rocscience

SWedge

Surface Wedge Analysis

Verification Manual

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1. SWedge Geometry Verification

This document presents several examples, which have been used as verification problems for *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 [1]. The results of these lab tests performed by Kumsar et al. [1] were used to confirm the validity of a limit equilibrium analysis method presented in Kovari and Fritz [2]. Two wedge examples presented by Priest [3] are also verified here.

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

1.1. *SWedge* Verification Problem #1

[SWedge Build 7.016]

1.1.1. Problem Description

In this verification example, a static stability assessment (SSA) is presented to verify that *SWedge* computes values using the correct equations. The equations used to verify the results produced by *SWedge* were originally presented by Kovari and Fritz [2]. These equations were later shown to be valid by laboratory tests of wedge models [1]. In the following verification problem, a wedge with joints having the same dip is examined. A tension crack is not present in this example.

1.1.2. Analytical Solution

Equations

The following equations, developed by Kovari and Fritz [2], were verified against lab tests [1]:

$$FS = \lambda \frac{\cos i_a \tan \phi}{\sin i_a} \quad (1.1.1)$$

$$\lambda = \frac{\cos \omega_1 + \cos \omega_2}{\sin(\omega_1 + \omega_2)} \quad (1.1.2)$$

$$\omega_1 + \omega_2 = 2\omega \quad (1.1.3)$$

Where:

ϕ is the friction angle

λ is the wedge factor derived by Kovári and Fritz [2]

ω is the half wedge angle

ω_1 is the angle between the surface of joint 1 and the vertical

ω_2 is the angle between the surface of joint 2 and the vertical

i_a is the inclination angle (or intersection angle)

Notice that $\omega_1 = \omega_2 = \omega$.

Figure 1.1.1

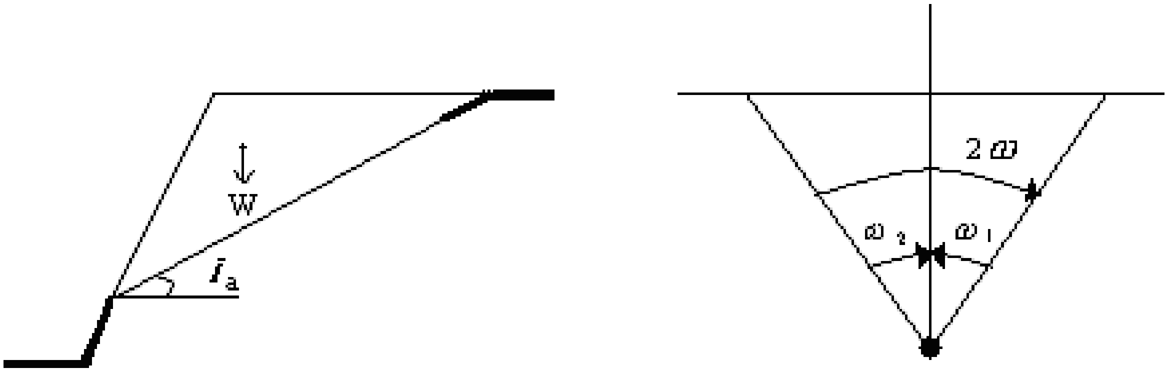


Figure 1.1.2: Front and Side Cross-Sectional Views of a Wedge Without a Tension Crack

Sample Calculation

Using Equations 1.1.1-1.1.3, which have been validated by experimental results [1], the calculation process for an example wedge is outlined below. From the plot of half wedge angle vs. wedge intersection angle (graphed using Equation 1.1.1, with a Factor of Safety FS = 1), the intersection angle for the example wedge is obtained.

$$i_a = \tan^{-1}\left(\frac{\tan\phi}{FS\sin\omega}\right)$$

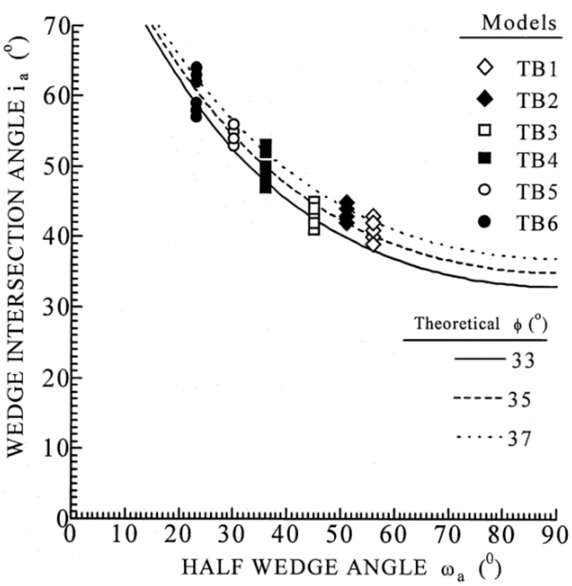


Figure 1.1.3: Comparison of Dry-Static Model Test Results with Theoretical Solution [1]

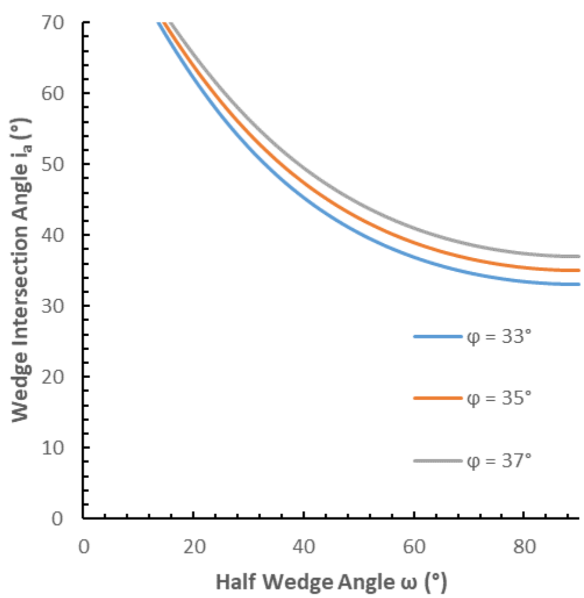


Figure 1.1.4: Graph of Equation 1 (ϕ = 33°, 35°, 37°; FS = 1)

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

In order to verify the *SWedge* results, the inclination angle (plunge) calculated by *SWedge* is compared to the inclination angle obtained using the analytical solution (from the graph).

Table 1.1.1 shows a set of joint dip and dip direction values for a sample wedge, for which $\omega_1 = \omega_2 = \omega$. When the dip and dip direction values from Table 1.1.1 are input into *SWedge* the resulting Factor of Safety FS ≅ 1. When ω is calculated, and ϕ is chosen, the corresponding intersection angle can be found using Figure 1.1.3.

Normal vectors to the joint planes have the following components:

$$l = \sin(dip) \times \cos(dip\ direction)$$

$$m = \sin(dip) \times \sin(dip\ direction)$$

$$n = \cos(dip)$$

Geometry

Table 1.1.1: Model Geometry for Sample Wedge

Plane	Dip (°)	Dip Direction (°)	ϕ (°)	l	m	n
Slope	70	180				
Upper Slope	0	180				
Joint 1	45	141	35	-0.5495	0.4450	0.7071
Joint 2	45	219	35	-0.5495	-0.4450	0.7071

Referring to Figure 1.1.1, the normal vectors to the planes of joints 1 and 2 intersect. 2ω is equal to their obtuse angle of intersection.

The half wedge angle, ω, is calculated as follows:

$$\cos\alpha = \frac{a \bullet b}{\|a\| \times \|b\|} = (0.5495)^2 - (0.4450)^2 + (0.7071)^2 = 0.6039$$

$$\alpha = 52.8491°$$

$$\omega = \frac{180 - \alpha}{2} = \frac{180 - 52.8491}{2} = 63.58°$$

Now that the half wedge angle (ω = 63.58°) is known, an intersection angle can be traced out using Figure 1.1.3. Let us choose the line plotted for ϕ = 35°. The intersection angle (if *approximately* traced using a pencil) is approximately i_a = 38°.

1.1.3. SWedge Analysis

Now verify that *SWedge* calculates the same intersection angle.

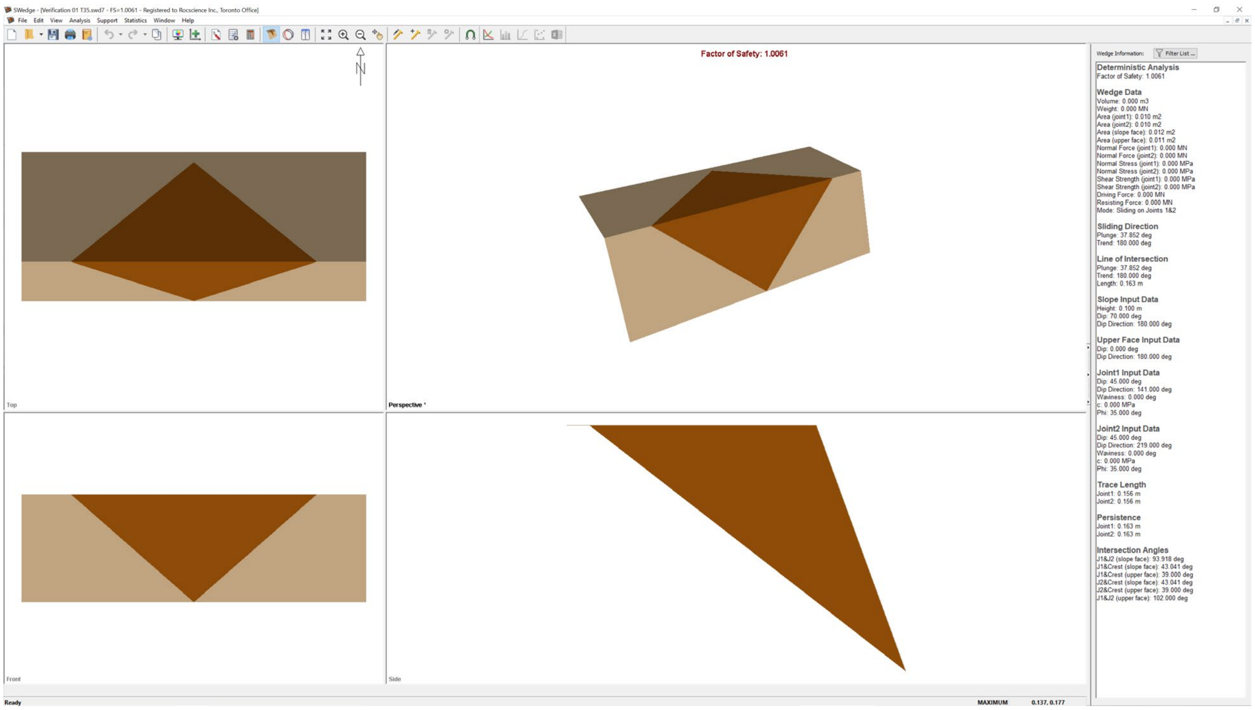


Figure 1.1.5: Input Data and Results

The values from Table 1.1.1 are input into *SWedge*, and the resulting plunge, or i_a = 37.85°. This is essentially the same value that was obtained from Figure 1.1.3.

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 in the equations used and therefore should not affect the plunge.

1.1.4. Results

In the previous section, *SWedge* was verified to work for the example problem.

More tests were done, as shown in Figure 1.1.5; *SWedge* results were plotted against the theoretical solution. Models were made for three friction angles, and *SWedge* results are shown as series **T33**, **T35**, and **T37**.

It should be noted that the wedges created in this exercise were symmetrical not only due to the dip but also in terms of dip direction. When looking at the Front view in *SWedge*, the wedge is symmetrical. To achieve this symmetry, use dip directions with a sum of 360°. Symmetry is maintained in order to reproduce the conditions for the model wedges described in [1].

Table 1.1.2: Model Geometry for Sample Wedge T33

Plane	Dip (°)	Dip Direction (°)	ϕ (°)	l	m	n	α (°)	ω (°)
Slope	70	180						
Upper Slope	0	180						
Joint 1	42.7	141	33	-0.5270	0.4268	0.7349	50.5267	64.7366
Joint 2	42.7	219	33	-0.5270	-0.4268	0.7349	50.5267	64.7366

Table 1.1.3: Model Geometry for Sample Wedge T35

Plane	Dip (°)	Dip Direction (°)	ϕ (°)	l	m	n	α (°)	ω (°)
Slope	70	180						
Upper Slope	0	180						
Joint 1	45	141	35	-0.5495	0.4450	0.7071	52.8463	63.5769
Joint 2	45	219	35	-0.5495	-0.4450	0.7071	52.8463	63.5769

Table 1.1.4: Model Geometry for Sample Wedge T37

Plane	Dip (°)	Dip Direction (°)	ϕ (°)	l	m	n	α (°)	ω (°)
Slope	70	180						
Upper Slope	0	180						
Joint 1	47.5	141	37	-0.5730	0.4640	0.6756	55.2889	62.3555
Joint 2	47.5	219	37	-0.5730	-0.4640	0.6756	55.2889	62.3555

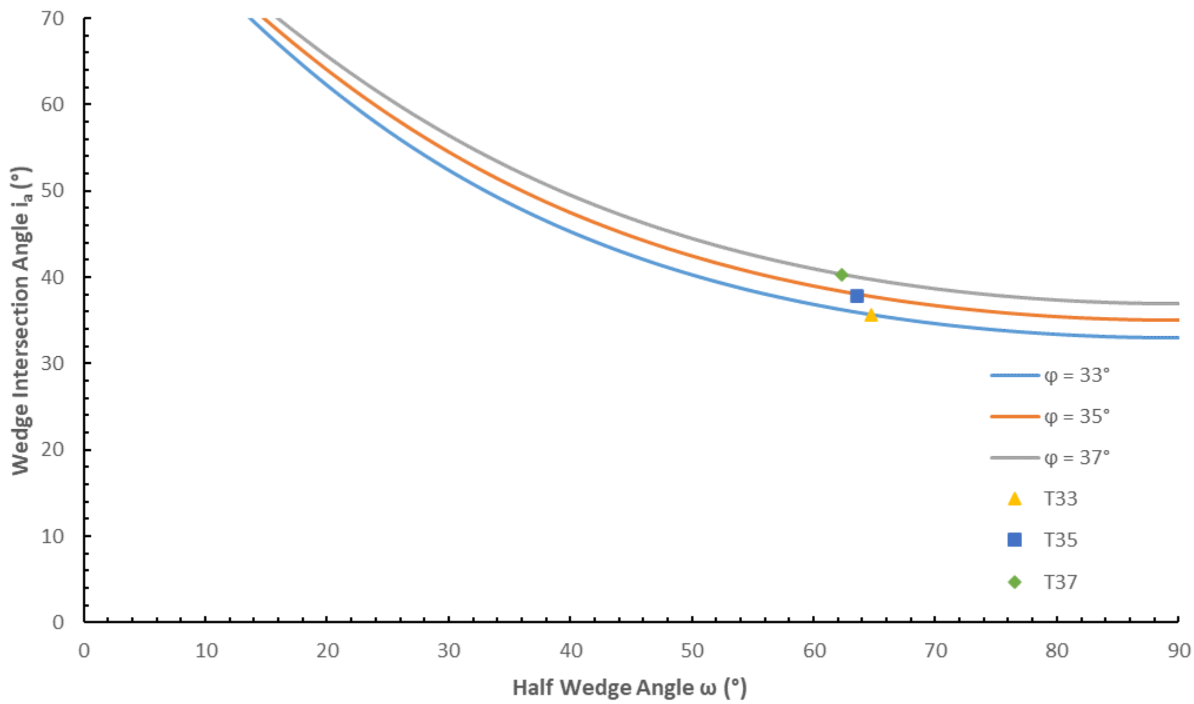


Figure 1.1.6: *SWedge* Results Compared to Theoretical Solution for FS = 1

Table 1.1.5: SWedge Sample Data

SWedge **Sample**	ω **(°)**	i_a **(°)**
T33	64.737	35.645
T35	63.577	37.852
T37	62.356	40.301

1.2. *SWedge* Verification Problem #2

[SWedge Build 7.016]

1.2.1. Problem Description

In Verification Problem #1, *SWedge* was verified for static stability. The program will now be verified for dynamic stability assessment (DSA). In this experiment, the intersection angles are set at certain values yielding FS > 1. The dips will once again be identical for both joints and the dip directions will sum up to 360˚ for symmetry. If a seismic co-efficient is included in the analysis within *SWedge*, a Factor of Safety FS = 1 will be generated. Wedge acceleration will be calculated from this seismic coefficient and compared to a graph of the analytical solution.

The equations used to verify those used within *SWedge* have been validated by experimental results [1]. There is no tension crack in any of the analyses in this verification.

1.2.2. Analytical Solution

The following is a derivation of seismicity coefficient, η. The equations were all verified by lab tests [1]:

$$FS = \frac{\lambda[\cos i_a - \eta \sin(i_a + \beta)] \tan\phi}{\sin i_a + \eta \cos(i_a + \beta)} \tag{1.2.1}$$

$$\beta = 0 \text{ (seismic forces have a horizontal trend – refer to Figure 1)} \tag{1.2.2}$$

$$\omega_1 + \omega_2 = 2\omega \tag{1.2.3}$$

$$\lambda = \frac{\cos\omega_1 + \cos\omega_2}{\sin(\omega_1 + \omega_2)} = \frac{1}{\sin\omega} \tag{1.2.4}$$

$$FS = \frac{\lambda(\cos i_a - \eta \sin i_a) \tan\phi}{\sin i_a + \eta \cos i_a} = 1 \tag{1.2.5}$$

$$\eta = \frac{\lambda \cos i_a \tan\phi - \sin i_a}{\cos(i_a + \beta) + \lambda \sin(i_a + \beta) \tan\phi} \tag{1.2.6}$$

$$\therefore \eta = \frac{\cos i_a \tan\phi - \sin i_a \sin\omega}{\cos i_a \sin\omega + \sin i_a \tan\phi} \tag{1.2.7}$$

$$\eta = \frac{a}{g} \tag{1.2.8}$$

Where:

λ	is the wedge factor from Kovári and Fritz [2]
ω	is the half wedge angle
ω_1	is the angle between the surface of joint 1 and the vertical
ω_2	is the angle between the surface of joint 2 and the vertical
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 2-1)
a	is acceleration
g	is acceleration (981 cm/s^2)

Note that $\omega_1 = \omega_2 = \omega$.

