.73	0.7	2.8	2.261	1.549	0.85	5.816	2.038
12	1	30	1.73	0.9	3.6	2.784	1.309	0.93	5.816	2.689
13	0.5	30	1.73	0.1	0.4	1.611	1.648	0.90	6.087	1.508
14	0.5	30	1.73	0.2	0.8	1.668	1.741	0.83	6.087	1.468
15	0.5	30	1.73	0.4	1.6	1.841	1.974	0.72	6.087	1.455
16	0.5	30	1.73	0.5	2	1.969	2.263	0.71	6.087	1.525
17	0.5	30	1.73	0.7	2.8	2.341	1.467	0.74	6.087	1.871
18	0.5	30	1.73	0.9	3.6	2.918	1.293	0.88	6.087	2.672
19	0	45	1.00	0.1	0.4	1.617	1.592	0.86	5.767	1.363
20	0	45	1.00	0.2	0.8	1.644	1.593	0.76	5.767	1.269
21	0	45	1.00	0.4	1.6	1.785	1.576	0.62	5.767	1.191
22	0	45	1.00	0.5	2	1.900	1.912	0.60	5.767	1.223
23	0	45	1.00	0.7	2.8	2.265	1.091	0.66	5.767	1.575

24	0	45	1.00	0.9	3.6	2.915	/	0.80	5.767	2.309
25	0	60	0.58	0.1	0.4	1.373	1.366	0.84	5.25	1.211
26	0	60	0.58	0.2	0.8	1.401	1.372	0.72	5.25	1.100
27	0	60	0.58	0.4	1.6	1.525	1.337	0.56	5.25	0.976
28	0	60	0.58	0.5	2	1.623	1.598	0.54	5.25	0.997
29	0	60	0.58	0.7	2.8	1.925	/	0.58	5.25	1.265
30	0	60	0.58	0.9	3.6	2.456	/	0.81	5.25	2.129
31	0	90	0.00	0.1	0.4	1.018	/	0.82	3.83	0.861
32	0	90	0.00	0.2	0.8	1.040	/	0.67	3.83	0.750
33	0	90	0.00	0.4	1.6	1.127	/	0.48	3.83	0.607
34	0	90	0.00	0.5	2	1.193	/	0.44	3.83	0.594
35	0	90	0.00	0.7	2.8	1.400	/	0.47	3.83	0.742
36	0	90	0.00	0.9	3.6	1.793	/	0.72	3.83	1.375

3.2.4. FEM REVISITING ON INFLUENCE OF TENSION CRACKS

Under **tension cracks** condition, a reduction factor μ_t is introduced in JSC. And the Fs is calculated by

$$F_s = \mu_t N_0 \frac{c}{\gamma H} \quad (3.3)$$

- **Example revisiting and method introduce**

Example case is named E03 and chosen from Janbu 1954a, P6. The original parameters are shown in the follows table

TABLE 46 BASIC PARAMETERS OF E03

C	550	lb/ft2	26.33	kN/m2
weight	130	lb/ft3	20.42	kN/m3
q	0	lb/ft2	0	kN/m2
H	18	ft	5.49	m
D	3.5	ft	1.07	m
L	38.60	ft	11.77	m
beta	25			
b	0.47			
d	0.19			
Hw	0	ft	0	m
*Ht	6	ft	1.83	m

*a,b is different from that full hydrostatic pressure is equal to zero in case A and full hydrostatic pressure is acting in the tension cracks.

μ_{ta}=0.9 for Ht/H=0.33 and d=0.195 from figure A-5

μ_{tb}=0.85 for Ht/H=0.33 and d=0.195 from figure A-4

The Plaxis geometry simulation is shown in the next figure

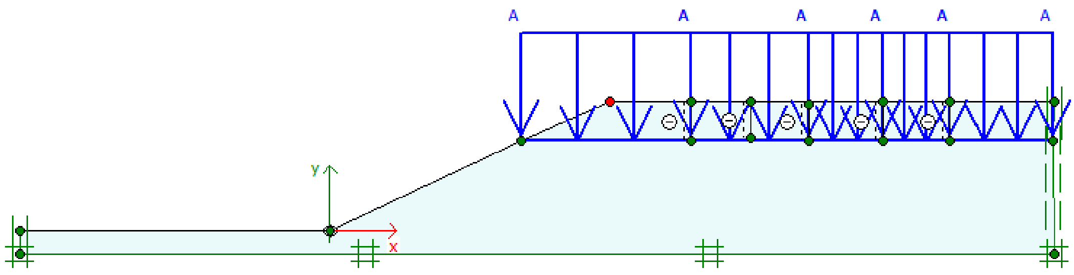

FIGURE 15 GEOMETRY SIMULATION

The main problem in Plaxis is how to simulate the tension cracks. The first method is to keep the top soil and insert several interfaces into the top soil body. The second method is use distribution loading instead of top soil. And the loading for saturated soil is saturated weight.

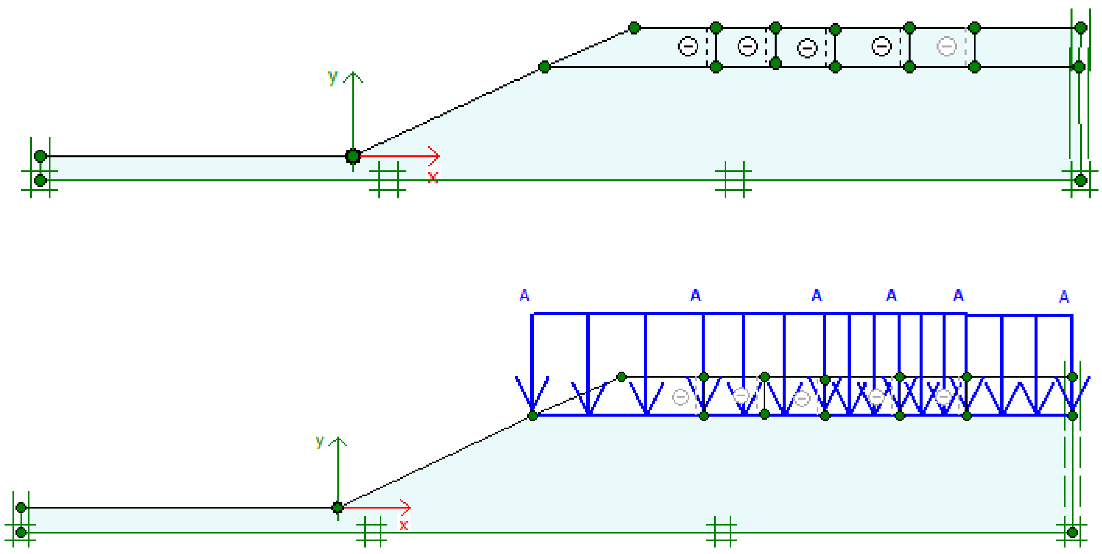

FIGURE 16 "METHOD 1" (UP) "METHOD 2" (DOWN)

Follows the analysis phrase unit, the result of safety factors is shown in,

TABLE 47 FOS OF E03 FROM PLAXIS AND JSC

	Fs P M1	Fs P M2	Fs J
Case a	1.761	1.459	1.44
Case b	/ *	1.652	1358

*Plaxis simulation for case b cannot be realized in that the water condition cannot be satisfied.

- **Systematical tests for submergence and drawdown conditions**

From the previous tests and Janbu theory, factor of safety is influenced by slope angle, depth, and height and water condition of crack. So a group of tests are designed to analysis the factors, as follows:

D=0, 0.5, 1. For geometry simulation, Y coordinate for point D, E is 0, 2m, 4m.

β=30°, 45°,60°, 90°. Ht/H=0.2, 0.4,.09. and Hw= 0.8m, 1.6m

Under condition that full hydrostatic pressure is equal to zero, the cases defined and factor of safety by two methods in Plaxis and Janbu stability chart is shown in the next table as follow

TABLE 48 FOS FROM PLAXIS AND JSC. HW/H, ZERO HYDROSTATIC PRESSURE

No.	d	beta	b	Ht/H	Hw (m)	weight	Fs P M1	μt	No	Fs J
1	1	30	1.73	0.2	0.8	15.0816	1.483	0.990	5.816	1.500
2	1	30	1.73	0.4	1.6	30.1632	1.655	0.983	5.816	1.489
3	0.5	30	1.73	0.2	0.8	15.0816	1.522	0.964	6.087	1.527
4	0.5	30	1.73	0.4	1.6	30.1632	1.900	0.945	6.087	1.497
5	0	45	1.00	0.2	0.8	15.0816	1.465	0.938	5.767	1.407
6	0	45	1.00	0.4	1.6	30.1632	1.467	0.909	5.767	1.364
7	0	60	0.58	0.2	0.8	15.0816	1.225	0.904	5.25	1.235
8	0	60	0.58	0.4	1.6	30.1632	1.229	0.844	5.25	1.153
9	0	90	0.00	0.2	0.8	15.0816	/	0.846	3.83	0.844
10	0	90	0.00	0.4	1.6	30.1632	/	0.731	3.83	0.729

Under condition that full hydrostatic pressure is acting in the tension cracks, the cases defined and factor of safety by two methods in Plaxis and Janbu stability chart is shown in the next table

TABLE 49 FOS FROM PLAXIS AND JSC. HW/H FULL HYDROSTATIC PRESSURE

No.	d	beta	b	Ht/H	Hw (m)	weight	Fs P M1	μt	No	Fs J
1	1	30	1.73	0.2	0.8	15.0816	1.848	0.980	5.816	1.484
1	1	30	1.73	0.4	1.6	30.1632	2.225	0.960	5.816	1.454
1	0.5	30	1.73	0.2	0.8	15.0816	1.650	0.958	6.087	1.518
1	0.5	30	1.73	0.4	1.6	30.1632	2.227	0.917	6.087	1.453
1	0	45	1.00	0.2	0.8	15.0816	1.849	0.930	5.767	1.396
1	0	45	1.00	0.4	1.6	30.1632	2.008	0.859	5.767	1.290
1	0	60	0.58	0.2	0.8	15.0816	1.560	0.901	5.25	1.231
1	0	60	0.58	0.4	1.6	30.1632	1.675	0.800	5.25	1.093
1	0	90	0.00	0.2	0.8	15.0816	1.129	0.839	3.83	0.836
1	0	90	0.00	0.4	1.6	30.1632	1.150	0.678	3.83	0.676

4.1. DATA ANALYSIS ON GEOMETRY FACTORS

4.1.1. COMPARISON ON VARIATION OF SLOPE ANGLE B

Follows the Chapter 3.2.1.2, Group 1, d=0.5 or D=2m. The factor of safety from Plaxis calculation, Janbu stability chart and difference between these two groups of value

