ROCSCIENCE

RocSlope2

3D Stability Analysis of Rock Slopes for Wedge, Planar, and Toppling Failures

Verification Manual

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Introduction

RocSlope2 is an engineering analysis program for 3D stability assessments of rock slopes susceptible to wedge, planar, and toppling failure, produced by Rocscience Inc. of Toronto, Canada. This document presents several examples, which have been used as verification problems for *RocSlope2*.

1. *RocSlope2* Wedge Geometry Verification

The wedge analysis 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 *RocSlope2* are consistent with the documented examples and confirm the reliability of *RocSlope2* results.

1.1. *RocSlope2* Wedge Geometry Verification Problem #1

[RocSlope2 Build 1.005]

1.1.1. Problem Description

In this verification example, a static stability assessment (SSA) is presented to verify that *RocSlope2* computes values using the correct equations. The equations used to verify the results produced by *RocSlope2* 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]:

$$FS = \lambda \frac{\cos i_a \tan \phi}{\sin i_a} \tag{1.1.1}$$

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

$$\omega_1 + \omega_2 = 2\omega \tag{1.1.3}$$

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 $\omega_1 = \omega_2 = \omega$.

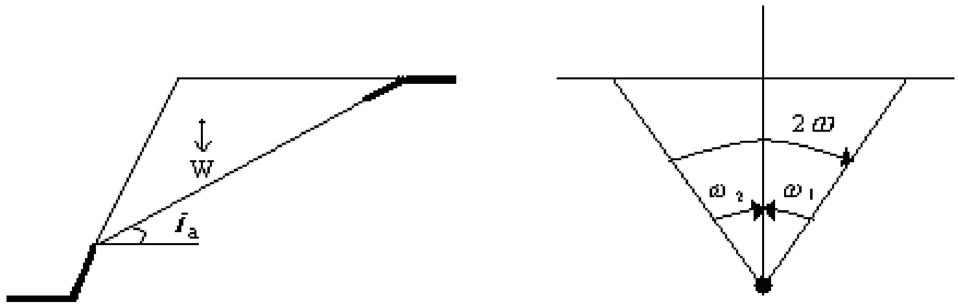


Figure 1.1.1: Front and Side Cross-Sectional Views of a Wedge Without a Tension Crack

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.

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

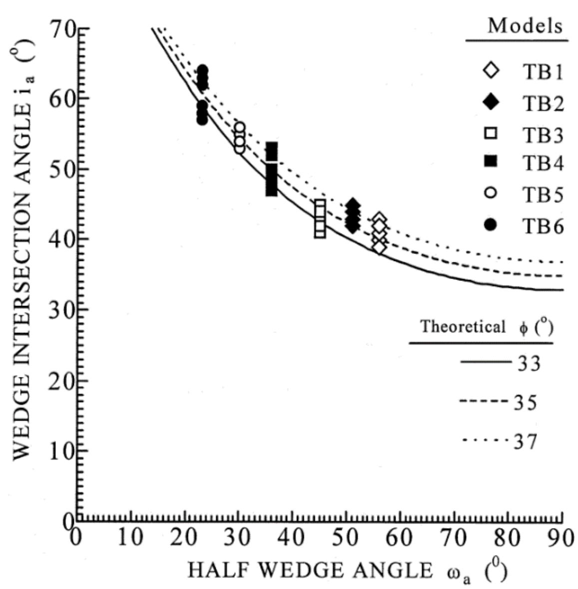


Figure 1.1.2: Comparison of Dry-Static Model Test Results with Theoretical Solution [1]

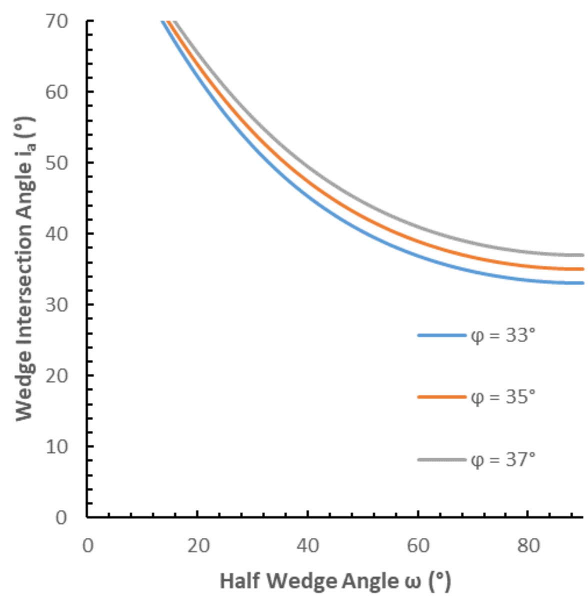


Figure 1.1.3: Graph of Equation 1 (ϕ = 33°, 35°, 37°; FS = 1)

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

In order to verify the *RocSlope2* results, the inclination angle (plunge) calculated by *RocSlope2* 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 *RocSlope2* the resulting Factor of

Safety FS ≅ 1. When ω is calculated, and ϕ is chosen, the corresponding intersection angle can be found using Figure 1.1.2.

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 1.1.2. Let us choose the line plotted for ϕ = 35°. The intersection angle (if *approximately* traced using a pencil) is i_a = 38°.

1.1.3. *RocSlope2* Analysis

Now verify that *RocSlope2* calculates the same intersection angle.

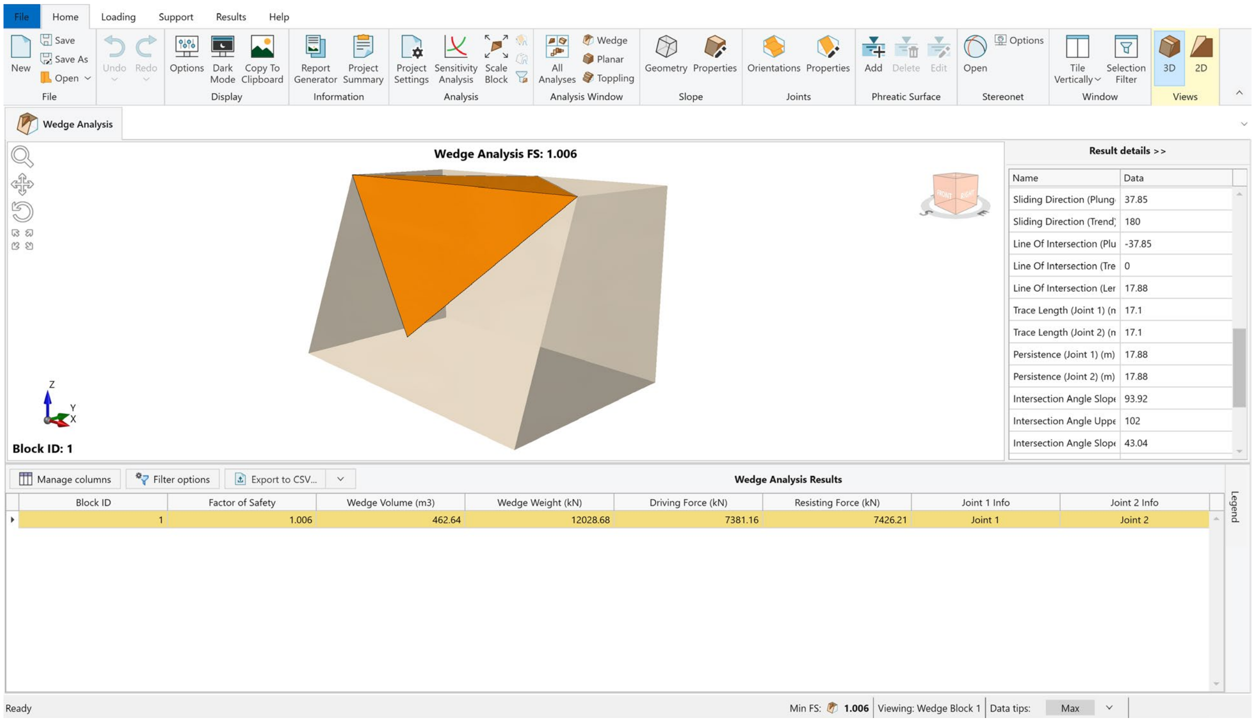


Figure 1.1.4: Input Data and Results

The values from Table 1.1.1 are input into *RocSlope2*, and the resulting plunge, or i_a = 37.85°. This is essentially the same value that was obtained from Figure 1.1.2.

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, *RocSlope2* was verified to work for the example problem.

More tests were done, as shown in Figure 1.1.5; *RocSlope2* results were plotted against the theoretical solution. Models were made for three friction angles, and *RocSlope2* 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 3D Wedge View in *RocSlope2*, 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

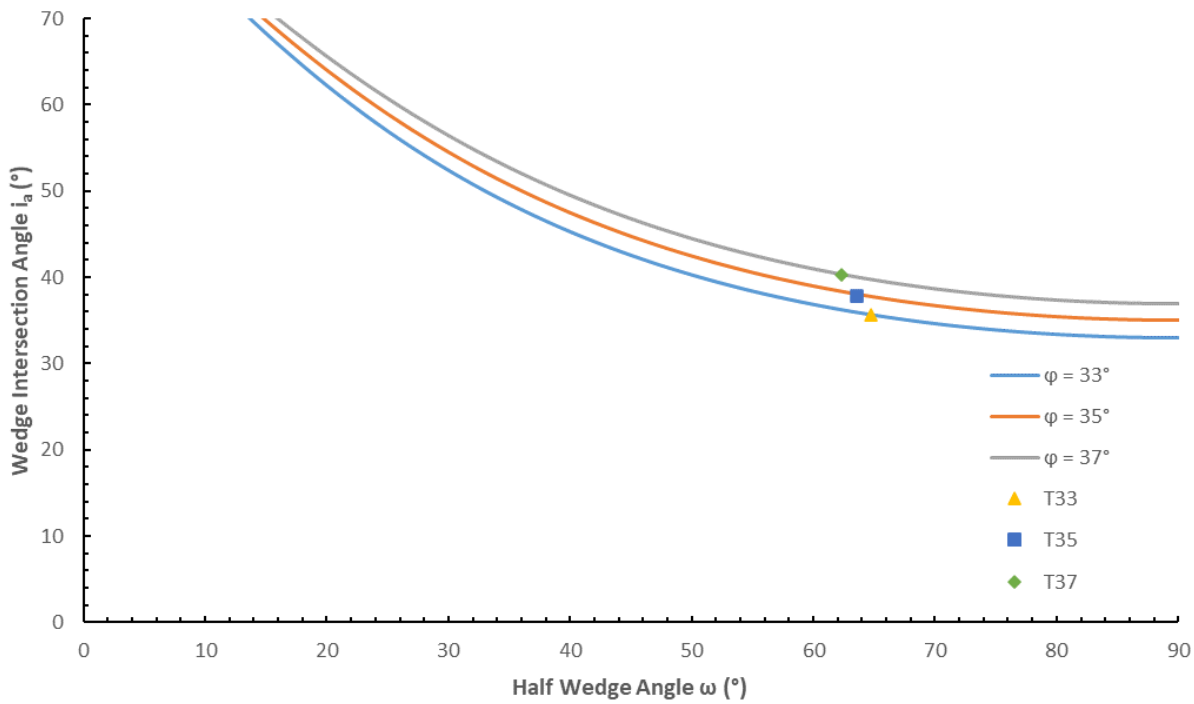


Figure 1.1.5: *RocSlope2* Results Compared to Theoretical Solution for FS = 1

Table 1.1.5: *RocSlope2* Sample Data

***RocSlope2* Sample**	ω **(°)**	i_a **(°)**
T33	64.737	35.65
T35	63.577	37.85
T37	62.356	40.30

1.2. *RocSlope2* Wedge Geometry Verification Problem #2

[RocSlope2 Build 1.005]

1.2.1. Problem Description

In *RocSlope2* Wedge Geometry Verification Problem #1, *RocSlope2* was verified for static stability. In this problem, the program will 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 *RocSlope2*, 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 *RocSlope2* 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]:

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

$\beta = 0$ (seismic forces have a horizontal trend – refer to Figure 1.2.1) (1.2.2)

$$\omega_1 + \omega_2 = 2\omega \quad (1.2.3)$$

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

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

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

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

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

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 1.2.1)
a	is acceleration
g	is acceleration (981 cm/s^2)

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

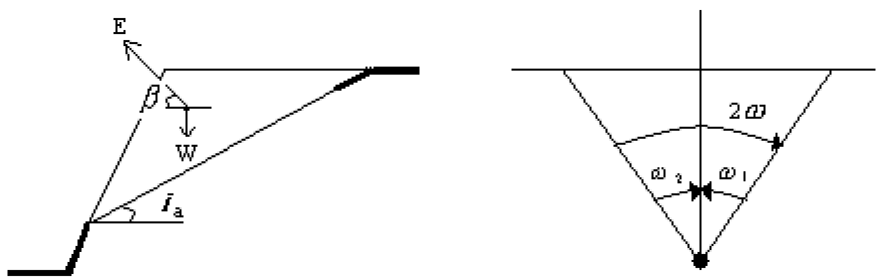


Figure 1.2.1: Front and Side Cross-Sectional Views of a Wedge Without a Tension Crack (dynamic force "$\boldsymbol{E}$" has an inclination of $\boldsymbol{\beta}$)

Sample Calculation

It is now assumed (based on Verification Problem #1) that the inclination angle function in *RocSlope2* is accurate. The dynamic stability assessment calculation for a specific wedge (using the equations shown above) is performed. The *RocSlope2* 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.

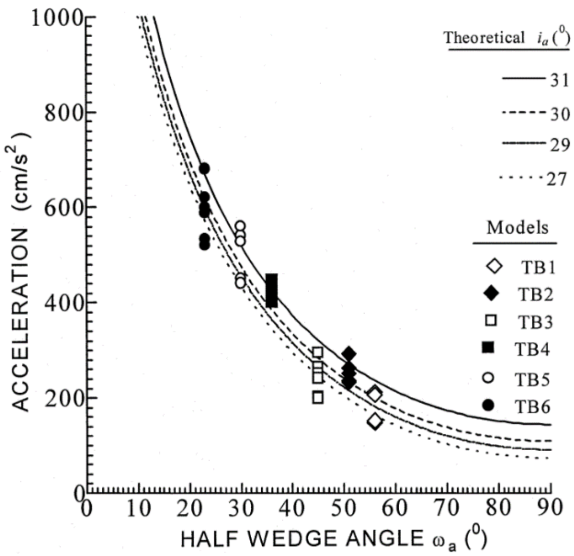


Figure 1.2.2: Comparison of Dynamic Model Test Results with Analytical Solution [1]

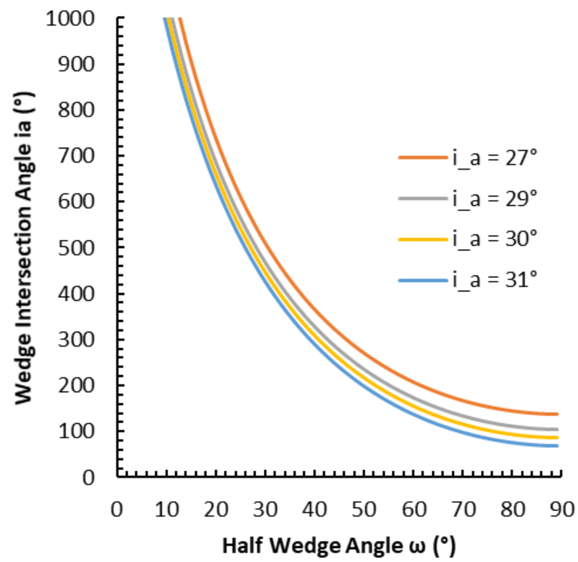


Figure 1.2.3: Analytical Solution for Dynamic Stability Assessment with FS = 1
($\boldsymbol{\phi}$ = 35°; $\boldsymbol{i_a}$ = 27°, 29°, 30°, and 31°)

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 directions into *RocSlope2*. FS = 1.632 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 acting 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. *RocSlope2* Analysis

Enter η = 0.2365 into *RocSlope2* (Figure 1.2.4). 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.

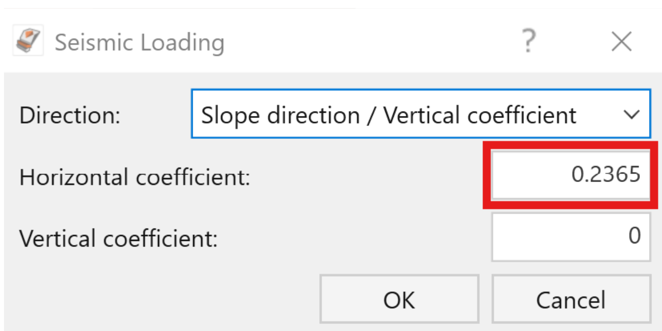


Figure 1.2.4: Seismic Force Specified in *RocSlope2* Input

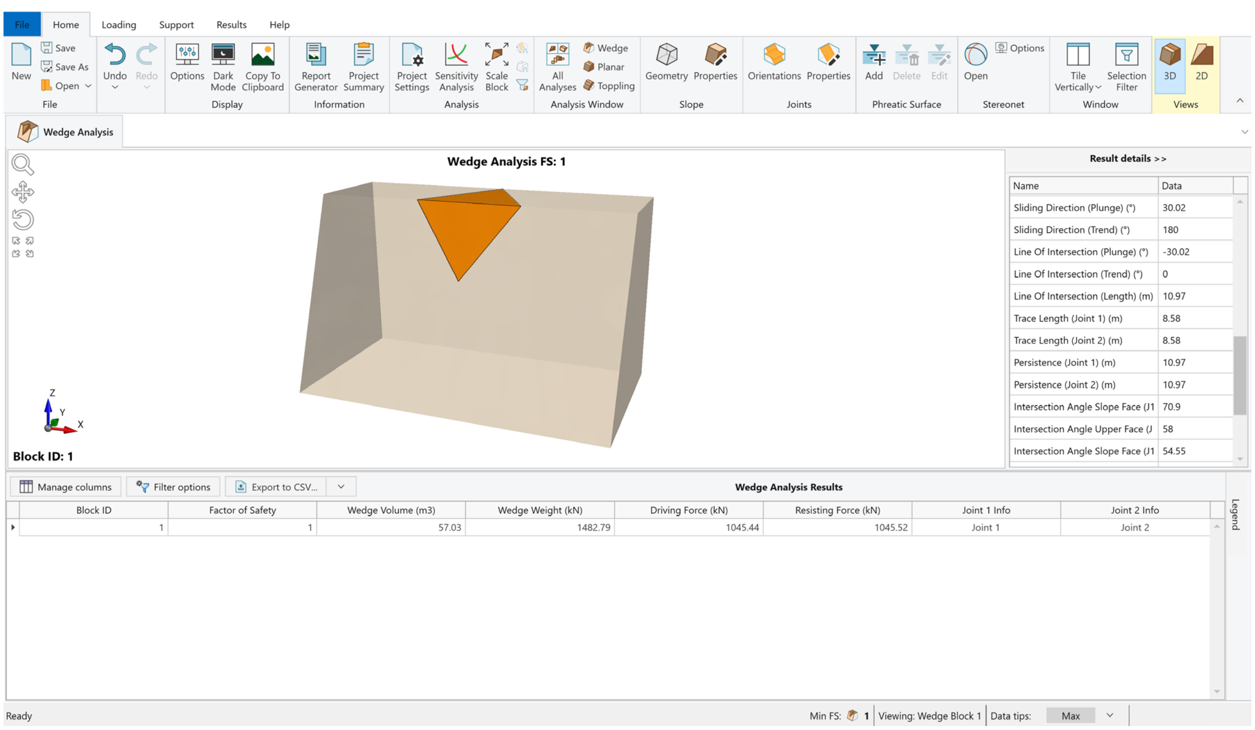


Figure 1.2.5: *RocSlope2* Seismic Results

Since the Factor of Safety has changed to FS = 1, the analysis functions for *RocSlope2* in DSA are functioning correctly. To further verify this, see if the acceleration (derived from Equation 8) using the seismic coefficient in *RocSlope2* 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.