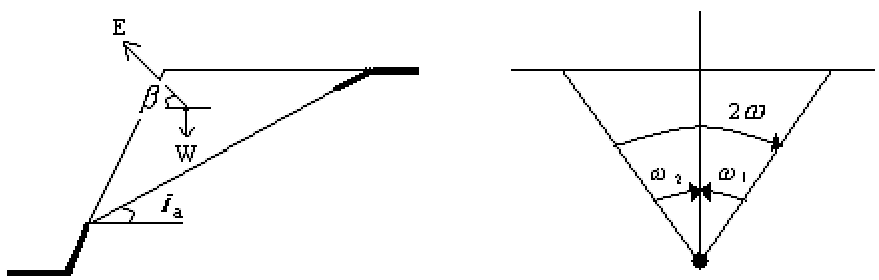


Figure 1.2.1: Front and Side Cross-Sectional Views of a Wedge Without a Tension Crack (dynamic force "$\boldsymbol{E}$" has an inclination of $\boldsymbol{\beta}$)

Sample Calculation

It is now assumed (based on Verification Problem #1) that the inclination angle function in *SWedge* is working correctly. The dynamic stability assessment calculation for a specific wedge (using the equations shown above) is performed. The *SWedge* results are then verified against the analytical solution, which is plotted in Figure 1.2.3, based on FS = 1, for four different inclination angles.

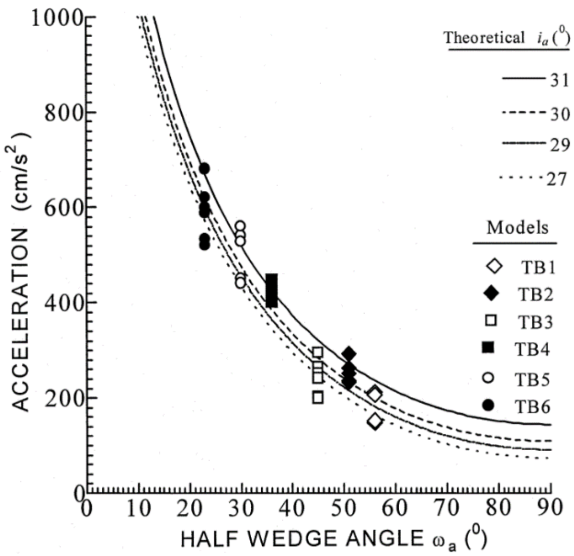


Figure 1.2.2: Comparison of Dynamic Model Test Results with Analytical Solution [1]

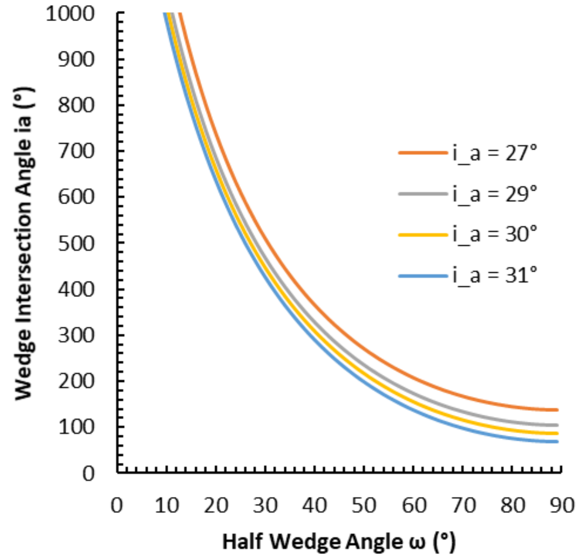


Figure 1.2.3: Analytical Solution for Dynamic Stability Assessment with FS = 1
(ϕ = 35°; i_a = 27°, 29°, 30°, and 31°)

Derive ω, using the same procedure as was used Verification Problem #1.

Normal vectors to the joint planes have components:

$$l = \sin(dip) \times \cos(dip\ direction)$$

$$m = \sin(dip) \times \sin(dip\ direction)$$

$$n = \cos(dip)$$

Table 1.2.1: Model Geometry for Sample Wedge

Plane	Dip (°)	Dip Direction (°)	l	m	n
Slope	70	180			
Upper Slope	0	180			
Joint 1	50	119	-0.3714	0.6700	0.6428
Joint 2	50	241	-0.3714	-0.6700	0.6428

Enter the above values for joint dip and dip direction into *SWedge*. FS = 1.6325 is computed which suggests that the wedge is statically stable. This is an expected result because the values in Table 1.2.1 are chosen specifically to get i_a = 30.0182 ≅ 30. Remember that the plots in Figure 1.2.3 are based on 4 different inclination angles.

Now, suppose there is a seismic force on the wedge. Using Equation 1.2.7, the seismic coefficient lowers the Factor of Safety to FS = 1. The inclination angle (i_a = 30.0182°) and the friction angle (ϕ = 35°) are known. Solve for the wedge angle and the seismic coefficient (η).

$$\cos\alpha = \frac{a \bullet b}{\|a\| \times \|b\|} = (0.3714)^2 - (0.6700)^2 + (0.6428)^2$$

$$\omega = \frac{180 - \alpha}{2} = 47.9300$$

$$\eta = \frac{\cos i_a \tan\phi - \sin i_a \sin\omega}{\cos i_a \sin\omega + \sin i_a \tan\phi}$$

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

1.2.3. SWedge Analysis

Enter η = 0.2365 into *SWedge*. Notice that the plunge (or i_a) in Figure 1.2.5 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 used, and they do not affect the plunge.

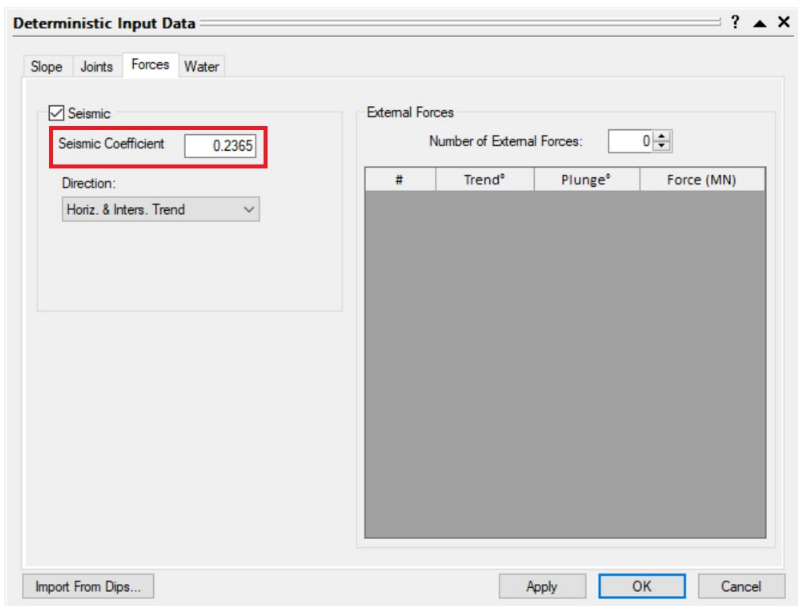


Figure 1.2.4: Seismic Force Specified in *SWedge* Input

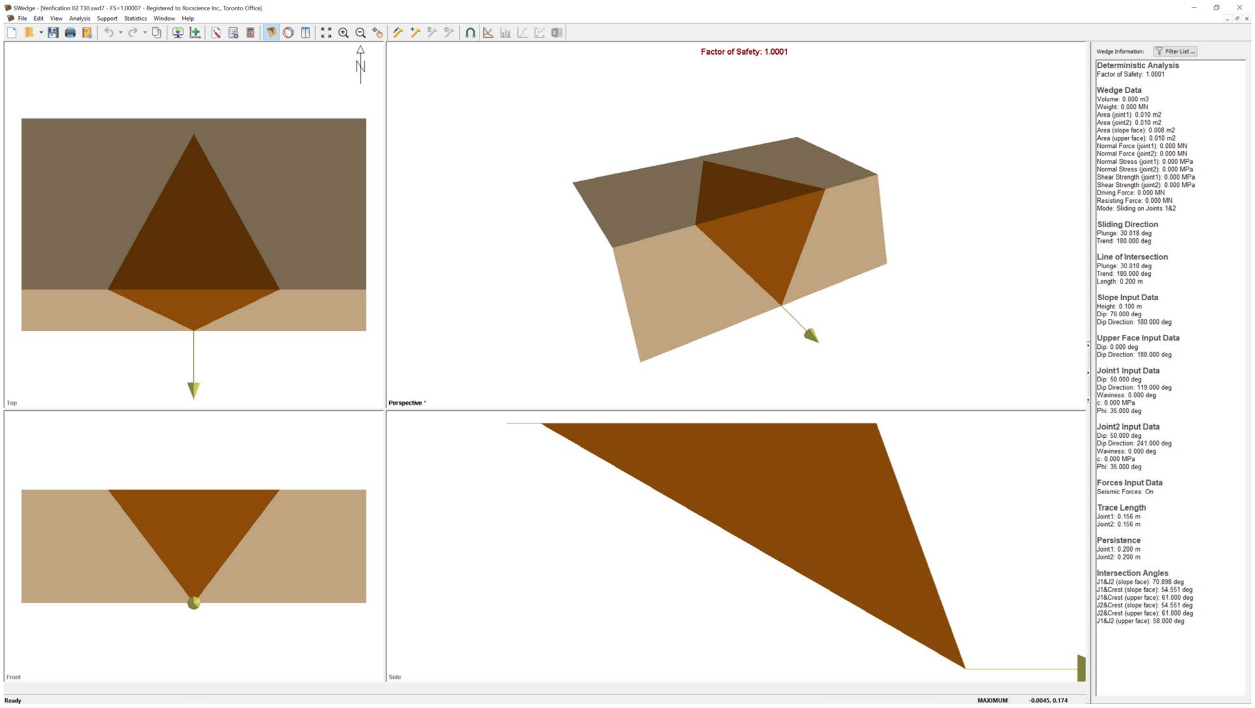


Figure 1.2.5: *SWedge* Seismic Results

Since the Factor of Safety has changed to FS = 1, the analysis functions for *SWedge* in DSA are functioning correctly. To further verify this, 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 1.2.3. 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 1.2.4) is 232 cm s^{-2}. Such an accurate result justifies the reliability of the *SWedge* program.

1.2.4. Results

In the previous section, *SWedge* is verified to work for the specific example discussed.

More tests were done, as shown in Figure 1.2.6. A number of *SWedge* results for each i_a value was plotted against the analytical solution. *SWedge* results for i_a = 27°, i_a = 29°, i_a = 30°, and i_a = 31° are shown as series T27, T29, T30, and T31, respectively.

Table 1.2.2: Model Geometry for Sample Wedge T27

Plane	Dip (°)	Dip Direction (°)	ϕ (°)	l	m	n	α (°)	ω (°)
Slope	70	180						
Upper Slope	0	180						
Joint 1	46.4	119	35	-0.3511	0.6334	0.6896	78.5991	50.7004
Joint 2	46.4	241	35	-0.3511	-0.6334	0.6896	78.5991	50.7004

Table 1.2.3: Model Geometry for Sample Wedge T29

Plane	Dip (°)	Dip Direction (°)	ϕ (°)	l	m	n	α (°)	ω (°)
Slope	70	180						
Upper Slope	0	180						

Joint 1	48.8	119	35	-0.3648	0.6581	0.6587	82.3067	48.8466
Joint 2	48.8	241	35	-0.3648	-0.6581	0.6587	82.3067	48.8466

Table 1.2.4: Model Geometry for Sample Wedge T30

Plane	Dip (°)	Dip Direction (°)	ϕ (°)	l	m	n	α (°)	ω (°)
Slope	70	180						
Upper Slope	0	180						
Joint 1	50	119	35	-0.3714	0.6700	0.6428	84.1338	47.9331
Joint 2	50	241	35	-0.3714	-0.6700	0.6428	84.1338	47.9331

Table 1.2.5: Model Geometry for Sample Wedge T31

Plane	Dip (°)	Dip Direction (°)	ϕ (°)	l	m	n	α (°)	ω (°)
Slope	70	180						
Upper Slope	0	180						
Joint 1	51.1	119	35	-0.3773	0.6807	0.6280	85.7915	47.1042
Joint 2	51.1	241	35	-0.3773	-0.6807	0.6280	85.7915	47.1042

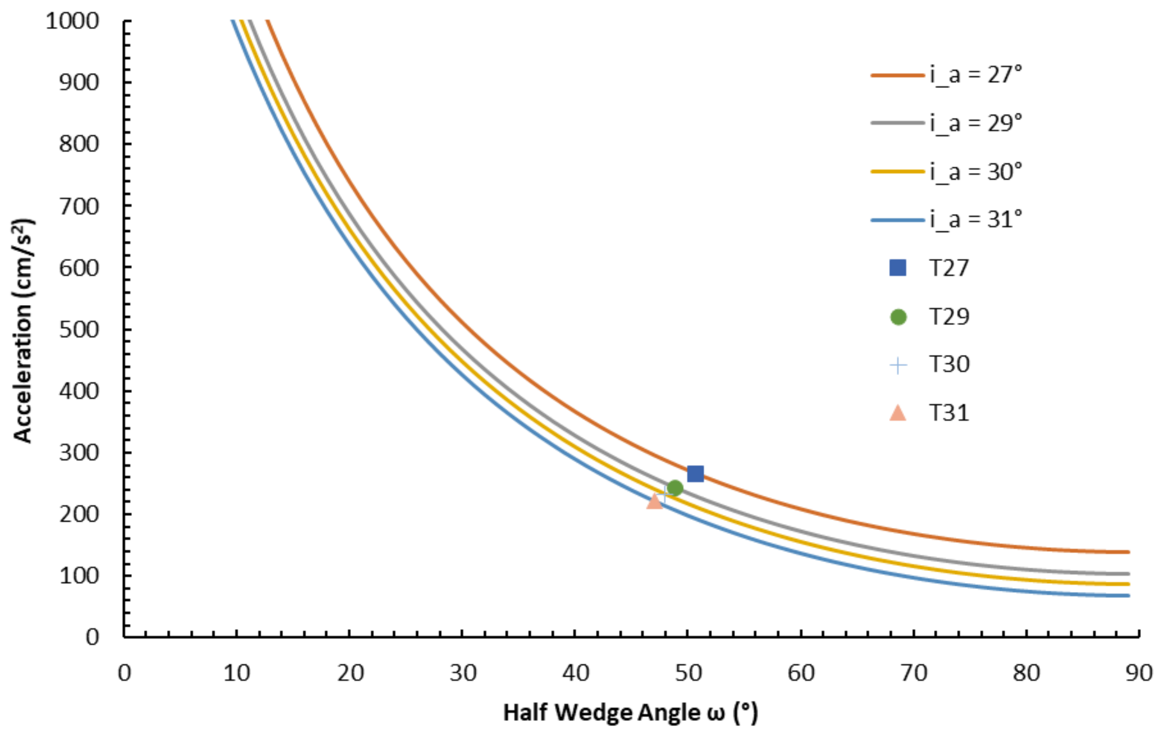


Figure 1.2.6: *SWedge* Results Compared to Analytical Solution

Table 1.2.6: SWedge Sample Data

SWedge Sample	ω (°)	i_a (°)	η	Acceleration (cm/s^2)
T27	50.7004	26.981	0.2709	265.7803491
T29	48.8466	28.977	0.2483	243.5786091
T30	47.9331	30.018	0.2365	232.0457605
T31	47.1042	30.999	0.2255	221.1887897

1.3. *SWedge* Verification Problem #3

[SWedge Build 7.016]

1.3.1. Problem Description

This verification problem is based on the case study presented as Case 3 on page 43 of [1]. A rock mass near Ankara Castle in Bent Deresi region of Ankara City had a wedge failure. Kumsar et al. [1] studied this wedge and found that the wedge block was unstable.

During their analysis, they found that the friction angle was ϕ = 30°. A stability assessment of the block was carried out under dry-static conditions, and the test yielded a Factor of Safety of FS = 0.73. *SWedge* is verified to calculate approximately the same Factor of Safety.

Geometry

Table 1.3.1: Joint Dip and Dip Direction [1]

Plane	Dip (°)	Dip Direction (°)
Joint #1	45	195
Joint #2	70	105
Upper Slope*	0	180
Slope	70	160

Table 1.3.2: Wedge Geometry [1]

Parameter	Value
ω_1 (°)	77
ω_2 (°)	28
i_a (°)	42
ϕ (°)	30

1.3.2. *SWedge* Analysis

The wedge geometry is summarized in Table 1.3.1 and Table 1.3.2. The dip and dip directions were derived from a stereonet presented in [1]. The values from Table 1.3.1 were used in *SWedge*. Note that the Upper Slope is assumed to be a horizontal plane.

