Swedge

Probabilistic analysis of the geometry and
stability of surface wedges

Verification Manual

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Introduction

This document presents several examples, which have been used as verification problems for the program SWEDGE. SWEDGE is an engineering analysis program for assessing the stability of wedges formed in rock slopes, produced by Rocscience Inc. of Toronto, Canada.

The first examples presented here, are based on examples and case studies presented in Kumsar, Aydan, and Ulusay (2000) [ref.1]. In ref. [1], lab tests were performed on wedge models. The results of these lab tests were used to confirm the validity of a limit equilibrium analysis method presented in Kovari and Fritz (1976) [ref. 2]. Two wedge examples presented by Priest [ref. 3] are also verified here.

The results produced by SWEDGE agree very well with the documented examples, and confirm the reliability of results produced by SWEDGE.

1.1 Introduction

Here we begin a static stability assessment (SSA) to verify that the SWEDGE program written by Rocscience Inc. computes values using the correct equations. The equations we will use to verify the results produced by SWEDGE, were originally presented by Kovari and Fritz (1976). These equations were later shown to be valid, by laboratory tests of wedge models discussed in ref. [1]. In the following example problem, a wedge with joints having the same dip allows a maximum wedging effect. A tension crack is not present.

1.2 Equations

The following equations were all verified against lab samples [1].

$$SF = \lambda \frac{\cos i_a \tan \phi}{\sin i_a} \quad (1)$$

$$\lambda = \frac{\cos \omega_1 + \cos \omega_2}{\sin(\omega_1 + \omega_2)} \quad (2)$$

$$\omega_1 + \omega_2 = 2\omega \quad (3)$$

θ is the apparent frictional angle due to the geometric configuration of the wedge. ϕ is the friction angle. λ is the wedge factor by Kovári and Fritz. ω is the half wedge angle. ω_1 and ω_2 are the angles between the surfaces of each joint with the vertical respectively. Notice that $\omega_1 = \omega_2 = \omega$. i_a is the inclination angle (or intersection angle).

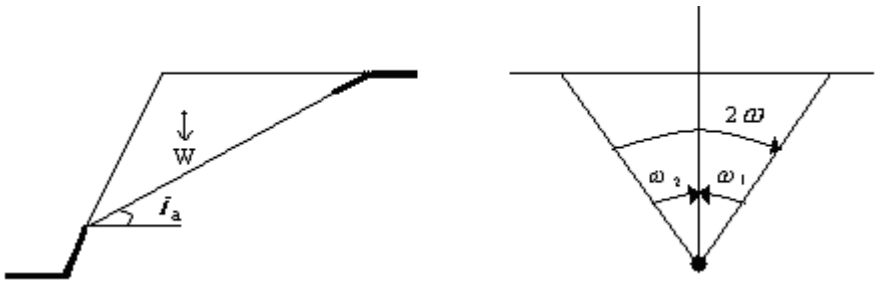


Figure 1.1 - Front and side cross-sectional views of a wedge without a tension crack

1.3 Description

Here we show the calculation process for a specific wedge (using the proven equations above), and then we use a graphed plot to get the inclination angle (ia). If the SWEDGE program will compute the same inclination angle and produce the similar plot as in ref. [1] (Figure 1.2), we then will know that it is functioning correctly. The plot is shown in Figure 1.3 and is based on a safety factor, SF = 1.

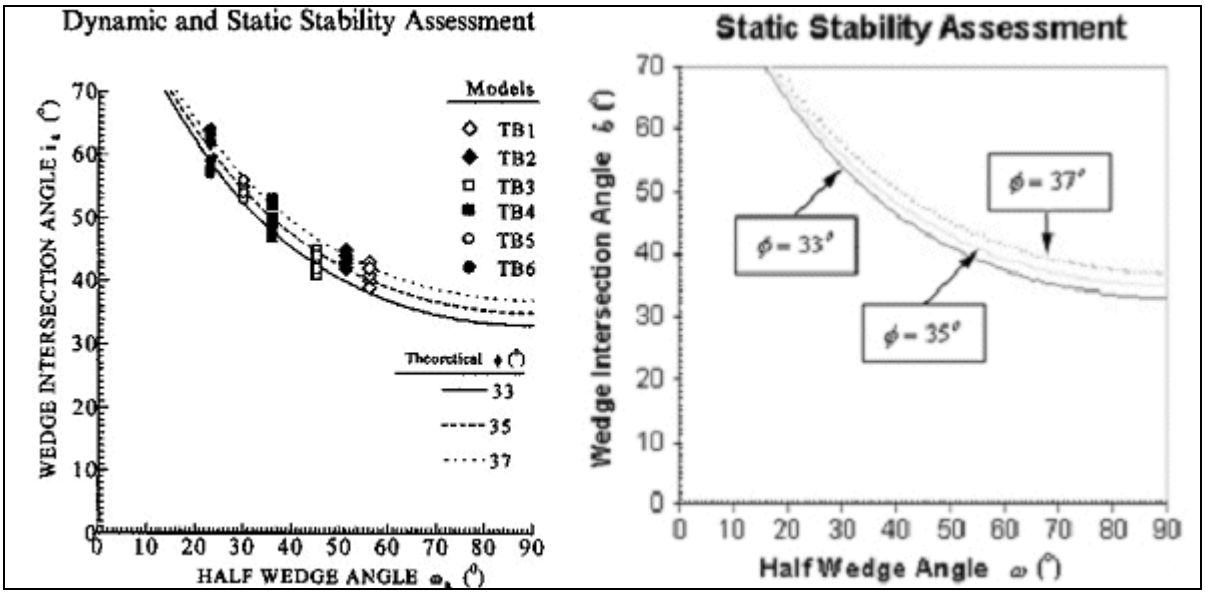


Figure 1.2 - The Comparison of the dry-static model test results with theoretical solutions from ref. [1]

Figure 1.3 - The graph lines are based on ϕ = 33^0, 35^0, 37^0 generated by the SWEDGE program. SF = 1.

Note: λ is simplified to $\lambda = \dfrac{1}{\sin\omega}$

When ω is calculated, and ϕ is chosen, a corresponding intersection angle can be found using Figure 3 - all which is based on equation (1).

Normal vectors to the joint planes have components:
l = sin(dip) x cos(dip direction)
m = sin(dip) x sin(dip direction)
n = cos(dip)

Table 1.1: Sample set of values where $\omega_1 = \omega_2 = \omega$.

Joint #	Dip (^{0})	Dip Direction (^{0})	l	m	n
1	45	141	-0.777	0.629	0.707
2	45	219	-0.777	-0.629	0.707

By inputting the above values (Table 1) for dip and dip direction for the joints in the 'input data' screen of the SWEDGE program, it shows us that we have a SF $\cong$ 1. Referring back to Figure 1, the normal vectors to the planes of joints 1 and 2 intersect. 2ω is equal to their obtuse angle of intersection.

Angle between vectors → $\cos\alpha = \dfrac{a \bullet b}{\|a\| \times \|b\|} = (0.777)^2 - (0.629)^2 + (0.707)^2$

$\therefore \quad \omega = \dfrac{180 - \alpha}{2} = 67.53^0$

Now that the half wedge angle ($\omega = 67.53^0$) is known, an intersection angle can be traced out using the graph of Figure 3. Let us choose the line plotted for $\phi = 35^0$. The intersection angle (if *approximately* traced using a pencil) is about $i_a = 37^0$. The equations used have been validated by experimental results [1]. The plotted graph that is based on equation (1) is also correct. All that is needed now is to verify that SWEDGE creates the same intersection angle.

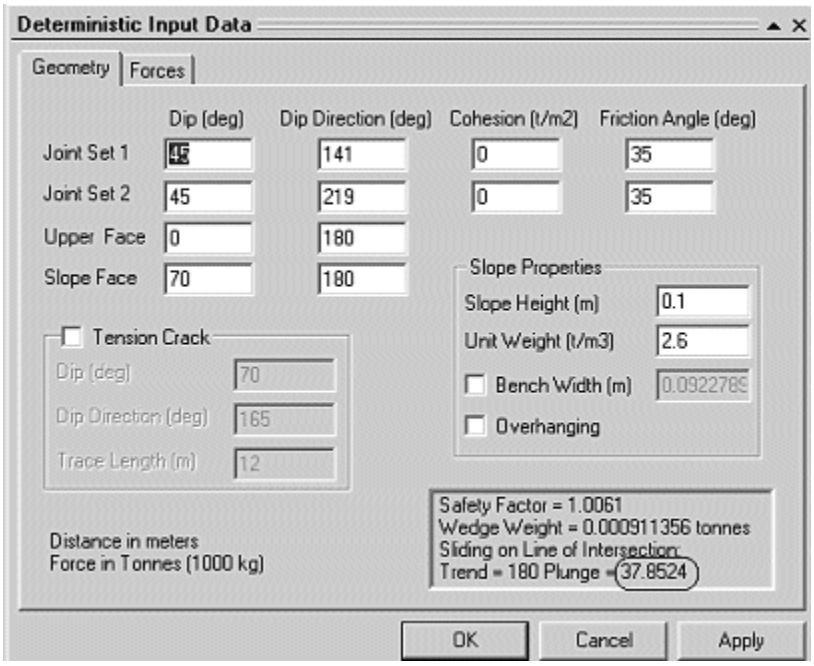


Figure 1.4 – Geometry input data

By inserting the settings from Table 1 into the input data dialog window within the SWEDGE program and clicking the 'Apply' button, the Plunge (or i_a) = 37.85 ^{0}. This is the same value as that which we traced out by hand before. Notice that the plunge is not affected by changing the slope height, unit weight, or values for the upper face and slope face. Such values are not included within the equations we used and therefore should not affect the plunge.