1.2.4. Results

In the previous section, *RocSlope2* is verified for the specific example discussed.

More tests were done, as shown in Figure 1.2.6. A number of *RocSlope2* results for each i_a value was plotted against the analytical solution. *RocSlope2* 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

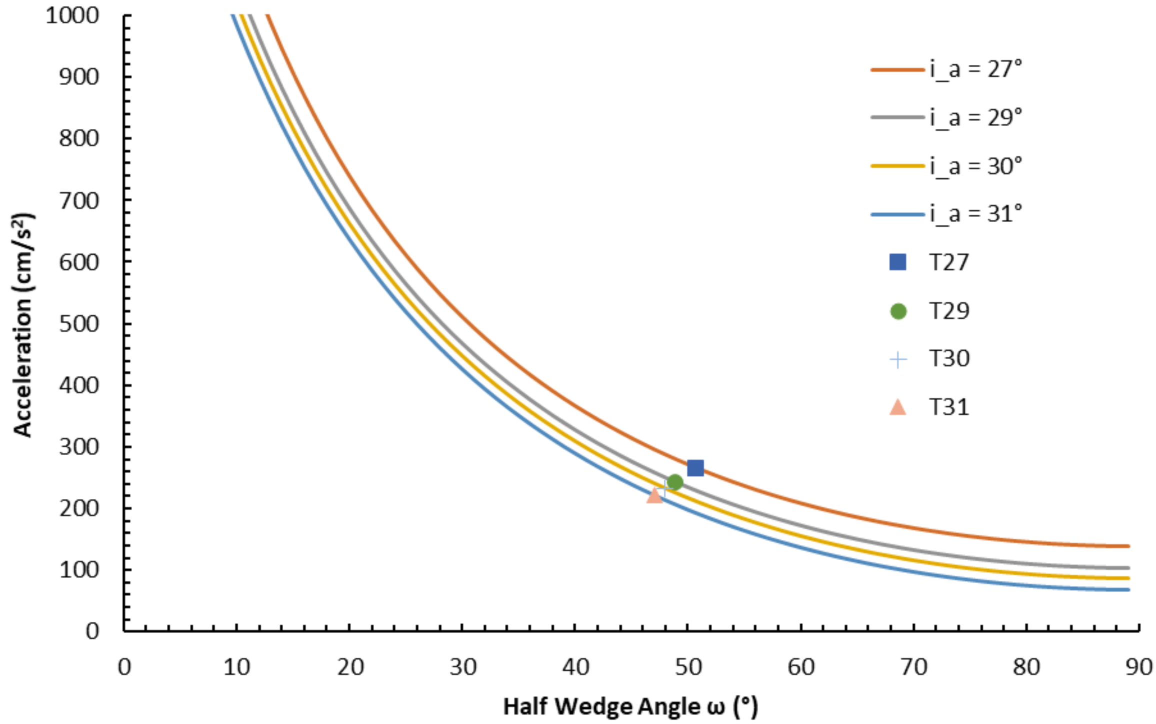


Figure 1.2.6: *RocSlope2* Results Compared to Analytical Solution

Table 1.2.6: RocSlope2 Sample Data

***RocSlope2* Sample**	ω (°)	i_a (°)	η	**Acceleration (cm/s²)**
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. *RocSlope2* Wedge Geometry Verification Problem #3

[RocSlope2 Build 1.005]

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. *RocSlope2* 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
$\boldsymbol{\omega_1}$ (°)	77
$\boldsymbol{\omega_2}$ (°)	28
$\boldsymbol{i_a}$ (°)	42
$\boldsymbol{\phi}$ (°)	30

1.3.2. *RocSlope2* 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 *RocSlope2*. Note that the Upper Slope is assumed to be a horizontal plane.

The *RocSlope2* model looks like this:

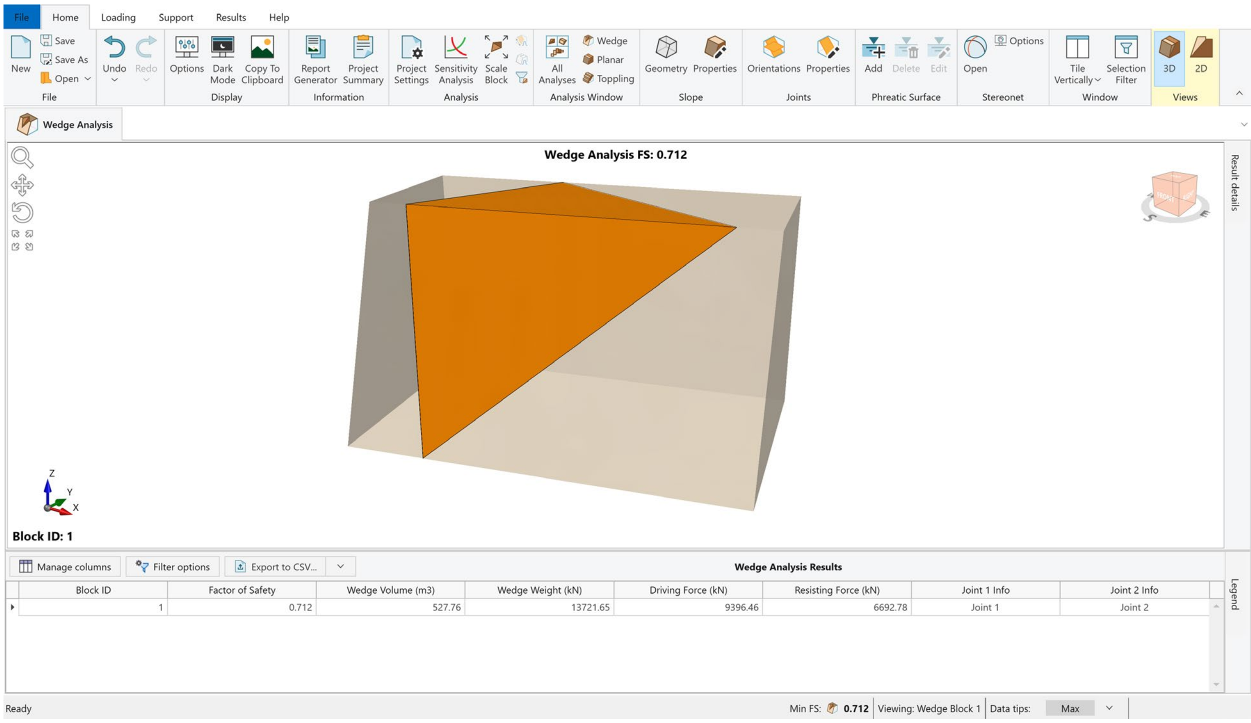


Figure 1.3.1: *RocSlope2* Results

1.3.3. Results

Looking at Figure 1.3.1, the Factor of Safety calculated by *RocSlope2* is FS = 0.712. The Factor of Safety calculated by *RocSlope2* agrees well with the experimental results (Table 1.3.3).

Table 1.3.3: *RocSlope2* Analysis Results

	RocSlope2	Kumsar et al. [1]
Factor of Safety	0.712	0.73

1.4. *RocSlope2* Wedge Geometry Verification Problem #4

[RocSlope2 Build 1.005]

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, using 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 *RocSlope2*, it is verified that *RocSlope2* 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 *RocSlope2* 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. *RocSlope2* 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 *RocSlope2* as is. Note that the Upper Slope is assumed to be a horizontal plane.

The *RocSlope2* models are shown below:

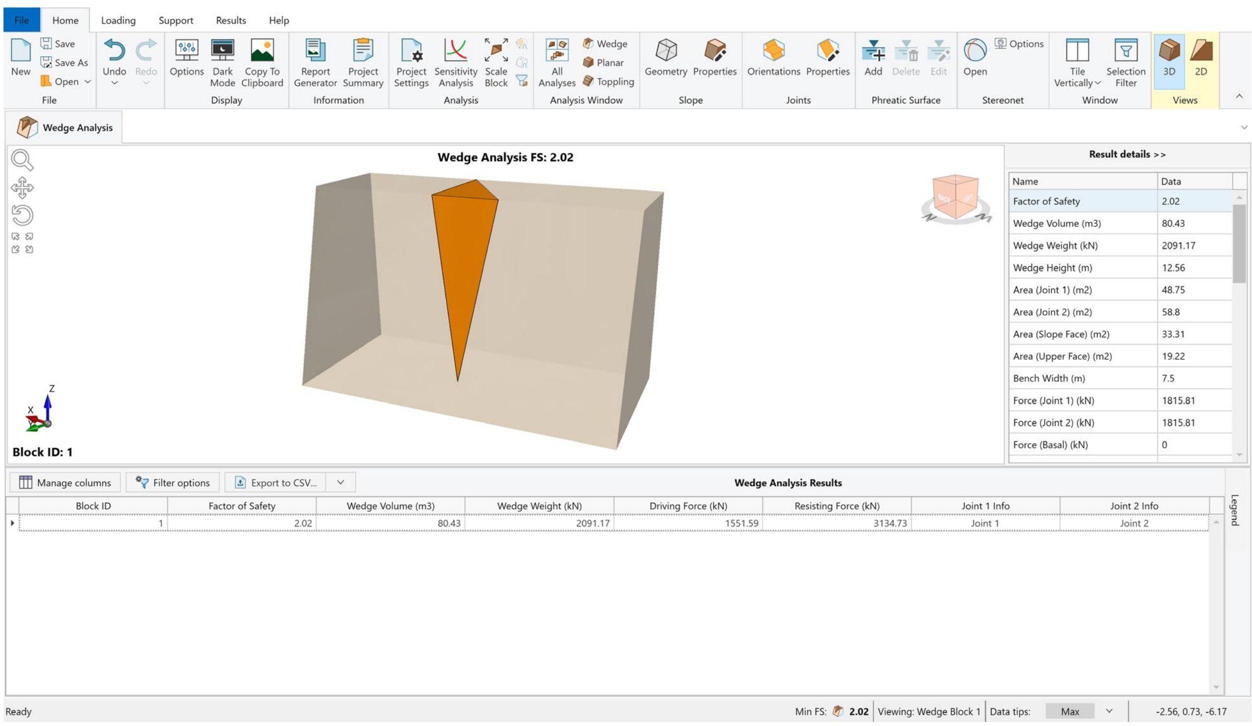


Figure 1.4.1: *RocSlope2* Static Stability Analysis

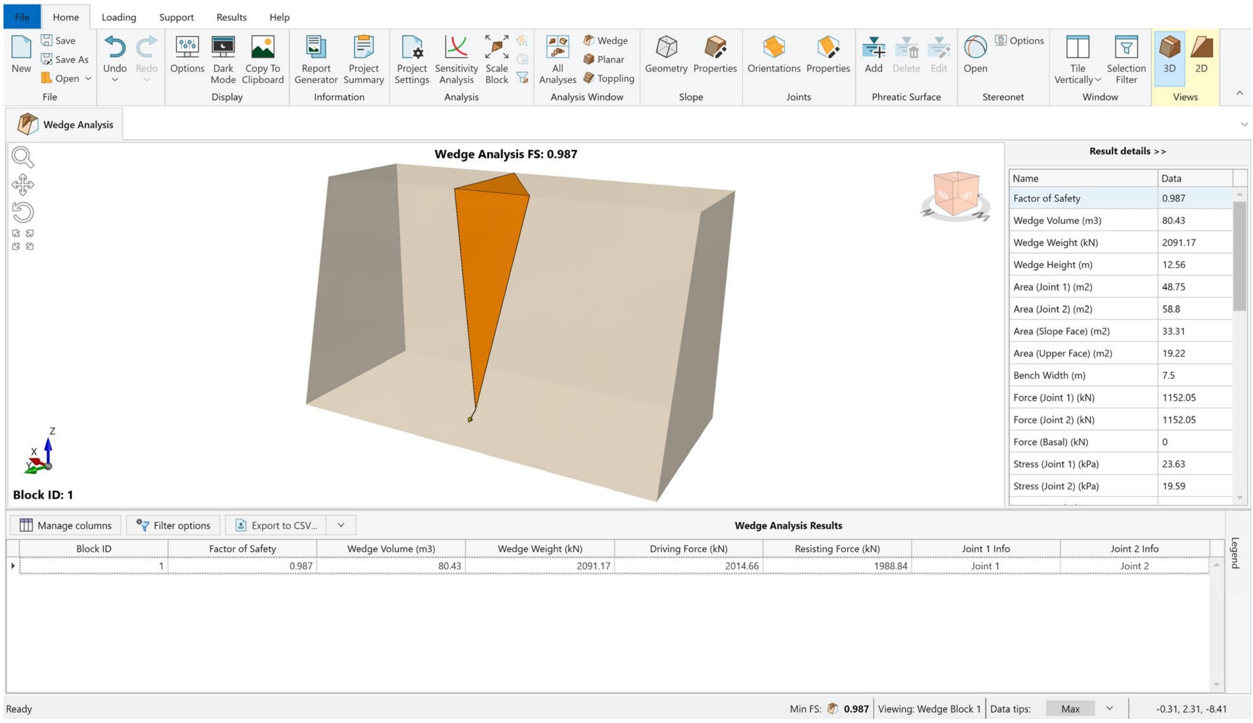


Figure 1.4.2: RocSlope2 Dynamic Stability Analysis

1.4.3. Results

For the static analysis, *RocSlope2* calculates FS = 2.02 (see Figure 1.4.1). With the seismic load, the Factor of Safety drops to FS = 0.987, as shown in Figure 1.4.2. Since the Factors of Safety calculated by *RocSlope2* match the experimental results closely, *RocSlope2* is verified for Factor of Safety calculations for dynamic stability assessments.

Table 1.4.4: RocSlope2 Analysis Results

Factor of Safety	*RocSlope2*	*Kumsar et al. [1]*
Static	2.02	2.02
Seismic η = 0.3303 EW	0.987	0.99

1.5. *RocSlope2* Wedge Geometry Verification Problem #5

[RocSlope2 Build 1.005]

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 *RocSlope2* 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 1.5.4. All these components are shown below in Figure 1.5.1.

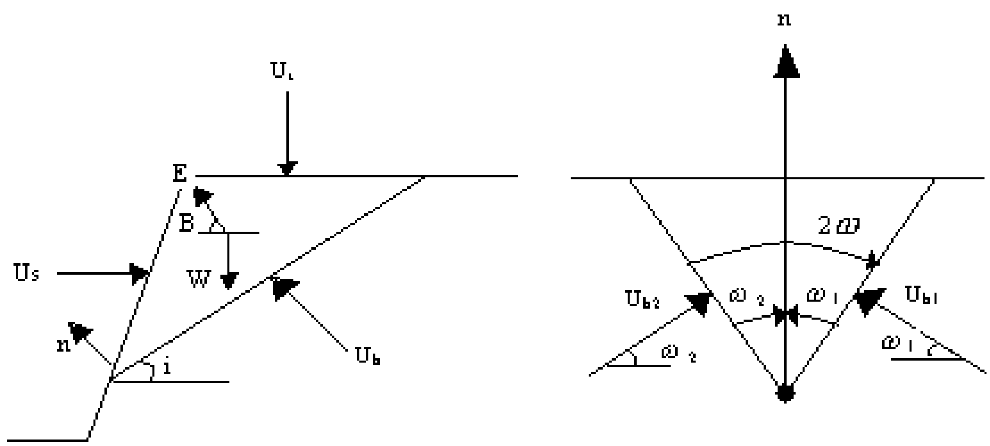


Figure 1.5.1: Front and Side Cross-Sectional Views of a Wedge Without a Tension Crack

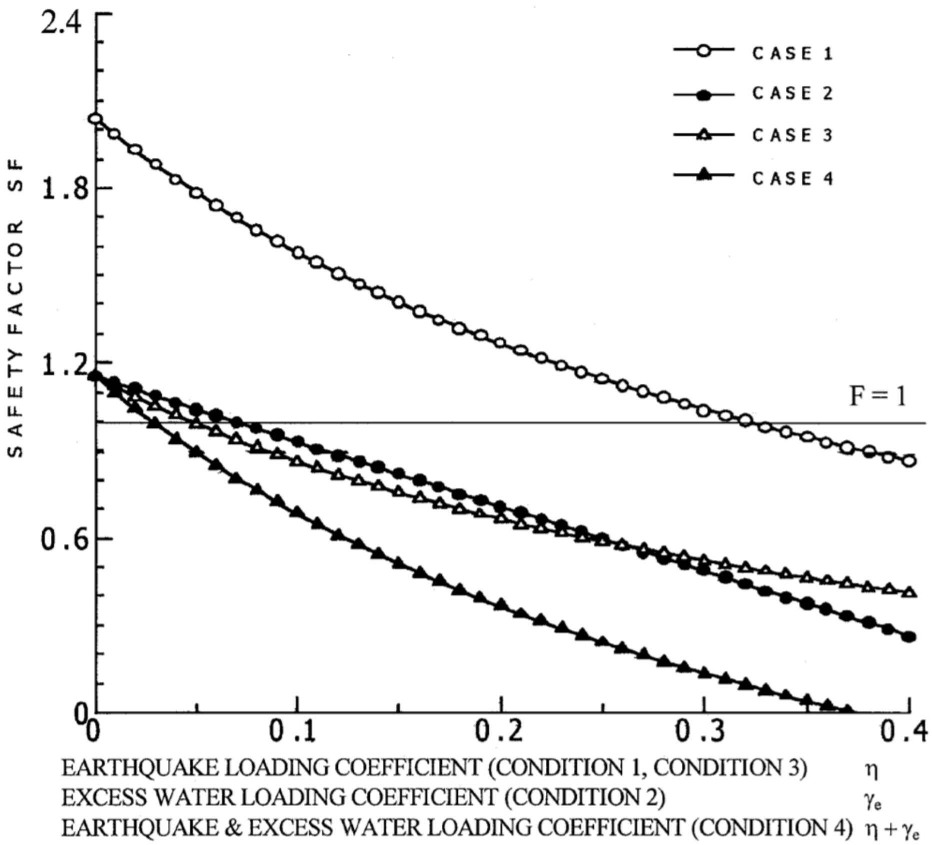


Figure 1.5.2: Case Results for Wedge Failure at Mt. Mayuyama
(assumed ϕ = 35°)

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:

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

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

$$i_a = 23°$$

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

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 $\eta \cong 0.325$, the Factor of Safety is FS = 1. By inserting this seismic coefficient into an *RocSlope2* analysis, FS = 1 at that point as well. The slope and joint inputs are found in Table 1.5.2 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].