The *SWedge* model looks like this:

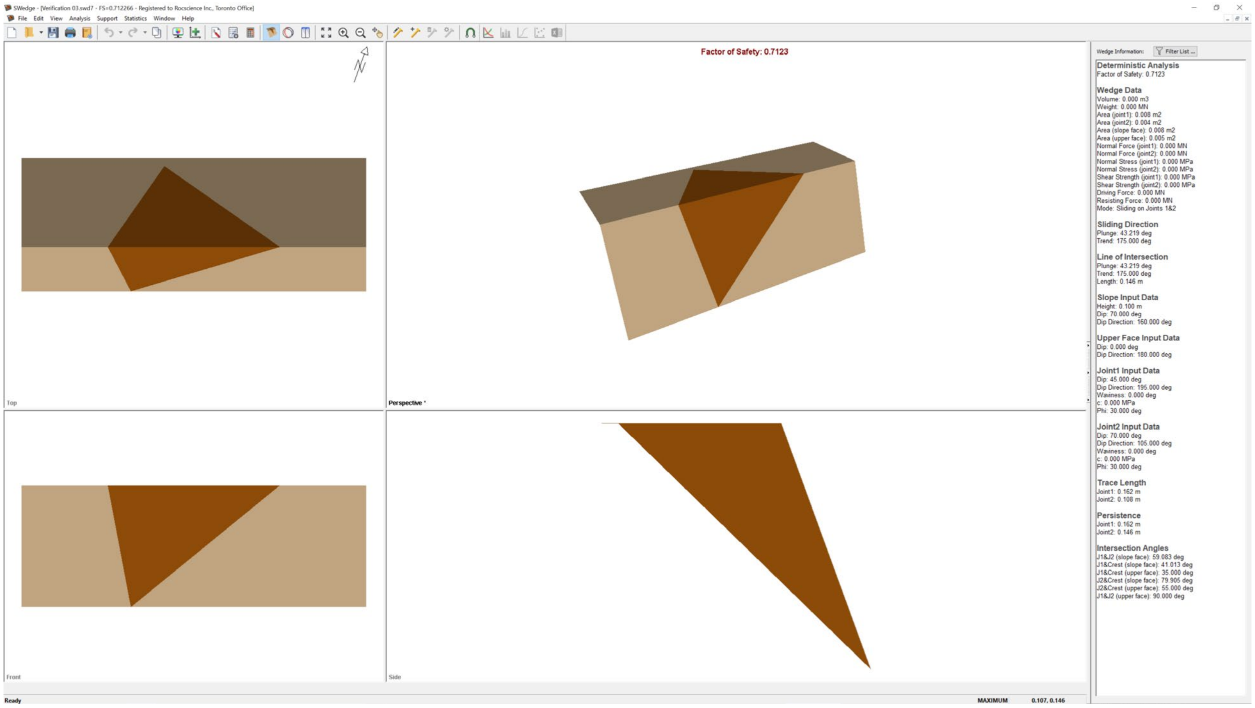


Figure 1.3.1: *SWedge* Results

1.3.3. Results

Looking at Figure 1.3.1, the Factor of Safety calculated by *SWedge* is FS = 0.71. The Factor of Safety calculated by *SWedge* agrees well with the experimental results.

Table 1.3.3: SWedge Analysis Results

	SWedge	Kumsar et al. [1]
Factor of Safety	0.7123	0.73

1.4. *SWedge* Verification Problem #4

[SWedge Build 7.016]

1.4.1. Problem Description

This verification problem is based on the case study presented as Case 4 on page 45 of Kumsar et al. [1]. This verification, based on data from Dinar in western Turkey, includes both a static and dynamic analysis.

Kumsar et al. [1] carried out a wedge analysis and determined the wedge friction angle was ϕ = 40.8°. Under static conditions, the wedge Factor of Safety was found to be FS = 2.02; the dynamic assessment yielded FS = 0.99.

In the following analysis using *SWedge*, verify that *SWedge* gives approximately the same results as the experiment.

Geometry and Material Properties

Table 1.4.1: Joint Dip and Dip Direction [1]

	Dip (deg.)	Dip Direction (deg.)
Joint #1	75	33.5
Joint #2	75	248
Upper Slope	0	180
Slope	75	337.5

Table 1.4.2: Wedge Geometry and Material Properties [1]

Parameter	Value
ω_1 (°)	17
ω_2 (°)	25
i_a (°)	50
ϕ (°)	40.8

Seismic Properties

Looking at the acceleration data presented in Table 1.4.3, the maximum acceleration is in the east-west direction. Assume that this acceleration is in the same direction as the intersection angle of the wedge being considered, as this is dynamically the worst condition for stability. Based on this, the seismic coefficient used in the *SWedge* analysis is:

$$\eta = \frac{a}{g}$$

(where g = 981 cm/s^2)

$$\eta = \frac{324}{981} = 0.3303$$

Table 1.4.3: Seismic Accelerations [1]

Parameter	Value
β (°)	0
a_{max} in NS direction (cm/s^2)	282
a_{max} in EW direction (cm/s^2)	324

1.4.2. *SWedge* Analysis

The wedge geometry, material properties, and accelerations are summarized in Table 1.4.1, Table 1.4.2, and Table 1.4.3. The data from Table 1.4.1 (derived from a stereonet), and the friction angle from Table 1.4.2, is input into *SWedge* as is. Note that the Upper Slope is assumed to be a horizontal plane.

The *SWedge* model looks like this:

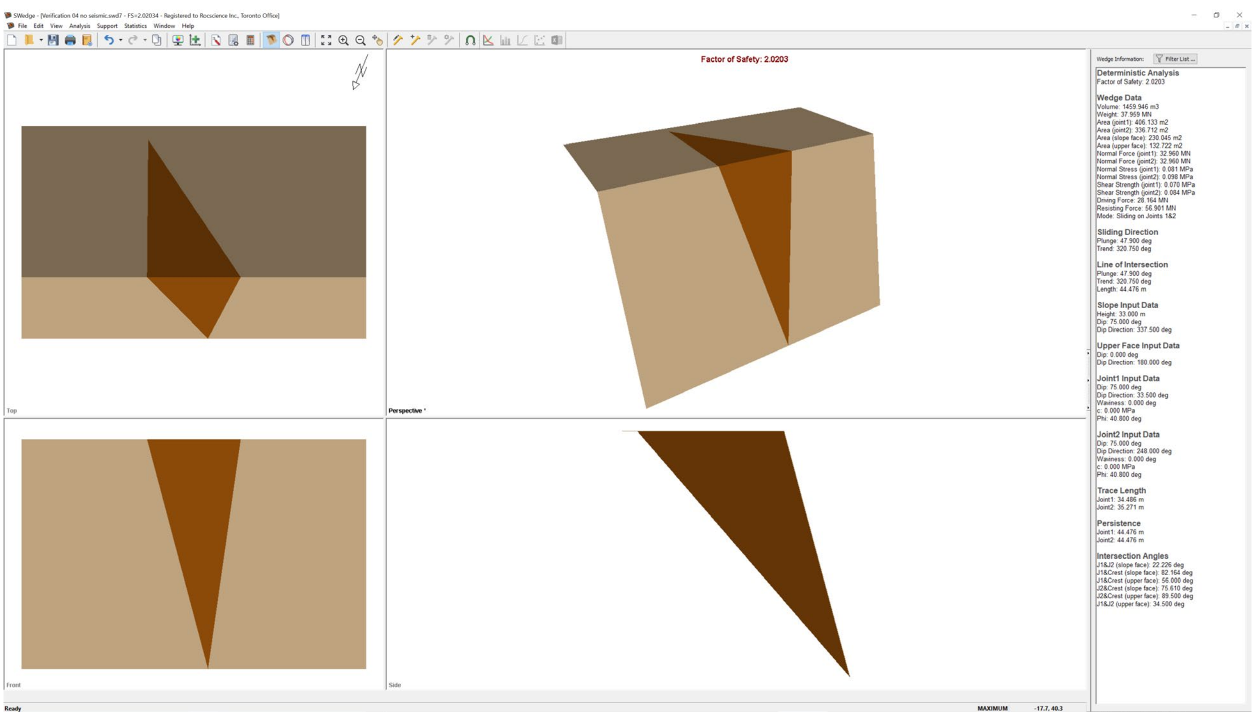


Figure 1.4.1: *SWedge* Static Stability Analysis

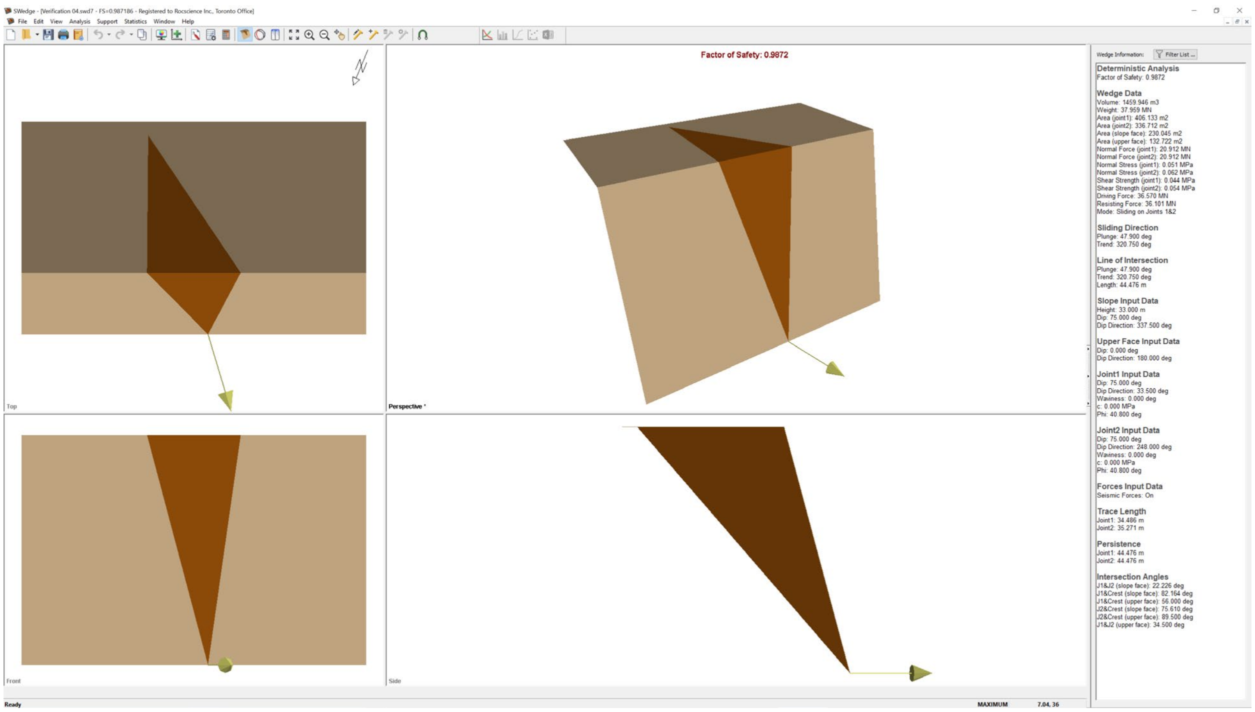


Figure 1.4.2: *SWedge* Dynamic Stability Analysis

1.4.3. Results

For the static analysis, *SWedge* calculates FS = 2.02 (see Figure 1.4.1). With the seismic load, the Factor of Safety drops to FS = 0.99, as shown in Figure 1.4.2. Since the Factors of Safety calculated by *SWedge* match the experimental results fairly well, *SWedge* is verified for Factor of Safety calculations for dynamic stability assessments.

Table 1.4.4: SWedge Analysis Results

Factor of Safety	*SWedge*	*Kumsar et al. [1]*
Static	2.0203	2.02
Seismic η = 0.3303 EW	0.9872	0.99

1.5. *SWedge* Verification Problem #5

[SWedge Build 7.016]

1.5.1. Problem Description

This example is based on Case 5, presented on p.46 of [1]. In this verification problem, a wedge failure at Mt. Mayuyama (Japan), is examined. This failure occurred in 1792 after an earthquake. Kumsar et al. [1] carried out a number of tests to determine the possible wedge failure mechanisms, considering four different conditions.

In this verification, four different cases are analyzed, using Joint 1 and Joint 2 geometry discussed in [1].

1.5.2. Analytical Solution and *SWedge* Analysis

The wedge geometry is summarized in Table 1.5.1.

Table 1.5.1: Wedge Geometry

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

The following equations, which were all verified from lab samples in [1], are the basis of Figure 1.5.2, which illustrates the four different conditions.

$$FS = \frac{\{\lambda[W(\cos i_a - \eta\sin(i_a+\beta)) + U_s \sin i_a + U_t \cos i_a] - \alpha U_b\}\tan\phi + c(A_1+A_2)}{W[\sin i_a + \eta\cos(i_a+\beta)] - U_s\cos i_a + U_t \sin i_a} \quad (1.5.1)$$

$$\lambda = \frac{\cos\omega_1 + \cos\omega_2}{\sin(\omega_1+\omega_2)} \quad (1.5.2)$$

$$U_b = U_{bs} + U_{be} = (\gamma_s + \gamma_e)W \quad (1.5.3)$$

$$U_b = U_{b1}\sin\omega_1 + U_{b2}\sin\omega_2 \quad (1.5.4)$$

Where:

λ is the wedge factor from Kovári and Fritz [2]

i_a is the inclination angle

β is the inclination angle of the dynamic force

ω_1, ω_2 are the half wedge angles

U_s, U_t are the water forces acting on the face and the upper part of the slope

A_1, A_2 are the joint surface areas

U_b is a force caused by fluid pressure with components normal to each joint

γ_s is the static fluid pressure coefficient

γ_e is the excess fluid pressure coefficient

W is the weight of the wedge

Both ω_1 and ω_2 are equal to 54° since $\omega_1 = \omega_2 = \omega$, the half wedge angle. U_b itself is the force, which points vertically, hence the trigonometric system shown in Equation 4. All these components are shown below in Figure 5-1. Refer to Figure 5-1 to assure the calculations.

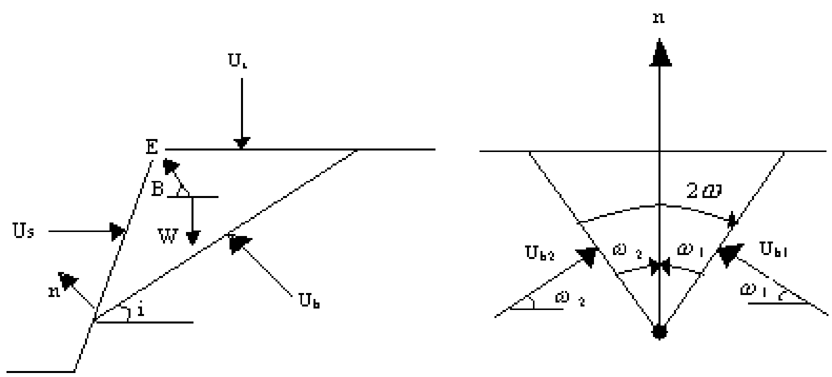


Figure 1.5.1: Front and Side Cross-Sectional Views of a Wedge Without a Tension Crack

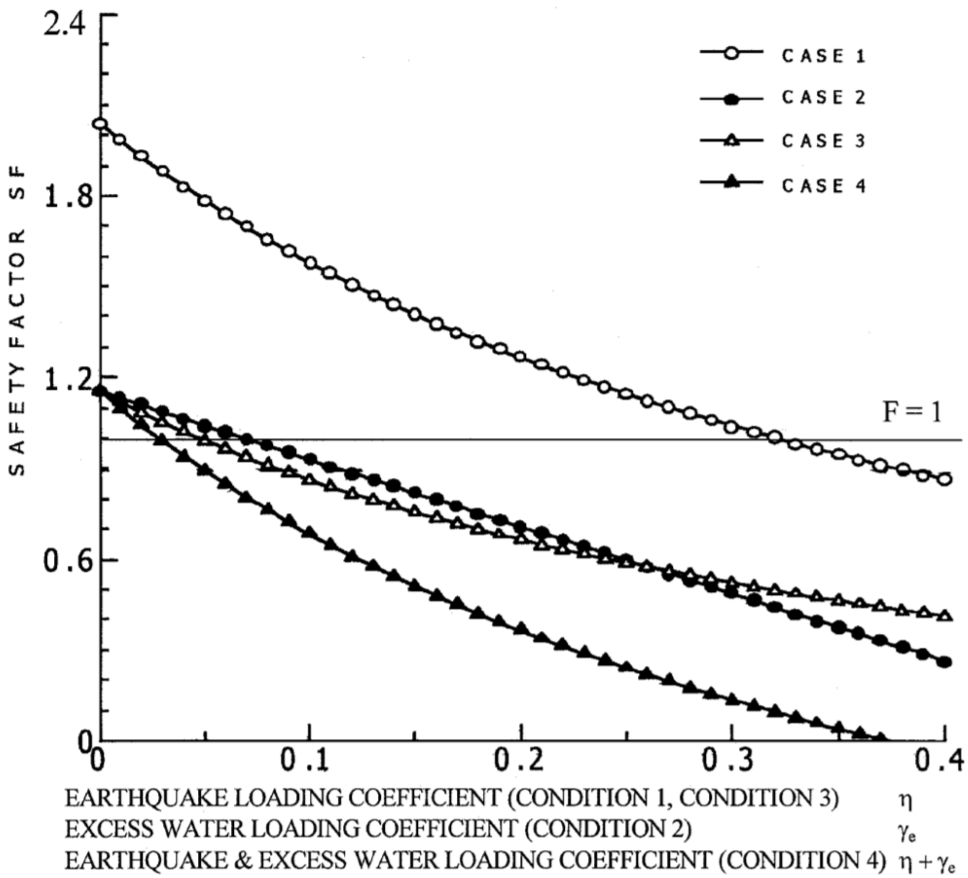


Figure 1.5.2: Case Results for Wedge Failure at Mt. Mayuyama
(assumed ϕ = 35°)

Case 1:

A mass of dry rock with an earthquake is present. The seismic coefficient (η) is constantly increasing from 0.0 to 0.4 as shown in Figure 1.5.2. On p.49 [1] the following are given for Condition 1:

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

Based on the parameters defined for Condition 1, and the equations defined above, the Factor of Safety can be determined:

$$FS = \frac{\lambda(\cos i_a - \eta \sin i_a)\tan\varphi}{\sin i_a + \eta \cos i_a}$$

$$\lambda = \frac{2\cos 54}{\sin(2\cdot 54)} = \frac{1}{\sin 54}$$

$$i_a = 23°$$

$$\therefore FS = \frac{(\tan 35)(\cos 23 - \eta \sin 23)}{(\sin 54)(\sin 23 + \eta \cos 23)} \qquad (1.5.5)$$

Equation 1.5.5 is used to plot the line in Figure 1.5.2 for Case 1. Notice in Figure 1.5.2 that when the seismic coefficient is $\eta \cong 0.32$, the Factor of Safety is FS = 1. By inserting this seismic coefficient into an *SWedge* analysis, FS = 1 at that point as well. The settings for dip and dip directions are found in Figure 1.5.3 and are the same for all the cases. The dip and dip direction values for the joints were determined from a stereonet presented in [1].

The Factor of Safety without the earthquake load is FS = 1.9577. Once the seismic coefficient is introduced the Factor of Safety reduces to FS = 1.0822 ≅ 1. This verifies *SWedge* results.