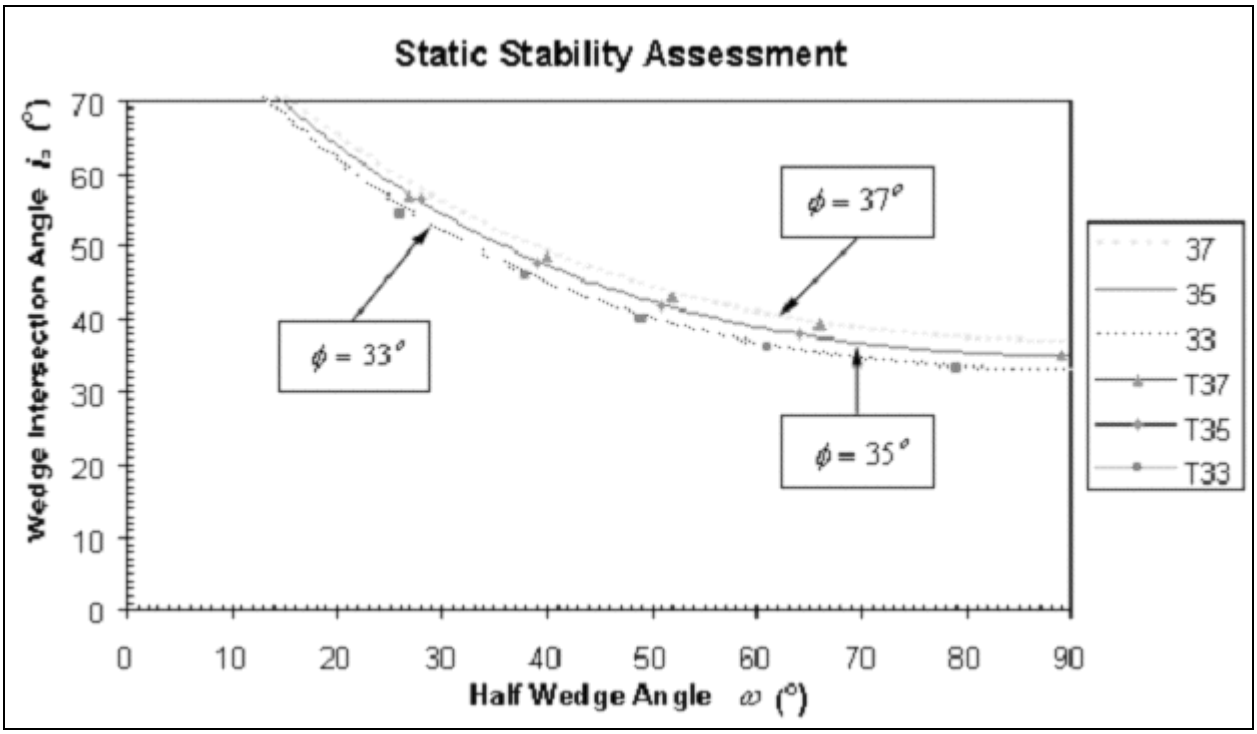


Figure 1.5 - Tests performed with different ω angle values all with a SF = 1. Separate tests were done for specific ϕ values in the same way. For example, T33 measures a specific test for a friction angle of 33^0.

We have now verified that SWEDGE works for this example problem. Many more tests were made as shown in Figure 1.5. Each test was done with the same method as this example problem. For example, T33 stands for a test done with a friction angle of 33^0. Many values were derived and lie on the line on which their friction angle is based in the graph of Figure 1.5. It should be noted that the wedge created in this exercise as well as the others tested were symmetrical not only due to the dip but also in dip direction. When viewing the 'front' view in the SWEDGE program, the wedge has symmetry. To make this symmetry, we maintained the dip directions with a sum of 360^0. Symmetry was maintained in order to reproduce the conditions for the model wedges that were described in [1].

2.1 Introduction

In the previous verification example, we tested SWEDGE for static stability. The SWEDGE program will now be used for a dynamic stability assessment (DSA). In this experiment, we will set the intersection angle at certain values yielding SF > 1. The dips will once again be identical for both joints and the dip directions will sum up to 360^0 for symmetry. If a seismic co-efficient will be included in the analysis within SWEDGE, a safety factor SF = 1 can be generated. Wedge acceleration will be calculated from this seismic coefficient and then compared to a graph. The equations we use to verify those used within SWEDGE have been validated by experimental results [1]. There is no tension crack.

2.2 Equations / Derivations

The following equations were all verified from lab samples [1].

$$SF = \frac{\lambda(\cos i_a - \eta \sin(i_a + \beta))\tan\phi}{\sin i_a + \eta \cos(i_a + \beta)} \quad (1)$$

β = 0 (seismic forces have a horizontal trend – refer to figure 1) (2)

$$\omega_1 + \omega_2 = 2\omega \quad (3)$$

$$\lambda = \frac{\cos\omega_1 + \cos\omega_2}{\sin(\omega_1 + \omega_2)} = \frac{1}{\sin\omega} \quad (4)$$

$$\therefore \quad SF = \frac{\lambda(\cos i_a - \eta \sin i_a)\tan\phi}{(\sin i_a + \eta \cos i_a)} = 1 \quad (5)$$

$$\eta = \frac{\lambda \cos i_a \tan\phi - \sin i_a}{\cos(i_a + \beta) + \lambda \sin(i_a + \beta)\tan\phi} \quad (6)$$

$$\therefore \eta = \frac{\cos i_a \tan\phi - \sin i_a \sin\omega}{\cos i_a \sin\omega + \sin i_a \tan\phi} \quad (7)$$

$$\eta = \frac{a}{g} \quad (8)$$

λ is the wedge factor by Kovári and Fritz (1975) [2]. ω is the half wedge angle. ω_1 and ω_2 are the angles between the surfaces of each joint with the vertical respectively. Notice that $\omega_1 = \omega_2 = \omega$. i_a is the inclination angle (or intersection angle). η is the seismicity coefficient. ϕ is the friction angle. β is the inclination of the dynamic force (labeled 'E' in figure 1). a, g are accelerations. g = 981 cm s^{-2}.

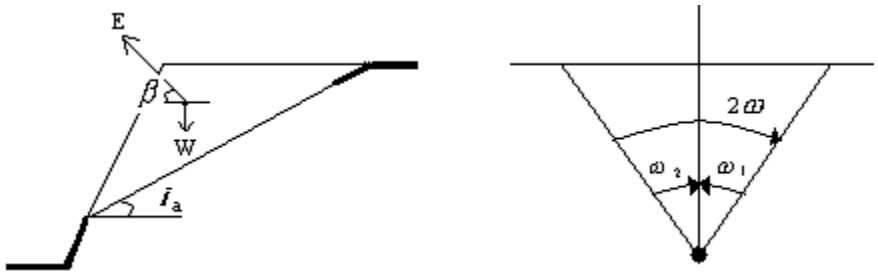


Figure 2.1 - Front and side cross-sectional views of a wedge without a tension crack. There is a dynamic force 'E' pointed at an inclination of β .

2.3 Description

We will now introduce the calculation process for a specific wedge (using the proven equations). It is now assumed (due to the previous verification exercise) that the inclination angle function in SWEDGE is working correctly. A plot is shown in Figure 2.2 that is based on a safety factor, SF = 1.

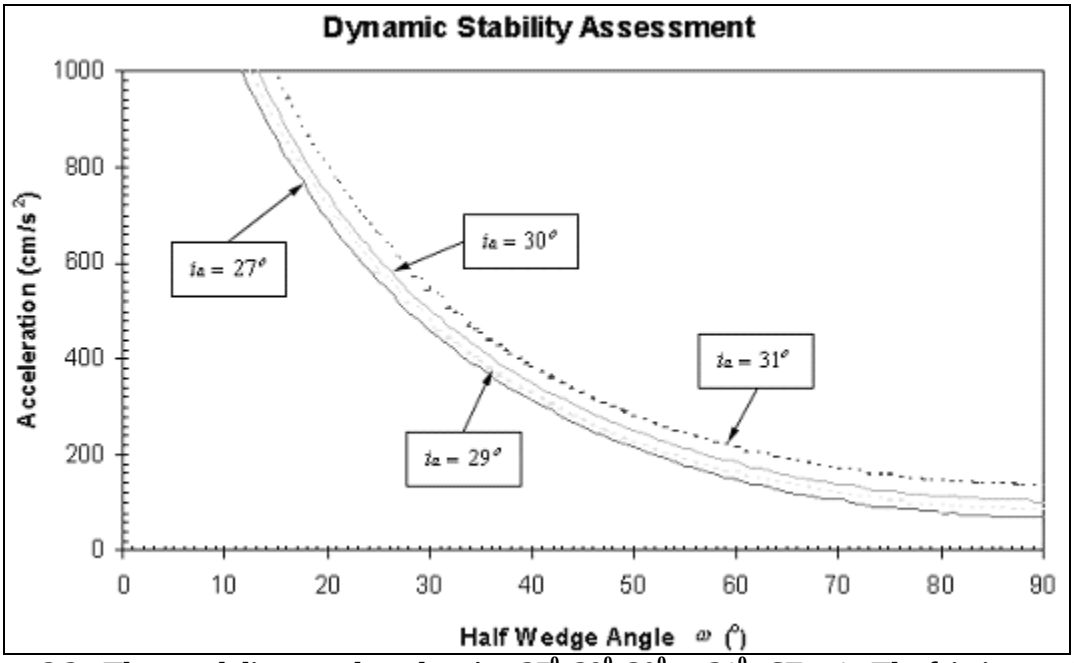


Figure 2.2 - The graph lines are based on $i_a = 27^0, 29^0, 30^0$ or 31^0. SF = 1. The friction angle is assumed to be $\phi = 35^0$.