TABLE 50 FOS FROM PLAXIS, JDM AND DIFFERENCE GROUP 1

b	Bx	Fs J	FS P	Difference
0.941	3.763	1.492	1.418	5.20%
1.166	4.662	1.512	1.464	3.27%
1.468	5.871	1.548	1.519	1.90%
1.864	7.458	1.607	1.586	1.33%
2.323	9.291	1.688	1.679	0.54%
2.877	11.508	1.800	1.814	-0.75%
3.499	13.996	1.961	1.975	-0.72%
4.121	16.485	2.151	2.129	1.03%
4.734	18.937	2.335	2.286	2.12%
5.545	22.180	2.561	2.499	2.46%
6.666	26.664	2.865	2.785	2.87%

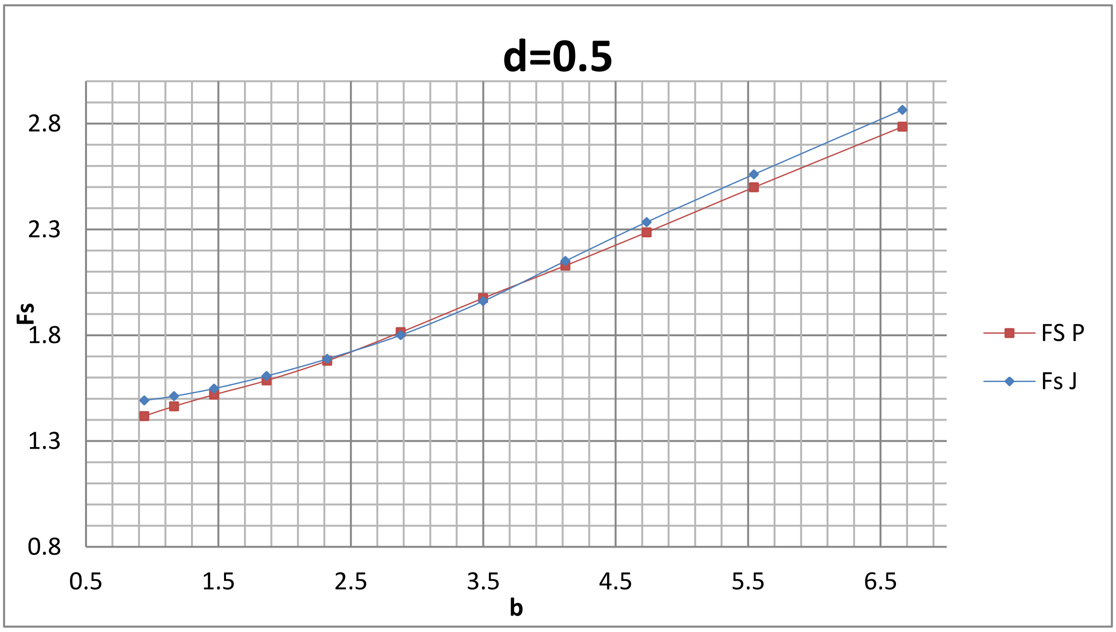

FIGURE 17 COMPARISON OF FOS VS B WITH PLAXIS TO JDM

Follows the Chapter 3.2.1.1, Group 2, d=0.2 or D=0.8m

TABLE 51 FOS FROM PLAXIS, JDM AND DIFFERENCE GROUP 2

b	Bx	Fs J	FS P	Difference
0.94	3.76	1.278449	1.233	3.69%
1.17	4.66	1.3139	1.277	2.89%
1.47	5.87	1.375939	1.355	1.55%
1.86	7.46	1.495586	1.482	0.92%
2.32	9.29	1.668409	1.631	2.29%
2.88	11.51	1.865605	1.814	2.84%
3.50	14.00	2.073879	2.007	3.33%
4.12	16.49	2.273291	2.196	3.52%
4.70	18.82	2.43282	2.371	2.61%

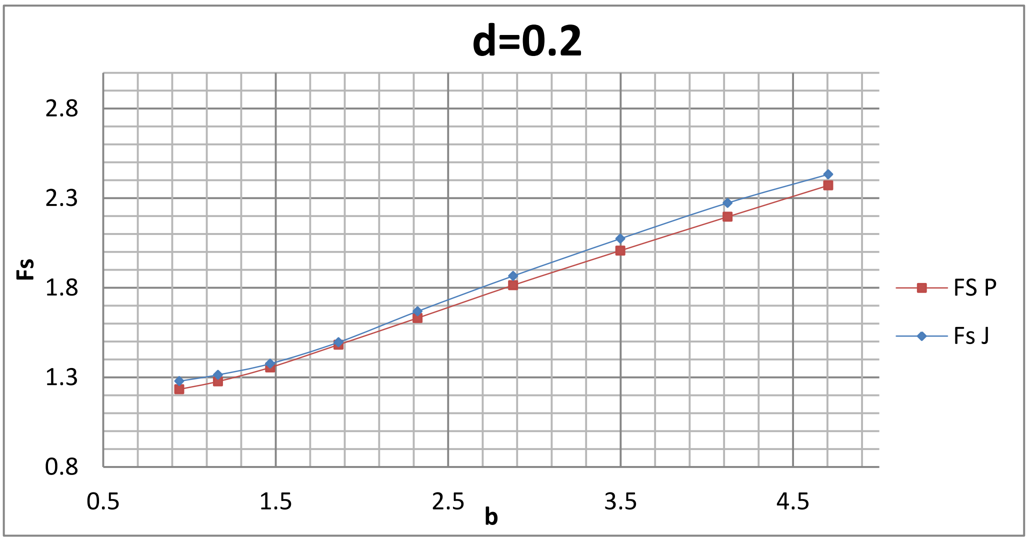

FIGURE 18 COMPARISON OF FOS VS B WITH PLAXIS TO JDM

In group 1, it can be seen that the difference between Fs when d=0.5. The maximum value is 5.2%. The minimum difference is 0.72%. And the average difference is 2.02%. Overview the figure, the tendency is the same shown in two methods.
In group 2, it can be revealed that the difference between Fs when d=0.2. The maximum value is 3.69%. The minimum difference is 0.92%. And the average difference is 2.63%. Overview the figure, the tendency is also the same shown in two methods.

- **Conclusions** Totally, since that average difference is lower than 5%, it can be concluded that the effect of slope angle β to factor of safety are very close in Janbu stability chart method and the finite element method.

4.1.2. COMPARISON ON VARIATION OF DEPTH D

Follows the Chapter 3.2.1.3, the FOS in from Plaxis and JDM method are shown in the next table

TABLE 52 FOS FROM PLAXIS, JDM VARIATION OF DEPTH D GROUP 1, 2, 3

D	0	0.1	0.2	0.3	0.5	1	1.5	2	3
Fs J	1.916	1.768	1.627	1.585	1.557	1.497	1.479	1.463	1.458
FS P	1.832	1.705	1.617	1.575	1.524	1.457	1.427	1.407	1.388
Diff.	4.59%	3.67%	0.62%	0.66%	2.15%	2.74%	3.62%	3.98%	5.03%
Fs J	2.192	2.005	1.822	1.703	1.632	1.533	1.502	1.484	1.458
FS P	2.082	1.928	1.860	1.708	1.613	1.508	1.459	1.432	1.403
Diff.	5.28%	3.97%	-2.03%	-0.32%	1.19%	1.68%	2.95%	3.62%	3.91%
Fs J	2.434	2.226	2.020	1.874	1.721	1.572	1.523	1.492	1.471
FS P	2.332	2.143	2.067	1.871	1.720	1.562	1.497	1.459	1.421
Diff.	4.38%	3.86%	-2.27%	0.18%	0.04%	0.66%	1.73%	2.24%	3.51%

* Group 1, b=1.5 (β= 33.7°)