The *SWedge* model looks like this:

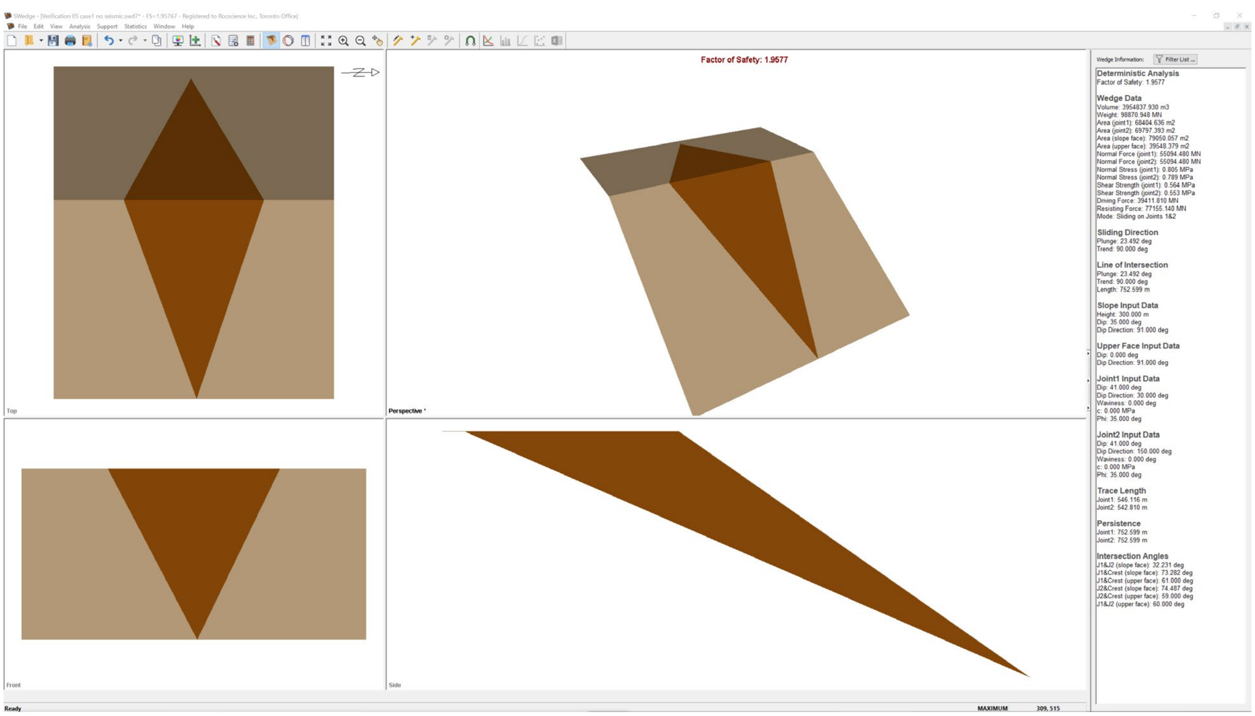


Figure 1.5.3: *SWedge* Results for Static Case

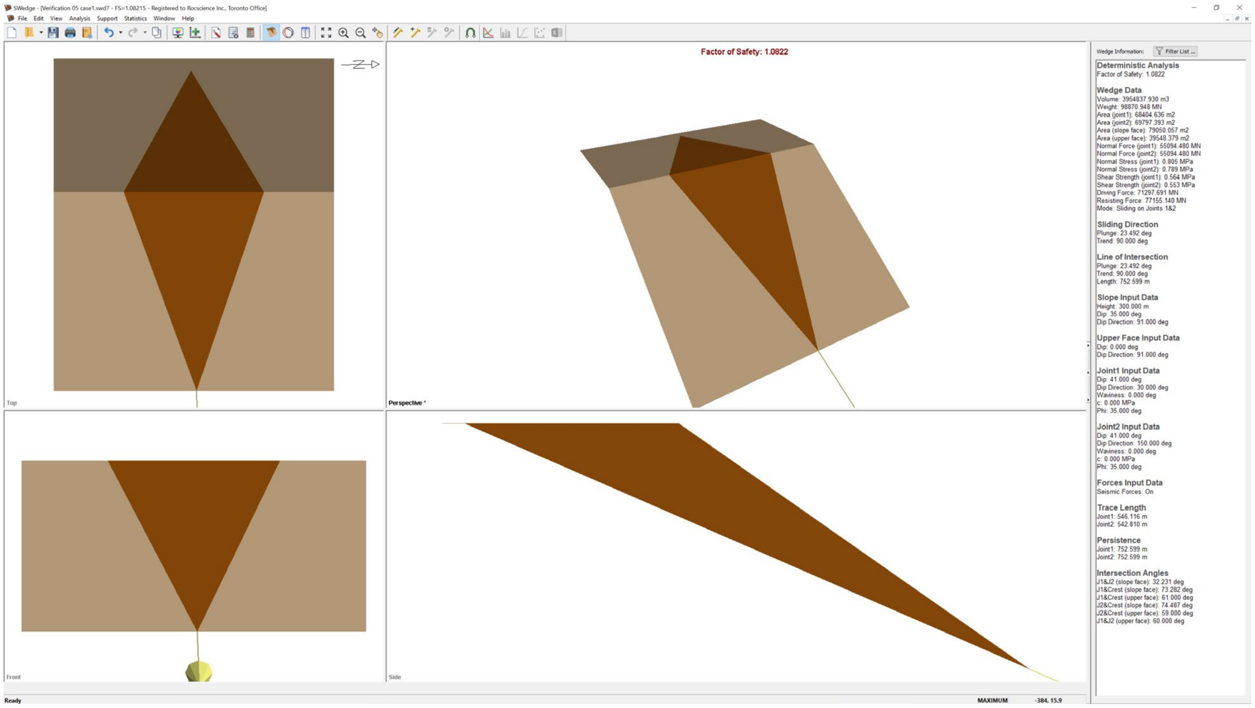


Figure 1.5.4: *SWedge* Results for Case with Earthquake Load

Case 2:

In this case that the excess fluid pressure (γ_e) is changing as the domain in Figure 1.5.2 from 0.0 to 0.4. The static fluid pressure is constant at γ_s = 0.4. The following are defined for Condition 2 [1]:

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

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

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

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

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

$$\lambda = \frac{2\cos 54}{\sin(2\cdot 54)} = \frac{1}{\sin 54}$$

$$i_a = 23°$$

$$\therefore FS = \frac{(\tan 35)(\cos 23 - 0.4 - \gamma_e)}{(\sin 23)(\sin 54)} \quad (1.5.6)$$

Equation 1.5.6 is used to plot the line in Figure 1.5.2 for Case 2. Notice in Figure 1.5.2 that when the excess fluid pressure coefficient is γ_e = 0.06, the Factor of Safety is FS = 1. By inserting this into an *SWedge* analysis, FS = 1 there as well. The settings for dip and dip directions are found in Figure 1.5.3 and are the same for all the cases.

Add the water forces to the wedge in *SWedge*. The following is a derivation of how much pressure is put on the surface of each joint. A few assumptions were made.

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

$$U_b = P_1 A_1 \sin \omega_1 + P_2 A_2 \sin \omega_2$$

(P is pressure (MN/m^2) and A is surface area of each joint)

Click on the Infoviewer in *SWedge* and make sure that the analysis input is set up as shown in Figure 1.5.3. The wedge weight and the two joint areas are provided in the Info Viewer:

Wedge weight = 98870.95 MN

Wedge area (joint 1) = 68404.636 m^2

Wedge area (joint 2) = 69797.393 m^2

The following assumptions are made in determining the water pressure. These assumptions are considered valid due to the fact that the wedge areas are almost the same, and so the assumption will not have an overwhelming effect on the results:

$$P_1 \cong P_2 \cong P$$

$$A_1 \cong A_2 \cong A$$

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

Based on the assumptions above and the wedge geometry, the water pressure to be applied in *SWedge* is calculated:

$$P = \frac{U_b}{2A \sin \omega}$$

$$A_{average} = 69101 \text{ m}^2$$

$$W = 98870.95 \text{ MN}$$

Given $\gamma_e = 0.06$, $U_b = (0.4 + 0.06)(98870.95) = 45480.64$ MN:

$$P = \frac{45480.64}{2(69101) \sin 54} = 0.406 \frac{\text{MN}}{\text{m}^2}$$

Below, the Factor of Safety is FS ≅ 1.

The *SWedge* model looks like this:

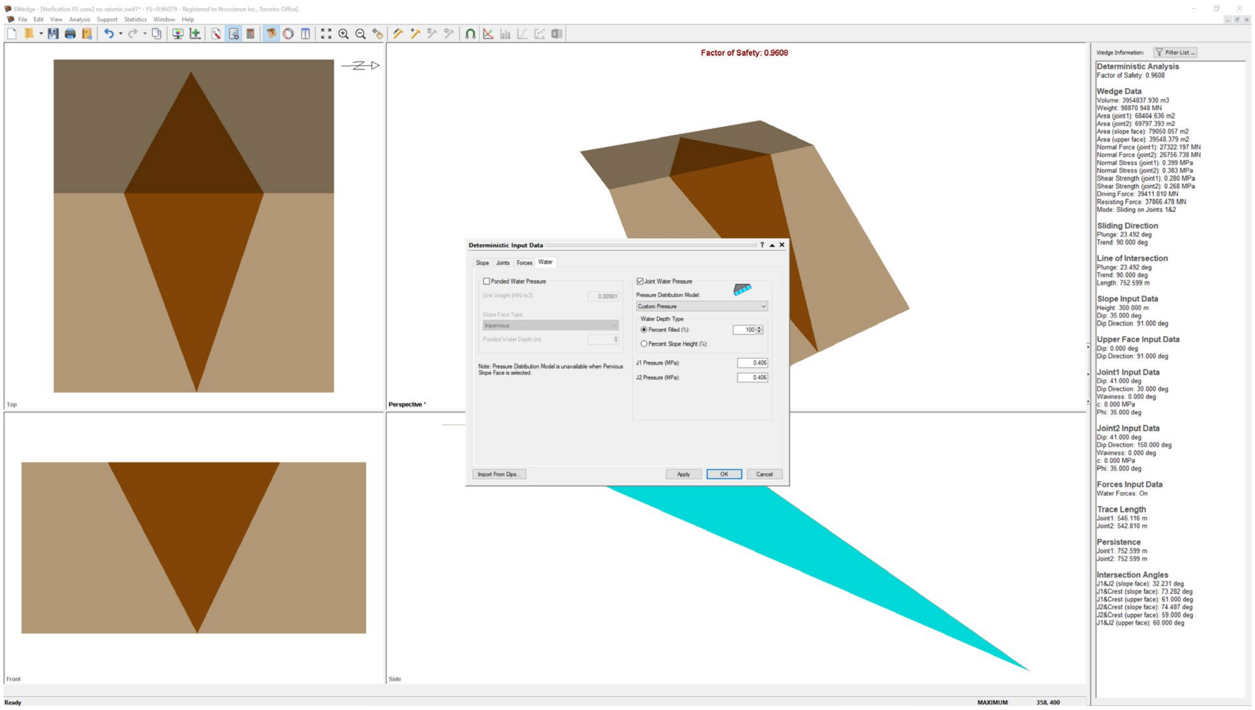


Figure 1.5.5: *SWedge* Analysis with Custom Water Pressure

Looking at Figure 1.5.5, *SWedge* calculates FS = 0.9608 ≅ 1. *SWedge* is now verified for Case 2.

Case 3:

A mass of rock is present with an earthquake of increasing seismicity.

The seismic coefficient (η) is constantly increasing from 0.0 to 0.4 as described in Figure 1.5.2. The following information is given for Condition 3 [1]:

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

The fluid pressure was kept constant during the earthquake, at γ_s = 0.4. The equation for Factor of Safety is developed below:

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

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

Given $\gamma_e = 0,\ U_b = 0.4W$

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

Equation 1.5.7 is used to plot the line in Figure 1.5.2 for Case 3. Notice in Figure 1.5.2 that when the seismic coefficient is η = 0.05, the Factor of Safety is FS = 1. Remember that the equation used for this plot is based on a constant fluid pressure. By applying this seismic coefficient, along with water pressure, the FS = 1 in *SWedge* as well.

SWedge is utilized 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. Note that the same assumption is made in terms of wedge area as was made in Case 2.

$$U_b = 0.4W$$

$$W = 98870.95 \text{ MN}$$

$$U_b = 39548.38 \text{ MN}$$

$$P = \frac{U_b}{2A \sin \omega} = 0.3537 \ \frac{\text{MN}}{\text{m}^2}$$

The *SWedge* model looks like this:

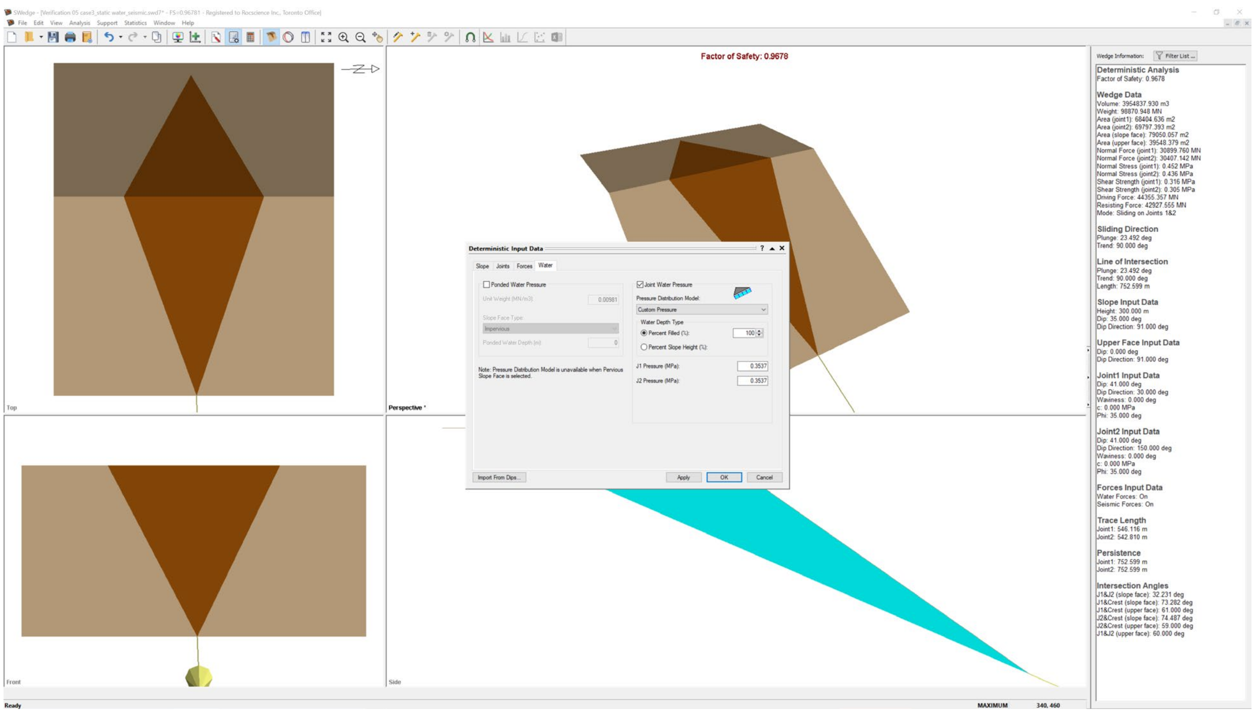


Figure 1.5.6: *SWedge* Analysis with Custom Water Pressure and Seismic Force Defined

Looking at Figure 1.5.6, *SWedge* calculates FS = 0.9678 ≅ 1. *SWedge* is now verified for Case 3.

Case 4:

A mass of rock is present with an earthquake. Both the seismic coefficient (η) and the excess fluid pressure (γ_e) are constantly increasing (at the same time) from 0.0 to 0.4 as described in Figure 1.5.2. The following are defined for Condition 4 [1]:

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

The Factor of Safety equation is developed below:

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

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

$$\therefore FS = \frac{(\cos 23 - \eta \sin 23 - 0.4 - \gamma_e) \tan 35}{(\sin 54)(\sin 23 + \eta \cos 23)} \quad \textbf{(8)}$$

Equation 8 is used to plot the line in Figure 1.5.2 for Case 3. Notice in Figure 1.5.2 that when $\eta = \gamma_e = 0.02$, the Factor of Safety is FS = 1. Now verify this with *SWedge*.

Calculate the water pressure to be applied (the same assumptions as in Case 2 and 3 with regard to wedge area and water pressure are used):

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

$$W = 98870.95 \text{ MN}$$

$$\therefore U_b = 41525.799 \text{ MN}$$

$$P = \frac{U_b}{2A \sin \omega}$$

$$\therefore P = \frac{41525.799}{2(69101) \sin 54} = 0.3414 \text{ MN/m}^2$$

Enter the values for seismicity and pressure into *SWedge* as shown in Figure 1.5.7 below. The resulting Factor of Safety is FS = 1.0659 ≅ 1. This result verifies *SWedge* for this example.