Table 1.5.2: Slope and Joint Inputs

Parameter	Value
Slope Dip (°)	35
Slope Dip Direction (°)	91
Slope Height (m)	300
Upper Slope Dip (°)	0
Upper Slope Dip Direction (°)	91
Joint 1 Dip (°)	41
Joint 1 Dip Direction (°)	30
Joint 2 Dip (°)	41
Joint 2 Dip Direction (°)	150

The Factor of Safety without the earthquake load is FS = 1.958. Once the seismic coefficient is introduced the Factor of Safety reduces to FS = 1.078 ≅ 1. This verifies *RocSlope2* results.

The *RocSlope2* models are pictured below:

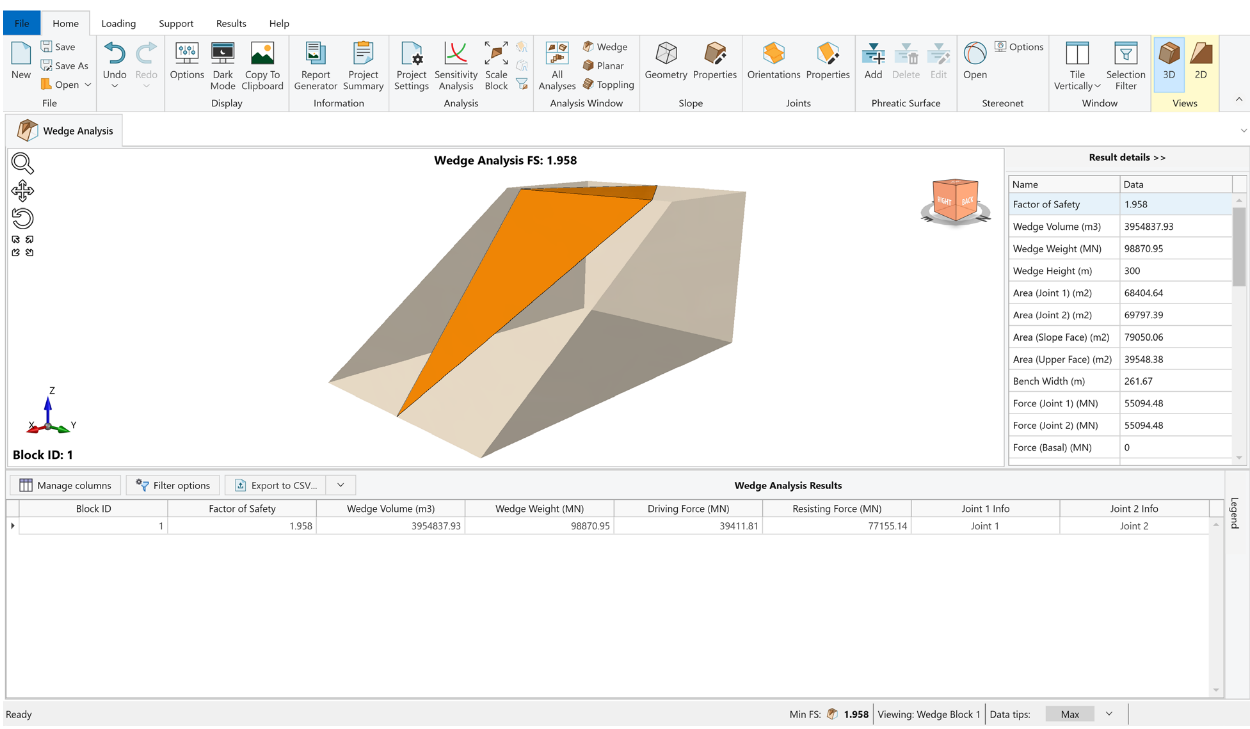


Figure 1.5.3: *RocSlope2* Results for Static Case

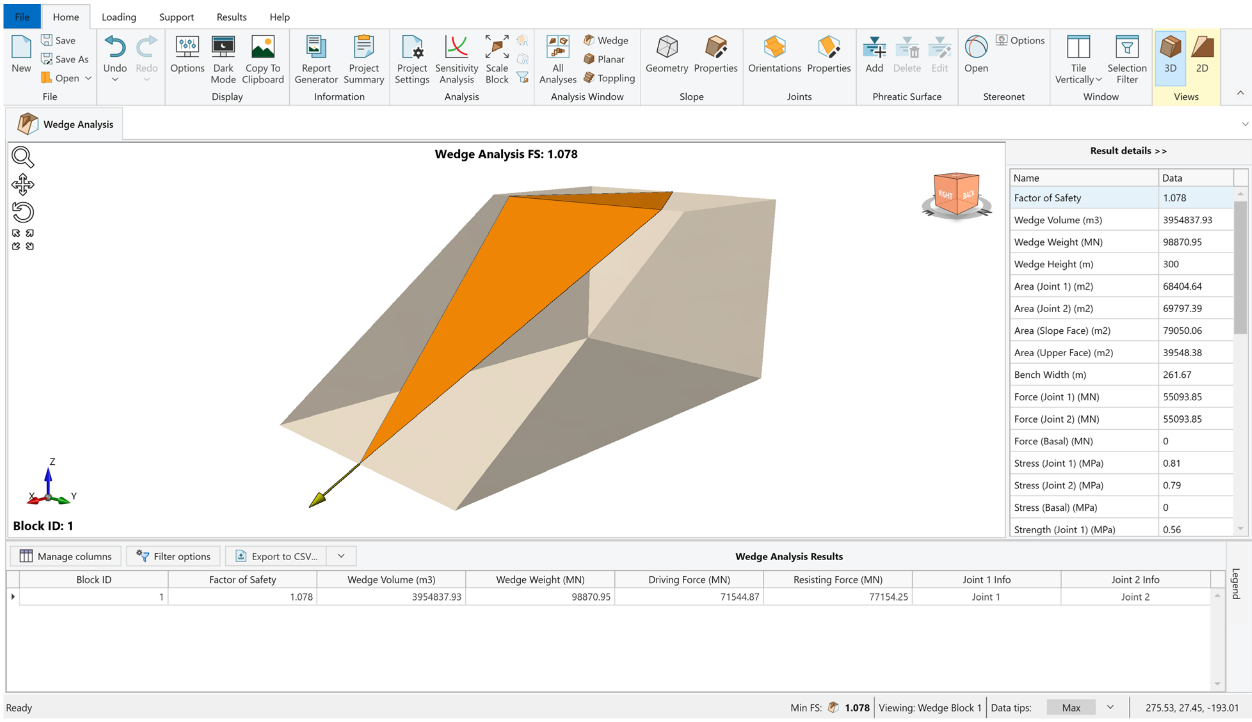


Figure 1.5.4: *RocSlope2* Results for Case with Earthquake Load

Case 2:

In this case, 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 a *RocSlope2* analysis, FS = 1 there as well. The slope and joint inputs are found in Table 1.5.2 and are the same for all the cases.

Add the water forces to the wedge in *RocSlope2*. The following is a derivation of how much pressure is put on the surface of each joint (a few assumptions are 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)

The wedge weight and the two joint areas are provided in the Result Details:

Wedge Weight = 98870.95 MN

Area (Joint 1) = 68404.636 m^2

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 similarity of the wedge areas, 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 *RocSlope2* is calculated:

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

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

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

Given $\gamma_e = 0.06$, $U_b = (0.4 + 0.06)(98870.95) = 45480.64 \text{ MN}$

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

Below, the Factor of Safety is FS ≅ 1.

The *RocSlope2* model looks like this:

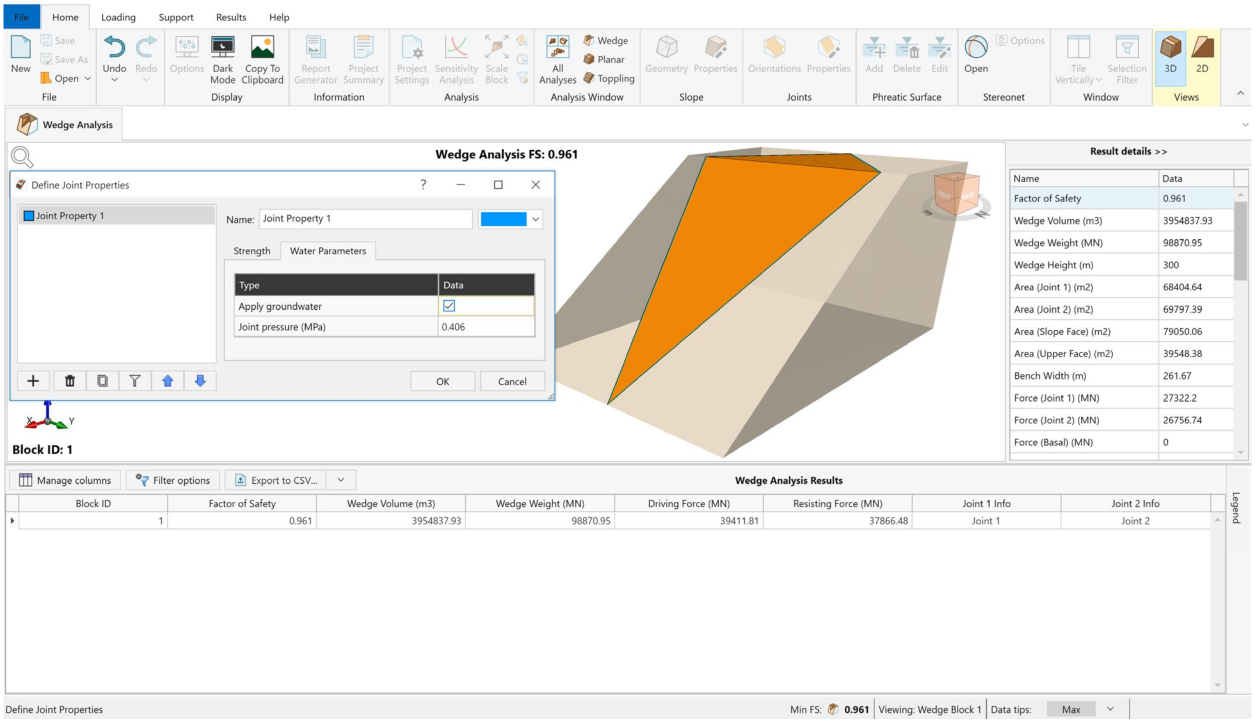


Figure 1.5.5: *RocSlope2* Analysis with Custom Water Pressure

Looking at Figure 1.5.5, *RocSlope2* calculates FS = 0.961 ≅ 1. *RocSlope2* 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 $\gamma_e = 0$, $U_b = 0.4W$

$$\therefore FS = \frac{(\cos 23 - \eta \sin 23 - 0.4)(\tan 35)}{(\sin 23 + \eta \cos 23)(\sin 54)} \qquad (1.5.7)$$

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 *RocSlope2* as well.

RocSlope2 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 *RocSlope2* model looks like this:

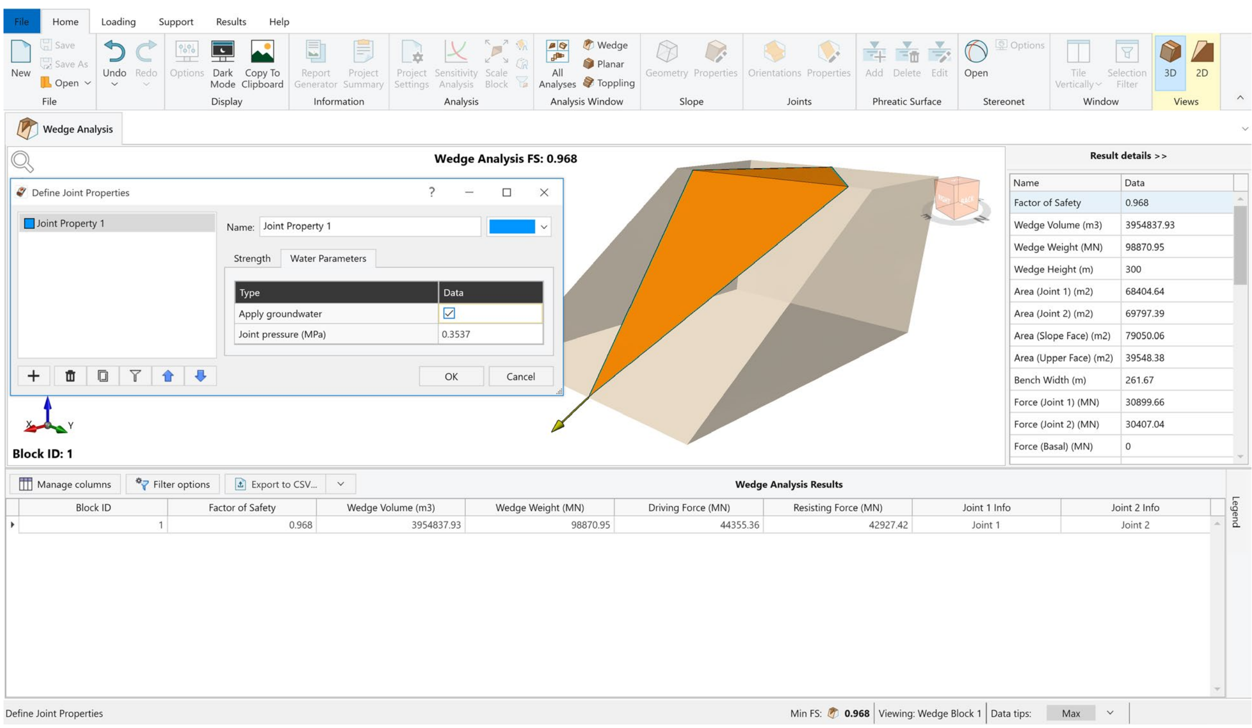


Figure 1.5.6: *RocSlope2* Analysis with Custom Water Pressure and Seismic Force Defined

Looking at Figure 1.5.6, *RocSlope2* calculates FS = 0.968 ≅ 1. *RocSlope2* 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:

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

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

$$\therefore FS = \frac{(\cos 23 - \eta \sin 23 - 0.4 - \gamma_e) \tan 35}{(\sin 54)(\sin 23 + \eta \cos 23)} \qquad (1.5.8)$$

Equation 1.5.8 is used to plot the line in Figure 1.5.2 for Case 4. Notice in Figure 1.5.2 that when $\eta = \gamma_e = 0.02$, the Factor of Safety is FS = 1. Now verify this with *RocSlope2*.

Calculate the water pressure to be applied (the same assumptions regarding wedge area and water pressure as in Case 2 and 3 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 *RocSlope2* as shown in Figure 1.5.7 below. The resulting Factor of Safety is FS = 1.066 ≅ 1. This result verifies *RocSlope2* for this example.