We use the same procedure as in the SSA example problem to derive ω.

Normal vectors to the joint planes have components:
l = sin(dip) x cos(dip direction)
m = sin(dip) x sin(dip direction)
n = cos(dip)

Table 2.1: Sample set of values

Joint #	Dip (^{0})	Dip Direction (^{0})	l	m	n
1	50	119	-0.37139	0.669998	0.642788
2	50	241	-0.37139	-0.669998	0.642788

When we insert the above values for dip and dip direction for the joints in the 'input data' dialog of the SWEDGE program, SF = 1.6325 is computed which suggests that the wedge is statically stable. This is expected because the values in Table 1 were chosen specifically to get ia = 30.0182 $\cong$ 30. Remember that the plots in Figure 2 are based on 4 different inclination angles. Now, suppose there is a seismic force on the wedge. We seek a seismic coefficient which will lower the safety factor to SF = 1. To do so we use equation (7). We know the inclination angle (ia), the friction angle (ϕ = 350), and now we will solve for the wedge angle all in order to solve for the seismic coefficient (η).

Angle between vectors → $\cos\alpha = \dfrac{a \bullet b}{\|a\| \times \|b\|}$ = $(0.37139)^2$ - $(0.669998)^2$ + $(0.642788)^2$

$$\therefore \quad \omega = \frac{180 - \alpha}{2} = 47.93^0$$

Equation (7) is used to get a seismic coefficient which changes the safety factor to SF = 1.

$$\therefore \eta = \frac{\cos i_a \tan\phi - \sin i_a \sin\omega}{\cos i_a \sin\omega + \sin i_a \tan\phi} = \frac{\cos(30.0182)\tan(35) - \sin(30.0182)\sin(47.93)}{\cos(30.0182)\sin(47.93) + \sin(30.0182)\tan(35)} = 0.2365$$

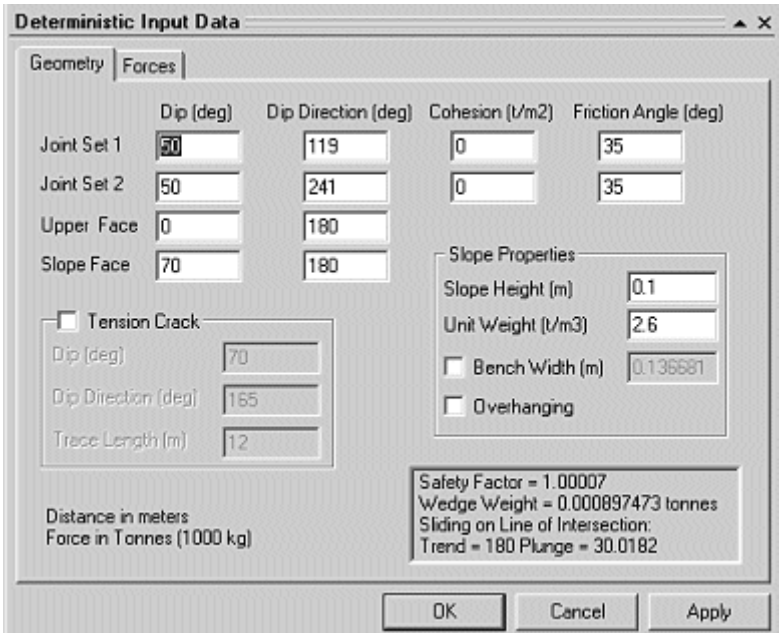


Figure 2.3 – Geometry input

Notice that the plunge (or i_a) in Figure 2.3 is not affected by changing the slope height, unit weight, or values for upper face and slope face. Such values are not factors in the equations we used and they do not affect the plunge.

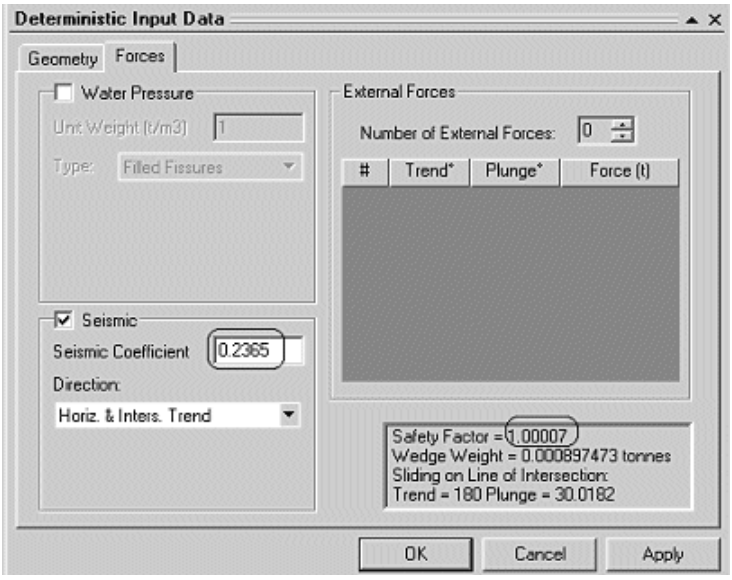


Figure 2.4 - Dynamic forces checked in the analysis input.

Since the safety factor has changed to SF = 1, we know that the analysis functions for SWEDGE in DSA are functioning correctly. To make sure that this is so, we can go a little further and see if the acceleration (derived from equation (8)) using the seismic coefficient in SWEDGE is equal to the acceleration range of the graph in Figure 2. The acceleration (if approximately traced using a pencil) is about 235 cm s^{-2}. By using equation (8), the acceleration from the seismic coefficient (shown in Figure 4) is 232 cm s^{-2}. Such an accurate result justifies the reliability of the SWEDGE program.

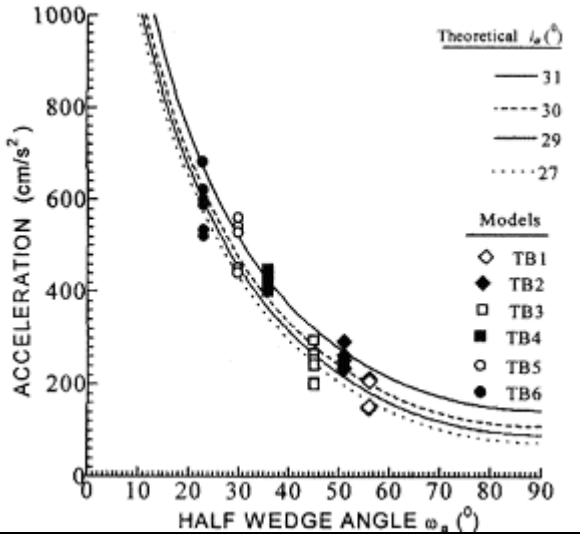


Figure 2.5 - Comparison of the dynamic model test results with theoretical solutions from ref. [1]

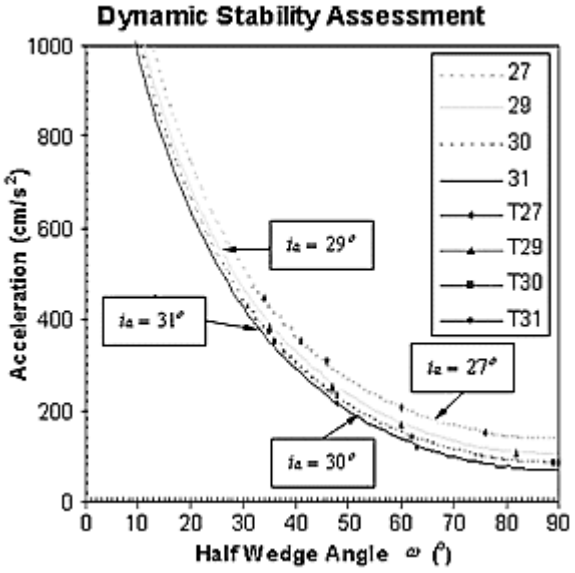


Figure 2.6 - Tests performed with different ω angle values all with a SF = 1. Separate tests were done for specific i_a values. All tests were done in the same way for DSA.

The SWEDGE program is now verified to work for this specific example. Many more tests were made as shown above in figure 6. Each test was done with the same method as this example problem. For example, T30 stands for a test done with an inclination angle of 30^0. Many values were derived and lie on the line on which their inclination angle is based in the graph of Figure 2.6.

3.1 Introduction

This example verification is based on the case study presented as "case 3" on page 43 of reference [1]. A rock mass near Ankara Castle in Bent Deresi region of Ankara City had a wedge failure. The authors of [1] studied this wedge and found that the wedge block was unstable. During their analysis, they found that the friction angle was $\phi = 30^0$. There was a stability assessment with dry-static conditions. The experiment yielded a safety factor of SF = 0.73. In the following, we will verify that SWEDGE will give the same safety factor.