The *SWedge* model looks like this:

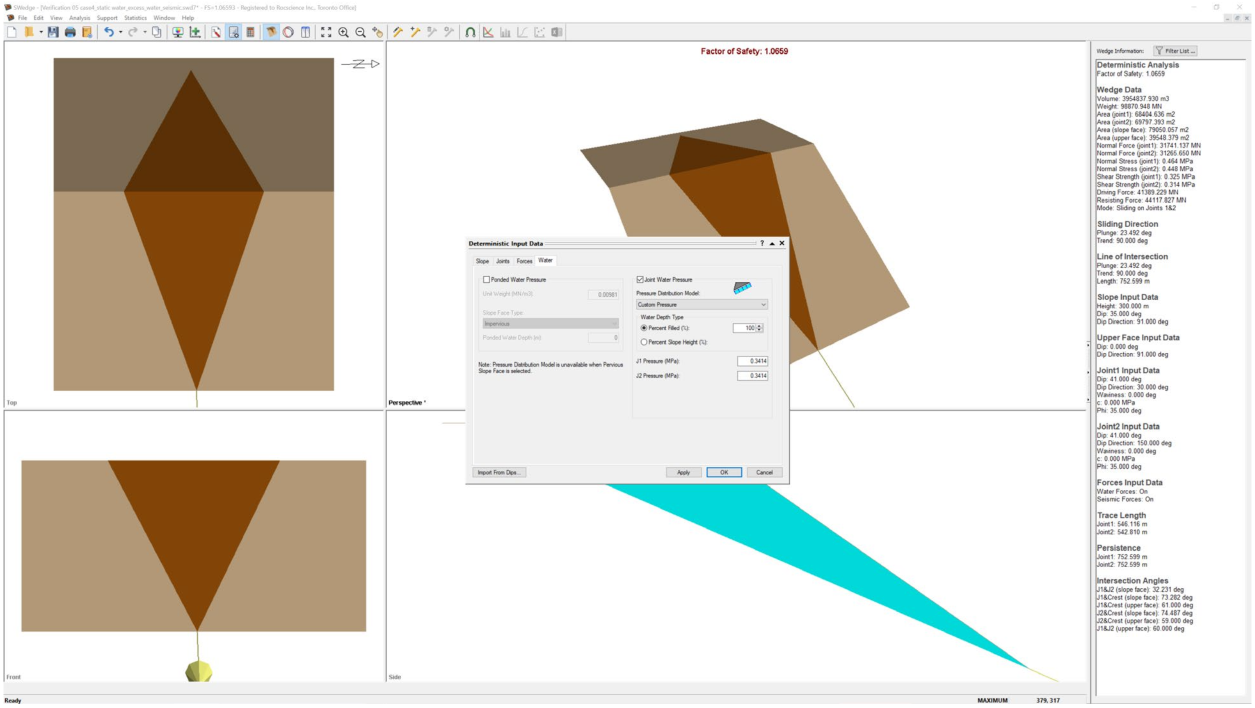


Figure 1.5.7: *SWedge* Analysis with Custom Water Pressure and Seismic Force Defined (Pressure and Seismicity are Changing at the Same Rate)

The summary of results is below.

Table 1.5.2: SWedge Analysis Results

Case	η	γ_s	γ_e	***SWedge* Factor of Safety**	***Kumsar et al. [1]* Factor of Safety**
1	0.3225	0	0	1.0822	2.02
2	0	0.4	0.06	0.9608	
3	0.05	0.4	0	0.9678	
4	0.02	0.4	0.02	1.0659	0.99

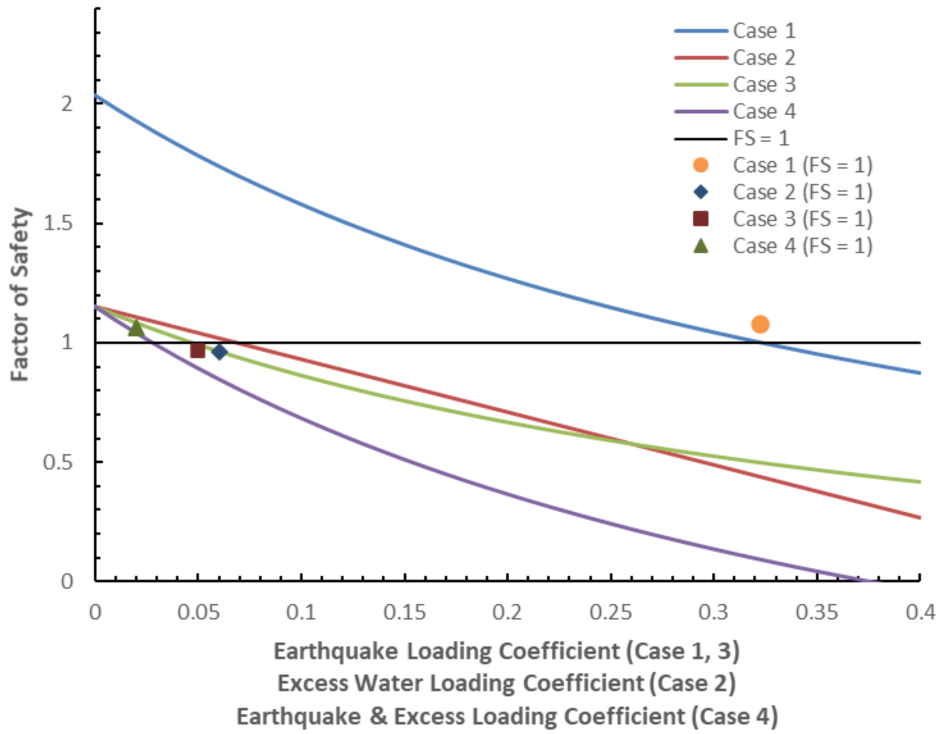


Figure 1.5.8: *SWedge* Results Compared to Analytical Solution

Note that slight discrepancies between theoretical and SWedge computed results are due to estimations of friction angle. Based on the stereonet [1], the friction angle is simply within the range of 35 and 40 degrees. By changing it to a friction angle of ϕ = 36°, better accuracy may be achieved.

1.6. *SWedge* Verification Problem #6

[SWedge Build 7.016]

1.6.1. Problem Description

This problem was taken from Priest [3]. 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. In this verification, the Factor of Safety for the block is determined.

1.6.2. *SWedge* Analysis

Verification Problem #6 models a non-overhanging rock slope with two planar discontinuities (orientations given in Table 1.6.1).

Geometry and Material Properties

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.

Table 1.6.1: Slope and Joint Geometry

Plane	Dip (°)	Dip Direction (°)
Joint Set 1	47	203
Joint Set 2	52	287
Upper Slope (Bench)	5	225
Slope	60	230

Table 1.6.2: Material Properties

Joint Set	Cohesion (MPa)	Friction Angle (°)
1	0.01	40
2	0.02	35

Water Pressure

Table 1.6.3: Water Pressure

Joint Set	Mean Water Pressure (MPa)
1	0.005
2	0.015

1.6.3. *SWedge* Analysis

Enter the values from Table 1.6.1 and Table 1.6.3 into *SWedge*.

The *SWedge* model looks like this:

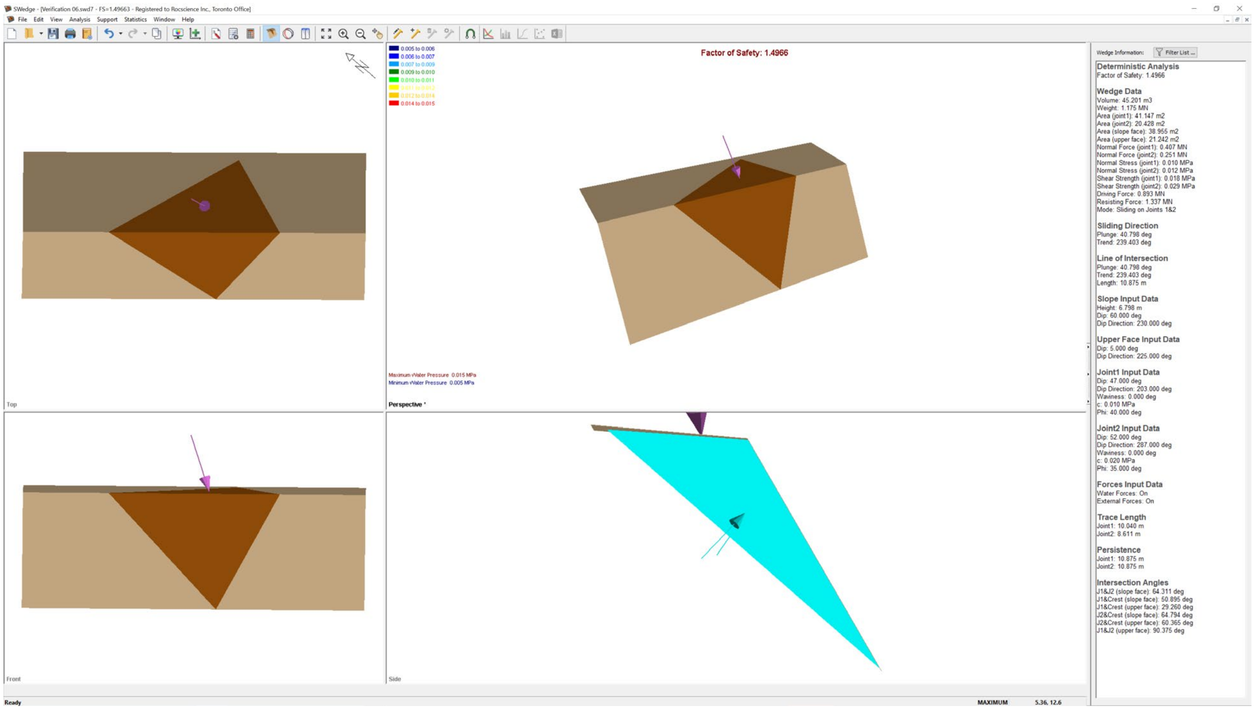


Figure 1.6.1: *SWedge* Results

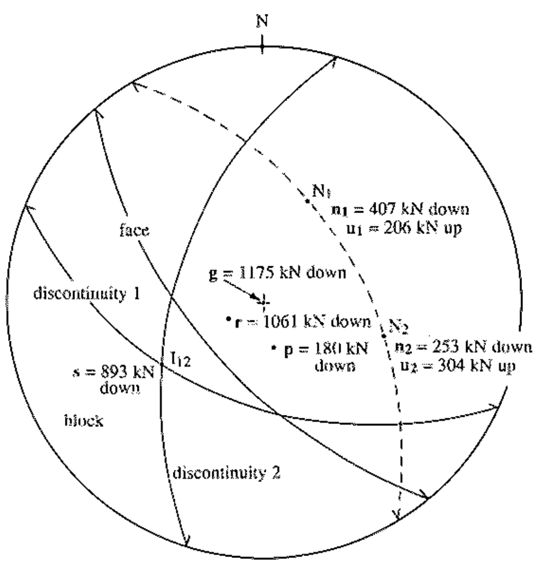


Figure 1.6.2: Stereonet from Priest [3]
(Upper Face Not Shown)

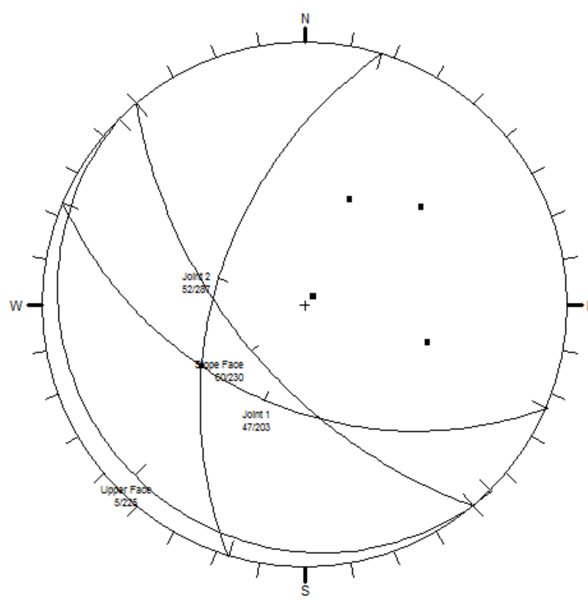


Figure 1.6.3: *SWedge* Stereonet

1.6.4. Results

The *SWedge* analysis results are summarized in this section.

***SWedge* Analysis Results:**

Factor of Safety=1.4966

Volume: 45.201 m3

Weight: 1.175 MN

Area (joint1): 41.147 m2

Area (joint2): 20.428 m2

Area (slope face): 38.955 m2

Area (upper face): 21.242 m2

Normal Force (joint1): 0.407 MN

Normal Force (joint2): 0.251 MN

Normal Stress (joint1): 0.010 MPa

Normal Stress (joint2): 0.012 MPa

Shear Strength (joint1): 0.018 MPa

Shear Strength (joint2): 0.029 MPa

Driving Force: 0.893 MN

Resisting Force: 1.337 MN

Mode: Sliding on Joints 1&2

Water Pressures/Forces:

Average pressure on joint1=0.005 MN/m2

Average pressure on joint2=0.015 MN/m2

Water force on joint1=0.206 MN

Water force on joint2=0.306 MN

Priest's Factor of Safety is FS ≅ 1.5, which verifies that the results obtained from *SWedge* are correct. The failure mode also agrees with Priest's double plane sliding mechanism.

1.7. *SWedge* Verification Problem #7

[SWedge Build 7.016]

1.7.1. Problem Description

This problem was taken from Priest [3]. 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. In this verification, the Factor of Safety for the block is determined.

1.7.2. *SWedge* Analysis

Verification Problem #7 analyzes a non-overhanging planar rock slope with two joint sets, or discontinuities (Table 1.7.1). 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 m. There is no tension crack in this problem. The unit weight of rock is 25 kN m^{-3}.

Geometry and Material Properties

Table 1.7.1: Plane Orientation

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

Table 1.7.2: Material Properties

Joint Set	Cohesion (MPa)	Friction Angle (deg.)
1	0.015	32
2	0.005	40

Water Pressure

Table 1.7.3: Water Pressure

Joint Set	Mean Water Pressure (MPa)
1	0.025
2	0.015

1.7.3. SWedge Analysis

Enter the values from Table 1.7.1 and Table 1.7.2 into *SWedge*.

The *SWedge* model looks like this:

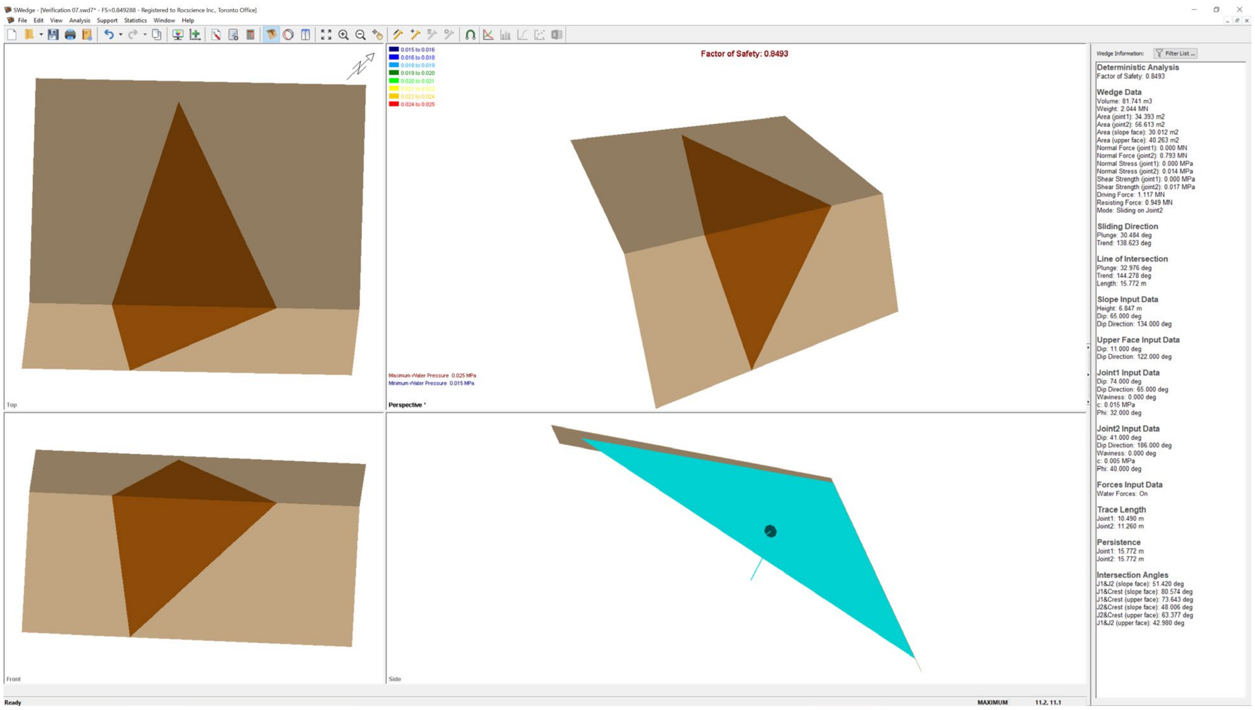


Figure 1.7.1: *SWedge* Results

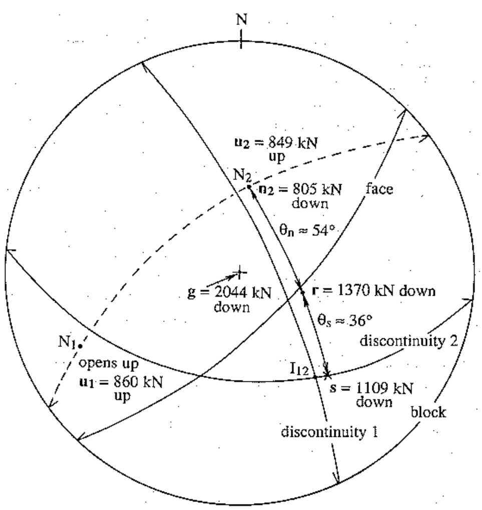


Figure 1.7.2: Stereonet from Priest [3]
(Upper Face Not Shown)

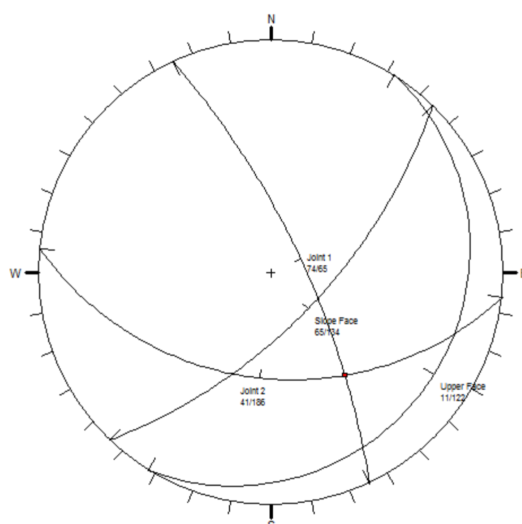


Figure 1.7.3: *SWedge* Stereonet

1.7.4. Results

The *SWedge* analysis results are summarized in this section.