The *RocSlope2* model is pictured below:

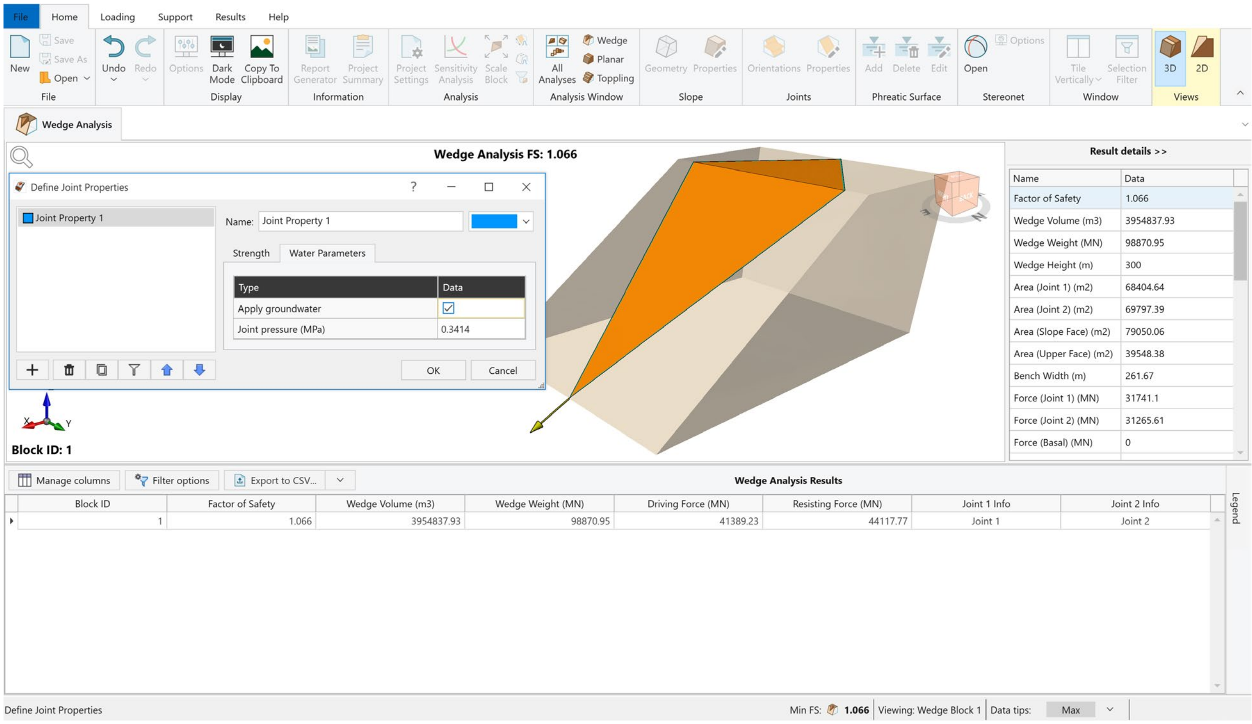


Figure 1.5.7: *RocSlope2* Analysis with Custom Water Pressure and Seismic Force Defined (Pressure and Seismicity are Changing at the Same Rate)

The summary of results is below.

Table 1.5.3: *RocSlope2* Analysis Results

Case	η	γ_s	γ_e	***RocSlope2* Factor of Safety**
1	0.3225	0	0	1.078
2	0	0.4	0.06	0.961
3	0.05	0.4	0	0.968
4	0.02	0.4	0.02	1.066

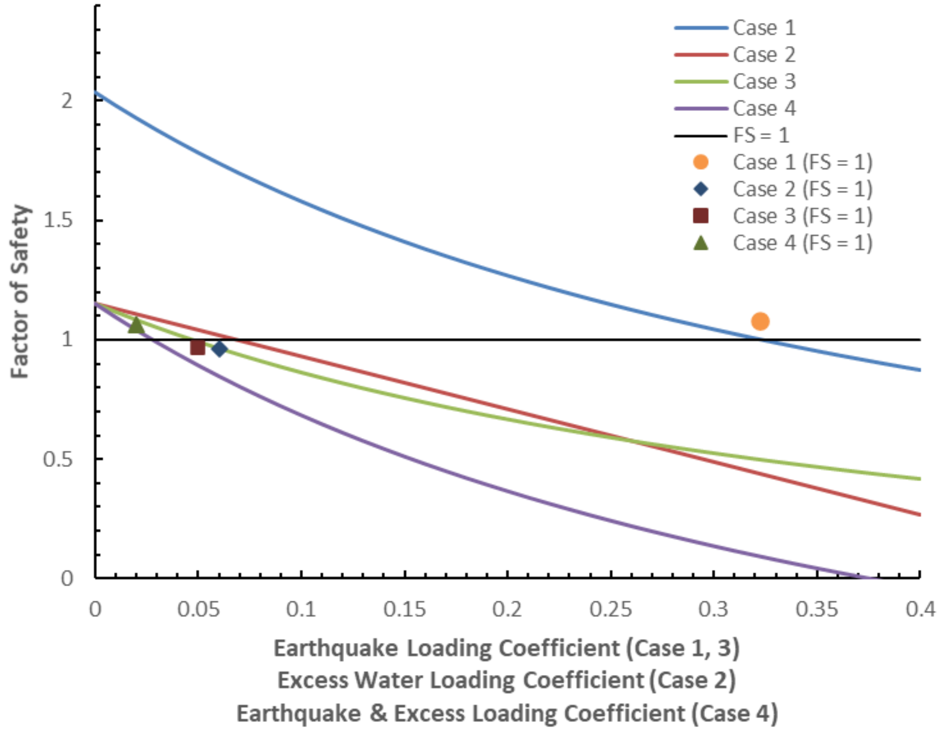


Figure 1.5.8: *RocSlope2* Results Compared to Analytical Solution

Note that slight discrepancies between theoretical and RocSlope2 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. *RocSlope2* Wedge Geometry Verification Problem #6

[RocSlope2 Build 1.005]

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. *RocSlope2* Analysis

Wedge Geometry 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 1	47	203
Joint 2	52	287
Upper Slope (Bench)	5	225
Slope	60	230

Table 1.6.2: Material Properties

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

Water Pressure

Table 1.6.3: Water Pressure

Joint	Mean Water Pressure (MPa)
1	0.005
2	0.015

Enter the values from Table 1.6.1, 1.6.2 and Table 1.6.3 into *RocSlope2*.

The *RocSlope2* model is pictured below:

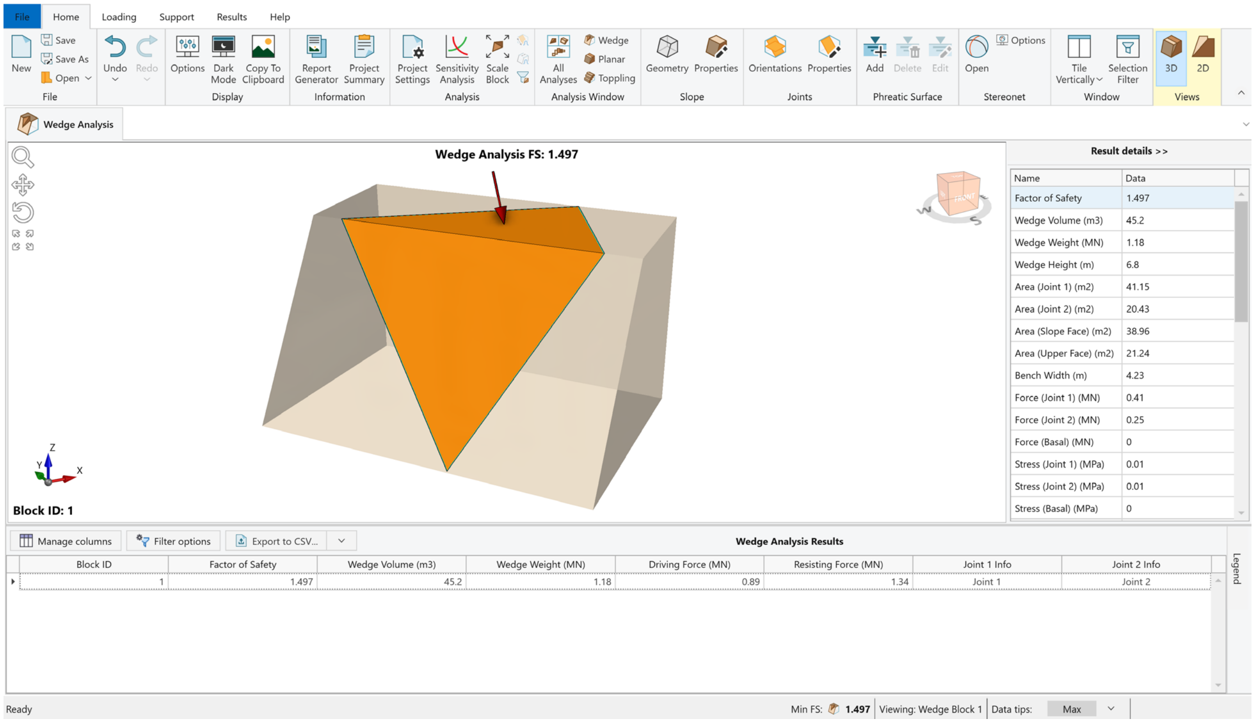


Figure 1.6.1: *RocSlope2* Results

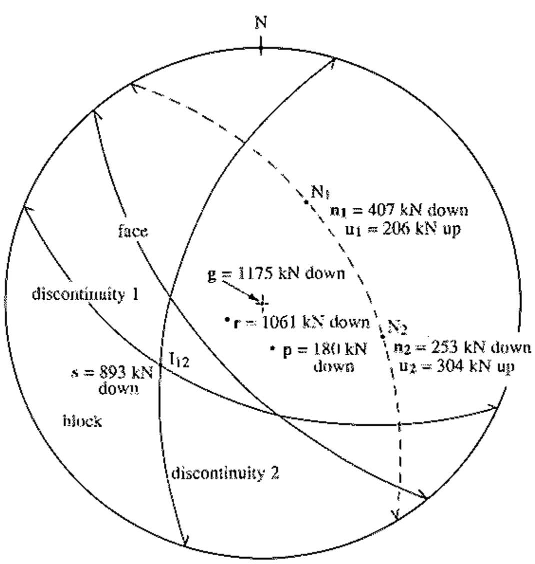


Figure 1.6.2: Stereonet from Priest [3] (Upper Face Not Shown)

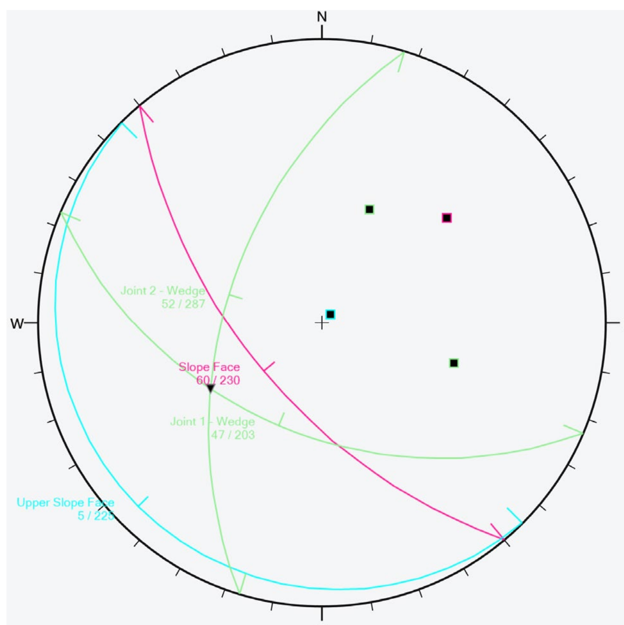


Figure 1.6.3: *RocSlope2* Stereonet

1.6.3. Results

The *RocSlope2* analysis results are summarized in this section.

***RocSlope2* Analysis Results:**

Factor of Safety=1.497

Volume: 45.20 m3

Weight: 1.18 MN

Area (joint1): 41.15 m2

Area (joint2): 20.43 m2

Area (slope face): 38.96 m2

Area (upper face): 21.24 m2

Normal Force (joint1): 0.41 MN

Normal Force (joint2): 0.25 MN

Normal Stress (joint1): 0.01 MPa

Normal Stress (joint2): 0.01 MPa

Shear Strength (joint1): 0.02 MPa

Shear Strength (joint2): 0.03 MPa

Driving Force: 0.89 MN

Resisting Force: 1.34 MN

Mode: Sliding on Joints 1&2

Priest's Factor of Safety is FS $\cong$ 1.5, which verifies that the results obtained from *RocSlope2* are correct. The failure mode also agrees with Priest's double plane sliding mechanism.

1.7. *RocSlope2* Wedge Geometry Verification Problem #7

[RocSlope2 Build 1.005]

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. *RocSlope2* 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 1	74	65
Joint 2	41	186
Upper Slope (Bench)	11	122
Slope	65	134

Table 1.7.2: Material Properties

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

Water Pressure

Table 1.7.3: Water Pressure

Joint	Mean Water Pressure (MPa)
1	0.025
2	0.015

Enter the values from Table 1.7.1, Table 1.7.2 and Table 1.7.3 into *RocSlope2*.

The *RocSlope2* model is pictured below:

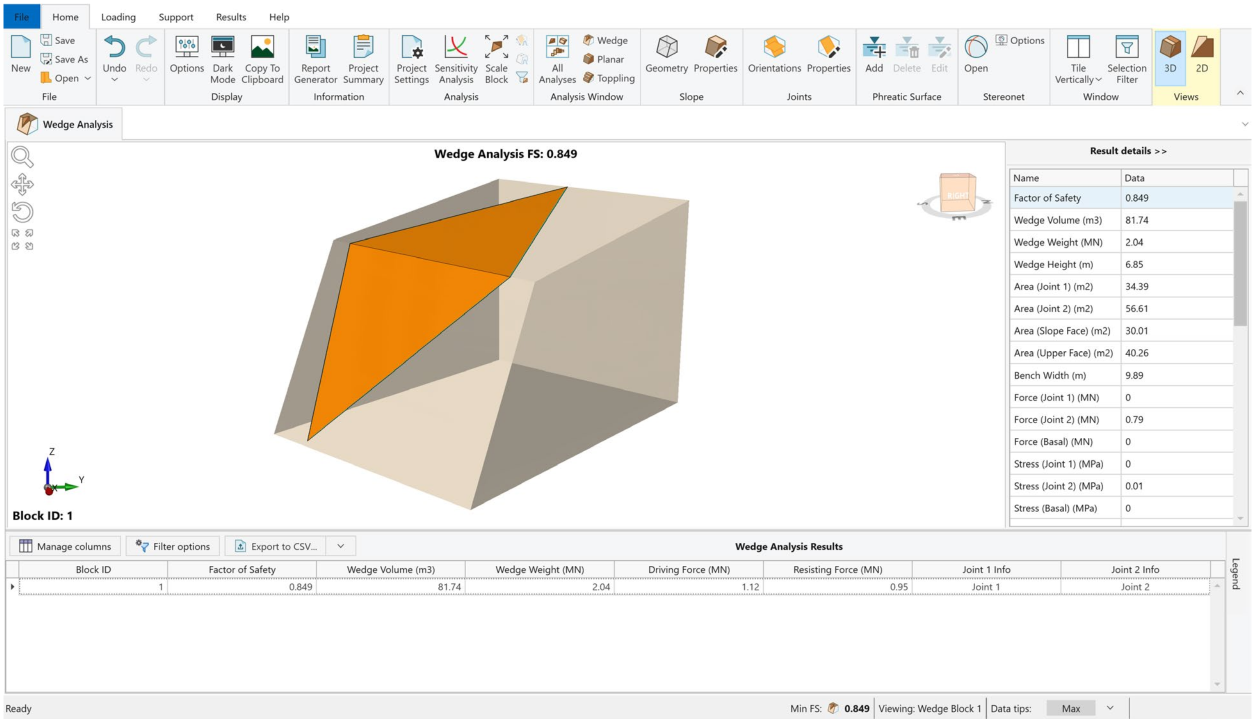


Figure 1.7.1: *RocSlope2* Results

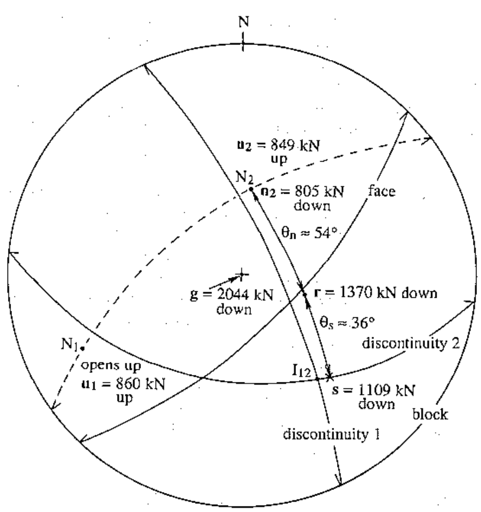


Figure 1.7.2: Stereonet from Priest [3] (Upper Face Not Shown)

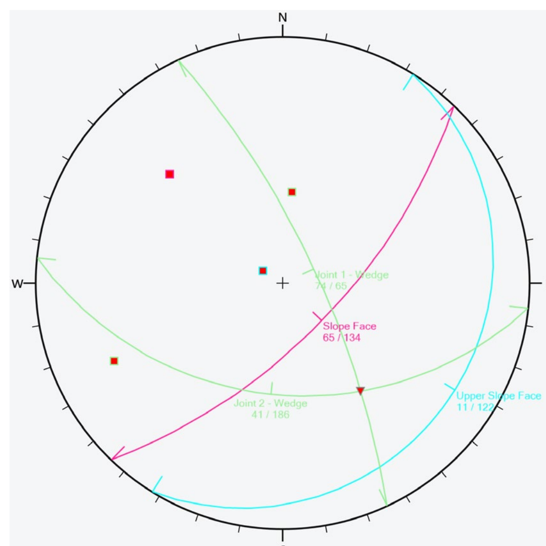


Figure 1.7.3: *RocSlope2* Stereonet

1.7.3. Results

The *RocSlope2* analysis results are summarized in this section.

***RocSlope2* Analysis Results:**

Factor of Safety=0.849

Volume: 81.74 m3

Weight: 2.04 MN

Area (joint1): 34.39 m2

Area (joint2): 56.61 m2

Area (slope face): 30.01 m2

Area (upper face): 40.26 m2

Normal Force (joint1): 0.000 MN

Normal Force (joint2): 0.79 MN

Normal Stress (joint1): 0.00 MPa

Normal Stress (joint2): 0.01 MPa

Shear Strength (joint1): 0.00 MPa

Shear Strength (joint2): 0.02 MPa

Driving Force: 1.12 MN

Resisting Force: 0.95 MN

Mode: Sliding on Joint2

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 *RocSlope2* calculated FS = 0.85. The small difference in Factor of Safeties 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, *RocSlope2*'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 programmable 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. *RocSlope2* Planar Geometry Verification

The planar analysis examples presented here are taken from articles, technical notes and papers written in the field of Geotechnical Engineering. The results produced by *RocSlope2*, as documented in this section, are consistent with the examples from these sources, and confirm the reliability of results produced by *RocSlope2*.

The results produced by *RocSlope2* agree with the documented examples and confirm the reliability of *RocSlope2* results.