3.2 Geometry and Properties

Table 3.1: Stereonet on p.46, Fig. 13 (c), [1]

	Dip (deg)	Dip Direction (deg)
Joint #1	45	195
Joint #2	70	105
Slope	70	160

Table 3.2: Geometrical characteristics of the wedge on p.46, Fig. 13 (c), [1]

Parameter	Value
ω_1 **(degree)**	77
ω_2 **(degree)**	28
i_a **(degree)**	42

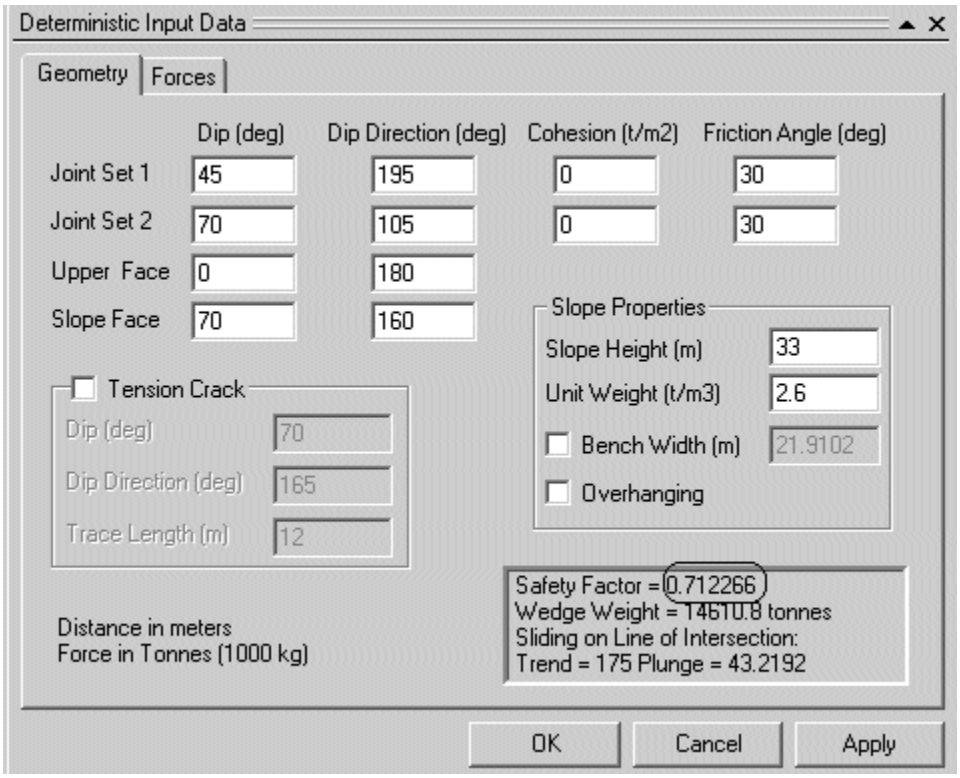


Figure 3.2 – Geometry analysis input.

3.3 Conclusion

From Figure 2, the safety factor is SF = 0.71. Such a result was expected when compared to the result of the experiment for which this exercise is based on. The SWEDGE program has verified the experimental result taken from p.45 [1].

4.1 Introduction

This example is based on the case study presented as "case 4" on page 45 of reference [1]. In this case study, we turn to the town of Dinar in western Turkey. This area has many earthquakes and therefore in this analysis verification we will make both static and dynamic assessments. The author of reference [1] made a wedge analysis and the wedge friction angle was determined to be $\phi = 40.8^0$. The first analysis (before an earthquake occurred) yielded a safety factor of SF = 2.02. A second test was made during dynamic conditions and a safety factor of SF = 0.99 was found. In the following analysis using SWEDGE, we will verify that SWEDGE gives the same results as the experiment. For more information, refer to p.45, [1].

4.2 Geometry and Properties

Table 4.1: Stereonet on p.47, Fig. 14 (b), [1]

Plane	Dip (deg)	Dip Direction (deg)
Joint #1	75	33.5
Joint #2	75	248
Slope	75	337.5

Table 4.2: The information above can be used to calculate the same results as shown in SWEDGE.

Parameter name	Value
ω_1 (degree)	17
ω_2 (degree)	25
i_a (degree)	50
Friction angle (degree)	40.8
β (degree)	0
a_{max} in NS direction (cm/s^2)	282
a_{max} in EW direction (cm/s^2)	324

By inserting the values from Table 4.1 into SWEDGE, the result for the safety factor will be SF = 2.02 as shown below in Figure 4.1.

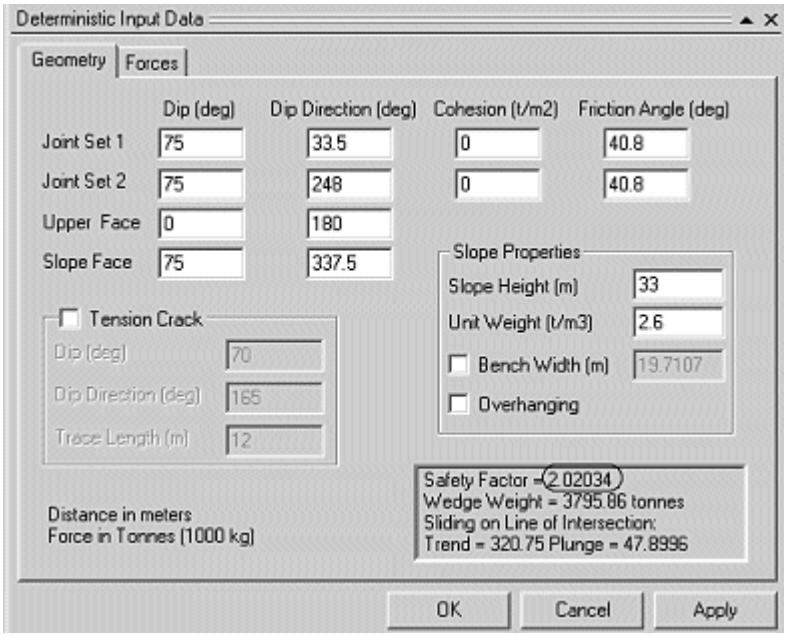


Figure 4.1 - Analysis input within SWEDGE.

From Table 4.2, the maximum acceleration is in the east – west direction. Suppose that this acceleration is in the same direction as the intersection angle of the wedge to be considered. We can then say that this is dynamically the worst condition for stability. Therefore, we choose $a = 324$ cm/s^2. The seismic co-efficient is:

$$\eta = \frac{a}{g} \quad (\text{where } g = 981 \text{ cm/s}^2) \qquad \therefore \eta = \frac{324}{981} = 0.3303$$

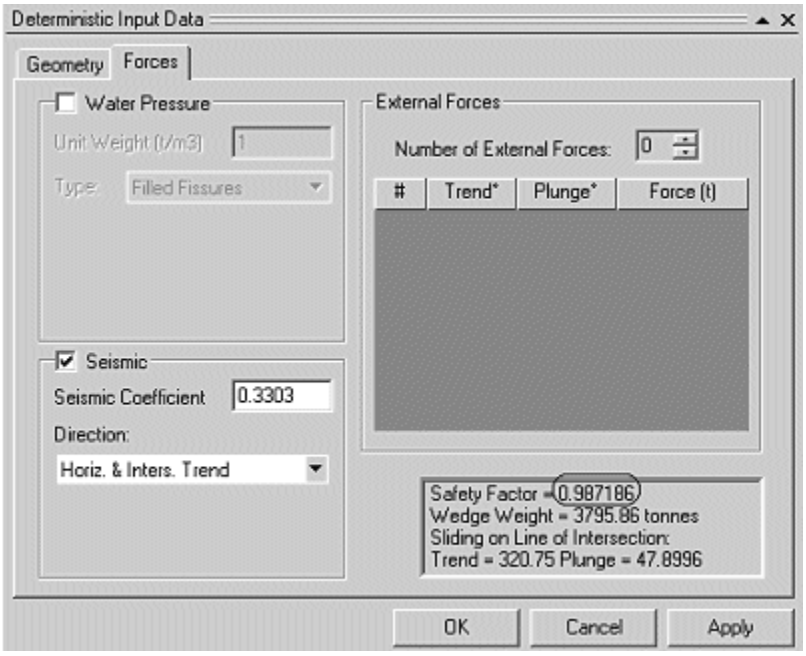


Figure 4.2 - Analysis input within SWEDGE

4.3 Conclusions

When inserting the calculated seismic coefficient, we get a safety factor of SF = 0.99 as shown above in Figure 2.

The safety factors determined by SWEDGE are equal to those that were found experimentally as written in [1]. Therefore SWEDGE has been confirmed for dynamic stability assessment with respect to the safety factor, for this example.

5.1 Introduction

This example is based on the "case 5" study on p.46 of reference [1]. In this case study, we study a wedge failure at Mt. Mayuyama (Japan), which occurred in 1792. This failure occurred after an earthquake. The authors of reference [1] made a few tests to determine the possible mechanisms of the wedge failure. Four conditions were considered in this analysis. We will use SWEDGE to verify the results of their experiments. The details of this experiment are written starting on p. 46, [1]. We utilized the following equations and information for each condition on p. 49, [1] to plot the graph shown in Figure 5.2. In this verification problem, we will use joints 1 and 2 for verification.

5.2 Geometry and Properties

Parameter	Value
ω_1 (degree)	54
ω_2 (degree)	54
i_a (degree)	23

The following equations were all verified from lab samples in [1].

$$SF = \frac{[\lambda[W(\cos i_a - \eta \sin(i_a + \beta)) + U_s \sin i_a + U_t \cos i_a] - \alpha U_b]\tan\phi + c(A_1 + A_2)}{W(\sin i_a + \eta \cos(i_a + \beta)) - U_s \cos i_a + U_t \sin i_a} \quad (1)$$

$$\lambda = \frac{\cos\omega_1 + \cos\omega_2}{\sin(\omega_1 + \omega_2)} \quad (2)$$

$$U_b = U_{bs} + U_{be} = (\gamma_s + \gamma_e)\, W \quad (3)$$

$$U_b = U_{b1} \sin\omega_1 + U_{b2} \sin\omega_2 \quad (4)$$

λ is called the wedge factor by Kovári and Fritz (1975) [2]. i_a is the inclination angle. β is the inclination angle of a dynamic force. ω_1 and ω_2 are the half wedge angles. Since both are equal to 54^0, $\omega_1 = \omega_2 = \omega$, the half wedge angle. U_s and U_t are the water forces acting on the face and the upper part of the slope (if such forces are there). A_1 and A_2 are the joint surface areas. U_b is a force caused by fluid pressure that has components normal to each joint. U_b itself is the force, which points vertically, hence the trigonometric system shown in equation (4). All these are shown below in figure 1. We will refer to figure 1 often to assure our calculations. γ_s and γ_e are the static and excess fluid pressure coefficients respectfully.