***SWedge* Analysis Results:**

Factor of Safety=0.8493

Volume: 81.741 m3

Weight: 2.044 MN

Area (joint1): 34.393 m2

Area (joint2): 56.613 m2

Area (slope face): 30.012 m2

Area (upper face): 40.263 m2

Normal Force (joint1): 0.000 MN

Normal Force (joint2): 0.793 MN

Normal Stress (joint1): 0.000 MPa

Normal Stress (joint2): 0.014 MPa

Shear Strength (joint1): 0.000 MPa

Shear Strength (joint2): 0.017 MPa

Driving Force: 1.117 MN

Resisting Force: 0.949 MN

Mode: Sliding on Joint2

Water Pressures/Forces:

Average pressure on joint1=0.025 MN/m2

Average pressure on joint2=0.015 MN/m2

Water force on joint1=0.860 MN

Water force on joint2=0.849 MN

Priest states that the Factor of Safety for this example is "approximately" = 0.9. The actual value is FS = 0.864, if the force values which he has calculated into the specified Factor of Safety equation (Equation 8.15 in [3]) are entered. This compares well with the *SWedge* calculated FS = 0.85. The small difference in Factor of Safetys 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.

1.8. 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.

2. *SWedge* Bolt Model Verification

This section presents several verification examples for the *UnWedge* bolt model in *SWedge.*

The users can select from a list of pre-defined different types of bolts, choose to use bolt shear strength instead of tensile and select to apply bolt orientation efficiency factor. Bolts in *SWedge* can still be defined as either Active or Passive. The option is now included in the Bolt Properties dialog. Analyses of the new bolt model were performed in *SWedge* and verified against *UnWedge*. FS was compared. The results produced by *SWedge* agree very well with *UnWedge*, which confirms the reliability of *SWedge* results.

2.1. *SWedge* Verification Problem #1

[SWedge Build 7.016]

2.1.1. Problem Description

In this verification example, several passive bolt types are modelled in *SWedge*. *SWedge* FS are then compared to *UnWedge*.

Geometry and Material Properties

Table 2.1.1: Slope and Joint Geometry

Slope	
Slope Dip Angle (°)	90
Dip Direction (°)	180
Height (m)	10
Upper Face Dip Angle (°)	0
Upper Face Dip Direction (°)	180
Rock Unit Weight (MN/m^3)	0.027
Joint 1	
Dip Angle (°)	45
Dip Direction (°)	125
Waviness (°)	0
Shear Strength Model	Mohr-Coulomb
Phi (°)	35
c (MPa)	0
Joint 2	
Dip Angle (°)	70
Dip Direction (°)	225
Waviness (°)	0
Shear Strength Model	Mohr-Coulomb
Phi (°)	35
c (MPa)	0

Bolt Properties

Table 2.1.2: Bolt Properties

Spot Bolt	
Trend (°)	0
Plunge (°)	0
Length (m)	17
Location (x, y, z)	(-5,0,6.5)
Bolt Properties	1

2.1.2. SWedge Analysis

Enter the geometry parameter values from Table 2.1.1 into *SWedge*.

Bolt Properties

Enter the bolt properties from Table 2.1.2 into *SWedge.*

The *SWedge* model looks like this:

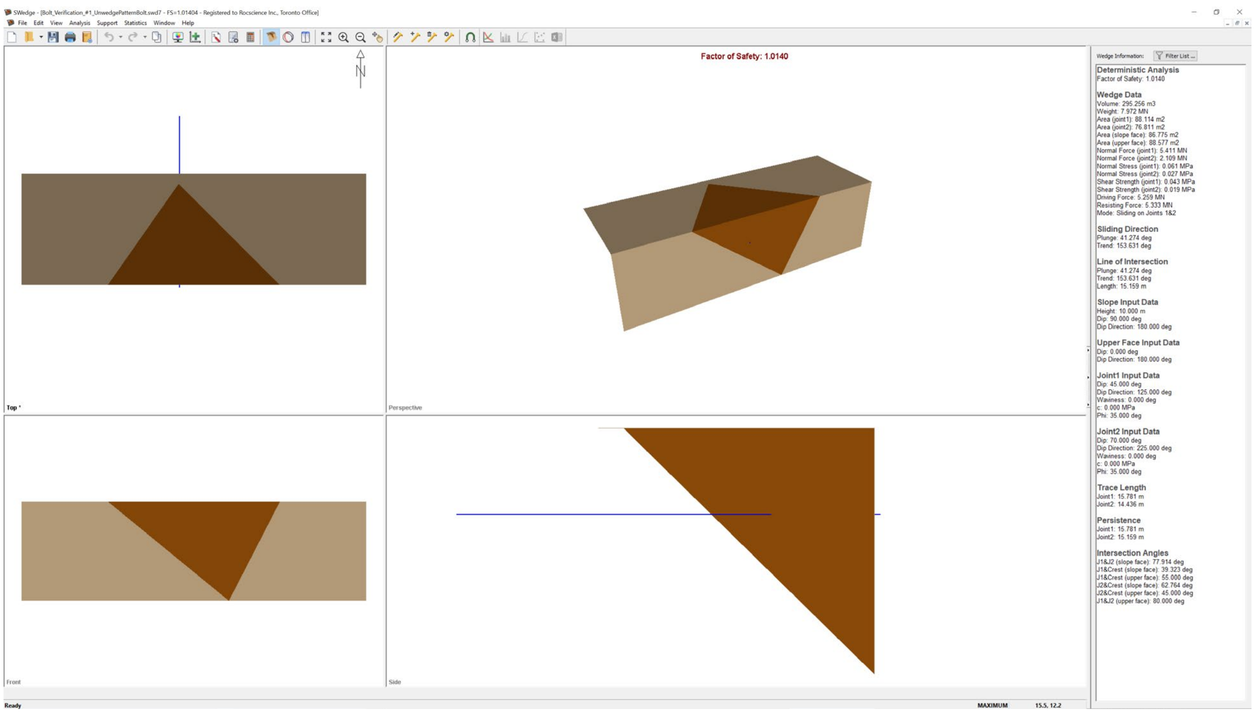


Figure 2.1.1: *SWedge* Model Geometry

Use the default capacity values for each Bolt Type. Be sure to select **Passive Bolt Model** in *SWedge* as all bolts in *UnWedge* are passive. Run analysis with each Bolt type, with/without **Use Shear Strength** checked and with/without **Use Bolt Orientation Efficiency** checked. When enabling Use Bolt Orientation Efficiency, use the default **Cosine Tension/Shear** Method. When testing shear bolts, uncheck the Use Bolt Orientation Efficiency option.

Note: The efficiency factor is not applied to the bolt shear strength. Bolt shear is only considered when Use Shear Strength is checked and when the bolt is in the corresponding deformation mode. Therefore, the bolt's tensile capacity can still be used when Use Shear Strength is checked. See ***Bolt Support Force*** *topic in Online Help for more information.*

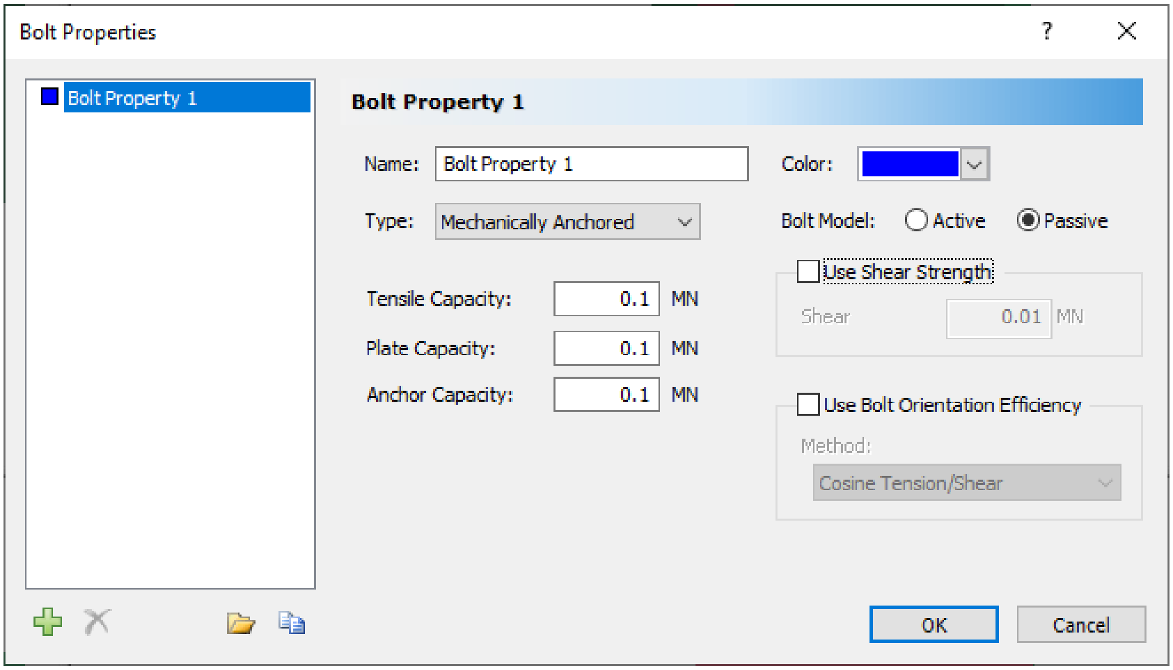


Figure 2.1.2: *SWedge* Bolt Property without using Bolt Orientation Efficiency

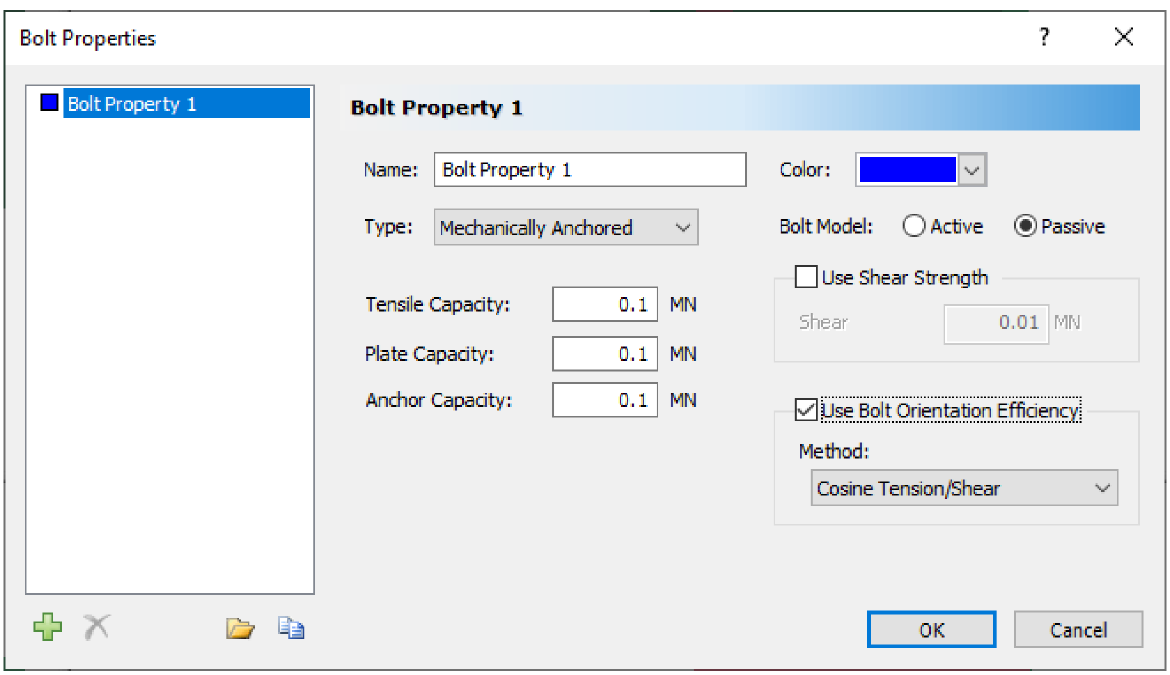


Figure 2.1.3: *SWedge* Bolt Property with Bolt Orientation Efficiency

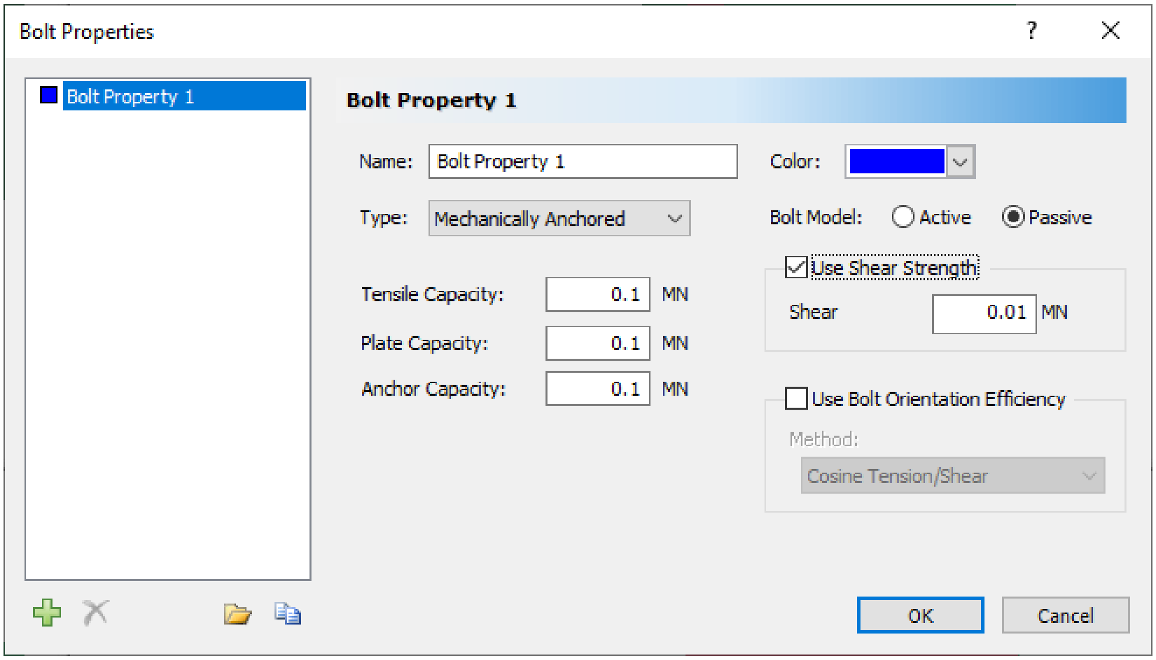


Figure 2.1.4: *SWedge* Bolt Property with using Shear Strength

2.1.3. Building a Compatible *UnWedge* Model

Enter the *UnWedge* geometry as below:

Table 2.1.3: *UnWedge* Slope and Joint Geometry

General Input Data	
Tunnel Axis Orientation Trend (°)	270
Tunnel Axis Plunge (°)	0
Design Factor of Safety	1
Rock Unit Weight (MN/m³)	0.027
Joint Orientations Input Data	
Joint 1 Dip Angle (°)	45
Joint 1 Dip Direction (°)	125
Joint 2 Dip Angle (°)	70
Joint 2 Dip Direction (°)	225
Joint 3 Dip Angle (°)	90
Joint 3 Dip Direction (°)	180
Joint Properties Input Data	

Name	Joint Properties 1
Shear Strength Model	Mohr-Coulomb
Phi (°)	35
c (MPa)	0

Use the following boundary coordinates for the *UnWedge* Opening Section:

Table 2.1.4**:** *UnWedge* Opening Section Coordinates

X	Y
-1	0
0	0
0	10
10.2	10
10.2	11
-1	11

In the Perimeter Support Designer for *UnWedge*, add a spot bolt Normal to the vertical leg with Length = **17m** and **Bolt Property 1** at coordinate **(0, 6.5)**.

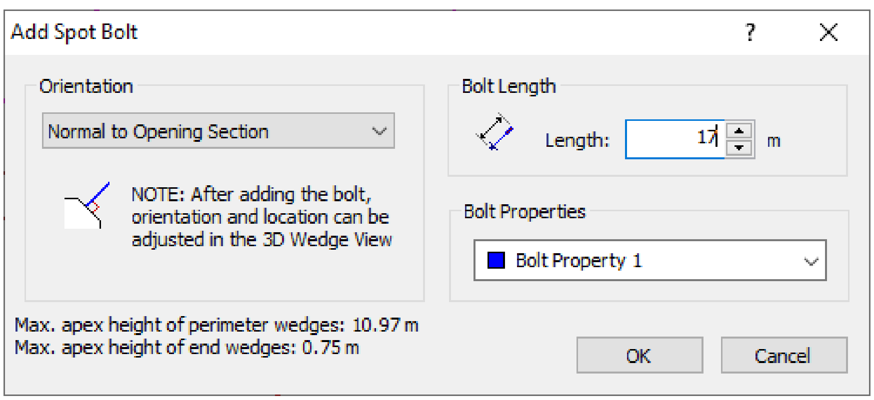


Figure 2.1.5: *UnWedge* Spot Bolt Input Data

The *UnWedge* Model looks like this:

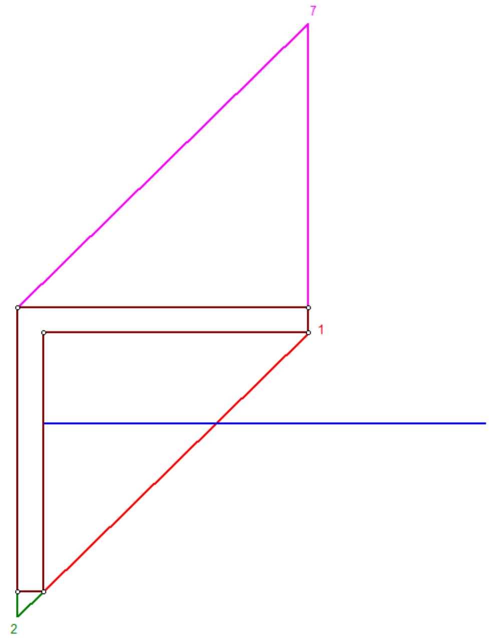


Figure 2.1.6: *UnWedge* Model Geometry

2.1.4. Results

The FS from both *SWedge* and *UnWedge* are listed below:

Table 2.1.5: *SWedge* and UnWedge Factor of Safety Comparison

Bolt Type	Use Shear Strength	Use Bolt Orientation Efficiency	FS	
			SWedge	***UnWedge***
Mechanically Anchored Tensile Capacity = 0.1 MN Plate Capacity = 0.1 MN Anchor Capacity = 0.1 MN Shear Strength = 0.01 MN	No	No	1.0140	1.014
	No	Yes	1.0057	1.006
	Yes	No	0.9905	0.990
Grouted Dowel with 100% Bond Length Tensile Capacity = 0.24 MN Plate Capacity = 0.1 MN Bond Strength = 0.34 MN Shear Strength = 0.02 MN	No	No	1.0497	1.050
	No	Yes	1.0297	1.030
	Yes	No	0.9924	0.992
Grouted Dowel with 8 m Bond Length	No	No	1.0140	1.014

Tensile Capacity = 0.24 MN Plate Capacity = 0.1 MN Bond Strength = 0.34 MN Shear Strength = 0.02 MN	No	Yes	1.0057	1.006
Cable Bolt Tensile Capacity = 0.2 MN Plate Capacity = 0.1 MN Bond Strength = 0.34 MN Shear Strength = 0.02 MN	No	No	1.0395	1.039
	No	Yes	1.0229	1.023
	Yes	No	0.9924	0.992
Split Set Tensile Capacity = 0.1 MN Plate Capacity = 0.05 MN Bond Strength = 0.03 MN Shear Strength = 0.01 MN	No	No	1.0140	1.014
	No	Yes	1.0057	1.006
	Yes	No	0.9905	0.990
Swellex Tensile Capacity = 0.1 MN Plate Capacity = 0.05 MN Bond Strength = 0.12 MN Shear Strength = 0.01 MN	No	No	1.014	1.014
	No	Yes	1.0057	1.006
	Yes	No	0.9905	0.990
Simple Bolt Force Force = 0.1 MN	N/A	N/A	1.0140	1.014

The results produced by *SWedge* agree well with *UnWedge* and confirm the reliability of the *SWedge* bolt model.