** Group 2, b=2.0 (β=26.5°)

*** Group 3, b=2.5 (β=21.8°)

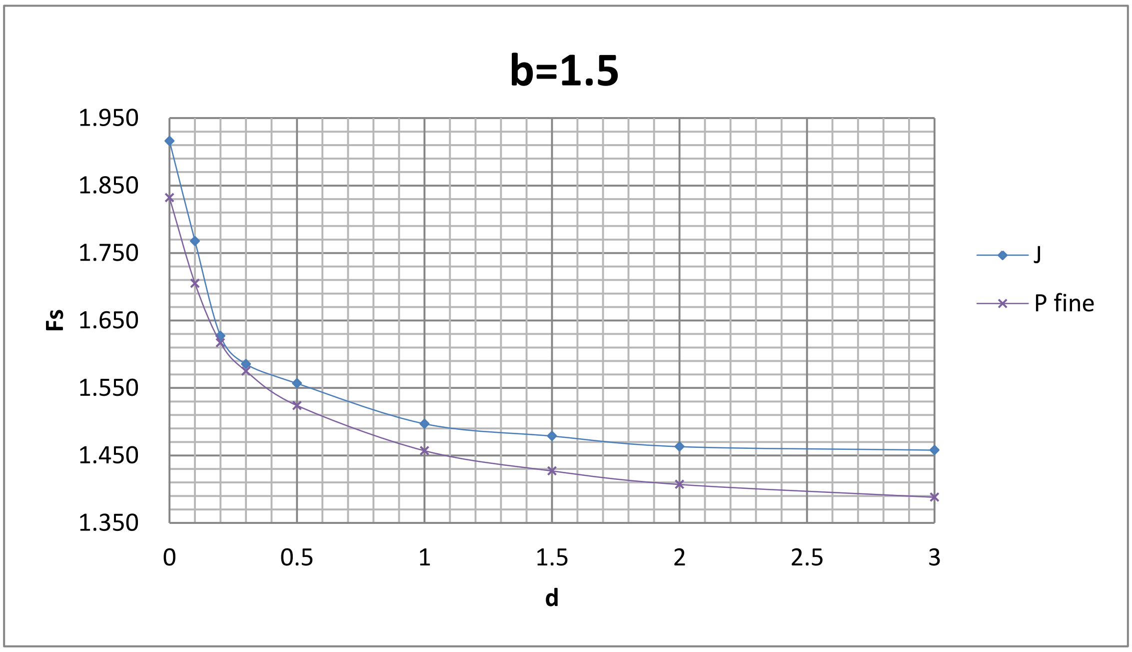

FIGURE 19 COMPARISON OF FOS VS D WITH PLAXIS TO JDM GROUP 1 B=1.5

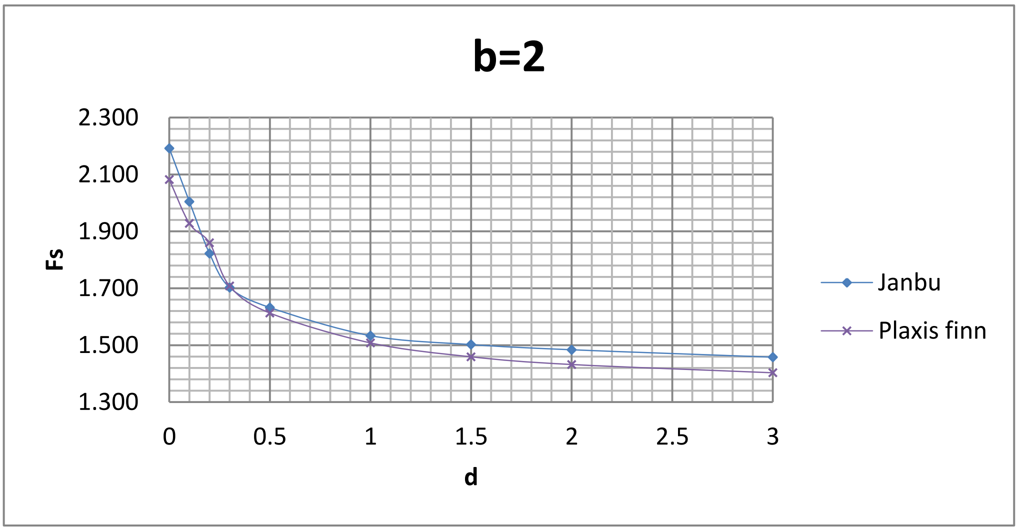

FIGURE 20 COMPARISON OF FOS VS D WITH PLAXIS TO JDM GROUP 2 B=2

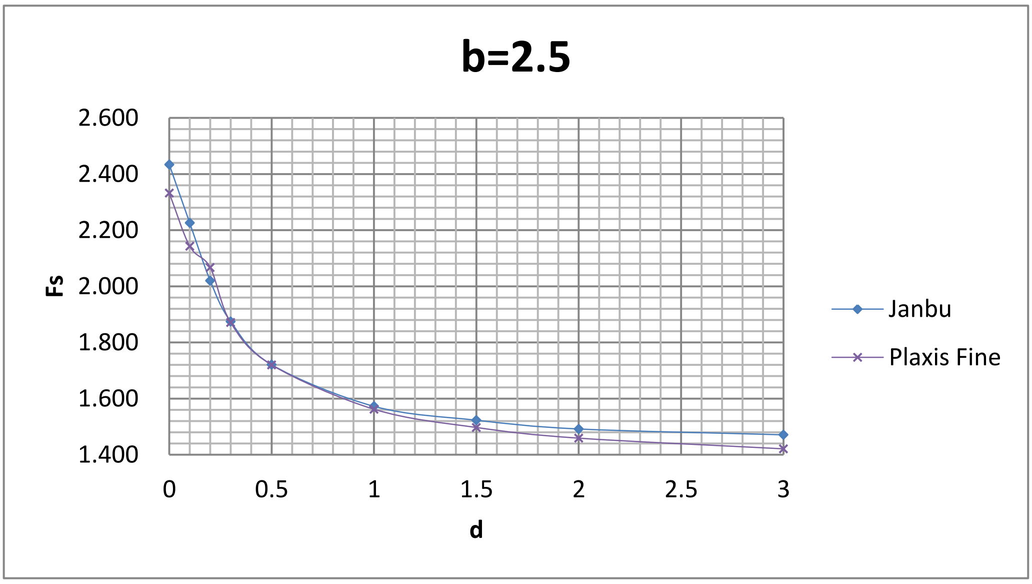

FIGURE 21 COMPARISON OF FOS VS D WITH PLAXIS TO JDM GROUP 3 B=3

In group 1, it can be seen that the difference between Fs when b=1.5. The maximum value is 5.03%. The minimum difference is 0.62%. And the average difference is 3.01%. In group 2, when b=2, the maximum value is 5.28%. The minimum difference is 0.32%. And the average difference is 2.27%. In group 3, when b=2.5, the maximum value is 4.38%. The minimum difference is 0.04%. And the average difference is 2.10%.

- **Conclusions** Overview all three figures, the tendency is the same shown in two methods. Totally, since that average difference is lower than 5%, it can be concluded that the effect of depth to factor of safety are very close in Janbu stability chart method and the finite element method.

4.1.3. EFFECT OF MESH SIZE

Follows the Chapter 3.2.1.4, Group 1,2

TABLE 53 FOS FROM PLAXIS OF DIFFERENT MESH SIZE GROUP 1,2

	Fs P 1	Fs P 2
very coarse	1.426	1.208
coarse	1.426	1.208
medium	1.421	1.207
fine	1.421	1.207
very fine	1.419	1.207

Follows the Chapter 3.2.1.4, Group 3, b=1.5 (β= 33.7°)

TABLE 54 FOS FROM PLAXIS, JDM OF DIFFERENT MESH SIZE GROUP 3

d	0	0.1	0.2	0.3	0.5	1	1.5	2	3
Fs J	1.916	1.768	1.627	1.585	1.557	1.497	1.479	1.463	1.458
coarse	1.851	1.720	1.628	1.585	1.530	1.462	1.431	1.411	1.392
medium	1.844	1.714	1.627	1.578	1.525	1.460	1.424	1.410	1.386
fine	1.832	1.705	1.617	1.575	1.524	1.457	1.427	1.407	1.388

Group 4, b=2.0 (β=26.5°)

TABLE 55 FOS FROM PLAXIS, JDM OF DIFFERENT MESH SIZE GROUP 4

d	0	0.1	0.2	0.3	0.5	1	1.5	2	3
Fs J	2.192	2.005	1.822	1.703	1.632	1.533	1.502	1.484	1.458
coarse	2.109	1.952	1.875	1.740	1.613	1.512	1.466	1.437	1.409
medium	2.093	1.941	1.871	1.719	1.616	1.511	1.458	1.433	1.409
fine	2.082	1.928	1.860	1.708	1.613	1.508	1.459	1.432	1.403

Group 5, b=2.5 (β=21.8°)

TABLE 56 FOS FROM PLAXIS, JDM OF DIFFERENT MESH SIZE GROUP 5

d	0	0.1	0.2	0.3	0.5	1	1.5	2	3
Fs J	2.434	2.226	2.020	1.874	1.721	1.572	1.523	1.492	1.471
coarse	2.353	2.175	2.082	1.911	1.741	1.570	1.502	1.463	1.426
medium	2.341	2.153	2.072	1.883	1.728	1.565	1.500	1.461	1.423
fine	2.332	2.143	2.067	1.871	1.720	1.562	1.497	1.459	1.421