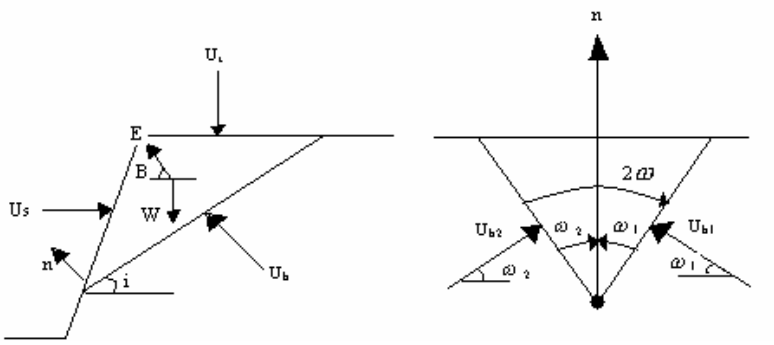


Figure 5.1 - Front and side cross-sectional views of a wedge without a tension crack.

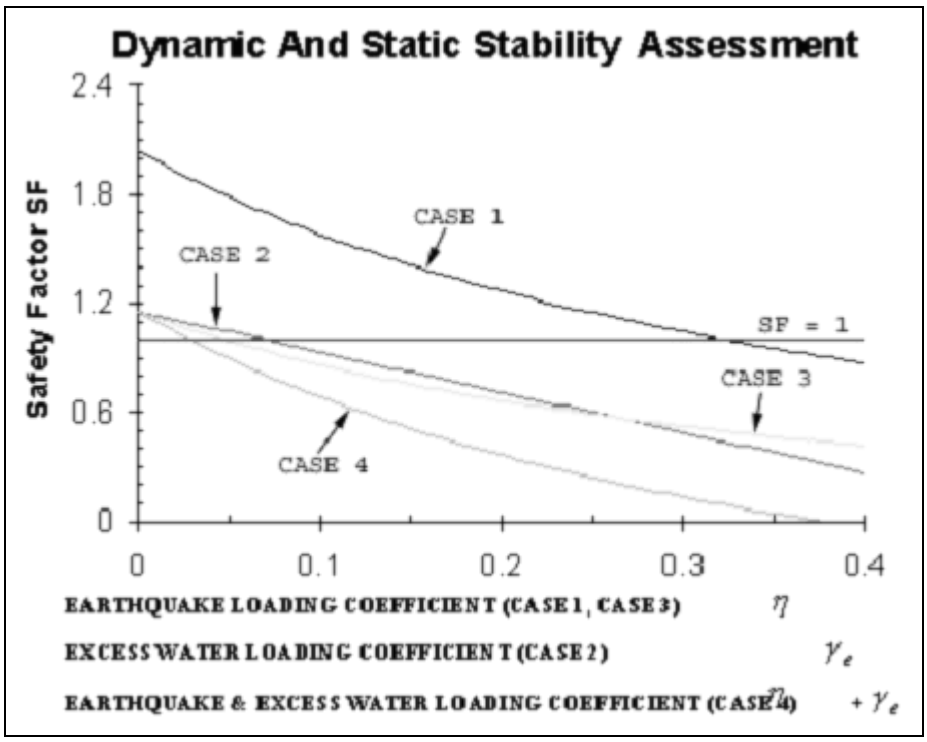


Figure 5.2 - The comparison of case results for the wedge failure at Mt. Mayuyama as described on p.49, [1].

Note that to derive the equations for this graph we took a friction angle $\phi = 35^o$.

CASE 1:

Here we have a mass of dry rock and there is an earthquake present. The seismic coefficient (η) is constantly increasing from 0.0 to 0.5 as described in Figure 2. On p.49, [1] the following is given:

$c = 0;\quad U_s = 0;\quad U_t = 0;\quad U_b = 0;\quad \alpha = 1;\quad \beta = 0$

$$\therefore SF = \frac{\lambda(\cos i_a - \eta \sin i_a)\tan\phi}{\sin i_a + \eta \cos i_a}$$

$$\lambda = \frac{2\cos 54^0}{\sin(2 \bullet 54^0)} = \frac{1}{\sin 54^0}$$

$i_a = 23^0$

$$\therefore SF = \frac{(\tan 35^0)}{(\sin 54^0)} \frac{(\cos 23^0 - \eta \sin 23^0)}{(\sin 23^0 + \eta \sin 23^0)} \qquad (5)$$

Equation (5) is used to plot the line in Figure 2 for CASE 1. Notice (from Figure 2) that when the seismic coefficient is $\eta \cong 0.32$, we reach a point on the line where the safety factor is SF = 1. By inserting this into an SWEDGE analysis, we should find that SF =1 there as well. The settings for dip and dip directions are found in figure 3 and are the same for all the cases.

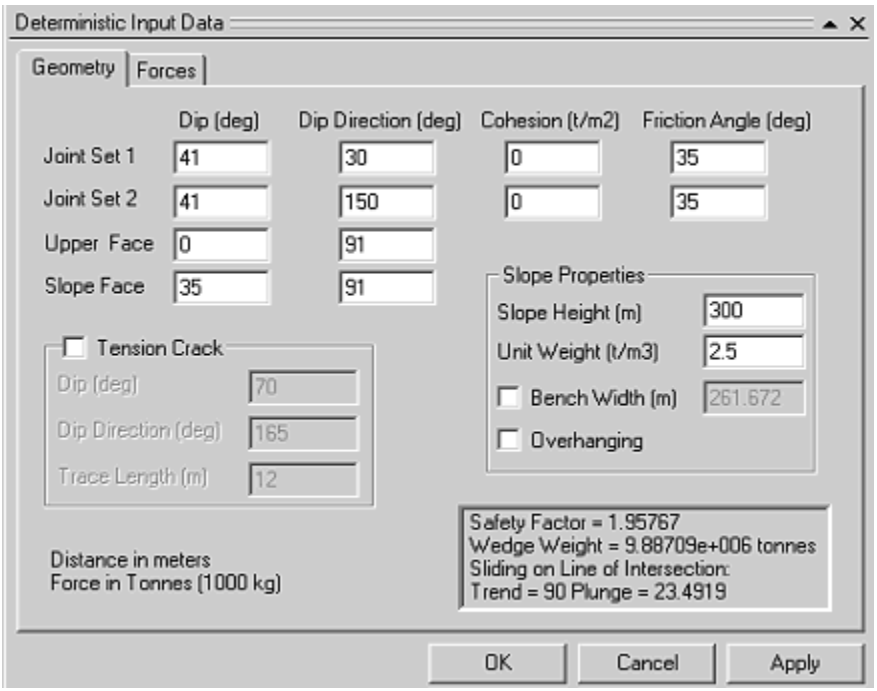


Figure 5.3 - Analysis input within SWEDGE. Values taken from the stereonet located on p.48 ,[1].

If we insert the seismic coefficient just discussed into the analysis, the safety factor will change to the value of SF $\cong$ 1. This once again will verify SWEDGE with the equations used in reference [1]. The result is shown in Figure 4 below.

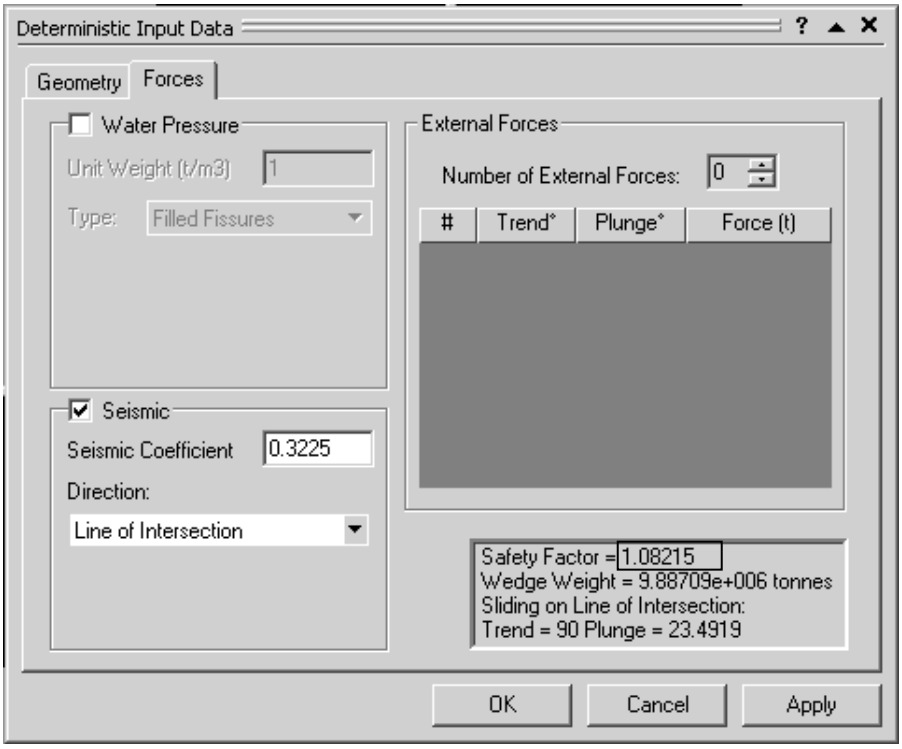


Figure 5.4 - Analysis input for forces

CASE 2:

In this case we know that the excess fluid pressure (γ_e) is changing as the domain in Figure 2 from 0.0 to 0.5. The static fluid pressure is constant at γ_s = 0.4. On p.49, [1], the following is given:

$$c = 0;\quad U_s = 0;\quad U_t = 0;\quad U_b = 0;\quad \alpha = 1;\quad \beta = 0;\quad \eta = 0$$

Static fluid pressure: $U_{bs} = \gamma_s$ W

Excess fluid pressure: $U_{be} = \gamma_e$ W

$$\therefore U_b = (0.4 + \gamma_e)W$$

$$\therefore SF = \frac{(\lambda \cos i_a - 0.4 - \gamma_e)\tan\phi}{\sin i_a}$$

$$\lambda = \frac{2\cos 54^0}{\sin(2 \bullet 54^0)} = \frac{1}{\sin 54^0}$$

$i_a = 23^0$

$$SF = \frac{(\tan 35^0)}{(\sin 23^0)}\frac{(\cos 23^0 - 0.4 - \gamma_e)}{(\sin 54^0)} \qquad (6)$$

Equation (6) is used to plot the line in Figure 2 for CASE 2. Notice (from Figure 2) that when the excess fluid pressure coefficient is γ_e=0.06, we reach a point on the line where the safety factor is SF = 1. By inserting this into an SWEDGE analysis, we should find that SF =1 there as well. The settings for dip and dip directions are found in figure 3 and are the same for all the cases.