2.1. *RocSlope2* Planar Geometry Verification Problem #1

[RocSlope2 Build 1.005]

2.1.1. Problem Description

This verification example is based on the reference article on modeling shear strength by S.M. Miller [5]. In this example, both linear and curved relationships between the shear strength and normal stress for rock failure planes are analyzed. Two types of shear strength models are examined:

1. The Barton-Bandis Model, which is based on JRC (joint roughness coefficient), friction angle, and JCS (joint-wall compressive strength); and,
2. The Power Curve Model, for which both linear and curved models are used:
    - A power curve model that is fitted to three data points;
    - A linear model (Linear 2) that is fitted to three data points; and,
    - A linear model (Linear 3) that is fitted to five shear data points.

Shear Model Equations

JRC Model: $\tau = \sigma_n \times \tan\left[JRC \times \log_{10}\left(\frac{JCS}{\sigma_n}\right) + \phi_b\right]$

Power Curve Model: $\tau = 0.017 + 1.340{\sigma_n}^{0.836}$

Linear 2: $\tau = 0.938 + 0.783\sigma_n$

Linear 3: $\tau = 2.978 + 0.624\sigma_n$

Geometry and Properties

Table 2.1.1: Slope and Plane Geometry

Parameter	Value
Slope Angle	64°
Slope Height	30, 15, 6 and 3 m
Upper Face (Bench) Angle	14°
Failure Plane Angle	35° and 50°

Table 2.1.2: Material Shear Strength Properties

Parameter	Value
Unit Weight of Slope	2.7 t/m^3
JCS*	10000 t/m^2
Friction Angle*	32°
JRC*	3, 7 and 11
Waviness**	3°, 11° and 20°

* JRC model only.
** Power Curve, Linear 2 and Linear 3 model.

2.1.2. *RocSlope2* Analysis

Enter the *RocSlope2* geometry and shear strength parameters from Table 2.1.1 and Table 2.1.2.

The *RocSlope2* model looks like this:

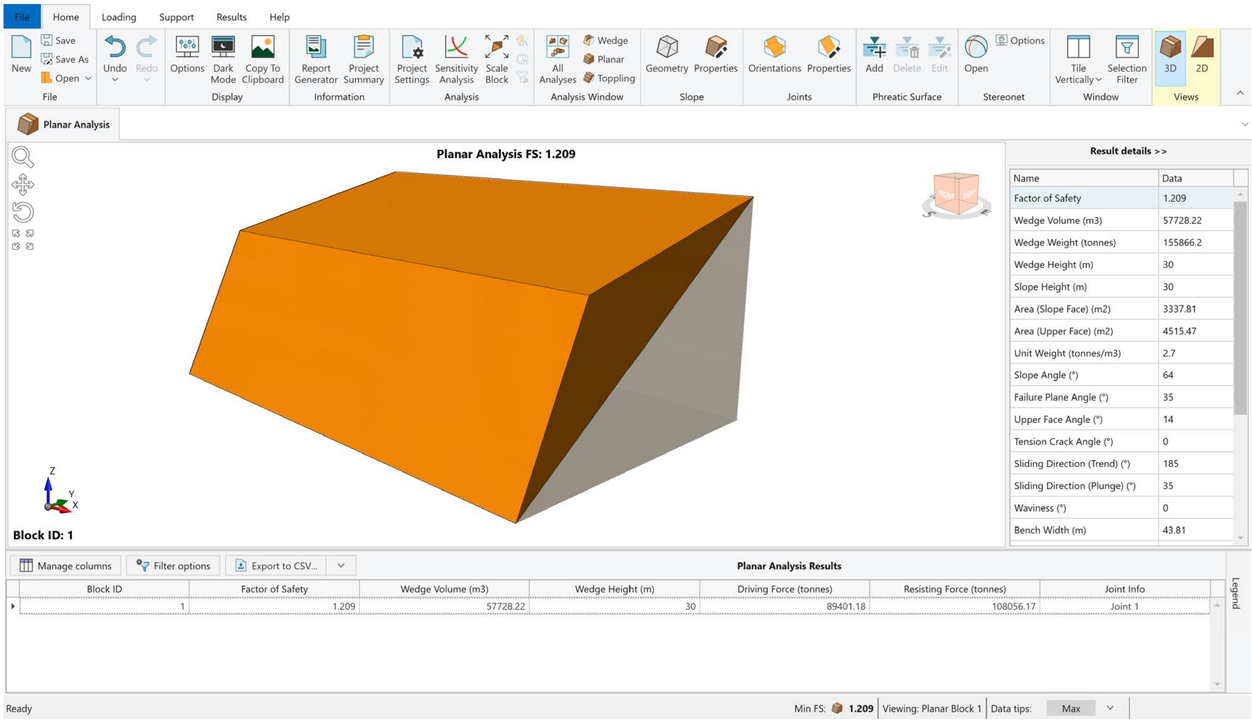


Figure 2.1.1: *RocPlane* Model

2.1.3. Results

In this example, a total of 96 different cases are considered with varying slope height, failure plane dip, JRC and waviness values. The computed values by M. Miller [5] are listed in Table 2.1.3, and the results produced by *RocSlope2* are listed in Table 2.1.4.

Table 2.1.3: Safety Factor Values Computed by M. Miller [5] for Plane-Shear Failure

	Failure Height (m)	Safety Factor Values 1. Power		2. Linear2		3. Linear3		4. JRC-Model	
Case A:	30	1.27	0.87	1.27	0.82	1.21	0.93	1.21	0.74
JRC = 3	15	1.42	0.97	1.35	0.93	1.45	1.29	1.25	0.76
Wav. = 3°	6	1.64	1.12	1.57	1.27	2.17	2.38	1.30	0.80
	3	1.83	1.26	1.95	1.84	3.38	4.19	1.34	0.82
Case B:	30	1.47	0.98	1.47	0.93	1.41	1.05	1.78	1.16
JRC = 7	15	1.62	1.09	1.55	1.05	1.65	1.41	1.92	1.26
Wav. = 11°	6	1.84	1.24	1.78	1.39	2.38	2.50	2.13	1.40
	3	2.04	1.38	2.16	1.96	3.58	4.31	2.31	1.52
Case C:	30	1.72	1.13	1.71	1.08	1.65	1.19	2.72	1.96
JRC = 11	15	1.86	1.23	1.79	1.19	1.89	1.55	3.15	2.32
Wav. = 20°	6	2.08	1.38	2.02	1.53	2.62	2.64	3.92	3.02
	3	2.28	1.52	2.40	2.10	3.82	4.45	4.76	3.87

The left column shows data with failure plane dip of 35° and the right column shows data with failure plane dip of 50°.

Table 2.1.4: Factor of Safety Computed by *RocSlope2* for Plane-Shear Failure with Failure Plane Angles at 35° and 50°

	Failure Height (m)	Factor of Safety							
		Power		Linear 2		Linear 3		JRC	
		Failure Plane Angle		Failure Plane Angle		Failure Plane Angle		Failure Plane Angle	
		35°	50°	35°	50°	35°	50°	35°	50°
JRC = 3 Waviness = 3°	30	1.269	0.863	1.268	0.813	1.204	0.924	1.209	0.741
	15	1.414	0.963	1.343	0.926	1.441	1.281	1.248	0.765
	6	1.634	1.118	1.567	1.263	2.154	2.351	1.301	0.798
	3	1.828	1.256	1.942	1.824	3.343	4.134	1.343	0.824
JRC = 7 Waviness = 11°	30	1.471	0.982	1.471	0.932	1.406	1.043	1.778	1.158
	15	1.616	1.083	1.546	1.045	1.644	1.400	1.919	1.253
	6	1.837	1.237	1.770	1.382	2.357	2.470	2.127	1.395
	3	2.031	1.375	2.144	1.943	3.545	4.253	2.306	1.519
JRC = 11 Waviness = 20°	30	1.714	1.124	1.713	1.075	1.649	1.186	2.711	1.948
	15	1.858	1.225	1.788	1.187	1.886	1.542	3.138	2.307
	6	2.079	1.379	2.012	1.524	2.599	2.612	3.904	3.003
	3	2.273	1.518	2.387	2.086	3.788	4.395	4.736	3.848

The sensitivity plot of factor of safety with varying slope height for failure plane dip at 50° and JRC = 7 and waviness = 11° is shown in Figure 2.1.2. A similar graph generated with Microsoft Excel with factor of safety data generated by *RocSlope2* is shown in Figure 2.1.3.

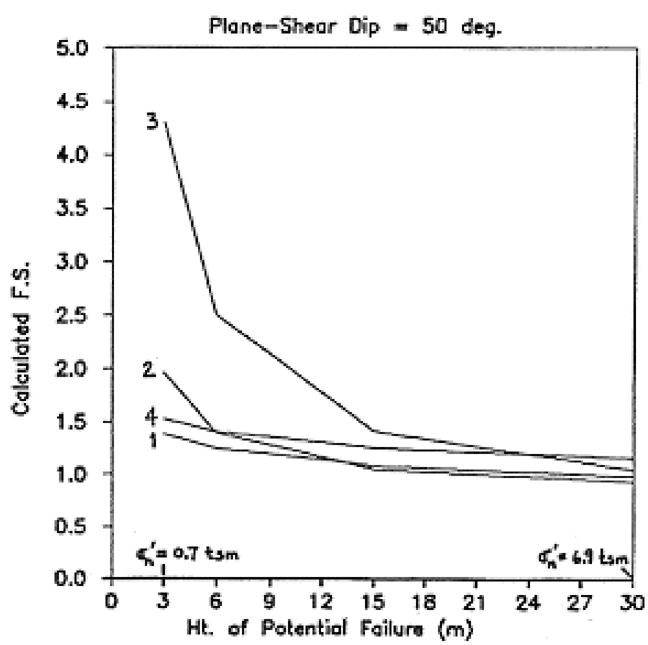


Figure 2.1.2: Sensitivity Plot of FS vs. Slope Height by Miller

(1 – Power Curve Model, 2 – Linear 2, 3 – Linear 3, 4 – JRC)

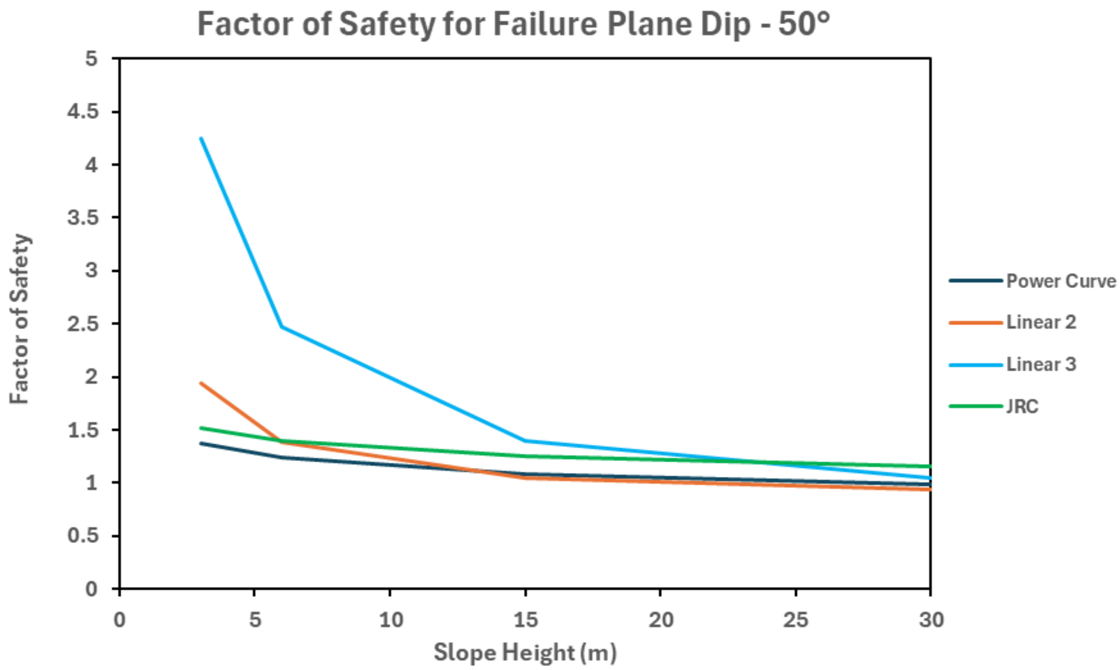


Figure 2.1.3: Sensitivity Plot of FS vs. Slope Height by *RocSlope2*

By comparison of the data in Table 2.1.3 with Table 2.1.4 and Figure 2.1.2 with Figure 2.1.3, the results are either the same or within a difference of 1.5%. Therefore, *RocSlope2* verifies the results provided by Miller [5].

2.2. *RocSlope2* Planar Geometry Verification Problem #2

[RocSlope2 Build 1.005]

2.2.1. Problem Description

This problem is taken from Watts and West (1985). It looks at slope stability analysis problems done by notebook computers in the early 80s. *RocSlope2* must do the analysis in imperial units in order to use the parameters quoted by the authors.

This verification problem analyzes a simple slope, which slope and failure plane geometries are provided in Table 2.2.1, using three different joint shear strength properties (Table 2.2.2). There is no tension crack present, and the failure surface is dry. The upper slope is horizontal. The planar block geometry is also given in Figure 2.2.1.

Note: Parameters are given in kg/ft^3. In order to change them into t/ft^3, divide by 907 (short tons).

Table 2.2.1: Slope and Failure Plane Geometry

Parameter	Value
Slope Angle (deg.)	85
Slope Height (ft.)	95
Failure Plane Angle (deg.)	45
Upper Face Angle (deg.)	0

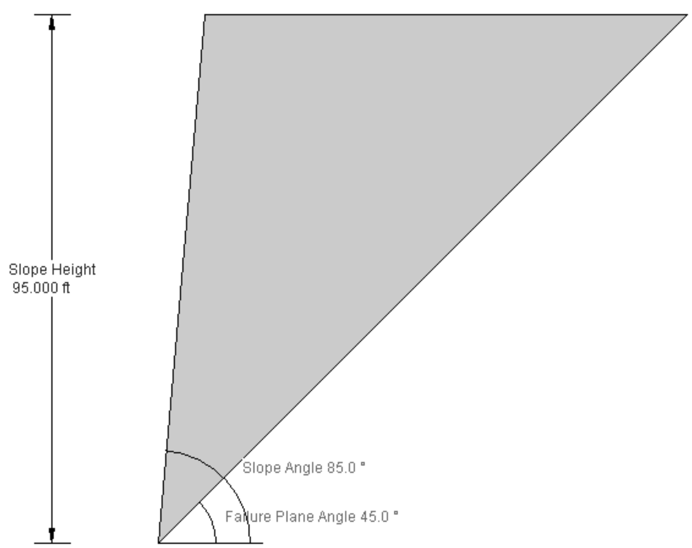


Figure 2.2.1: Geometry of Slope

Table 2.2.2: Joint Properties

Case	Cohesion c' (t/ft^2)	Friction Angle ϕ' (deg.)	Unit Weight of Slope γ (t/ft^3)
1	0	20	0.18192
2	1.1025	20	0.18192
3	2.2051	35	0.18192

2.2.2. *RocSlope2* Analysis

Enter the values from Table 2.2.1 and Table 2.2.2 into *RocSlope2*.

The *RocSlope2* models are pictured below:

<u>Case 1:</u>

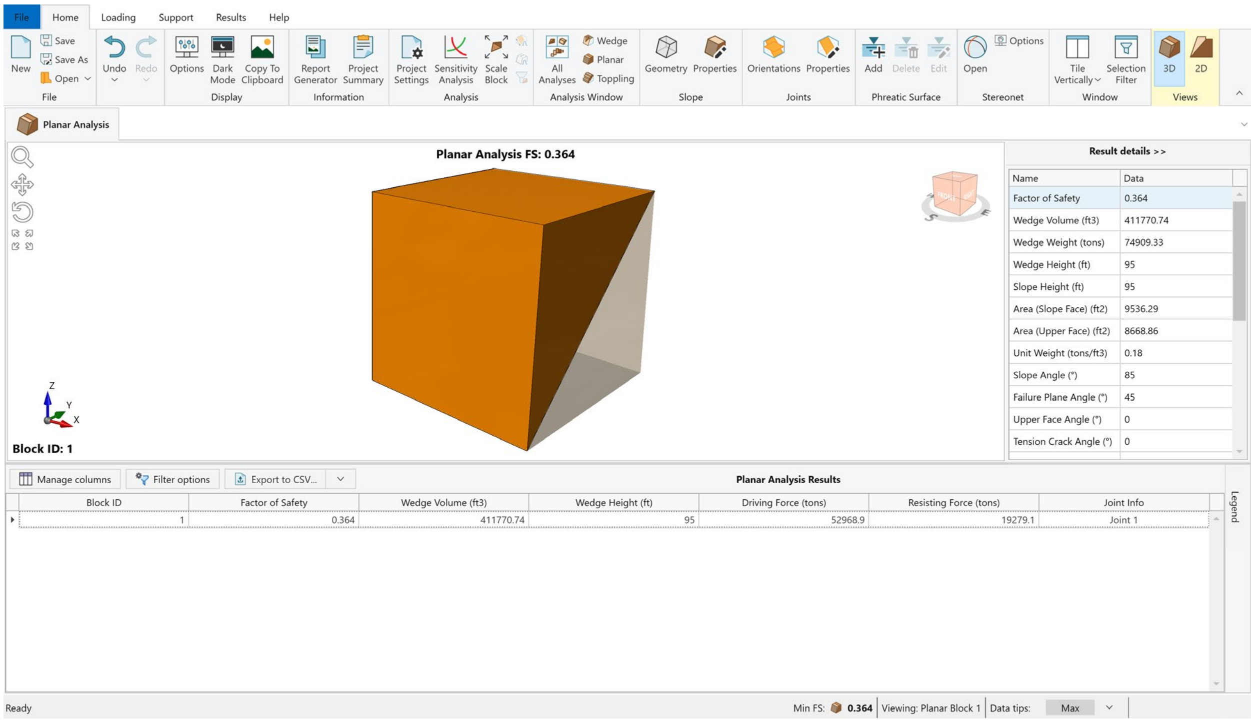


Figure 2.2.2: *RocSlope2* Model (Case 1)

Case 2:

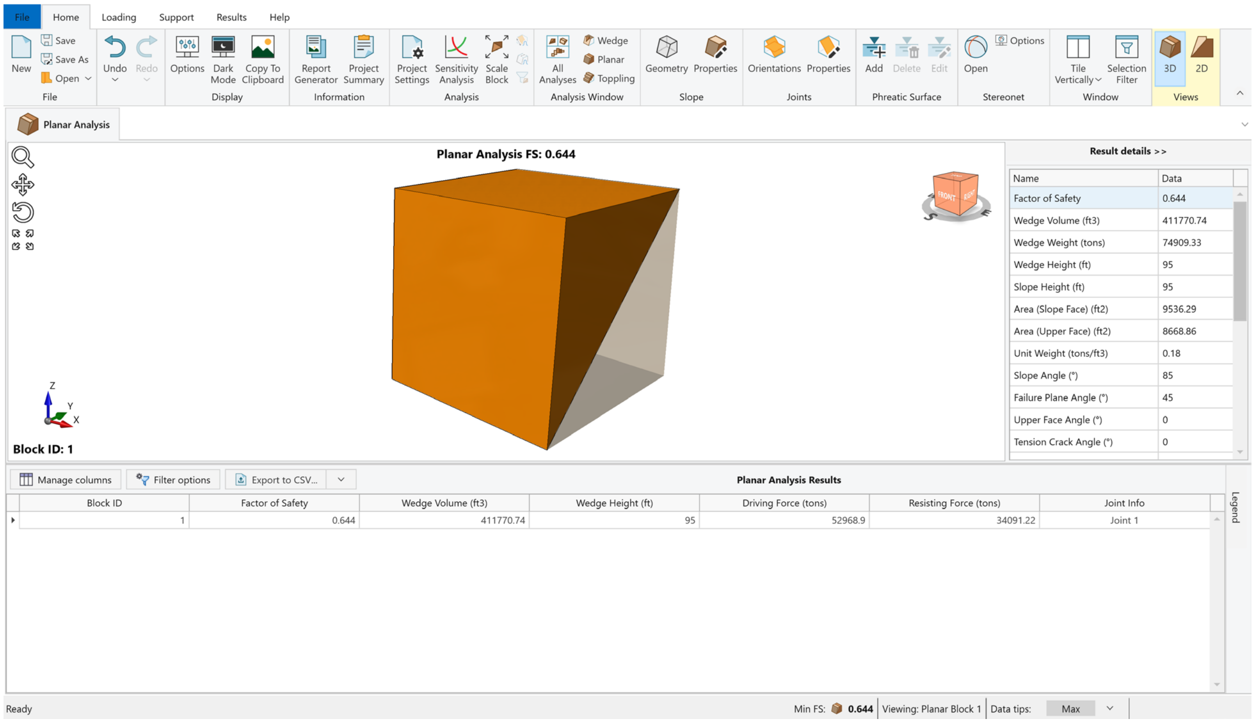


Figure 2.2.3: *RocSlope2* Model (Case 2)

Case 3:

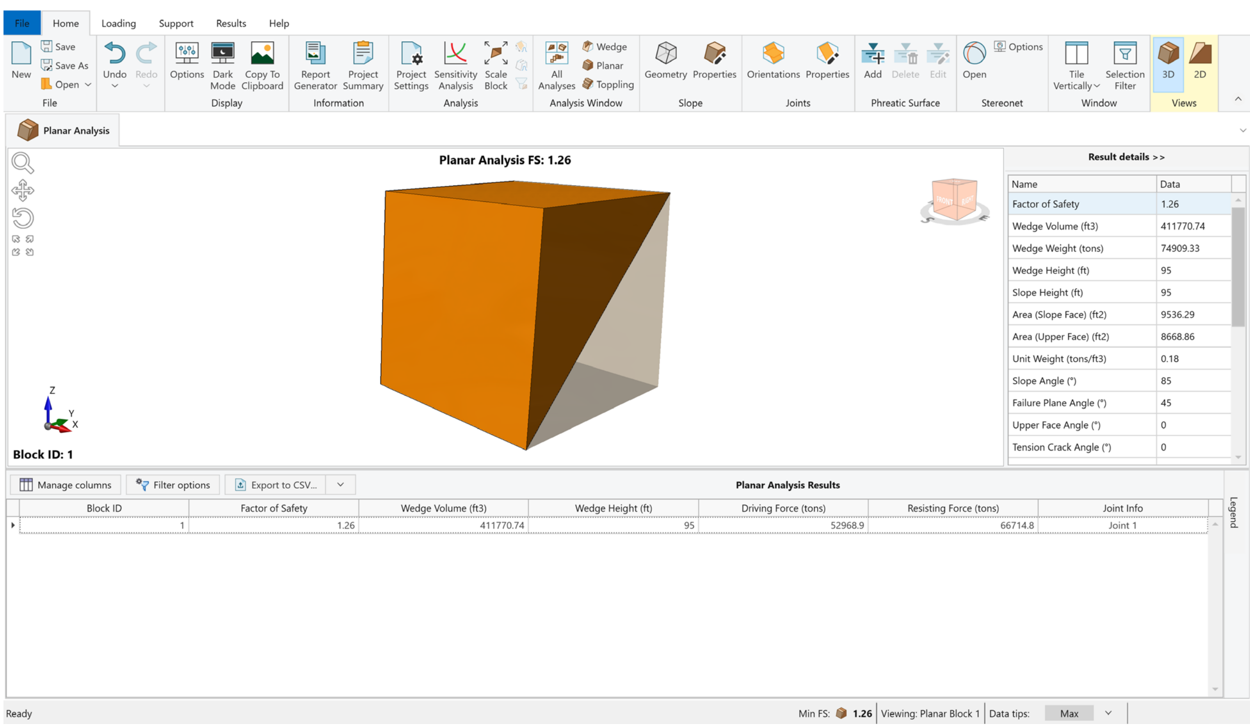


Figure 2.2.4: *RocSlope2* Model (Case 3)

2.2.3. Results

Table 2.2.3: Factor of Safety Comparison

Case	*RocSlope2* Factor of Safety	Watts and West Factor of Safety
1	0.364	0.364
2	0.644	0.644
3	1.260	1.260

Figure 2.2.5: *RocSlope2* Planar Block Analysis (Case 3)

```
GENERAL SLOPE GEOMETRY
Height = 95    ANGLES:  Slope = 85 ,  Upper Slope = 0 ,  Fail.Sfc. = 45
Cohesion = 2000   Friction = 35   Unit Wt. Rk. = 165   Wtr. = 62.4
Horizontal Accl. = 0    Rockbolt Tension = 0    Inclination = 0
Weight of Block = 679422      CONTACT AREA = 134.35

TENSION CRACK (None)
Horizontal Distance,  Crest to Failure Surface = 86.6886
Failure Surface is  * DRY *.

FACTOR OF SAFETY = 1.260
```

Figure 28. Sample printout from the safety factor program for plane failure analyses.

Figure 2.2.6: Case 3 Using the Author's Electronic Filed Notebook System

The factor of safety values computed by *RocSlope2* match those provided by Watts and West in all three cases. Therefore, *RocSlope2* verifies this example.

2.3. References

1. Stanley M. Miller, 1988, “Modeling Shear Strength at Low Normal Stresses for Enhanced Rock Slope Engineering”, *Proc. Of 39th Highway Geology Symp*, pp. 346-356.
2. Watts, C.F., and West, T.R., 1985, “Electronic notebook analysis of rock slope stability at Cedar Bluff, Virginia.”, *Bulletin of the Association of Engineering Geologists*, No. 1, pp. 67-85.

3. *RocSlope2* Block Toppling Verification

RocSlope2 block toppling analyses are verified against published examples and against results produced by *RocTopple*, *RS2* and UDEC.

The results produced by *RocSlope2* are consistent with the documented examples and confirm the reliability of *RocSlope2* results.

3.1. *RocSlope2* Block Toppling Verification Problem #1

[RocSlope2 Build 1.005]

3.1.1. Problem Description

This verification looks at Example 1 in the paper:

> Goodman, R. E., & Bray, J. W. (1976). Toppling of Rock Slopes. *Rock Engineering for Foundations and Slopes* (pp. 201 - 234). New York: American Society of Civil Engineers.

Four analyses of block toppling were performed in *RocSlope2* and verified using *RocTopple, RS2* and *UDEC*. The analyses comprised of computing the factor of safety for examples 1a and 1b and the same examples with higher friction (page 222 of the paper), named examples 1c and 1d here. All examples include a stabilizing force on the toe of the slope. In the case of examples 1a and 1b, this force establishes limit equilibrium (FS = 1) as computed by the Goodman and Bray method.

Geometry and Material Properties

Table 3.1.1: Material Properties

Analysis	ϕ' (deg.)	Force on Toe Block (kN)	γ (kN/m^3)
Example 1a	38.15	50	25.0
Example 1b	33.02	201300	25.0
Example 1c	38.66	50	25.0
Example 1d	38.66	201300	25.0

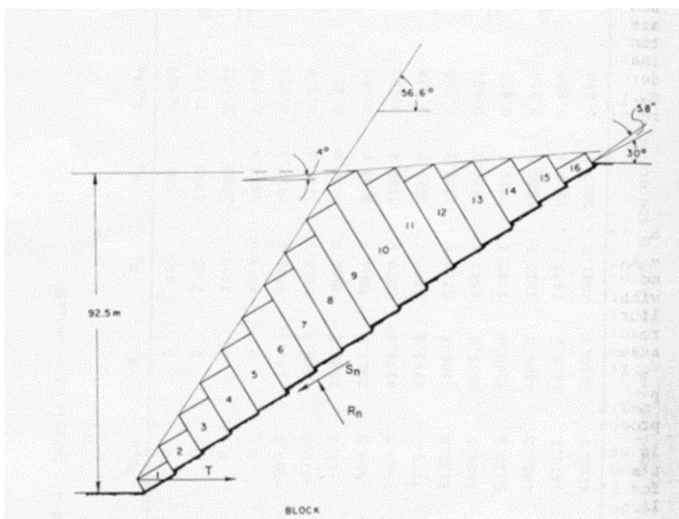


Figure 3.1.1: Geometry with 16 Blocks (Goodman and Bray, 1976)

3.1.2. *RocSlope2* Analysis

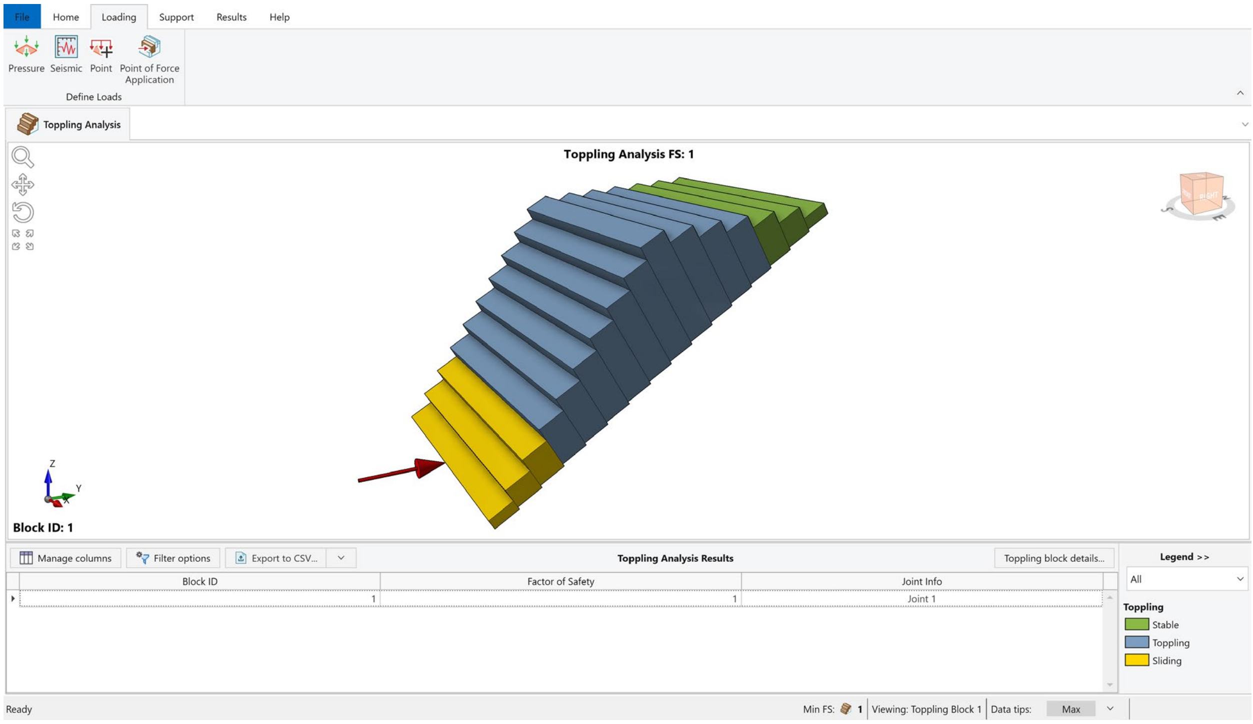


Figure 3.1.2: *RocSlope2* Model using Goodman and Bray Input Geometry (16 Blocks)

3.1.3. *RocTopple* Analysis

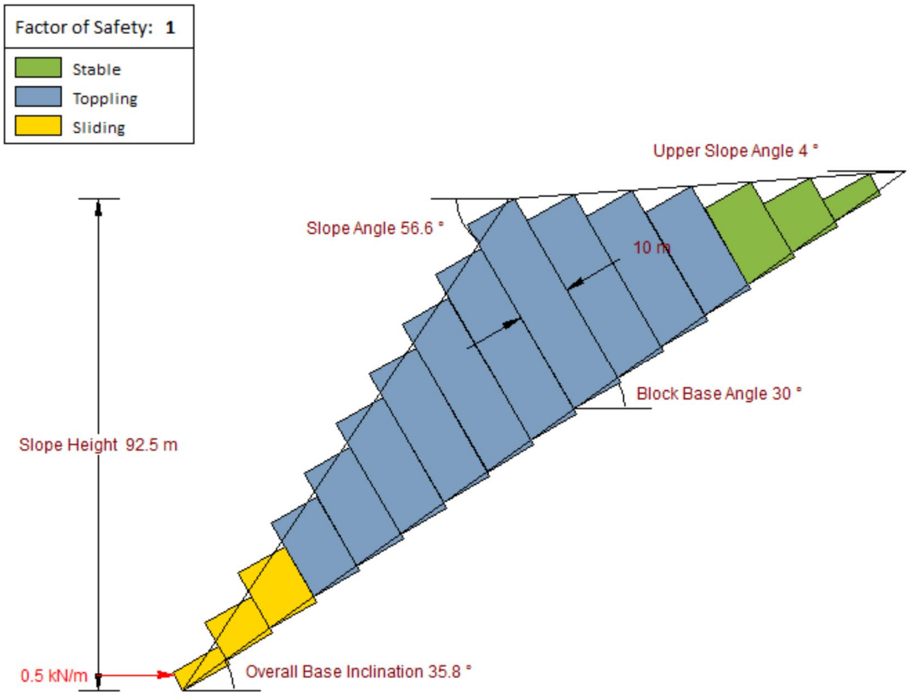
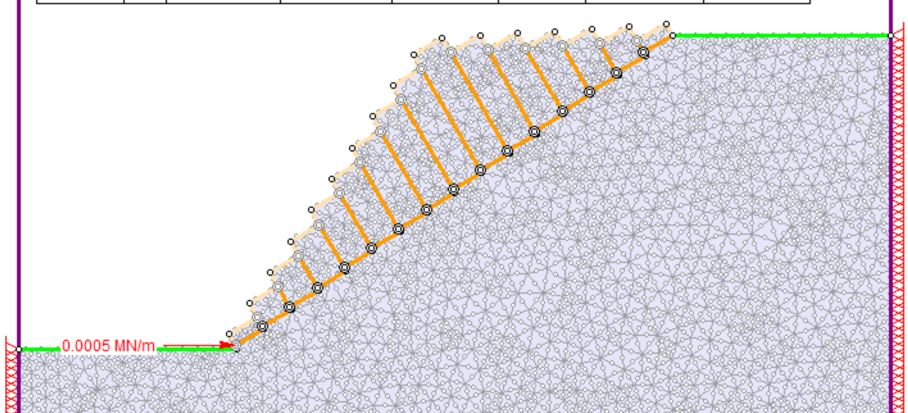


Figure 3.1.3: *RocTopple* Model using Goodman and Bray Input Geometry (16 Blocks)

3.1.4. Building a Compatible *RS2* Model

Joint Name	Color	Slip Criterion	Tensile Strength (MPa)	Peak Cohesion (MPa)	Peak Friction Angle (deg)	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)
Joints		Mohr_Coulomb	0	0	38.15	100000	10000



Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Unsaturated Shear Strength Angle (degrees)	Air Entry Value	Material Behaviour	Static Water Mode	Ru Value
Material 1		Field Stress and Body Force	0.025	Isotropic	0.3	20000	Mohr-Coulomb	Elastic	0	38.15	0	0	0	Drained	Ru	0

Figure 3.1.4: *RS2* Model of Example 1a (Geometry Exported from *RocTopple*)

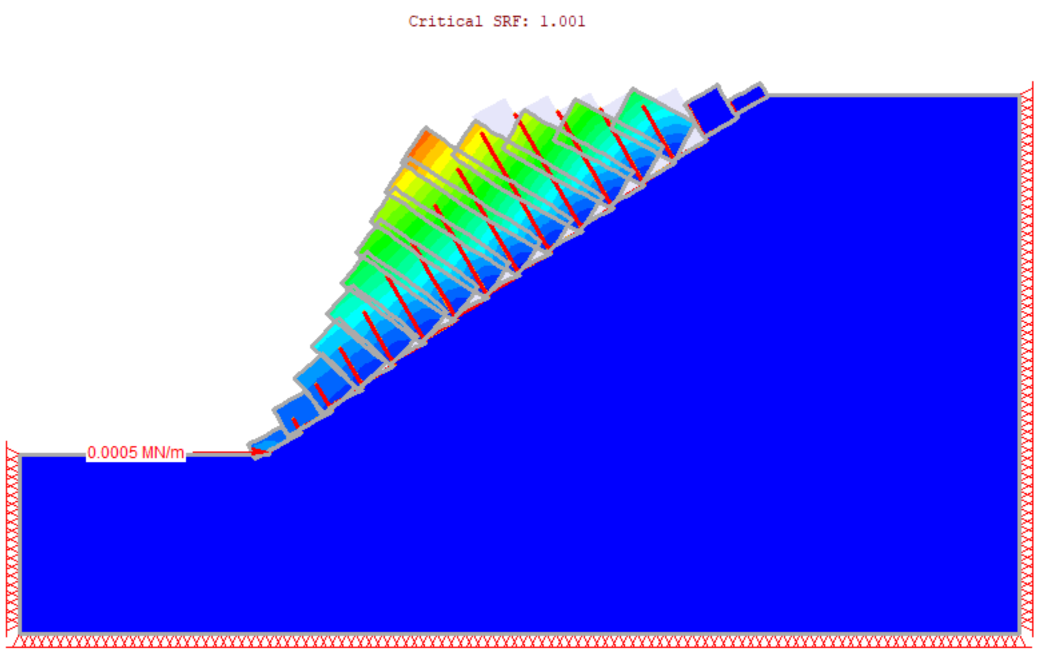


Figure 3.1.5: *RS2* Results of Example 1a at Critical SRF (Total Displacement Contours)