3. *SWedge* Ponded Water Pressure Model Verification

This section presents several verification examples for the ponded water pressure model in *SWedge.*

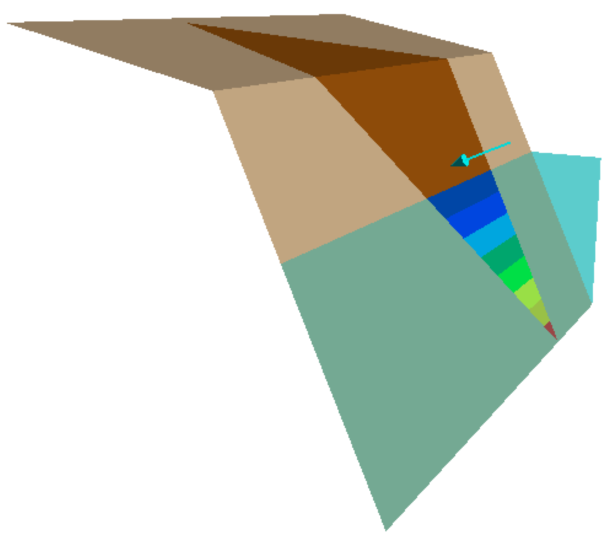
Two types of water pressures can be modelled in *SWedge*:

- Ponded Water Pressure – water pressure which acts on the slopes of the wedge
  and
- Joint Water Pressure (formerly Water Pressure) – water pressure which acts on the internal joints of the wedge.

The user can specify the unit weight of the ponded water and the ponded water depth, measured from the base of the slope. When ponded water pressure is modelled in conjunction with joint water pressure, the user can select from two slope face types:

- Impervious – the joint water pressure distribution is modelled independent of the ponded water, whereby users can select from a list of pre-defined pressure distribution models.
  or
- Pervious – the joint water pressure distribution depends on the elevation of the ponded water surface. The water table is defined by a combination of joint water surface planes and the ponded water surface plane.

Analyses of the Ponded Water Pressure model were performed in *SWedge* and verified by analytical solution and against *Slide3 2019.* FS was compared. The results produced by *SWedge* agree very well with *Slide3*, which confirms the reliability of *SWedge* results.



3.1. SWedge Verification Problem #1

[SWedge Build 7.016]

3.1.1. Problem Description

In this verification example, the effects of ponded water are presented by comparing the results of a dry slope face and fully ponded slope face in *SWedge*. The ponded water force computed in *SWedge* is then verified with a set of sample calculations to ensure that water pressure and force values are being computed using the correct equations.

Geometry and Material Properties

Table 3.1.1: Slope and Joint Geometry

Slope Input Data	
Slope Dip Angle (°)	60
Slope Dip Direction (°)	0
Height (m)	10
Upper Slope Dip Angle (°)	20
Upper Slope Dip Direction (°)	0
Rock Unit Weight (MN/m^3)	0.026
Joint Input Data	
Joint 1 Dip Angle (°)	55
Joint 1 Dip Direction (°)	320
Joint 1 Waviness (°)	0
Joint 1 Shear Strength Model	Mohr-Coulomb
Joint 1 Cohesion (MPa)	0
Joint 1 Friction Angle (°)	35
Joint 2 Dip Angle (°)	50
Joint 2 Dip Direction (°)	50
Joint 2 Waviness (°)	0
Joint 2 Shear Strength Model	Mohr-Coulomb
Joint 2 Cohesion (MPa)	0
Joint 2 Friction Angle (°)	35

Water Pressure

Table 3.1.2: Ponded Water and Joint Water

Ponded Water	
Unit Weight (MN/m^3)	0.00981
Slope Face Type	Impervious
Ponded Water Depth (m)	10
Joint Water	
Unit Weight (MN/m^3)	0.00981
Pressure Distribution Type	N/A
Percent Filled (%)	0

3.1.2. Analytical Solution

The ponded water force vector acting on the face of the wedge is calculated as follows:

$$U_{ponded} = \bar{P}A\hat{n}$$

Where:

$\bar{P}$ is the average ponded water pressure on the slope face

A is the area of the slope face

$\hat{n}$ is the inward (into wedge) normal of the slope face

The ponded water pressure at each vertex is computed as follows:

$$P_i = \gamma_w(H_w - d_i)$$

Where:

u_i is the water pressure at the ith slope vertex

γ_w is the unit weight of ponded water

H_w is the vertical height between the base of the slope and the ponded water surface

d_i is the vertical height between the base of the slope and the ith vertex

Sample Calculation

The top two slope vertices are at the ponded water surface:

$$P_1 = P_2 = 0 \text{ MPa}$$

The bottom slope vertex is at $10\ m$ below the ponded water surface:

$$u_3 = \gamma_w H_w = \left(0.00981\ \frac{\text{MN}}{\text{m}^3}\right)(10\text{ m} - 0\text{ m}) = 0.0981\text{ MPa}$$

The sample calculation is consistent with the Maximum Water Pressure results computed in *SWedge*.

The average ponded water pressure is computed from the vertex values:

$$\bar{P} = \frac{P_1 + P_2 + P_3}{3} = \frac{0\ \text{MPa} + 0\ \text{MPa} + 0.0981\ \text{MPa}}{3} = 0.0327\ \text{MPa}$$

The ponded water force magnitude:

$$U_{ponded} = \bar{P}A = (0.0327\ \text{MPa})(58.438\ \text{m}^2) = 1.9109\ \text{MN}$$

Converting using the dip and dip direction of the slope, the unit normal vector into the wedge is:

$$\hat{n} = (0, -0.8663, -0.5)$$

Converting the dip and dip direction of the sliding direction computed in *SWedge*, the unit vector is:

$$\hat{s} = (0.1301, 0.7262, -0.6751)$$

The component of the ponded water force that contributes to the direction of sliding is:

$$(U_{ponded} \cdot \hat{n}) \cdot \hat{s} = (1.9109\ \text{MN}) \cdot (0, -0.8663, -0.5) \cdot (0.1301, 0.7262, -0.6751) = -0.557\ \text{MN}$$

3.1.3. *SWedge* Analysis

Enter the geometry and material values from Table 3.1.1 into *SWedge*.

The *SWedge* model looks like this:

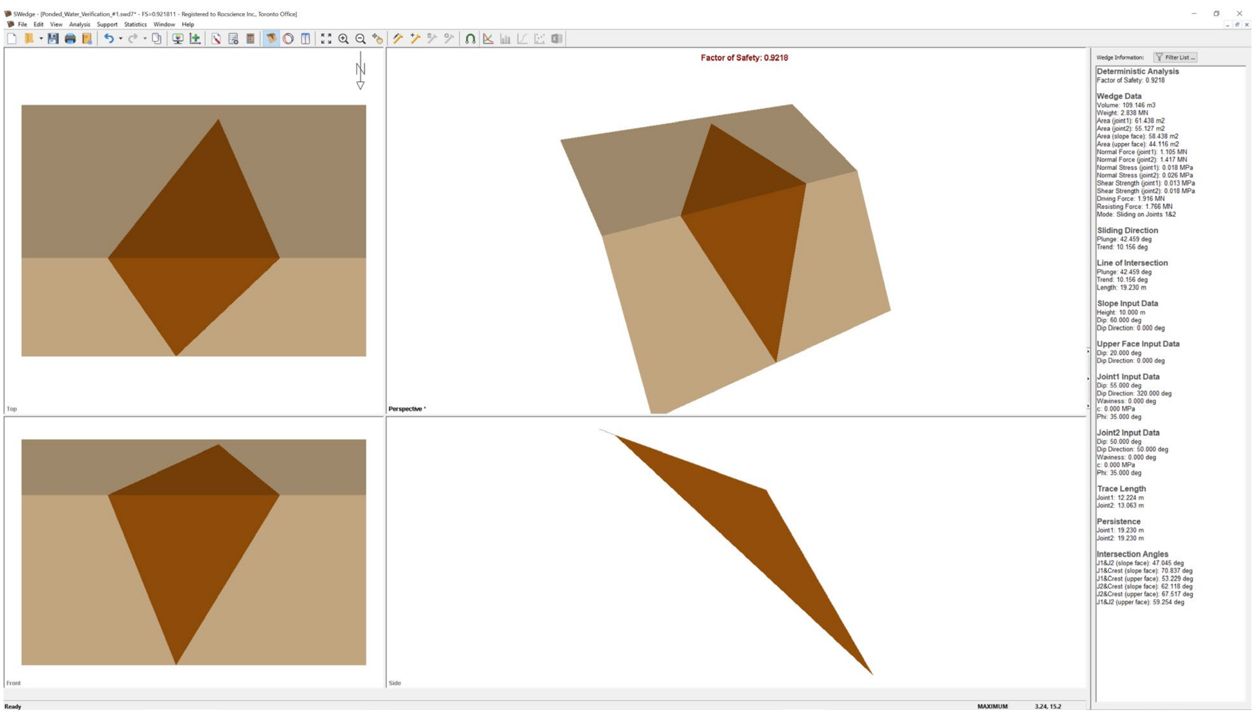


Figure 3.1.1: *SWedge* Model Geometry

Water Pressure

Enter the water parameter values from Table 3.1.2 into *SWedge*.

The analysis is run with **Ponded Water Pressure** checked only. Use the default unit weight values for ponded water. Set the **Ponded Water Depth** to **10 m**.

*Note: The **Slope Face Type** has no impact on the water pressure computation in SWedge when there is no Joint Water Pressure. See **Water Pressure** topic in Online Help for more information.*

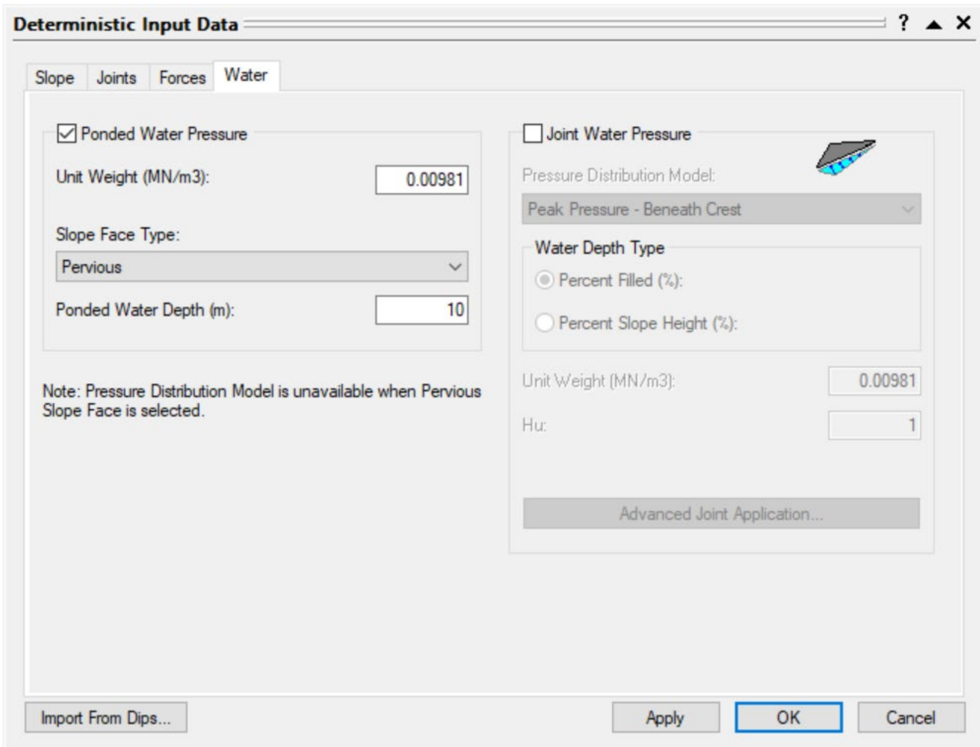


Figure 3.1.2: *SWedge* Water Deterministic Input Data with Ponded Water Pressure Only

The *SWedge* model looks like this:

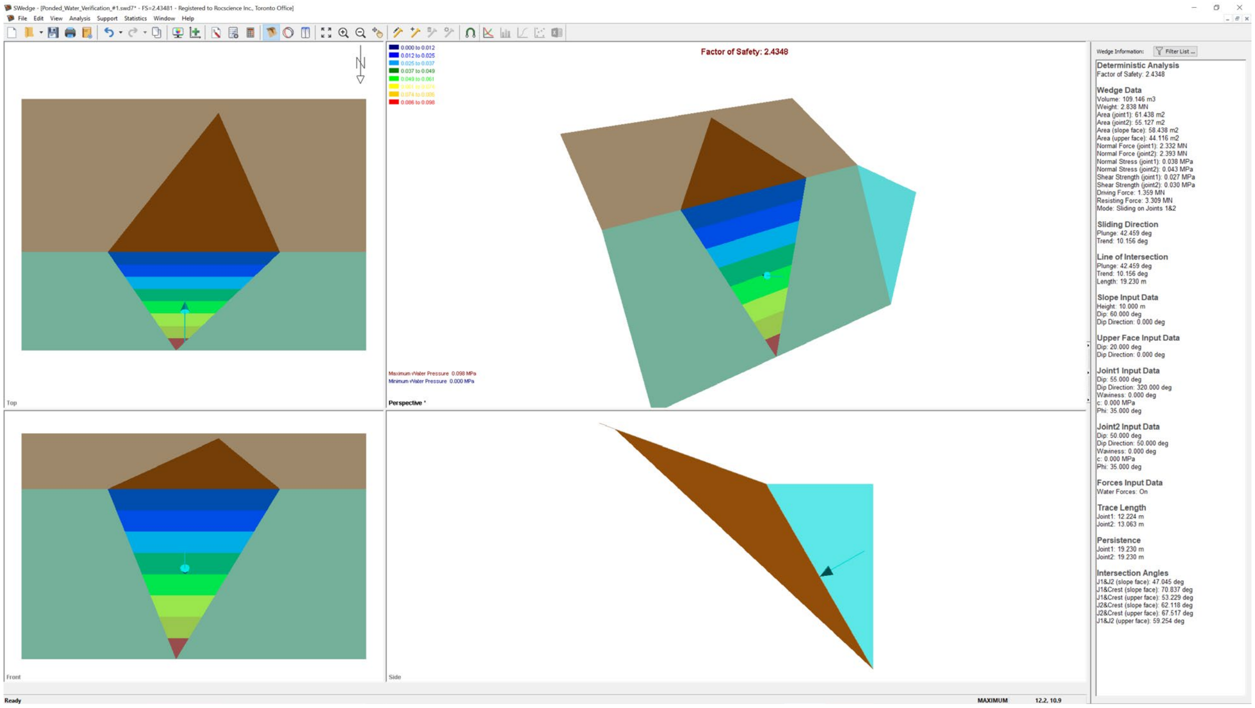


Figure 3.1.3: *SWedge* Ponded Water Model (Ponded Depth = 10m)

3.1.4. Results

Comparing *SWedge* results:

Table 3.1.3: *SWedge* Force and Factor of Safety Comparisons

Ponded Water Depth (m)	Joint Water Percent Filled (%)	Driving Force (MN)	Resisting Force (MN)	Factor of Safety
0	0	1.916	1.766	0.9218
10	0	1.359	3.309	2.4348

The slope is fully ponded. The Factor of Safety has increased from 0.9218 to 2.4348. In this case, the ponded water on the slope acts as a stabilizing force on the wedge (decreasing the total active force). The weight of the ponded water also increases the joint normal force and shear resistance, thereby increasing the resisting force.

The difference in Driving Force computed in *SWedge* before and after ponded water is applied is 1.916 MN - 1.359 MN = 0.557 MN. The sample calculation is consistent with the Active Force results computed in *SWedge*.

3.2. *SWedge* Verification Problem #2

[SWedge Build 7.016]

3.2.1. Problem Description

In this verification example, a cohesionless wedge is modelled with ponded water and joint water at various extents. The FS are verified against *Slide3*.

Geometry and Material Properties

The *SWedge* geometry and material properties are identical to Verification #1.

Water Pressure

Table 3.2.1: Ponded Water and Joint Water

Ponded Water	
Unit Weight (MN/m^3)	0.00981
Slope Face Type	Pervious
Ponded Water Depth (m)	0, 5, 10, or 15
Joint Water	
Unit Weight (MN/m^3)	0.00981
Pressure Distribution Type	N/A
Percent Filled (%)	0, 50, or 100

3.2.2. *SWedge* Analysis

Water Pressure

The analyses are run with both **Ponded Water Pressure** and **Joint Water Pressure** checked. Use the default unit weight value for ponded water and joint water. Model the **Slope Face Type** as **Pervious** for water pressure continuity across the slope faces. Vary the **Ponded Water Depth** from **0** m, **5** m, **10** m, to **15** m for “dry” joints and “fully wetted” joints.