We will now utilize the SWEDGE program for water forces analysis of the wedge. The following is a derivation of how much pressure is put on the surface of each joint. A few assumptions were made.

$U_b = U_{b1} \sin\omega_1 + U_{b2} \sin\omega_2$

$U_b = P_1A_1 \sin\omega_1 + P_2A_2 \sin\omega_2$ (P is pressure (t/m^2) and A is surface area of each joint)

Click on the info viewer within SWEDGE and make sure that the analysis input is set up to that shown in figure 3. When inside the infoviewer, you will be given the wedge weight and the two joint areas.

Wedge weight = 9.88709e+006 tonnes
Wedge area (joint1) = 68404.6 m^2
Wedge area (joint2) = 69797.4 m^2

Assume: $P_1 \cong P_2 \cong P$

$A_1 \cong A_2 \cong A$

$\omega_1 \cong \omega_2 \cong \omega$

ω

$\therefore P = U_b \big/ 2A\sin\omega$

A = average = 69101 m^2
W = 9.88709e+006 tonnes
At γ_e = 0.06, $\therefore U_b = (0.4 + 0.06)(9.88709e + 006)$ = (4.548e+006) tonnes

$$\therefore P = (4.548e + 006) \big/ 2(69101)\sin 54^0 = 40.6 \ \frac{tonnes}{m^2}$$

In this case, we increase the friction angle from $\phi = 35^0$ to $\phi = 36^0$. Notice that this will not change the settings for weight or surface area of the joints. Based on the stereonet, the friction angle is simply within the range of 35 and 40 degrees. By changing it to a friction angle of $\phi = 36^0$, we achieve a better accuracy. Below, the safety factor turns to SF $\cong$ 1.

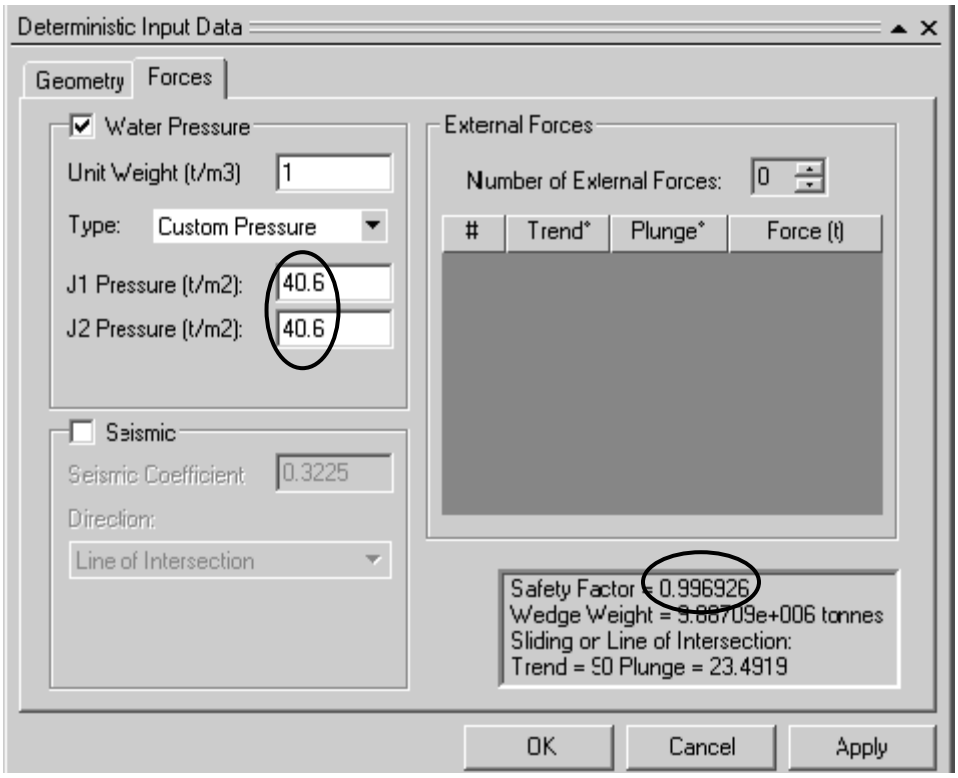


Figure 5.5 - Custom pressure force is chosen for each wedge.

Our assumptions were valid due to the areas being almost the same and the SWEDGE program yielding a safety factor of SF = 1.

CASE 3:

Now we have a mass of rock where there is an earthquake present with increasing seismicity. The seismic coefficient (η) is constantly increasing from 0.0 to 0.5 as described in Figure 2. On p.49, [1] the following is given:

$$c = 0; \quad U_s = 0; \quad U_t = 0; \quad \alpha = 1;$$

The fluid pressure was kept constant during the earthquake.

$$\therefore SF = \frac{\lambda[W(\cos i_a - \eta \sin i_a) - U_b]\tan\phi}{W(\sin i_a + \eta \cos i_a)}$$

$$U_b = (0.4 + \gamma_e)W$$

$$\gamma_{e=0} \qquad \therefore U_b = 0.4W$$

$$\therefore SF = \frac{(\cos 23^0 - \eta \sin 23^0 - 0.4)(\tan 35^0)}{(\sin 23^0 + \eta \cos 23^0)(\sin 54^0)} \qquad (7)$$

Equation (7) is used to plot the line in Figure 2 for CASE 3. Notice (from Figure 2) that when the seismic coefficient is η = 0.05 we reach a point on the line where the safety factor is SF = 1. Remember that the equation used for this plot is based on a constant fluid pressure. By inserting values for the seismic coefficient and also the fluid pressure into an SWEDGE analysis, we should find that SF =1 there as well.

We will now utilize SWEDGE for an analysis of the constant water and seismic forces. The following is a derivation of how much pressure is put on the surface of each joint.

$$U_b = 0.4W$$

$$W = 9.887e+006 \qquad \therefore U_b = 3.955e+006 \text{ tonnes}$$

$$P = U_b \big/ 2A\sin\omega \qquad \therefore P = (3.955e+006) \big/ 2(69101)\sin 54^0 = 35.35 \ \frac{tonnes}{m^2}$$

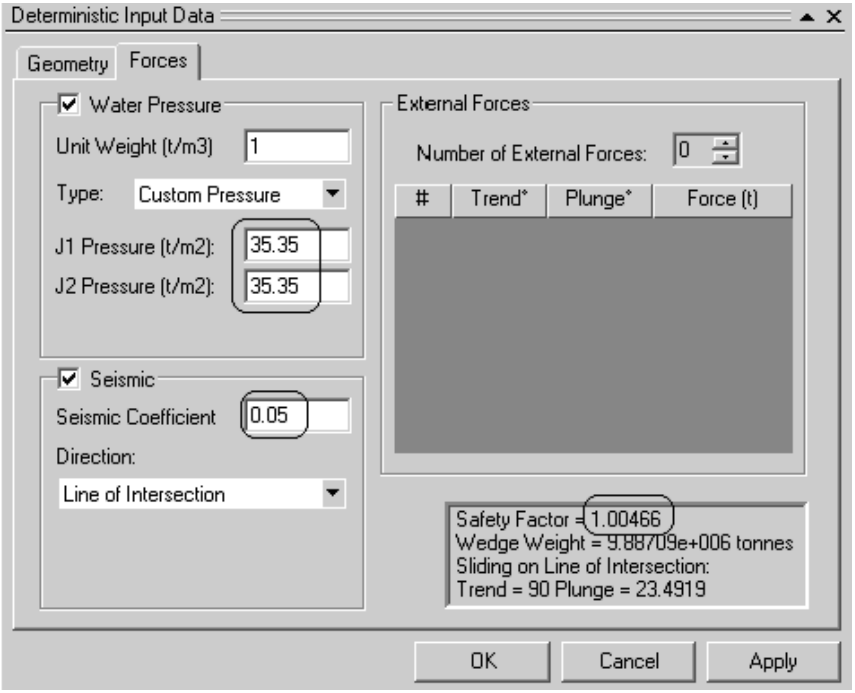


Figure 5.6 - Custom seismic force is chosen for each wedge. The static pressure is constant and there is no excess fluid pressure.

SWEDGE is now verified with the 3rd case of this verification exercise. Our assumptions were valid due to the areas being almost the same and SWEDGE yielding a safety factor of SF = 1.