3.1.5. *UDEC* Analysis

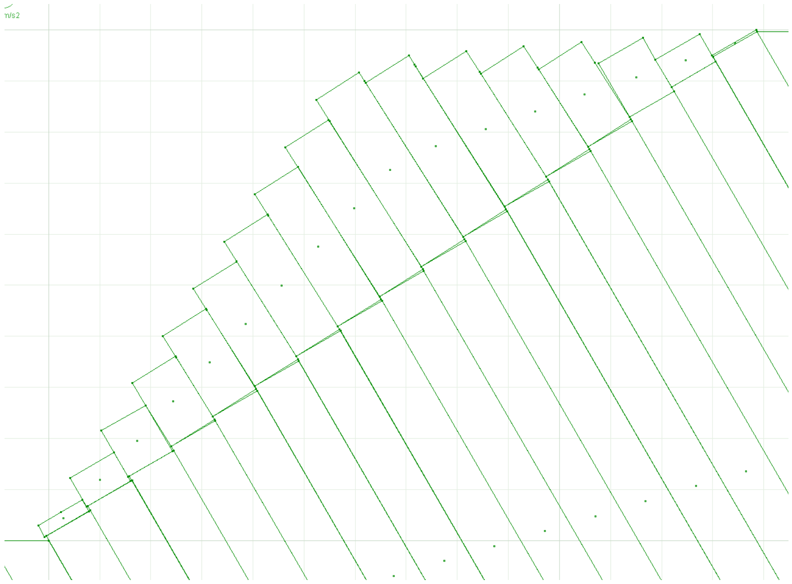


Figure 3.1.6: Deformation in *UDEC*

3.1.6. Results

Table 3.1.2: Factors of Safety

	RocSlope2	*RocTopple*	*RS2*	*UDEC*	Goodman and Bray
Example 1a	1.00	1.00	1.00	0.99	1.0
Example 1b	1.00	1.00	0.98	1.00	1.0
Example 1c	1.02	1.02	1.01	1.00	1.02
Example 1d	1.23	1.23	1.21	1.24	1.23

3.2. *RocSlope2* Block Toppling Verification Problem #2

[RocSlope2 Build 1.005]

3.2.1. Problem Description

This verification looks at Example 2 in the paper:

> Goodman, R. E., & Bray, J. W. (1976). Toppling of Rock Slopes. *Rock Engineering for Foundations and Slopes* (pp. 201 - 234). New York: American Society of Civil Engineers.

RocSlope2 was used to analyze a slope with geometry given in the article. The slope is subject to block toppling. The analysis comprised of computing the factor of safety in *RocSlope2* and verifying it using *RocTopple*. Then the RocTopple geometry was exported to *RS2* to find an equivalent shear strength reduction factor. *RocSlope2* results were also verified using rigid blocks in *UDEC*.

Geometry and Material Properties

Note that the geometry in *RocSlope2* has been modified. As a result, the model has different block heights than those calculated in the original publication. The key difference is that block 1 now stands alone (height does not exceed step) with a total of 14 blocks, and the failure of the slope depends on the equilibrium of block 2. We also performed analyses with only 13 blocks to observe the differences although the first block was still separate from the rest of the blocks. The 13 blocks *RocSlope2* model can be created by modifying the Joint Spacing to 10.4m.

Table 3.2.1: Material Properties

Analysis	ϕ' (deg.)	γ (kN/m^3)
Example 2	21.455	25.0

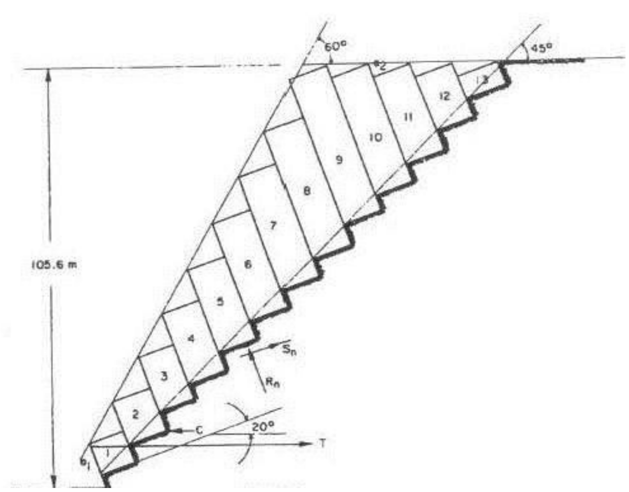


Figure 3.2.1: Goodman and Bray Example 2 Geometry (13 Blocks)

3.2.2. *RocSlope2* Analysis

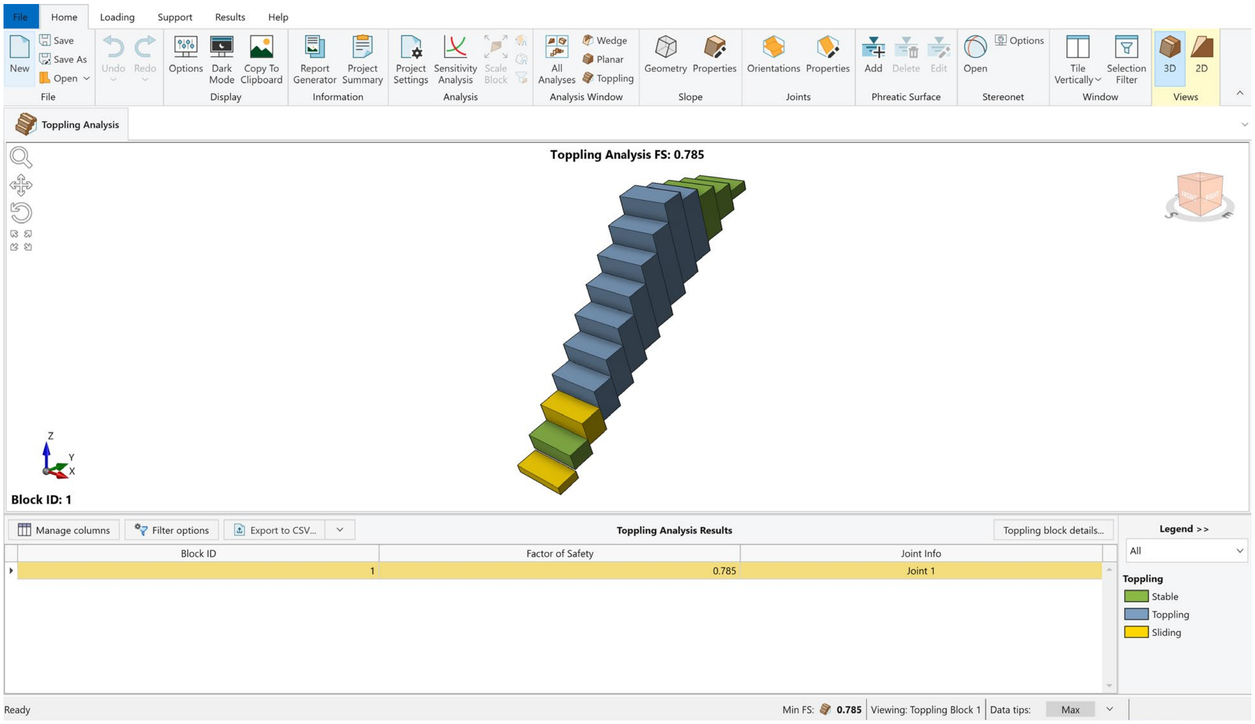


Figure 3.2.2: *RocSlope2* Geometry (14 Blocks, Separate First Block)

3.2.3. *RocTopple* Analysis

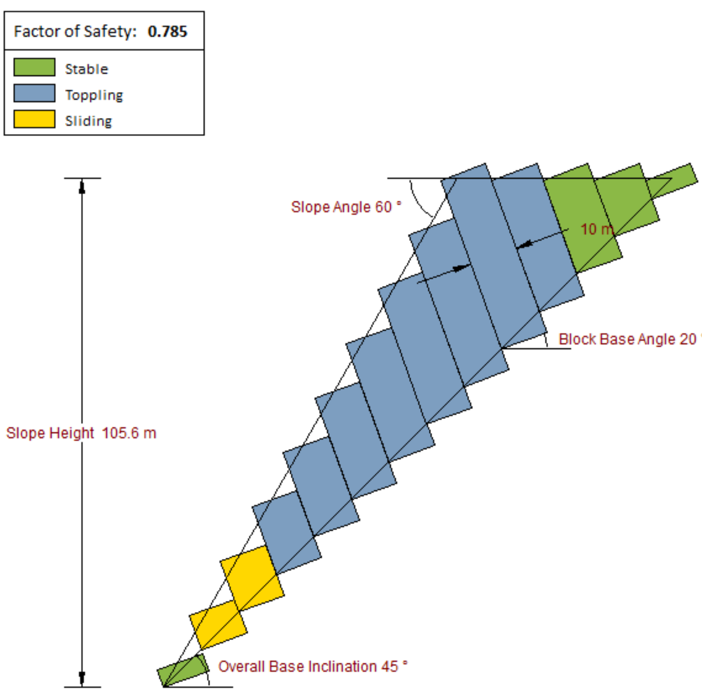
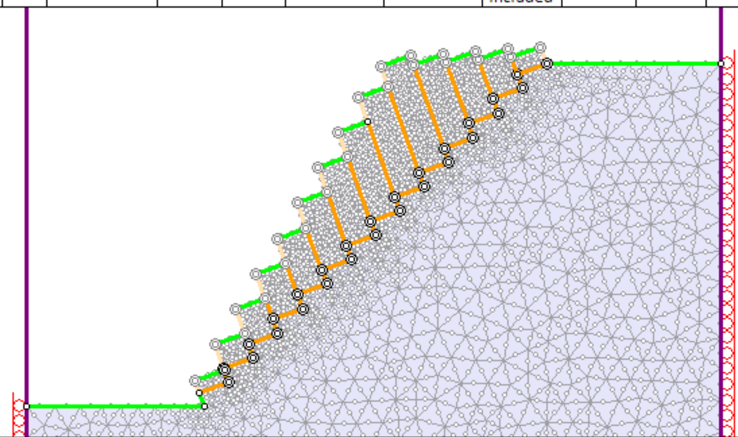


Figure 3.2.3: *RocTopple* Geometry (14 Blocks, Separate First Block)

3.2.4. Building a Compatible *RS2* Model

Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	1e+06	100000	No	No	Not Included	0	0	21.455	No	No



Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Unsaturated Shear Strength Angle (degrees)	Air Entry Value	Material Behaviour	Static Water Mode	Ru Value
Material 1		Body Force Only	0.025	Isotropic	0	1e+10	Mohr-Coulomb	Elastic	0	35	10.5	0	0	Drained	Ru	0

Figure 3.2.4: *RS2* Geometry and Properties (14 Blocks)

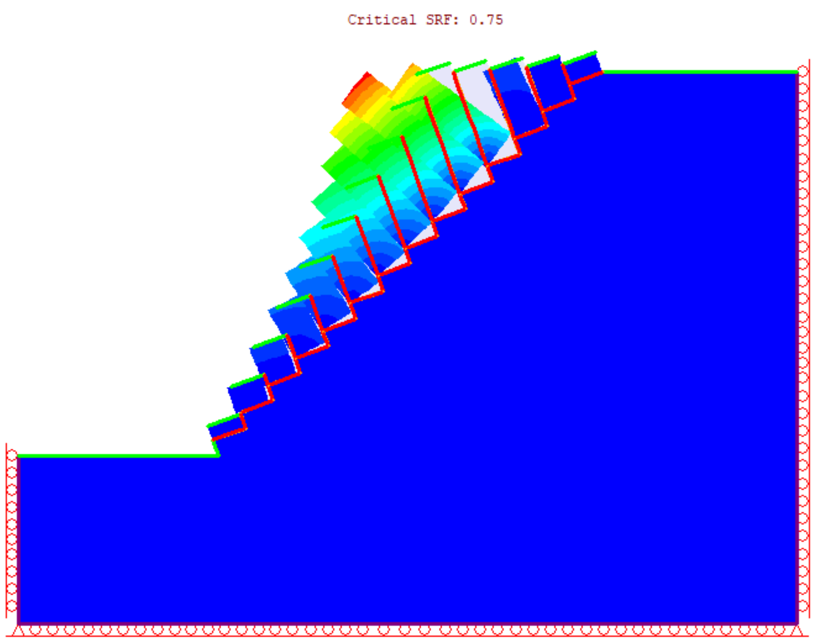


Figure 3.2.5: *RS2* Total Displacement Contours and Deformed Shape

3.2.5. *UDEC* Analysis

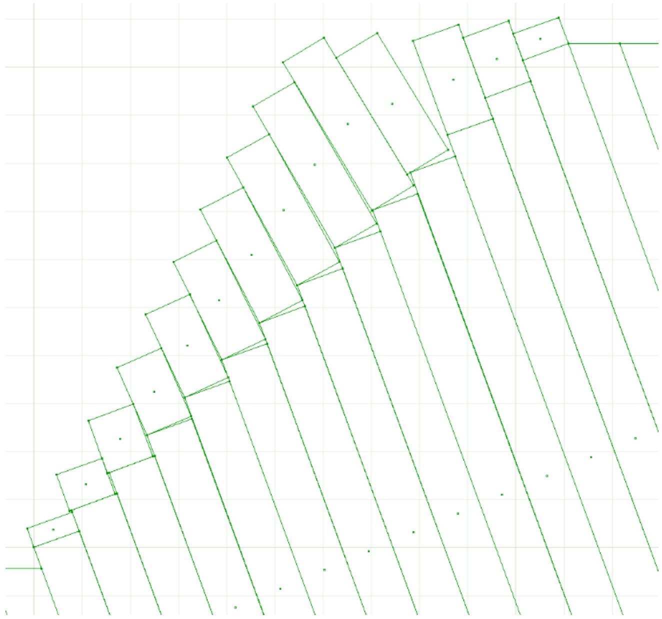


Figure 3.2.6: Deformation in *UDEC*

3.2.6. Results

Table 3.2.2: Factors of Safety

	RocSlope2	***RocTopple***	***RS2***	***UDEC***	**Goodman and Bray**
14 Blocks	0.79	0.79	0.75	0.69	N/A
13 Blocks	0.99	0.99	0.74	N/A	1.0

3.3. *RocSlope2* Block Toppling Verification Problem #3

[RocSlope2 Build 1.005]

3.3.1. Problem Description

This verification looks at the block toppling example from:

> Alejano, L. R., & Alonso, E. (2005). Application of the 'Shear and Tensile Strength Reduction Technique' to Obtain Factors of Safety of Toppling and Footwall Rock slopes. *Eurock: Impact of Human Activity on the Geological Environment*.

A block toppling model was constructed and analyzed in *RocSlope2* using geometric data given in the article. The model was then verified in *RocTopple* and exported to *RS2*, in which shear strength reduction analysis was used to verify factor of safety results. Results were also verified using rigid block *UDEC* analysis.

Note that the article does not specify a width for the blocks. Block width of 1.75m was used in the *RocSlope2* model to achieve the eleven blocks as seen in the article.