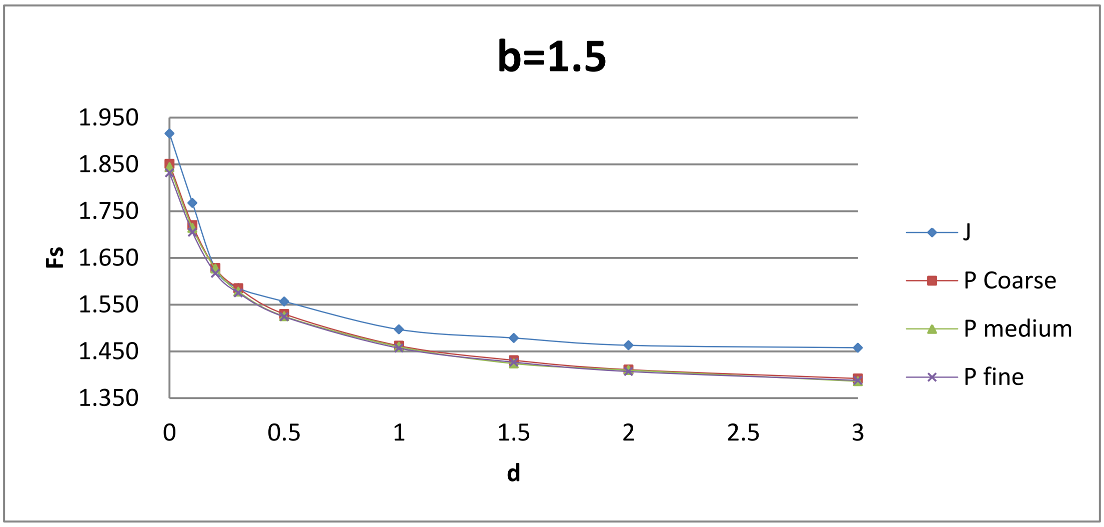

FIGURE 22 COMPARISON OF FOS VS D WITH PLAXIS TO JDM GROUP 3

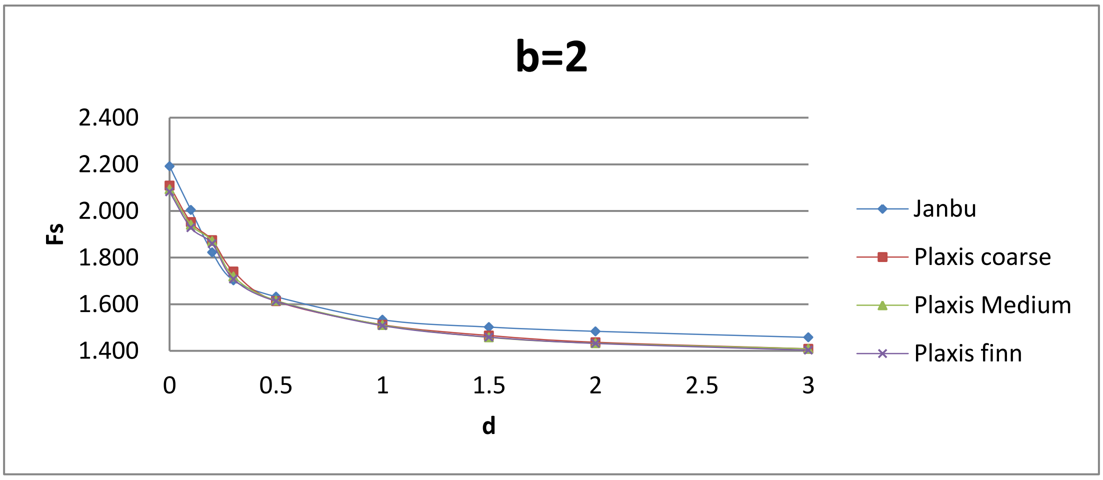

FIGURE 23 COMPARISON OF FOS VS D WITH PLAXIS TO JDM GROUP 4

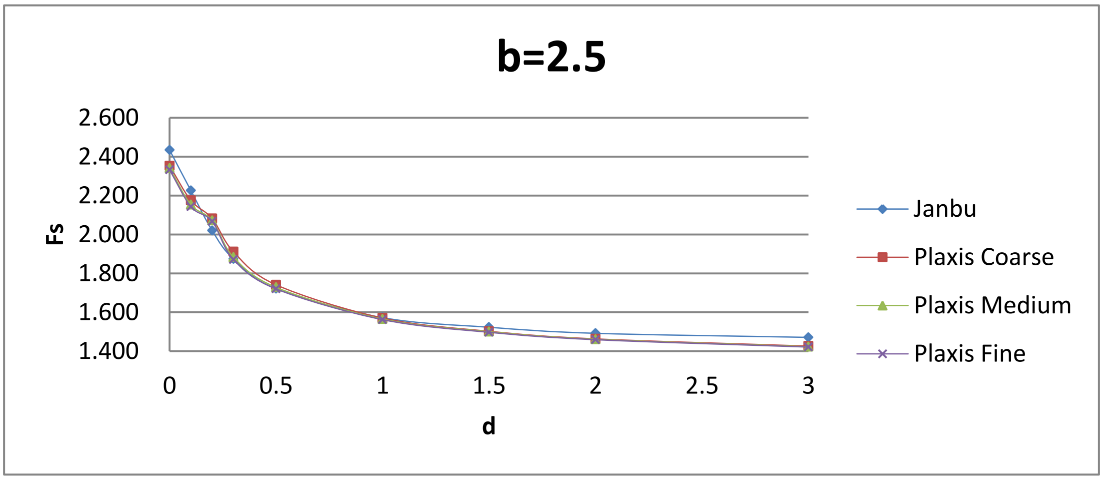

FIGURE 24 COMPARISON OF FOS VS D WITH PLAXIS TO JDM GROUP 5

- **Conclusion**: From all these four tables, the FOS is basically very close or even same when compared with FOS from JDM. And it is obviously that the coarser size meshed the higher factor of safety got.

4.2. FEM REVISITING ON EFFECT OF SURCHARGE

4.2.1. EFFECT OF SURCHARGE

Follows chapter 3.2.2.1,

TABLE 57 FOS FROM PLAXIS, JDM OF LOADING OR NO LOADING

b	Fs J L	FS P L	Fs J No L	FS P No L	ΔFs J	ΔFs P
0.94	1.49	1.418	1.27	1.21	0.22	0.21
1.17	1.51	1.464	1.29	1.249	0.23	0.22
1.47	1.55	1.519	1.32	1.296	0.23	0.22
1.86	1.61	1.586	1.37	1.361	0.24	0.23
2.32	1.69	1.679	1.44	1.445	0.25	0.23
2.88	1.80	1.814	1.53	1.565	0.27	0.25
3.50	1.96	1.975	1.67	1.711	0.29	0.26
4.12	2.15	2.129	1.83	1.847	0.32	0.28
4.73	2.33	2.286	1.99	1.986	0.35	0.30
5.55	2.56	2.499	2.18	2.172	0.38	0.33
6.67	2.86	2.785	2.44	2.419	0.43	0.37

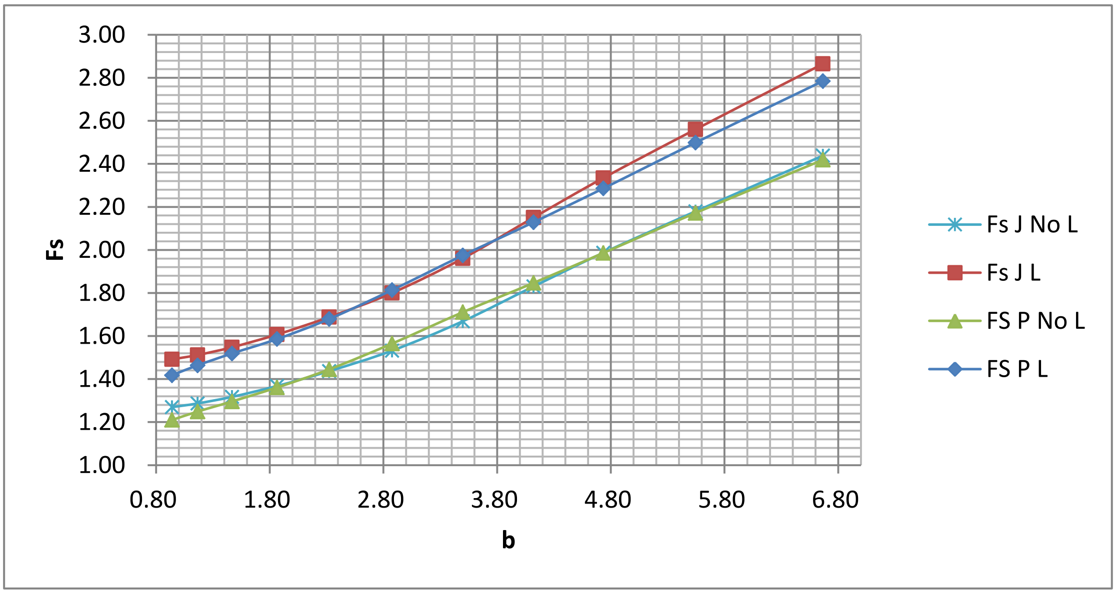

FIGURE 25 COMPARISON OF FOS VS B WITH PLAXIS TO JDM LOADING OR NO LOADING

The difference ΔFs J and ΔFs P are very close, which revealed that the influence of surcharge to factor of safety in two methods is the same.

4.2.2. MAGNITUDE AND LENGTH OF DISTRIBUTION LOADING

Follows chapter 3.2.2.2, Experimental case

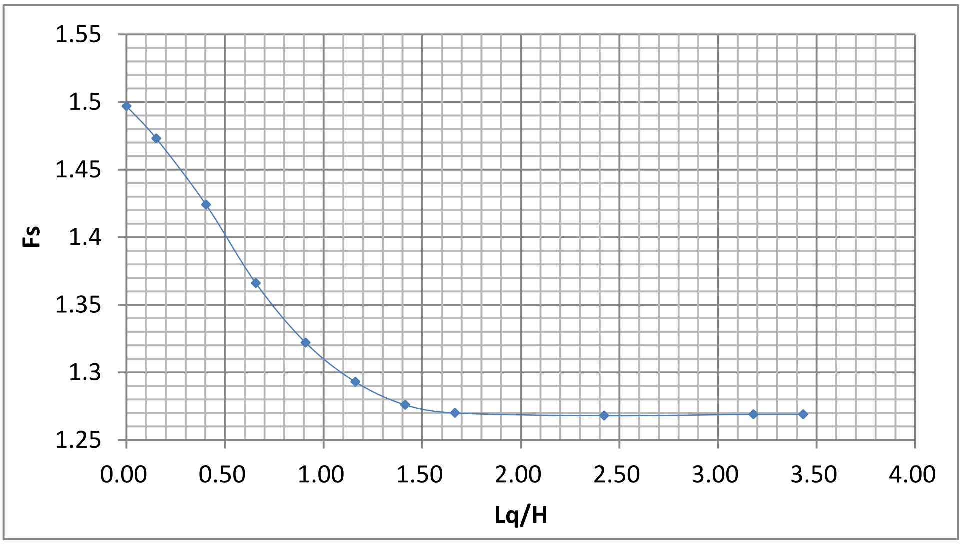

FIGURE 26 FOS VS LENGTH OF LOADING EXPERIMENTAL CASE

It shows that the Fs stop changing at Lq/H=1.8. So a series of systematical tests for surcharge effect may discover some principle.

TABLE 58 STABLE FOS AND STOP POINT ON LENGTH OF LOADING FROM PLAXIS, JDM

No.	d	beta	b	q/γH	q	Lq/H	Fs stb	uq	No	Fs J	Diff.
1	2	30	1.73	0.1	7.54	4	1.28	0.965	5.636	1.287	-0.56%
2	2	30	1.73	0.2	15.08	4	1.171	0.945	5.636	1.155	1.35%
3	2	30	1.73	0.3	22.62	3.5	1.077	0.928	5.636	1.047	2.83%
4	2	30	1.73	0.4	30.16	\	\	0.915	5.636	0.959	
5	2	30	1.73	0.5	37.70	\	\	0.898	5.636	0.878	
6	1	30	1.73	0.1	7.54	2.5	1.33	0.954	5.816	1.313	1.29%
7	1	30	1.73	0.2	15.08	2.5	1.212	0.917	5.816	1.157	4.75%
8	1	30	1.73	0.3	22.62	2.5	1.106	0.877	5.816	1.021	8.28%
9	1	30	1.73	0.4	30.16	2.5	1.021	0.839	5.816	0.907	12.52%
10	1	30	1.73	0.5	37.70	\	\	0.798	5.816	0.805	
11	0.5	30	1.73	0.1	7.54	1.5	1.392	0.902	6.087	1.299	7.13%
12	0.5	30	1.73	0.2	15.08	1.5	1.265	0.824	6.087	1.088	16.26%
13	0.5	30	1.73	0.3	22.62	1.5	1.149	0.758	6.087	0.924	24.36%
14	0.5	30	1.73	0.4	30.16	1.5	1.055	0.7	6.087	0.792	33.15%
15	0.5	30	1.73	0.5	37.70	\	\	0.646	6.087	0.682	
16	0	45	1.00	0.1	7.54	1	1.38	0.843	5.767	1.151	19.94%
17	0	45	1.00	0.2	15.08	1	1.232	0.715	5.767	0.895	37.73%
18	0	45	1.00	0.3	22.62	1.25	1.098	0.611	5.767	0.706	55.61%
19	0	45	1.00	0.4	30.16	\	\	0.523	5.767	0.561	
20	0	45	1.00	0.5	37.70	\	\	0.441	5.767	0.441	

No.	d	beta	b	q/γH	q	Lq/H	Fs stb	uq	No	Fs J	Diff.
21	0	60	0.58	0.1	7.54	1	1.174	0.789	5.25	0.980	19.76%
22	0	60	0.58	0.2	15.08	1.25	1.044	0.639	5.25	0.728	43.45%
23	0	60	0.58	0.3	22.62	\	\	0.513	5.25	0.539	
24	0	60	0.58	0.4	30.16	\	\	0.402	5.25	0.392	
25	0	60	0.58	0.5	37.70	\	\	0.332	5.25	0.303	
26	0	75	0.27	0.1	7.54	1	1.023	0.742	4.522	0.794	28.83%
27	0	75	0.27	0.2	15.08	\	\	0.563	4.522	0.552	
28	0	75	0.27	0.3	22.62	\	\	0.416	4.522	0.377	
29	0	75	0.27	0.4	30.16	\	\	0.297	4.522	0.250	
30	0	75	0.27	0.5	37.70	\	\	0.197	4.522	0.155	
31	0	90	0.00	0.1	7.54	\	\	0.671	3.83	0.608	
32	0	90	0.00	0.2	15.08	\	\	0.475	3.83	0.395	
33	0	90	0.00	0.3	22.62	\	\	0.308	3.83	0.236	
34	0	90	0.00	0.4	30.16	\	\	0.178	3.83	0.127	
35	0	90	0.00	0.5	37.70	\	\	0.071	3.83	0.047	