CASE 4:

Here we have a mass of rock and there is an earthquake present. Both the seismic coefficient (η) and the excess fluid pressure (γ_e) are constantly increasing (at the same time) from 0.0 to 0.5 as described in Figure 2. On p.49, [1] the following is given:

$$c = 0; \quad U_s = 0; \quad U_t = 0; \quad \alpha = 1;$$

$$\therefore SF = \frac{\lambda[W(\cos i_a - \eta \sin i_a) - U_b]\tan\phi}{W(\sin i_a + \eta \cos i_a)}$$

$$U_b = (0.4 + \gamma_e)W$$

$$\therefore SF = \frac{(\cos 23^0 - \eta \sin 23^0 - 0.4 - \gamma_e)\tan 35^0}{(\sin 54^0)(\sin 23^0 + \eta \cos 23^0)} \qquad (8)$$

Equation (8) is used to plot the line in Figure 2 for CASE 3. Notice (from Figure 2) that when $\eta = \gamma_e = 0.02$, the safety factor is SF = 1. We will now verify this with SWEDGE.

$$U_b = U_{bs} + U_{be} = (0.4 + 0.02)W$$

$$W = 9.887e + 006$$

$$\therefore U_b = 4.153e + 006 \; tonnes$$

$$P = U_b \big/ 2A\sin\omega$$

$$\therefore P = (4.153\text{e} + 006) \big/ 2(69101)\sin 54^0$$

$$= 37.14 \; \frac{tonnes}{m^2}$$

We will now insert the values for seismicity and pressure into the program as shown in Figure 5.7 below.

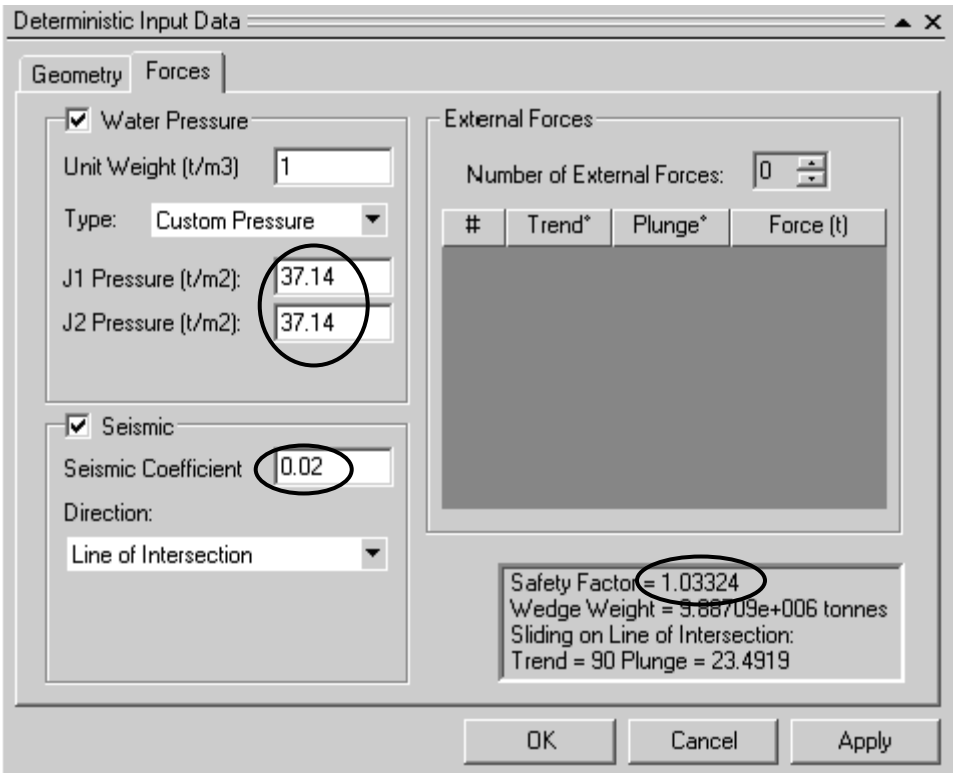


Figure 5.7 - Pressure and seismicity are changing at the same rate.

When both values are inserted above, equation (8) is satisfied by showing that the safety factor SF = 1. The SWEDGE program is now verified for this example. Our assumptions were valid due to the areas being almost the same and the SWEDGE program yielding a safety factor of SF = 1.

6.1 Introduction

This problem was taken from Priest (1993). It is his first example on 3-D plane sliding of tetrahedral blocks, and it demonstrates the double plane sliding mechanism. The fictitious example also includes an external force on the block due to infrastructure.

6.2 Description

Verification problem #6 models a non-overhanging rock slope with two planar discontinuities (orientations given in Table 6.1). A water table exists in this example, and is modeled by defining mean water pressure in each of the discontinuities equal to 5 kPa (joint 1) and 15 kPa (joint 2). A wedge volume of 45.20 m^3 is specified, which is equivalent to a wedge height of 6.7978 m. There is no tension crack. The unit weight of rock is 26 kN m^{-3}. The foundations of a pylon to be sited on the block will exert a force of 180 kN along a line of trend/plunge 168/70. Determine the factor of safety for the block.

6.3 Geometry and Properties

Table 6.1: Plane Orientation

Plane	Dip (deg)	Dip direction (deg)
Joint set 1	47	203
Joint set 2	52	287
Bench	5	225
Slope	60	230

Table 6.2: Discontinuity properties *

Joint Set	Cohesion (t/m^2)	Friction Angle (deg)	Mean Water Pressure (t/m^2)
1	1.0197	40	0.5099
2	2.0394	35	1.5296

* kPa units converted to tonnes / m^2

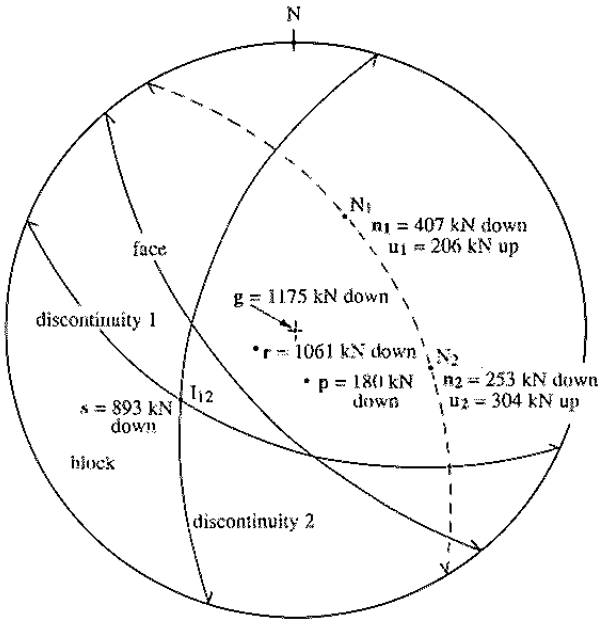


Figure 6.1 – Stereonet from Priest (1993). Note: upper face not shown.

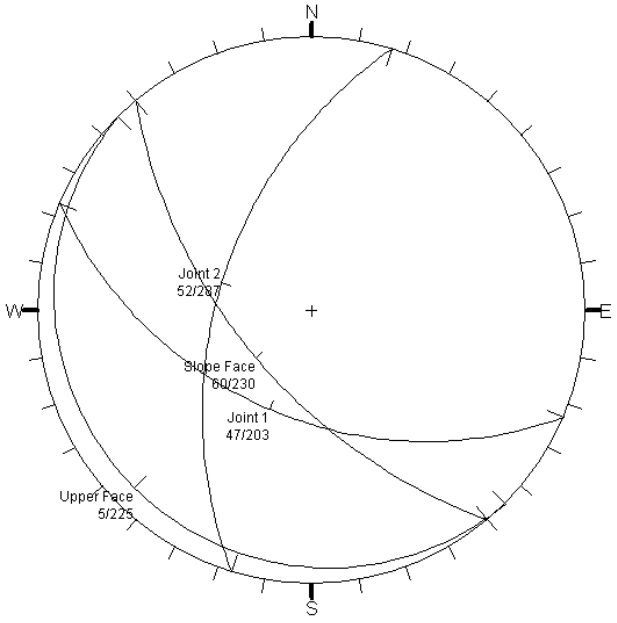


Figure 6.2 – Stereonet view of tetrahedral block in SWEDGE.