> *Note: The **Slope Face Type** impacts the water pressure computation in SWedge when Joint Water Pressure exists. See **Water Pressure** topic in Online Help for more information.*

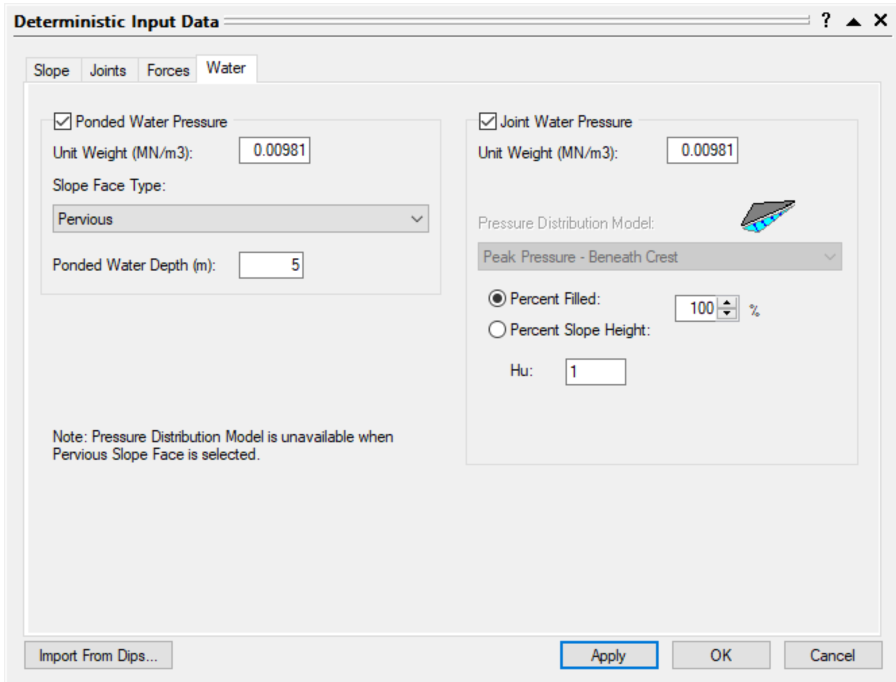


Figure 3.2.1: *SWedge* Water Input Data with Ponded Water Pressure and Joint Water Pressure

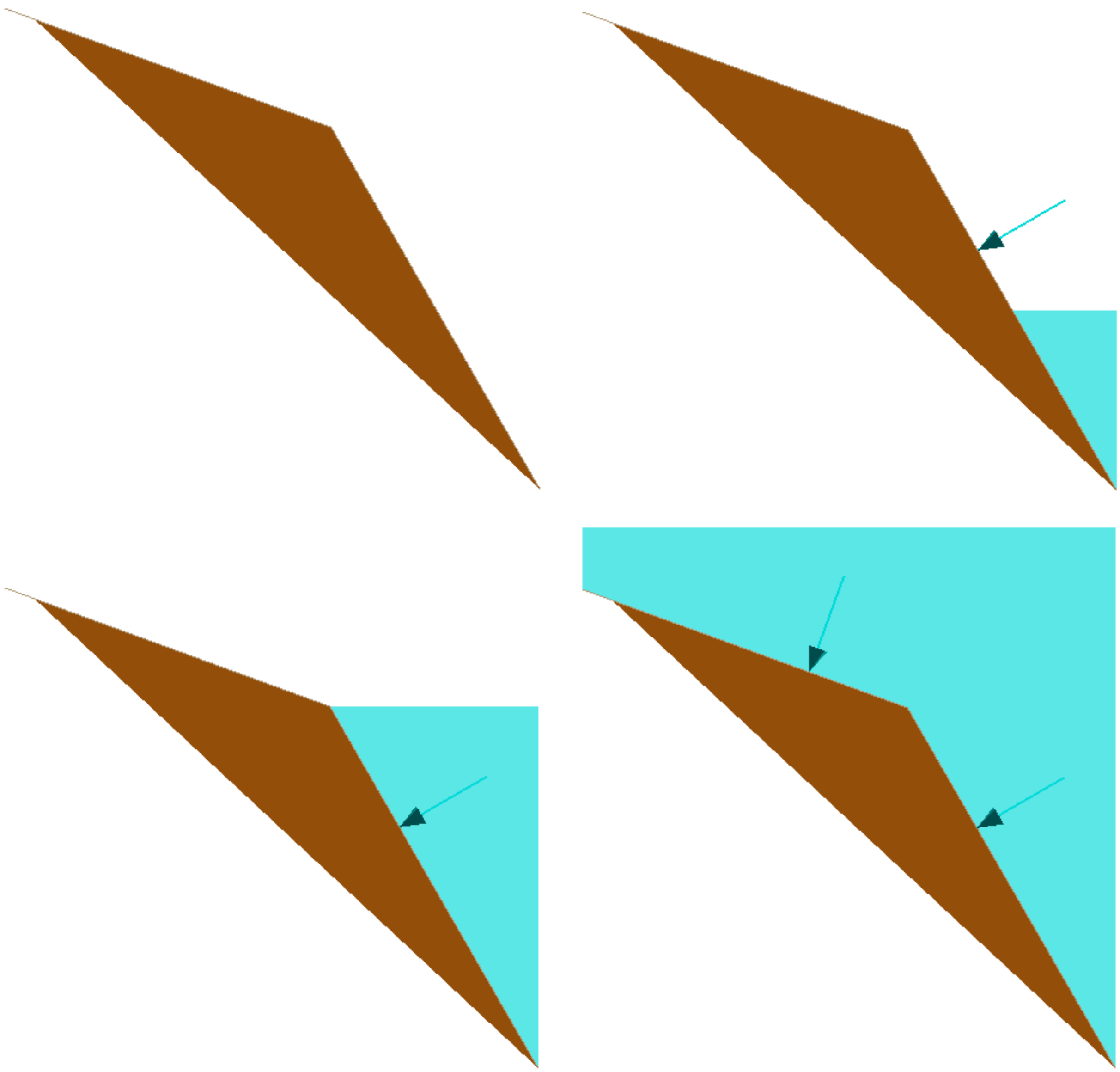


Figure 3.2.2: *SWedge* Water Pressure Contours for Ponded Water Depths 0 m, 5 m, 10 m, and 15 m with 0 Percent Filled Joint Water

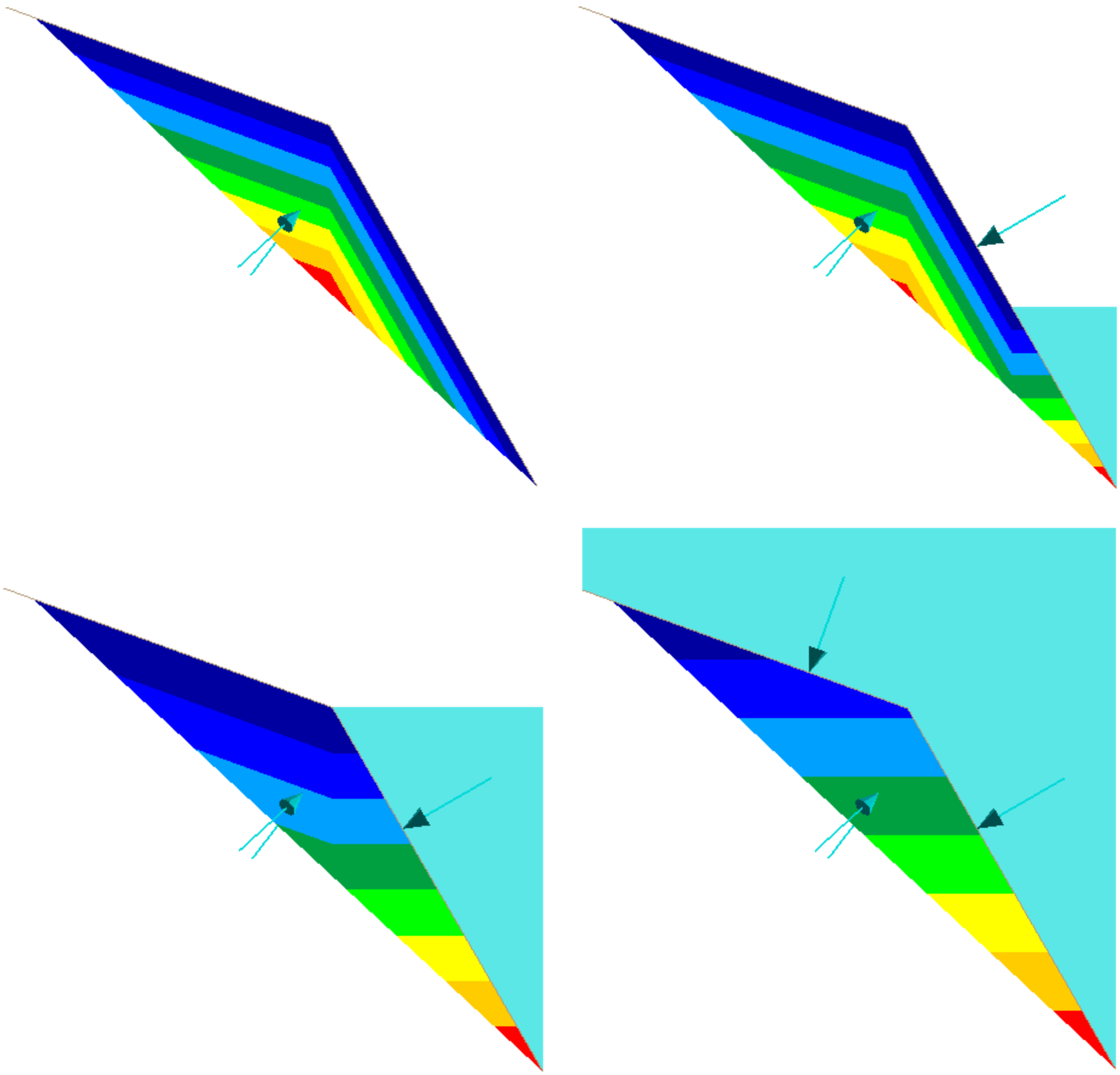


Figure 3.2.3: *SWedge* Water Pressure Contours for Ponded Water Depths 0 m, 5 m, 10 m, and 15 m with 100 Percent Filled Joint Water

3.2.3. Building a Compatible *Slide3* Model

A valid *Slide3* slope model is constructed by using an external box and two intersecting planes for the Slope and Upper Slope. A valid *Slide3* failure surface is created by setting a wedge as the user-defined slip surface and specifying the approximate crest point to produce a wedge with a height of 10 m. Under *Slide3* Project Settings, the Analysis Method is set to Janbu Simplified. Max Columns in X or Y are set to 200 to produce a smooth failure wedge.

Enter the *Slide3* geometry parameters as below:

Table 3.2.2: *Slide3* Slope and Joint Geometry

Slope Input Data	
External Slope Dip Angle (°)	60
External Slope Dip Direction (°)	0
External Upper Slope Dip Angle (°)	20
External Upper Slope Dip Direction (°)	0
External Rock Unit Weight (MN/m^3)	0.026
Wedge Surface Input Data	
Joint 1 Dip Angle (°)	55
Joint 1 Dip Direction (°)	320
Joint 2 Dip Angle (°)	50
Joint 2 Dip Direction (°)	50
Crest Point (m)	(8, 2.5, 18.42)

Enter the *Slide3* material properties as below:

Table 3.2.3: *Slide3* Material Properties

Material Input Data	
Shear Strength Model	Mohr-Coulomb
Cohesion (MPa)	0
Friction Angle (°)	35
Rock Unit Weight (MN/m^3)	0.026
Ponded Water Input Data	
Unit Weight (MN/m^3)	0.00981

The *Slide3* Model looks like this:

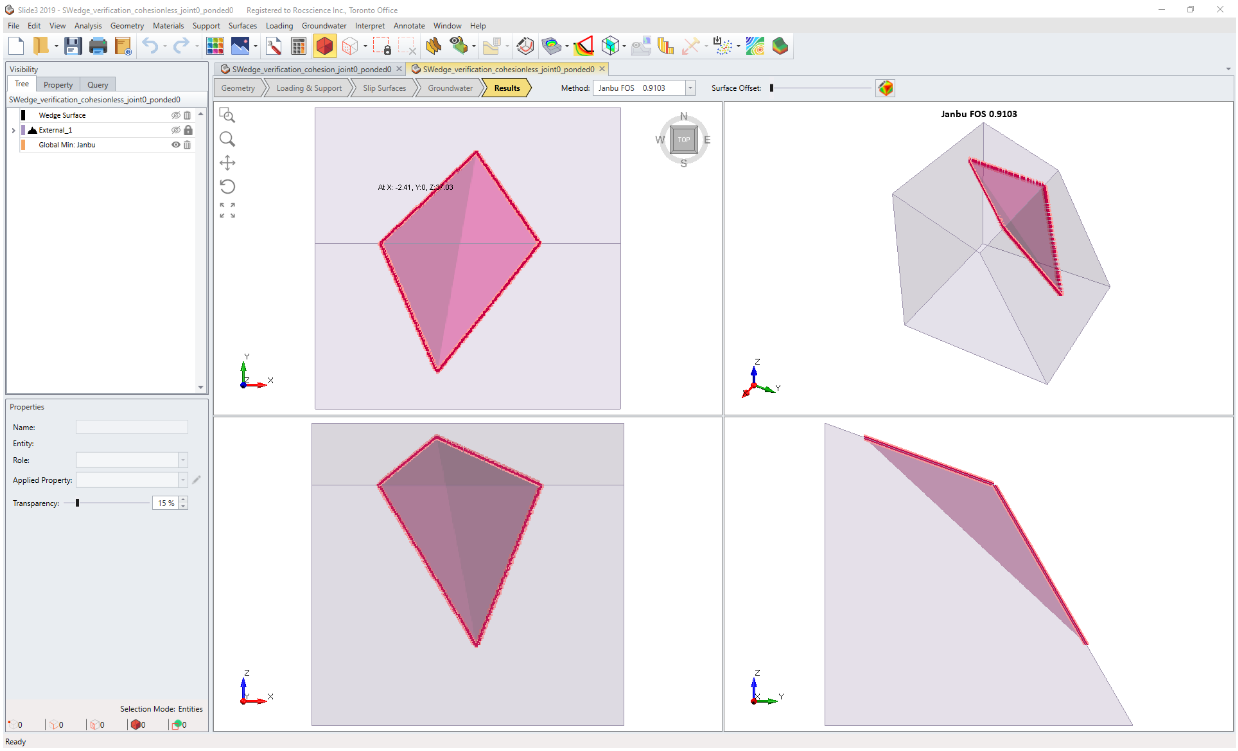


Figure 3.2.4: *Slide3* Model Geometry

The water table in *Slide3* is modelled by a horizontal plane or a set of planes at various elevations. **Hydraulic Assignments** are set to **None** for all materials when joints are “dry” and set to **Water Table** to when joints are “fully wetted”.

3.2.4. Results

The FS from both *SWedge* and *Slide3* are listed below:

Table 3.2.4: *SWedge* and *Slide3* Factor of Safety Comparison

Ponded Water Depth (m)	Joint Water Percent Filled (%)	FS	
		SWedge	***Slide3***
0	0	0.9218	0.9103
5		1.0610	1.0614
10		2.4348	2.4384
15		5.8483	5.8087
0	100	0.2763	0.2719
5		0.3165	0.3136

10		0.7128	0.7059
15		0.9218	0.9131

The results produced by *SWedge* agree well with Slide3 and confirm the reliability of the *SWedge* ponded water model.

3.3. *SWedge* Verification Problem #3

[SWedge Build 7.016]

3.3.1. Problem Description

In this verification example, a wedge with cohesion is modelled with ponded water and joint water at various extents. The FS are verified against *Slide3*.

3.3.2. *SWedge* Analysis

The *SWedge* geometry and material properties are identical to Verification #1, except the joints have a cohesion of 0.02 MPa. Slope Face Type is modelled as **Pervious** for water pressure continuity across the slope faces (same as Verification #1).

3.3.3. Building a Compatible *Slide3* Model

A valid *Slide3* slope model is constructed by using an external box and two intersecting planes for the Slope and Upper Slope. A valid *Slide3* failure surface is created by setting a wedge as the user-defined slip surface and specifying the approximate crest point to produce a wedge with a height of 10m. Under *Slide3* Project Settings, the Analysis Method is set to Janbu Simplified. Max Columns in X or Y are set to 200 to produce a smooth failure wedge.

Enter the *Slide3* geometry parameters as below:

Table 3.3.1: *Slide3* Slope and Joint Geometry

Slope Input Data	
External Slope Dip Angle (°)	60
External Slope Dip Direction (°)	0
External Upper Slope Dip Angle (°)	20
External Upper Slope Dip Direction (°)	0
External Rock Unit Weight (MN/m^3)	0.026
Wedge Surface Input Data	
Joint 1 Dip Angle (°)	55
Joint 1 Dip Direction (°)	320
Joint 2 Dip Angle (°)	50
Joint 2 Dip Direction (°)	50
Crest Point (m)	(8, 2.5, 18.42)

Enter the *Slide3* material properties as below:

Table 3.3.2: *Slide3* Material Properties

Material Input Data	
Shear Strength Model	Mohr-Coulomb
Cohesion (MPa)	0.02
Friction Angle (°)	35
Tensile Strength (MPa)	0.02
Rock Unit Weight (MN/m^3)	0.026
Ponded Water Input Data	
Unit Weight (MN/m^3)	0.00981

3.3.4. Results

The FS from both *SWedge* and *Slide3* are listed below:

Table 3.3.3: *SWedge* and *Slide3* Factor of Safety Comparison

Ponded Water Depth (m)	Joint Water Percent Filled (%)	FS	
		SWedge	***Slide3***
0	0	2.1388	2.1069
5		2.3239	2.3067
10		4.1504	4.1284
15		7.8026	7.7368
0	100	1.4933	1.4659
5		1.5793	1.5562
10		2.4284	2.3922
15		2.8761	2.8365

The results produced by *SWedge* agree well with *Slide3* and confirm the reliability of the *SWedge* ponded water model.

3.4. References

4. 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.

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6. Priest, S. (1993). *Discontinuity analysis for rock engineering.* London: Chapman and Hall.