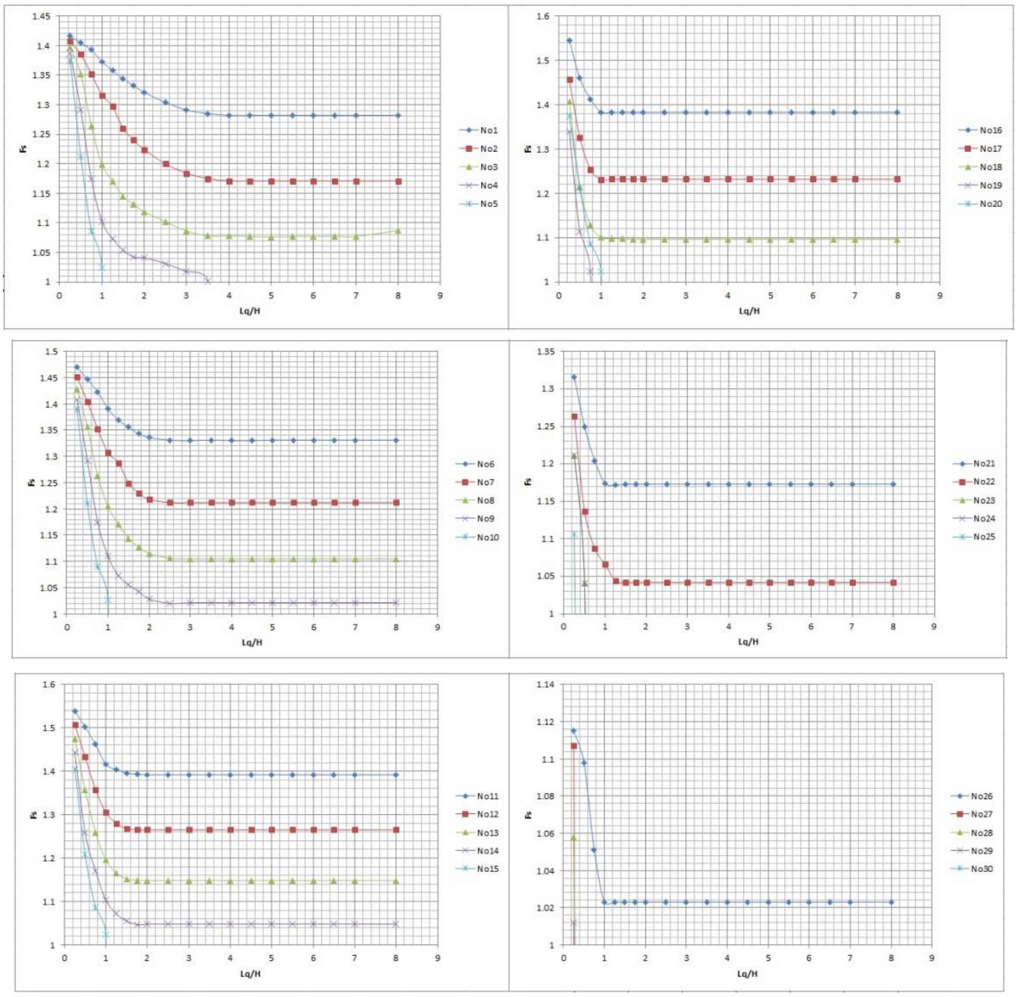

FIGURE 27 FOS VS LENGTH OF LOADING (Q/RH=0.1, 0.2, 0.3, 0.4, .05)

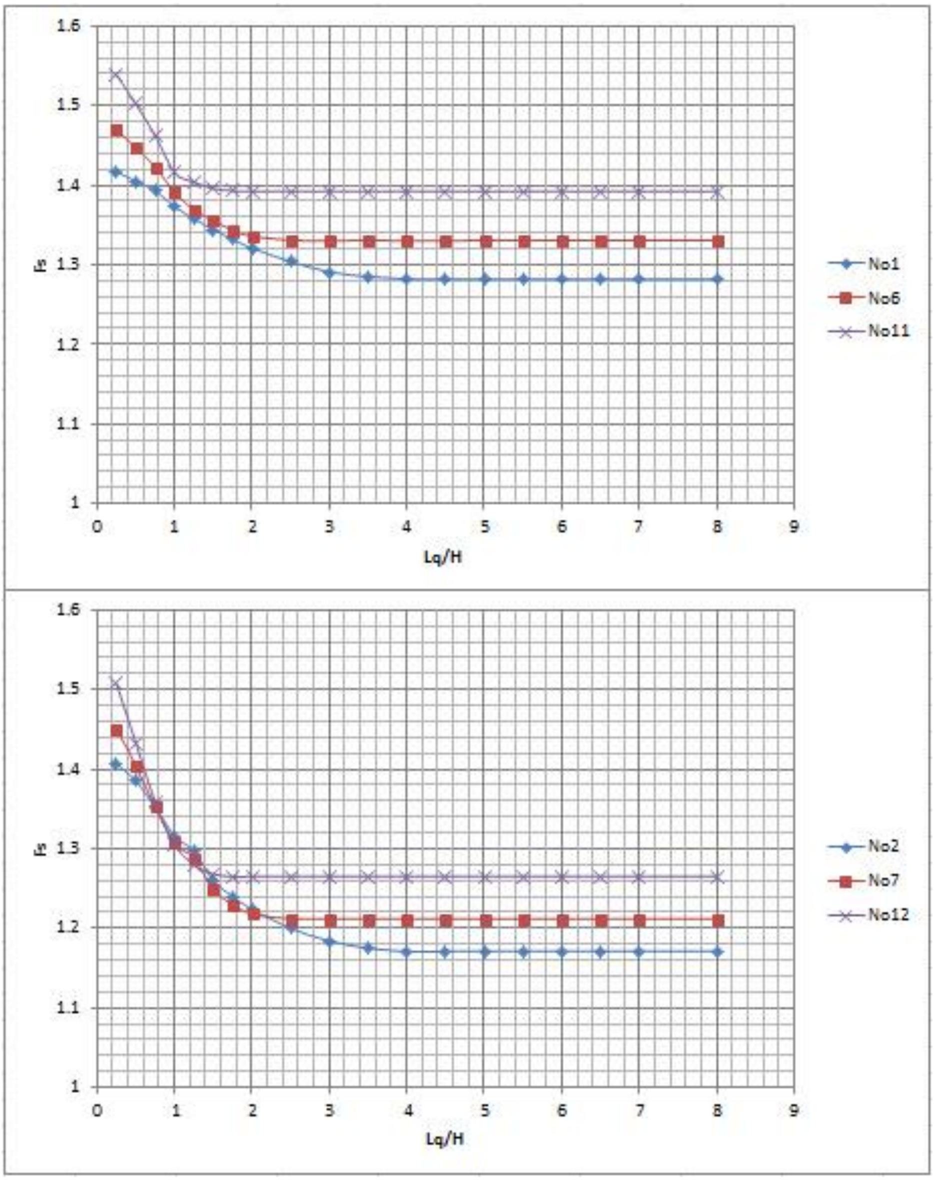

FIGURE 28 FOS VS LENGTH OF LOADING (D=2, 1, 0.5)

From the table 4-9 Figure 4-11, 4-12, several **conclusions** can be revealed:

- The tendency that with the increasing of magnitude of loading (q), increasing of slope angle (β), increasing of depth (D), FOS will be reduced.
- The magnitude of loading influences a lot to the FOS
- The difference between two methods is bigger when slope is close to dangerous situation. It may cite that the accuracy is low when FOS is close to collapse.
- The range of Lq/H is from 0 to 8 in each case. The maximum stop point is about 4. And the minimum point is about 1. It is different from the assumption that loading is unlimited in the Janbu stability chart.

- The stable point of Lq/H is reduced with the increasing of magnitude of loading (q), magnitude of loading (q).

4.3. FEM REVISITING ON PARTIAL SUBMERGENCE AND DRAWDOWN CONDITION

Follows chapter 3.2.3, the

TABLE 59 FOS FROM PLAXIS, JDM OF VARIATION OF SUBMERGENCE HEIGHT

No.	d	beta	b	Hw/H	Hw (m)	Fs P M1	Fs P M2	Fs J	Diff. J,M2
1	2	30	1.73	0.1	0.4	1.488	1.557	1.500	3.77%
2	2	30	1.73	0.2	0.8	1.563	1.714	1.538	11.47%
3	2	30	1.73	0.4	1.6	1.757	1.970	1.675	17.60%
4	2	30	1.73	0.5	2	1.881	2.253	1.785	26.24%
5	2	30	1.73	0.7	2.8	2.207	1.666	2.132	-21.85%
6	2	30	1.73	0.9	3.6	2.685	1.309	2.707	-51.65%
7	1	30	1.73	0.1	0.4	1.544	1.596	1.515	5.33%
8	1	30	1.73	0.2	0.8	1.611	1.726	1.525	13.16%
9	1	30	1.73	0.4	1.6	1.796	1.971	1.609	22.49%
10	1	30	1.73	0.5	2	1.922	2.267	1.703	33.12%
11	1	30	1.73	0.7	2.8	2.261	1.549	2.038	-23.98%
12	1	30	1.73	0.9	3.6	2.784	1.309	2.689	-51.31%
13	0.5	30	1.73	0.1	0.4	1.611	1.648	1.508	9.30%
14	0.5	30	1.73	0.2	0.8	1.668	1.741	1.468	18.62%
15	0.5	30	1.73	0.4	1.6	1.841	1.974	1.455	35.68%
16	0.5	30	1.73	0.5	2	1.969	2.263	1.525	48.37%
17	0.5	30	1.73	0.7	2.8	2.341	1.467	1.871	-21.61%
18	0.5	30	1.73	0.9	3.6	2.918	1.293	2.672	-51.62%
19	0	45	1.00	0.1	0.4	1.617	1.592	1.363	16.82%
20	0	45	1.00	0.2	0.8	1.644	1.593	1.269	25.56%
21	0	45	1.00	0.4	1.6	1.785	1.576	1.191	32.35%
22	0	45	1.00	0.5	2	1.900	1.912	1.223	56.37%
23	0	45	1.00	0.7	2.8	2.265	1.091	1.575	-30.73%
24	0	45	1.00	0.9	3.6	2.915	/	2.309	/
25	0	60	0.58	0.1	0.4	1.373	1.366	1.211	12.83%
26	0	60	0.58	0.2	0.8	1.401	1.372	1.100	24.78%
27	0	60	0.58	0.4	1.6	1.525	1.337	0.976	36.96%
28	0	60	0.58	0.5	2	1.623	1.598	0.997	60.20%
29	0	60	0.58	0.7	2.8	1.925	/	1.265	/
30	0	60	0.58	0.9	3.6	2.456	/	2.129	/
31	0	90	0.00	0.1	0.4	1.018	/	0.861	/