6.4 Results

SWEDGE Analysis Results:

Analysis type=Deterministic
Safety Factor=1.49663
Wedge height (on slope)=6.7978 m
Wedge width (on upper face)=4.24847 m
Wedge volume=45.2008 m3
Wedge weight=119.827 tonnes
Wedge area (joint1)=41.1469 m2
Wedge area (joint2)=20.4281 m2
Wedge area (slope)=38.955 m2
Wedge area (upper face)=21.2423 m2
Normal force (joint1)=41.4693 tonnes
Normal force (joint2)=25.5599 tonnes
Driving force=91.0797 tonnes
Resisting force=136.313 tonnes

Water Pressures/Forces:
Average pressure on joint1=0.5099 tonnes/m2
Average pressure on joint2=1.5296 tonnes/m2
Water force on joint1=20.9808 tonnes
Water force on joint2=31.2468 tonnes

Failure Mode:
Sliding on intersection line (joints 1&2)

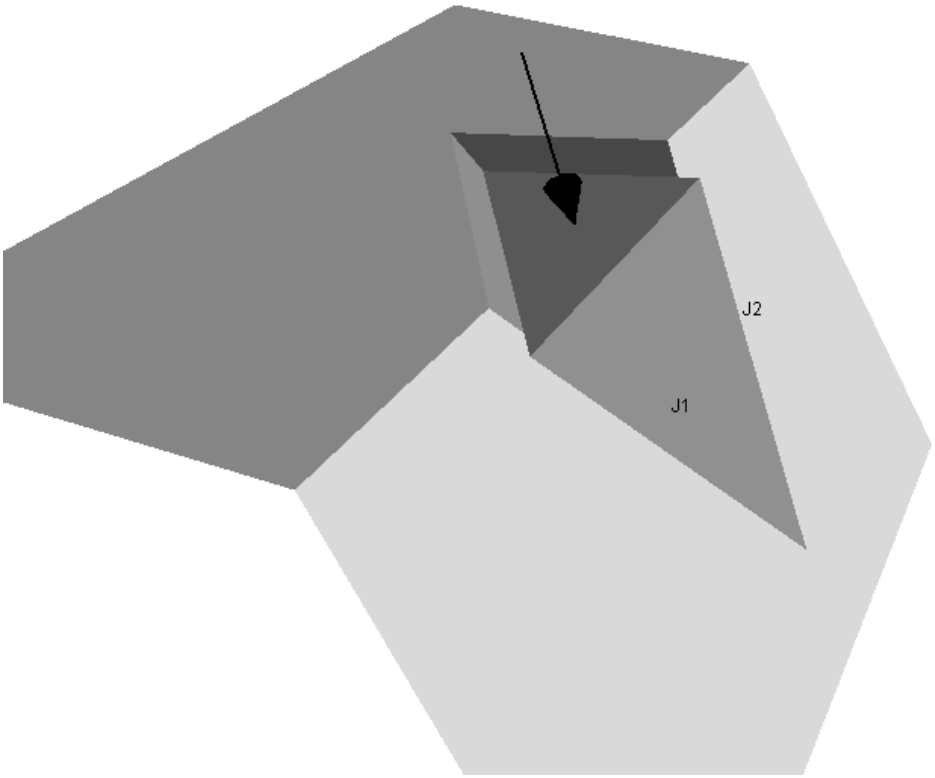


Figure 6.2 – The perspective view from SWEDGE of the modeled block and the external force.

Priest's Factor of Safety is $\cong 1.5$, which verifies that the results obtained from SWEDGE are correct. The failure mode also agrees with Priest's double plane sliding mechanism.

7.1 Introduction

This problem was taken from Priest (1993). It is his second example on 3-D plane sliding of tetrahedral blocks, and it demonstrates the single plane sliding mechanism, due to geometry and increased water pressure in one of the joint sets.

7.2 Description

Verification Problem #7 analyzes a non-overhanging planar rock slope with two joint sets, or discontinuities (Table 7.1). A water table exists in this example, and is modeled by defining mean water pressure in each of the discontinuities equal to 25 kPa (joint 1) and 15 kPa (joint 2). A wedge volume of 81.74 m^3 is specified, which is equivalent to a wedge height of 6.8471. There is no tension crack in this problem. The unit weight of rock is 25 kN m^{-3}. Determine the factor of safety for the block.

7.3 Geometry and Properties

Table 7.1: Plane Orientation

Plane	Dip (deg)	Dip direction (deg)
Joint set 1	74	65
Joint set 2	41	186
Bench	11	122
Slope	65	134

Table 7.2: Discontinuity properties *

Joint Set	Cohesion (t/m^2)	Friction Angle (deg)	Mean Water Pressure (t/m^2)
1	1.5296	32	2.5493
2	0.5099	40	1.5296

* kPa units converted to tonnes / m^2

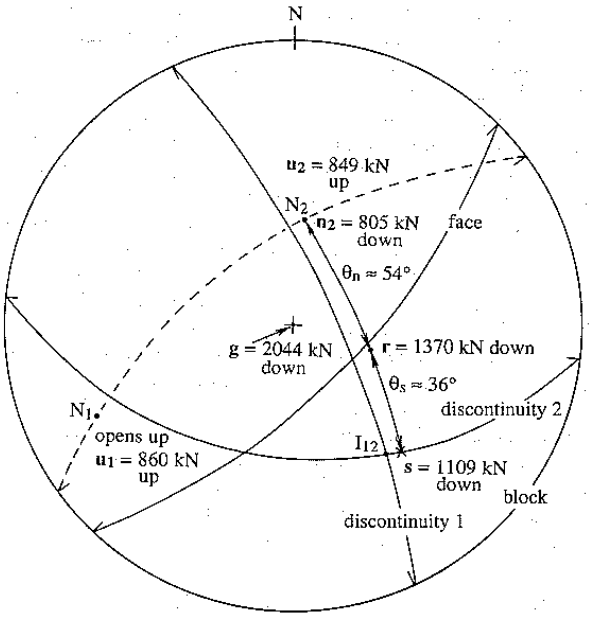


Figure 7.1 – Stereonet from Priest (1993). Note: Upper face not shown.

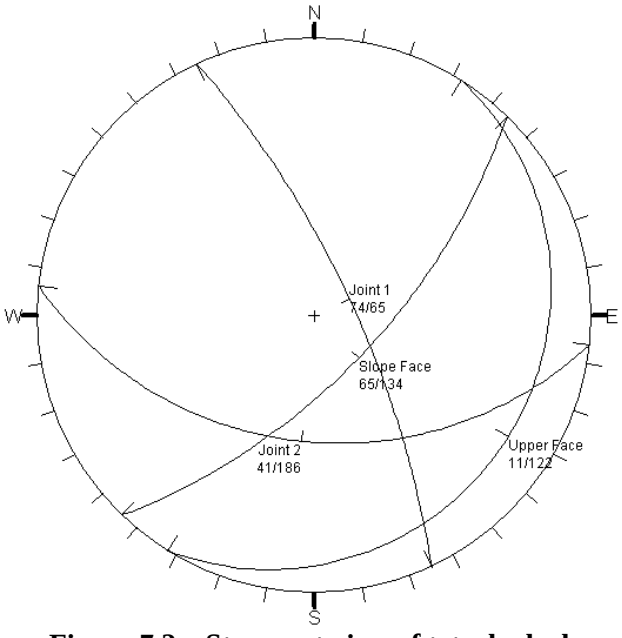


Figure 7.2 – Stereonet view of tetrahedral block in SWEDGE.

7.4 Results

SWEDGE Analysis Results:

Analysis type=Deterministic
Safety Factor=0.849299
Wedge height (on slope)=6.8471 m
Wedge width (on upper face)=10.0657 m
Wedge volume=81.741 m3
Wedge weight=208.382 tonnes
Wedge area (joint1)=34.3934 m2
Wedge area (joint2)=56.613 m2
Wedge area (slope)=30.0119 m2
Wedge area (upper face)=40.2627 m2
Normal force (joint1)= –10.8274 tonnes
Normal force (joint2)=79.6475 tonnes
Driving force=113.929 tonnes
Resisting force=96.7602 tonnes

Water Pressures/Forces:
Average pressure on joint1=2.5493 tonnes/m2
Average pressure on joint2=1.5296 tonnes/m2
Water force on joint1=87.6791 tonnes
Water force on joint2=86.5953 tonnes

Failure Mode:
Sliding on joint2

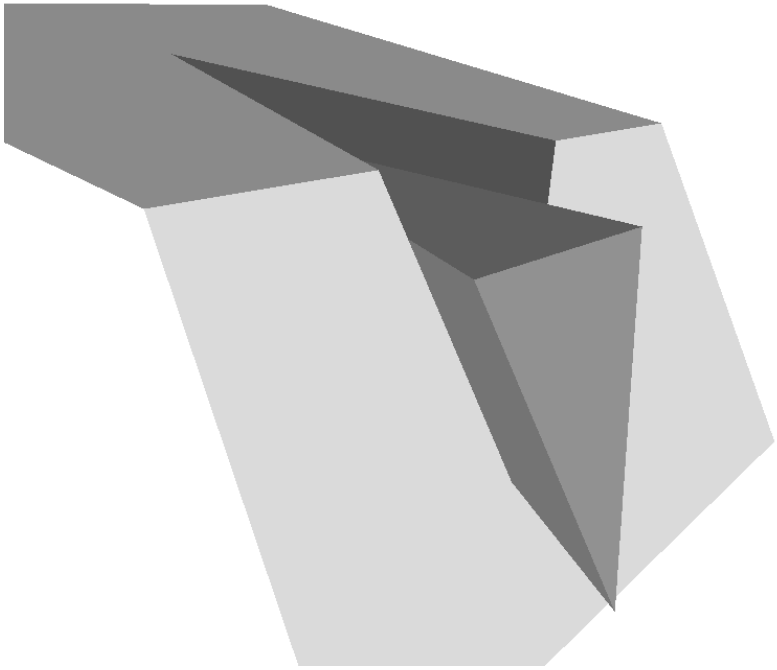


Figure 7.2 – Sliding block in perspective view.

Priest states that the safety factor for this example is “approximately” = 0.9. The actual value is FS = 0.864, if you enter the force values which he has calculated into the specified factor of safety equation (equation 8.15, ref. 3). This compares well with the SWEDGE calculated FS = 0.85. The small difference in safety factors can be attributed to the fact that Priest used a graphical method of decomposing forces on the stereonet, rather than an exact algebraic method, for this example. Therefore, SWEDGE’s results have been verified with Priest’s results; the failure modes are also in agreement.

References

1. Kumsar, H., Aydan, Ö., and Ulusay, R. (2000), “Dynamic and static stability assessment of rock slopes against wedge failures.” Rock Mechanics and Rock Engineering, No. 33, pp. 31-51.

2. Kovari, K., and Fritz, P. (1976), “Stability analysis of rock slopes for plane and wedge failure with the aid of a programmeable pocket calculator.” Rock Mechanics, vol.8, no.2, pp. 73-113.

3. Priest, Steven. 1993. *Discontinuity analysis for rock engineering.* London: Chapman and Hall.