32	0	90	0.00	0.2	0.8	1.040	/	0.750	/
33	0	90	0.00	0.4	1.6	1.127	/	0.607	/
34	0	90	0.00	0.5	2	1.193	/	0.594	/
35	0	90	0.00	0.7	2.8	1.400	/	0.742	/
36	0	90	0.00	0.9	3.6	1.793	/	1.375	/

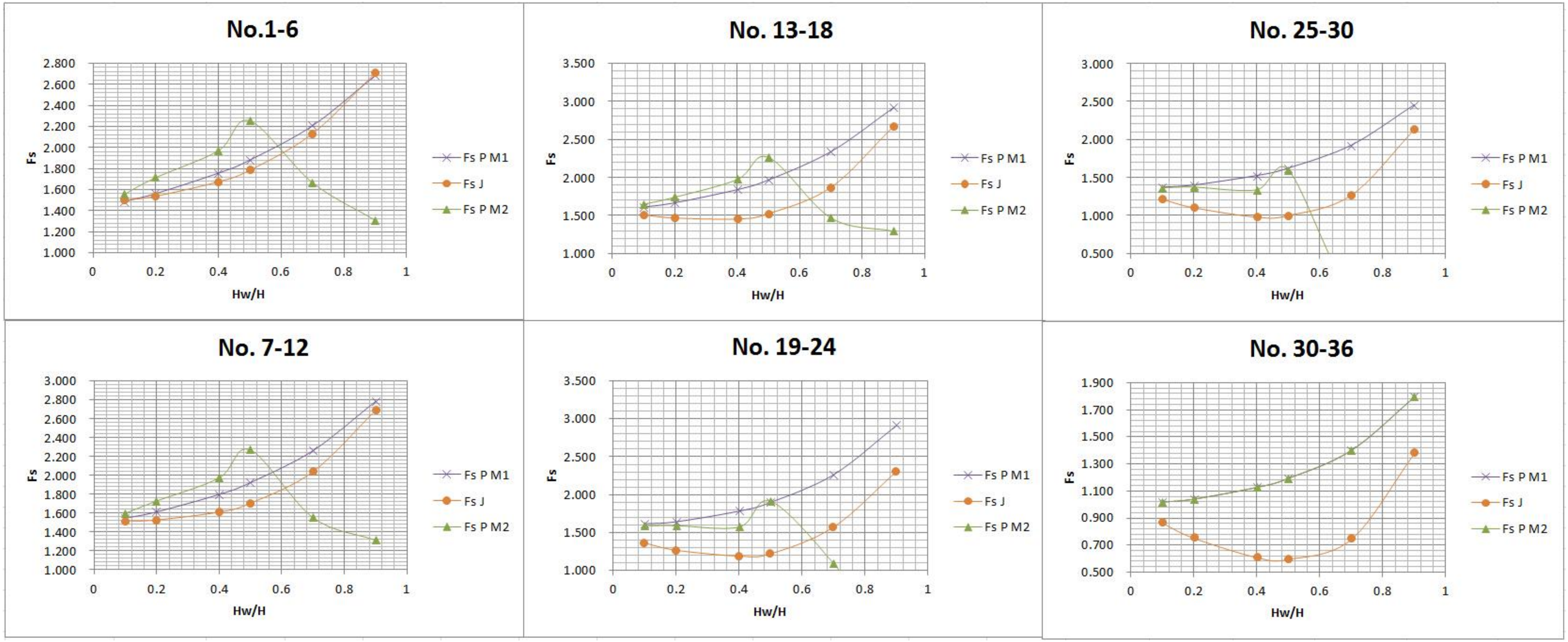

FIGURE 29 FOS WITH HW/H(0.1, 0.2, 0.3, 0.4, 0.5) FROM PLAXIS, JDM OF VARIATION OF SUBMERGENCE HEIGHT

From the table 4-10, figure 4-13, several **conclusions** can be revealed:

- Method reliability:

Method 1 is without submergence distribution loading. It fits for the tendency but with higher FOS.

Method 2 has distribution loading. The tendency of FOS with increasing Hw/H=0.1, 0.2, 0.4, 0.5 fits for the Janbu stability chart. But then tendency from Hw/H= 0.7 0.9 is opposite to the Janbu's theory.

- Theoretically, method 2 is more close to the reality. The difference between Plaxis method 2 to JDM is mostly larger than 30%. It cites that JDM can be modified in Hw/H range from 0.5 to 1.0.

4.4. FEM REVISITING ON INFLUENCE OF TENSION CRACKS

Follows chapter 3.2.4, the FOS FROM PLAXIS, JDM OF variation of tension cracks

TABLE 60 FOS FROM PLAXIS AND JDM. Hw/H, ZERO HYDROSTATIC PRESSURE

No.	d	beta	b	Ht/H	Hw (m)	Fs P M1	Fs J	Diff.
1	1	30	1.73	0.2	0.8	1.483	1.500	-1.10%
2	1	30	1.73	0.4	1.6	1.655	1.489	11.18%
3	0.5	30	1.73	0.2	0.8	1.522	1.527	-0.34%
4	0.5	30	1.73	0.4	1.6	1.900	1.497	26.92%
5	0	45	1.00	0.2	0.8	1.465	1.407	4.09%
6	0	45	1.00	0.4	1.6	1.467	1.364	7.54%
7	0	60	0.58	0.2	0.8	1.225	1.235	-0.83%
8	0	60	0.58	0.4	1.6	1.229	1.153	6.58%
9	0	90	0.00	0.2	0.8	/	0.844	/
10	0	90	0.00	0.4	1.6	/	0.729	/

TABLE 61 FOS FROM PLAXIS AND JDM. Hw/H FULL HYDROSTATIC PRESSURE

No.	d	beta	b	Ht/H	Hw (m)	Fs P M1	Fs J	Diff.
1	1	30	1.73	0.2	0.8	1.848	1.484	24.55%
2	1	30	1.73	0.4	1.6	2.225	1.454	53.08%
3	0.5	30	1.73	0.2	0.8	1.650	1.518	8.69%
4	0.5	30	1.73	0.4	1.6	2.227	1.453	53.26%
5	0	45	1.00	0.2	0.8	1.849	1.396	32.43%
6	0	45	1.00	0.4	1.6	2.008	1.290	55.70%
7	0	60	0.58	0.2	0.8	1.560	1.231	26.68%
8	0	60	0.58	0.4	1.6	1.675	1.093	53.19%
9	0	90	0.00	0.2	0.8	1.129	0.836	35.00%
10	0	90	0.00	0.4	1.6	1.150	0.676	70.24%

From the table 4-10, figure 4-13, several **conclusions** can be revealed:

- Under the condition of zero hydrostatic pressure in cracks, the maximum difference is 26.92%. The minimum difference is 0.34%. The average value is 7.32% Overview table 4-11, since that average difference is lower than 10%, it can be concluded that the effect of cracks to factor of safety are close in Janbu stability chart method and the finite element method.
- Under the condition of full hydrostatic pressure in cracks. The maximum difference is 55.72%. The minimum difference is 8.69%. The average value is

41.28%. Overview table 4-12, since that average difference is larger than 40%, the simulation in Plaxis is not satisfied the conclusion from Janbu's theory.

4.5. DATA EVALUTAION AND DISCUSSION

4.5.1. QUANTITY OF DATA

In data collection stage, 212 cases and 898 analyses unit has been calculated in Plaxis and 146 cases in Janbu stability charts method shown in the follows:

- Stage of comparison on variation of slope angle β, 22 cases in Plaxis and 22 cases in JDM have been calculated.
- Stage of comparison on variation depth D, 27 cases in Plaxis and 27 cases in JDM have been calculated.
- Stage of comparison of different mesh size, 64 cases in Plaxis have been calculated
- Stage of evaluate effect of surcharge, 11cases in Plaxis and 11 cases in JDM have been calculated.
- Stage of evaluate effect of magnitude and length of distribution loading, 36 cases in Plaxis and 36 cases in JDM have been calculated. For each case has 19 analysis units, 684 analysis units have been calculated.
- Stage of partial submergence and drawdown condition, 38 cases in Plaxis and 38 cases in JDM have been calculated. For each case has 2 analysis units, 76 analysis units have been calculated.
- Stage of influence of tension cracks, 14 cases in Plaxis and 12 cases in JDM have been calculated.

Totally 1044 factors of safety have calculated which is highly reliable and necessary to give a sufficient analysis which may closer to a proper conclusion.

4.5.2. GEOMETRY SIZE SIMULATION INFLUENCE ON RESULT

During the FOS calculation in Plaxis, the FOS will decrease because the improper geometry simulation.

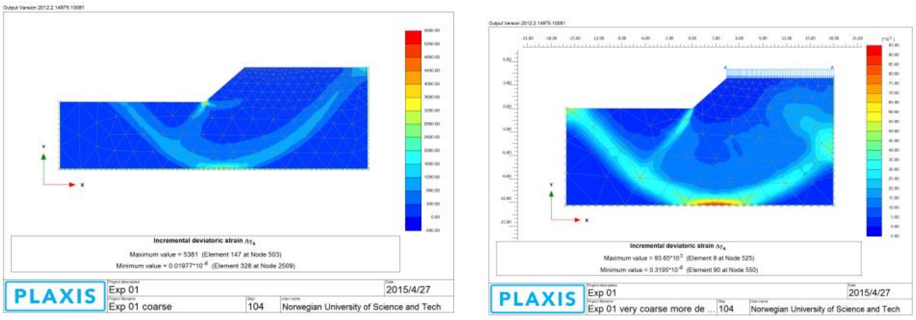

FIGURE 30 INCREMENTAL DEVIATORIC STRAIN IN DEPTH 7.5M (L) 12 (R)

Figure 4-1 (R) shows that the critical surface is concentrate at lower part in soil body when upper surface provides an insufficient space. The left shows the same problem but the critical surface may be concentrate at the corner. It is an uncertain circumstance. At this moment the FOS will decreased. But this problem will not occur in JDM in that perpendicular boundaries are unlimited.

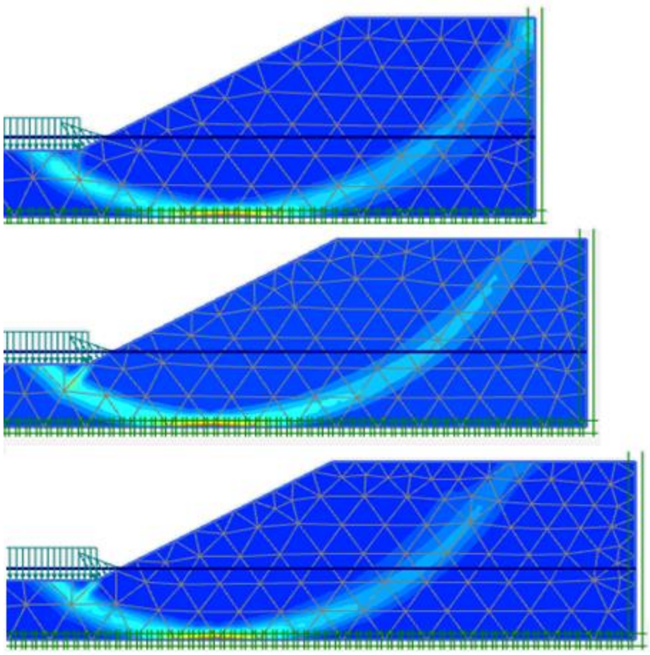

FIGURE 31 INFLUENCE OF INCREMENTAL X COORDINATE POINT B

The up right corner is point B, the x coordinate of B is 12m, 14m, and 16m. The FOS is 2.867, 2.911 and 2.911. The FOS stops increase when the length of upper surface is wide enough.

To prevent this kind of situation, for all cases, the length of upper surface should be 10 times as the H. Since then the x coordinate is about 40m. The disadvantage for this rule is that it costs more time to calculate.

4.5.3. PLAXIS PROGRAM BUG INFLUENCE ON RESULT

During using, Plaxis has some bugs, like missing files etc. Sometime the phrase will execute the previous phrase (shown in the follows figure)

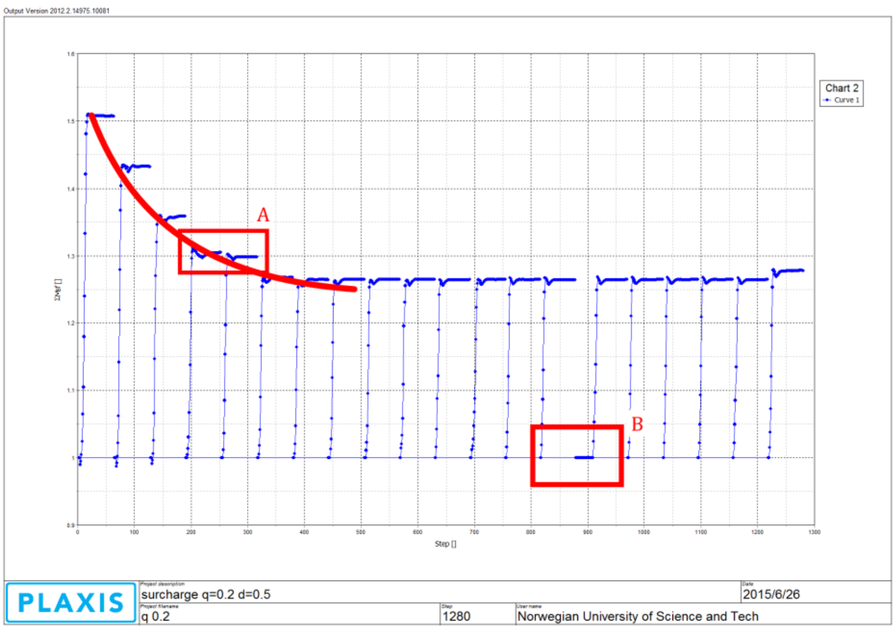

FIGURE 32 FOS WITH PROGRAMME BUGS

From A, the left FOS analysis should give a lower value, but the result is the same like the previous phrase. After resetting the stage construction, the result is still the same. The solution is to insert a new analysis with same condition and recalculate.

From B, the stage construction phrase runs more steps than normal condition. But it is harmless, because it has no effect on FOS.

CHAPETER 5 SUMMARY AND CONCLUSION

5.1. SUMMARY

The research described in this thesis has achieved the objectives outlined in chapter 1. The accomplishments can be summarized as follows:

- Properly simulate the slope angle β, depth D, effect of surcharge with the magnitude and length, partial submergence and influence of tension cracks in chapter 3.
- Successfully setup systematical tests with single variation in Plaxis in chapter 3.
- Successfully analysis and compare the results between Janbu stability chart method and FEM Plaxis in chapter 4
- The modified suggestion for partial submergence condition has been made.

5.2. CONCLUSION

Comparison of factors in Janbu stability chart methods were fully discussed in this research. Detailed conclusions have been presented in preceding paragraphs. The interesting points may be summarized as follows:

- The tendency of factor of safety varied by single factor is mostly same in Plaxis and Janbu stability chart analysis
- Length of upper surface is better to bigger than 10 times as height of slope in Plaxis which is unlimited in the Janbu stability charts
- And when length of surcharge is larger than 4, the factor of safety is tend to a stable value. But the length of loading is unlimited in the Janbu stability charts
- The difference is mostly low than 8-10%. But with the influence of water, the difference will increase to 40-50%. It cites that water plays a key role in slope stability.

5.3. SUGGESTIONS FOR FURTHER WORKS

The suggestions for further works as follows:

- The factor of stability number Ncf is based on the c and cohesion angle ϕ could be discussed in the further works
- Highly abstractive conclusion can be cited.
- The conclusion needs varied by suitable real case or via laboratory tests.
- Based on data from laboratory test, a certain and confidence theory may update the Janbu stability charts with FE knowledge.

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APPENDIX

APPENDIX A

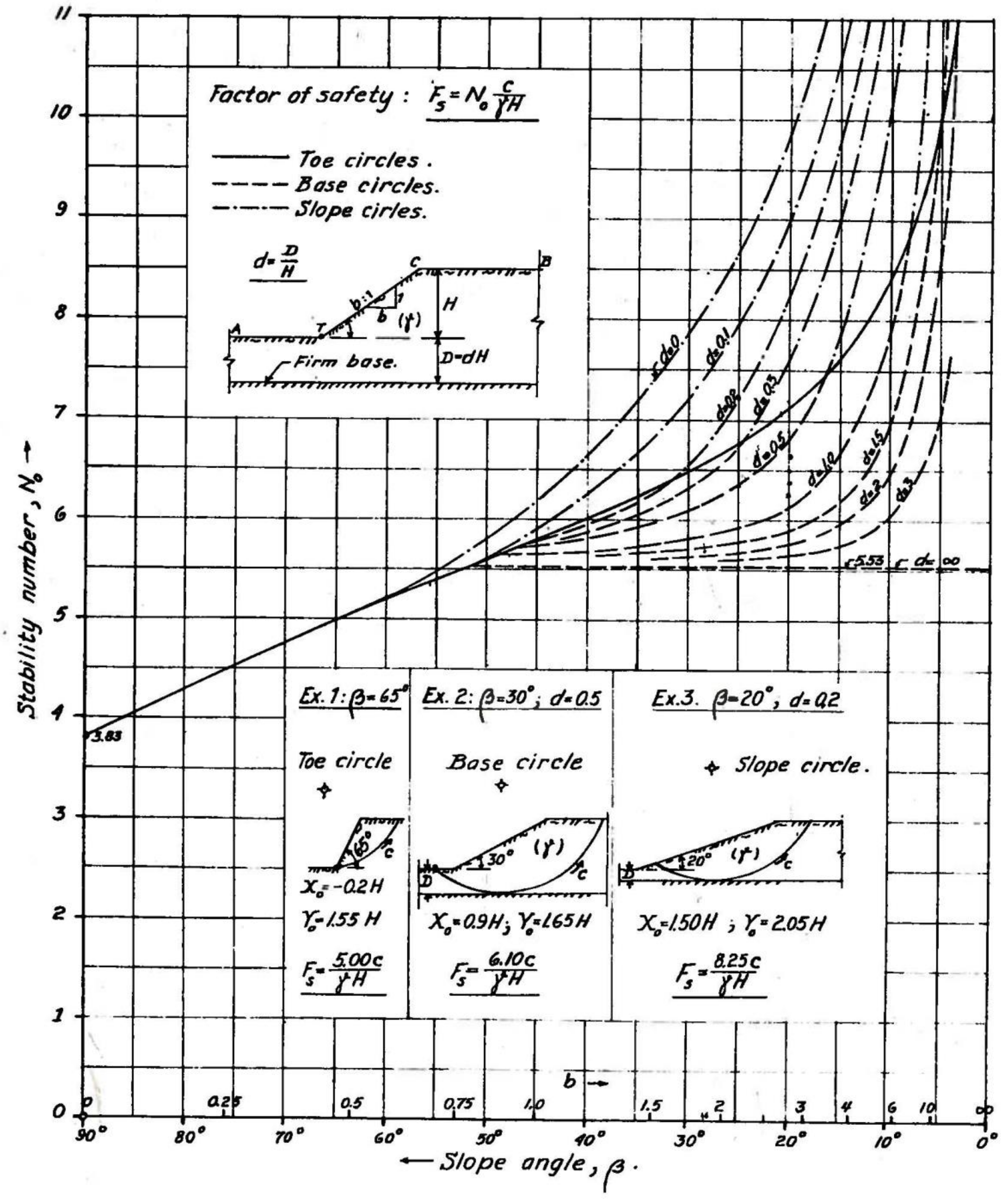

FIGURE A- 2 STABILITY NUMBER FOR SIMPLE SLOPES WHENΦ= 0

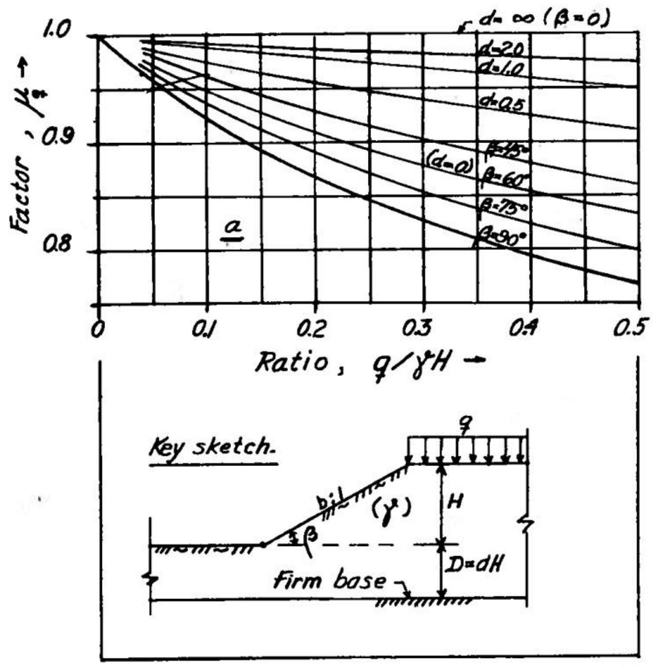

FIGURE A- 3 REDUCTION FACTOR μ_q

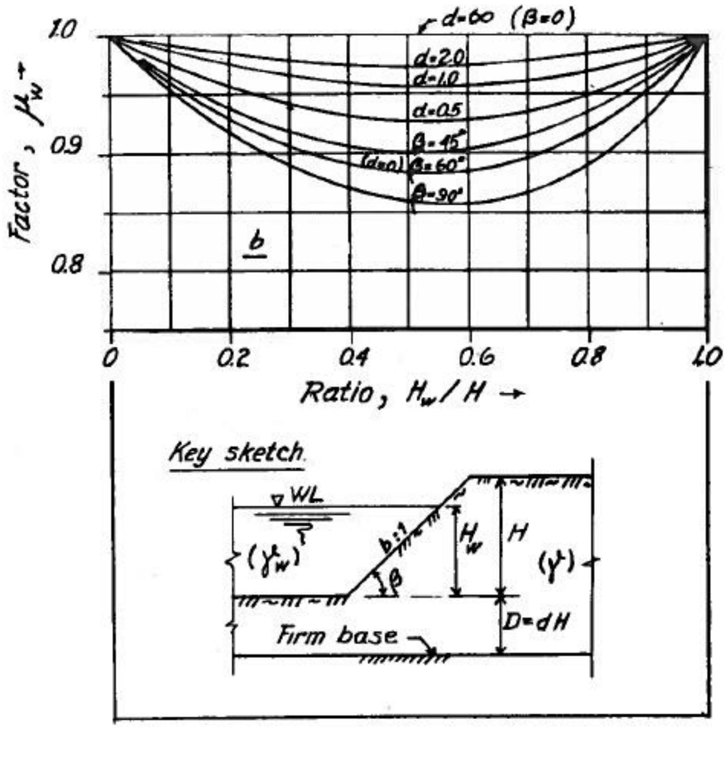

FIGURE A- 4 REDUCTION FACOTR μ_w

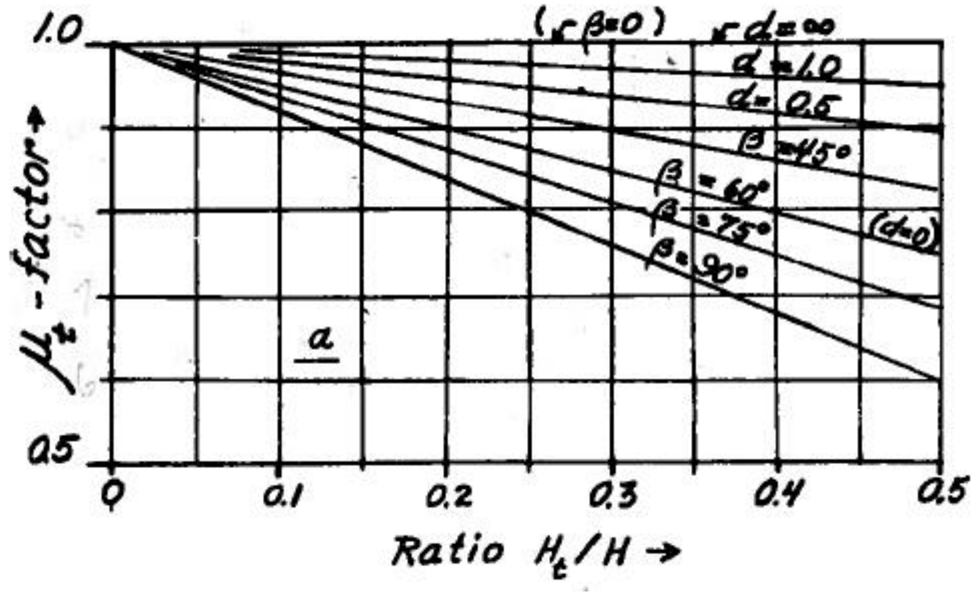

FIGURE A- 5 REDUCTION FACOTR μ_t (FULL HYDROSTATIC PRESSURE IS ACTING IN THE TENSION CRACKS).

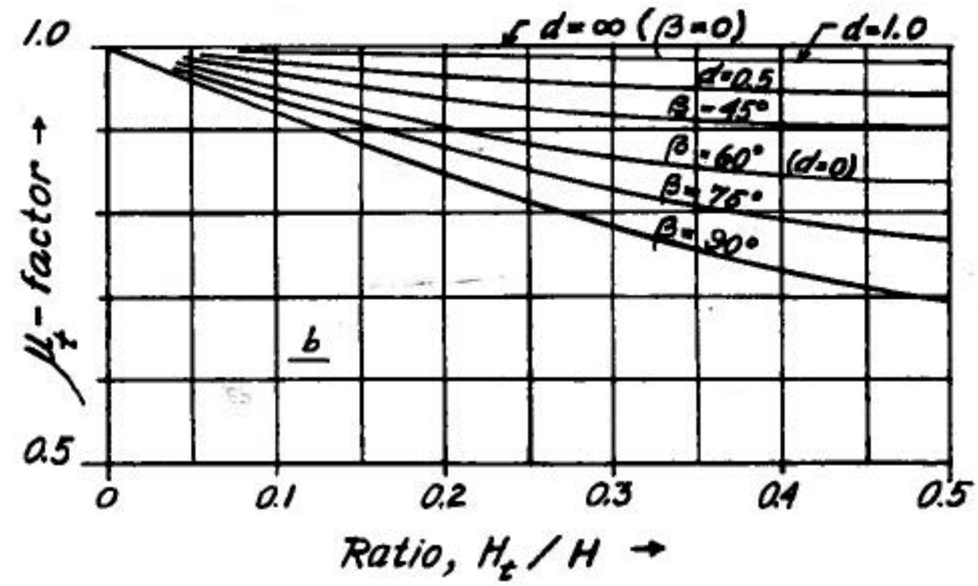

FIGURE A- 6 REDUCTION FACOTR μ_t (FULL HYDROSTATIC PRESSURE IS EQUAL TO ZERO)

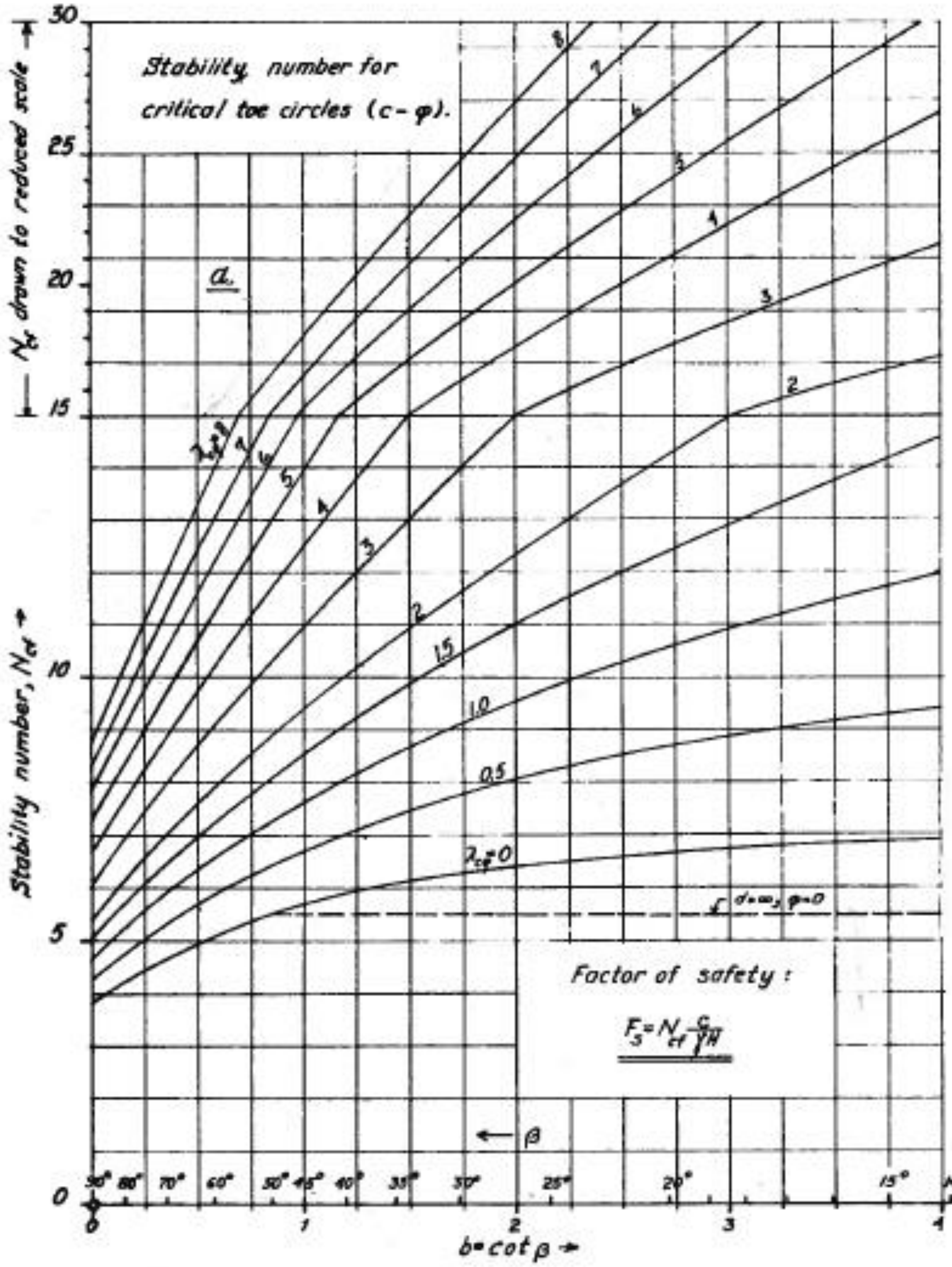

FIGURE A- 7 STABILITY NUMBER FOR SIMPLE SLOPES WHENΦ> 0