Geometry and Material Properties

Table 3.3.1: Geometry and Material Properties

Slope Height (m)	Slope Angle (deg)	Joint Angle (deg)	Overall Base Inclination (deg)	ϕ' (deg)	γ (kN/m^3)
9.85	58.65	64	30	31	25.0

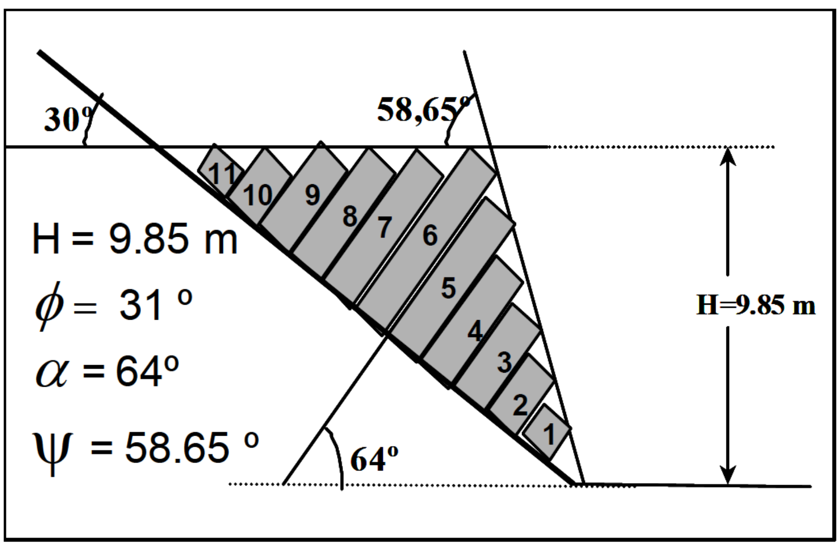


Figure 3.3.1: Goodman & Bray Geometry (Alejano & Alonso, 2005)

3.3.2. *RocSlope2* Analysis

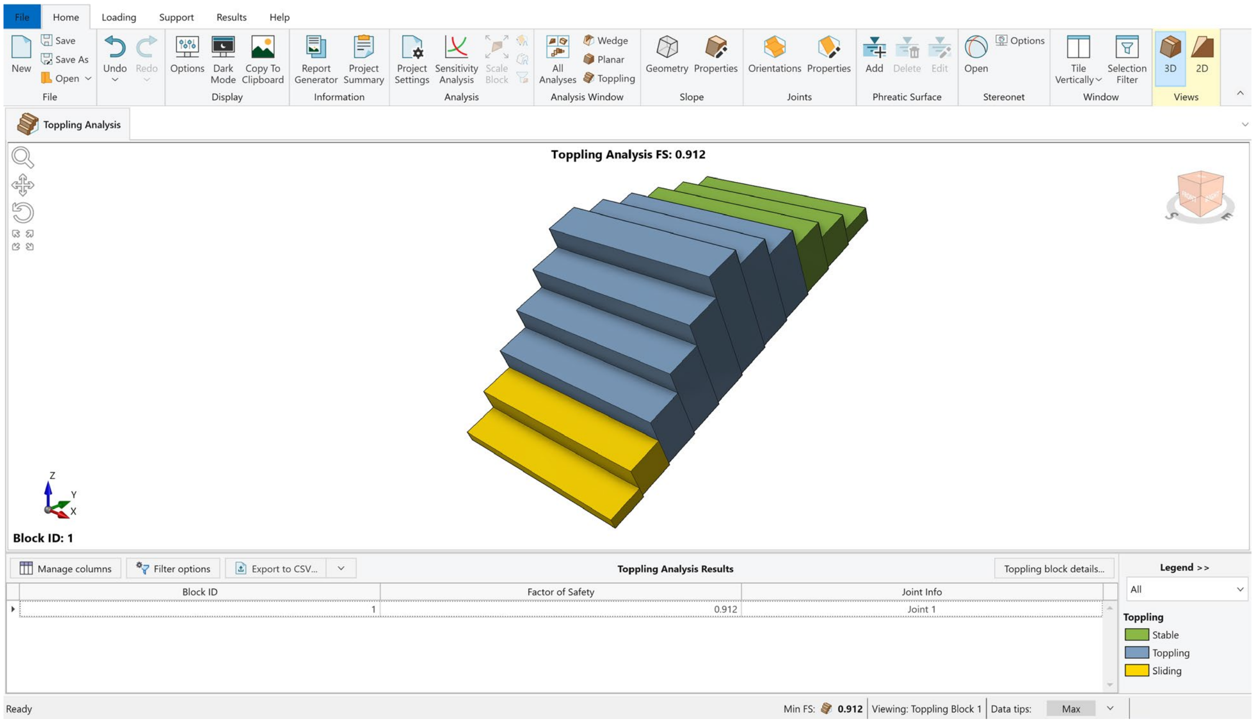


Figure 3.3.2: *RocSlope2* Geometry

3.3.3. *RocTopple* Analysis

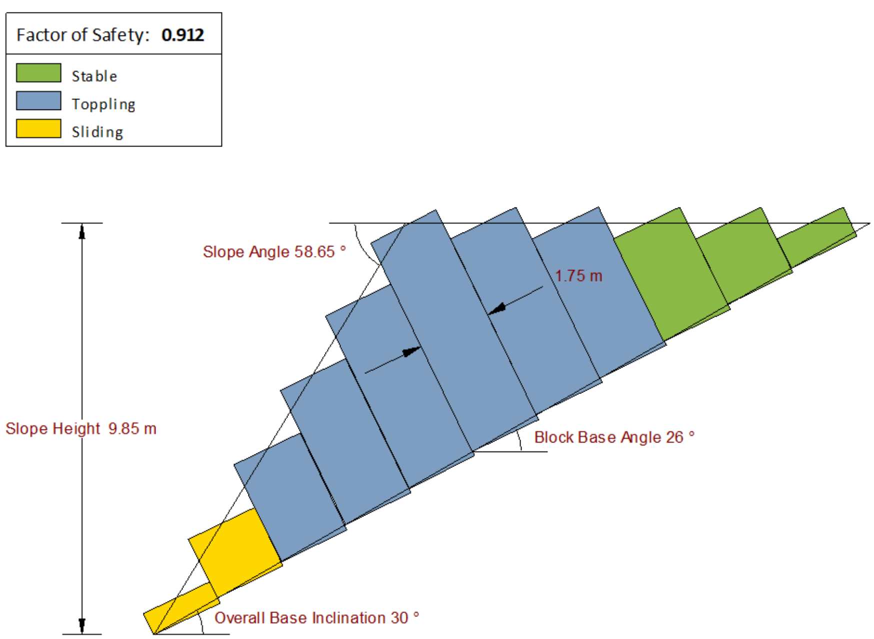
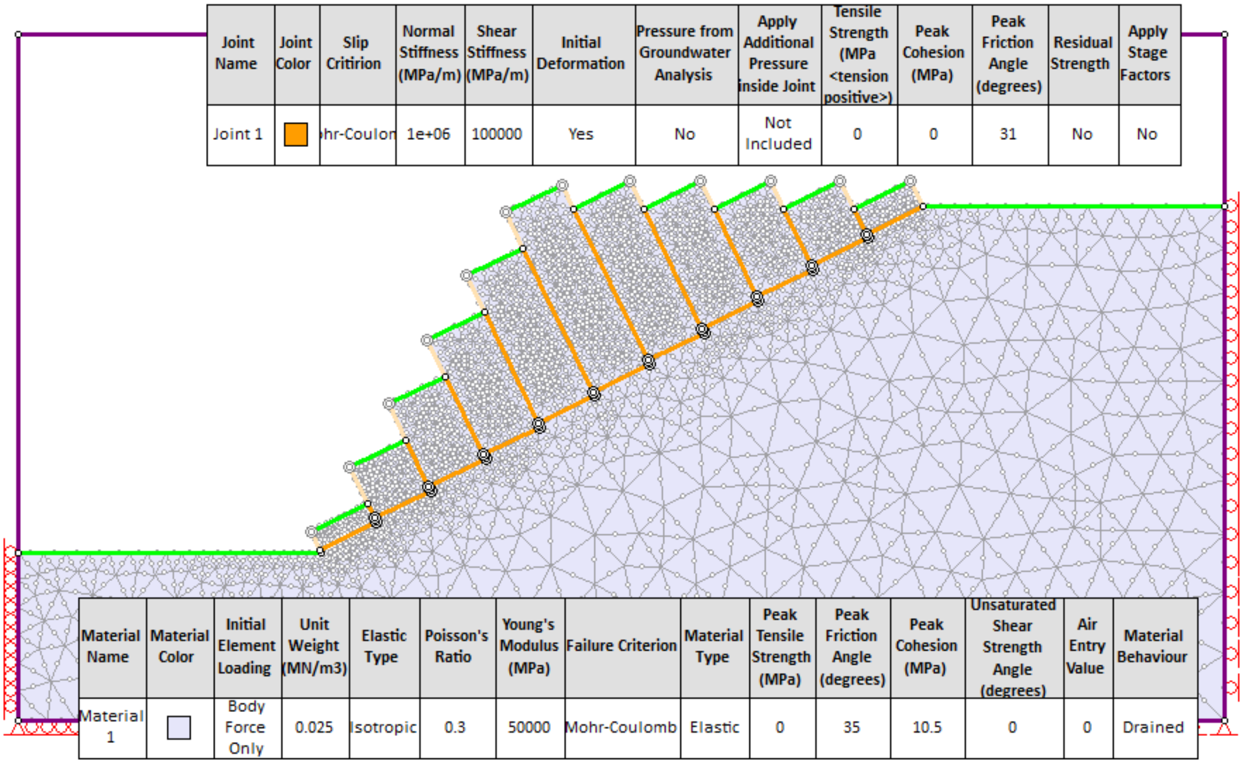


Figure 3.3.3: *RocTopple* Geometry

3.3.4. Building a Compatible *RS2* Model



Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		hr-Coulon	1e+06	100000	Yes	No	Not Included	0	0	31	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Unsaturated Shear Strength Angle (degrees)	Air Entry Value	Material Behaviour
Material 1		Body Force Only	0.025	Isotropic	0.3	50000	Mohr-Coulomb	Elastic	0	35	10.5	0	0	Drained

Figure 3.3.4: *RS2* Geometry and Properties

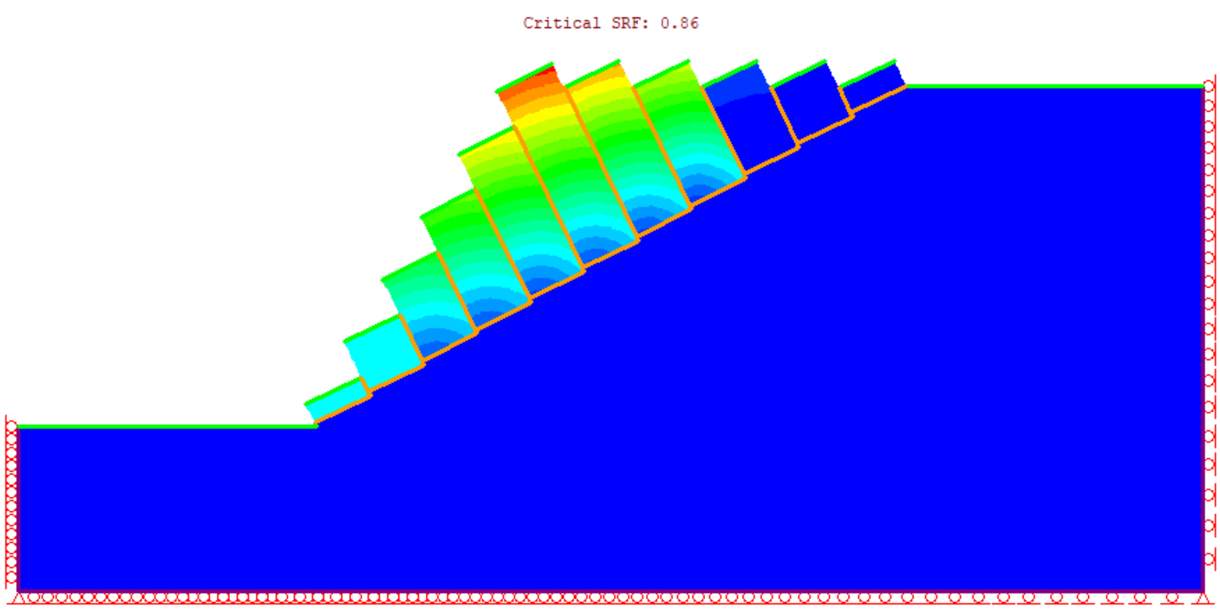


Figure 3.3.5: *RS2* Displacement Contours

3.3.5. *UDEC* Analysis

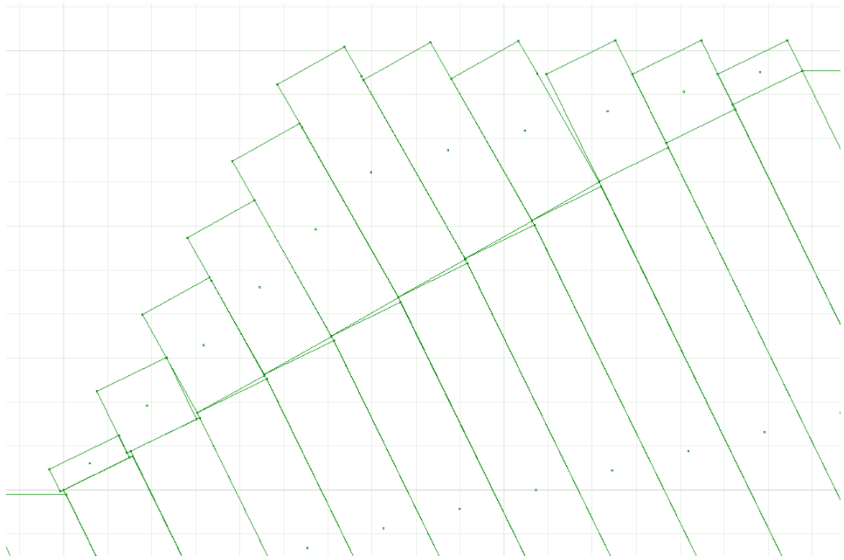


Figure 3.3.6: Deformation in *UDEC*

3.3.6. Results

Table 3.3.2: Factors of Safety

RocSlope2	*RocTopple*	*RS2*	*UDEC*	Alejano and Alonso
0.91	0.91	0.86	0.88	0.76

3.4. *RocSlope2* Block Toppling Verification Problem #4

[RocSlope2 Build 1.005]

3.4.1. Problem Description

This verification problem examines the case of block toppling in a steep slope.

A block toppling model was constructed and analyzed in *RocSlope2* using geometric data given in the Table 3.4.1. The model was then verified in *RocTopple* and exported to *RS2*, in which shear strength reduction analysis was used to verify factor of safety results. Results were also verified using rigid block *UDEC* analysis. Both *RS2* and *UDEC* programs also predict that blocks are toppling from the 7th block from the top all the way to the toe block. These programs also generated comparable factors of safety.

Note that block width (joint spacing) of 6.0m was used in the *RocSlope2* model.

Geometry and Material Properties

Table 3.4.1: Geometry and Material Properties

Slope Height (m)	Slope Angle (deg)	Joint Angle (deg)	Overall Base Inclination (deg)	ϕ' (deg)	γ (kN/m^3)
92.5	80	80	45	38.15	25.0

3.4.2. *RocSlope2* Analysis

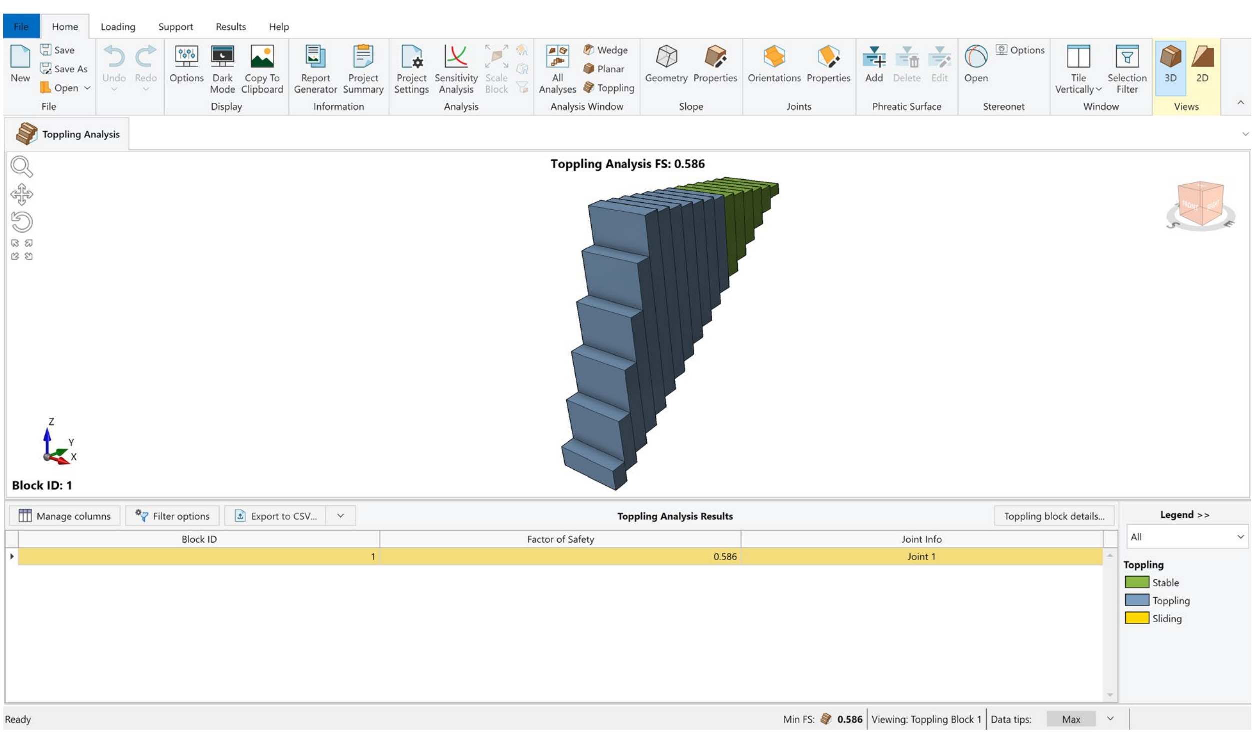


Figure 3.4.1: *RocSlope2* Geometry and Block Failure Modes

3.4.3. *RocTopple* Analysis

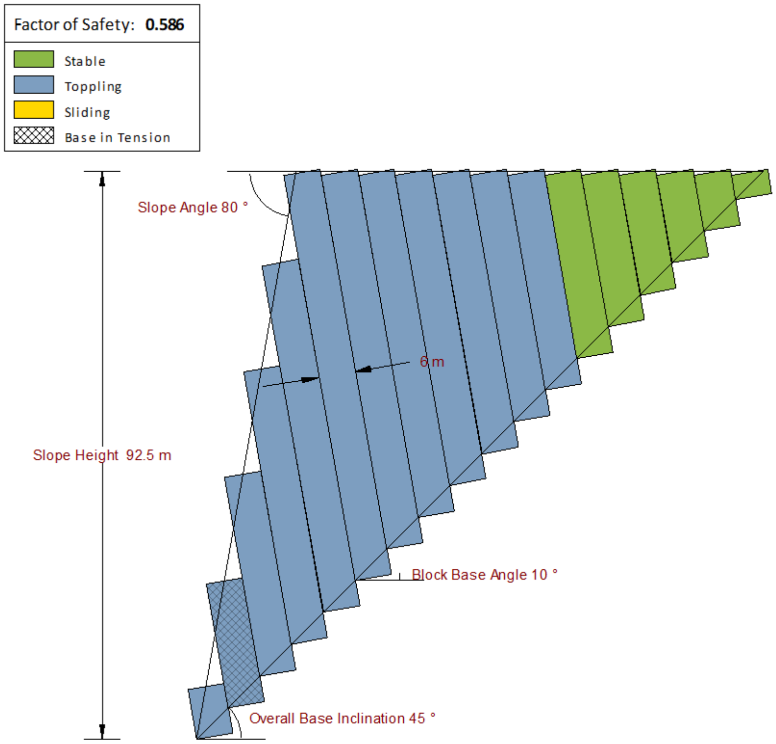
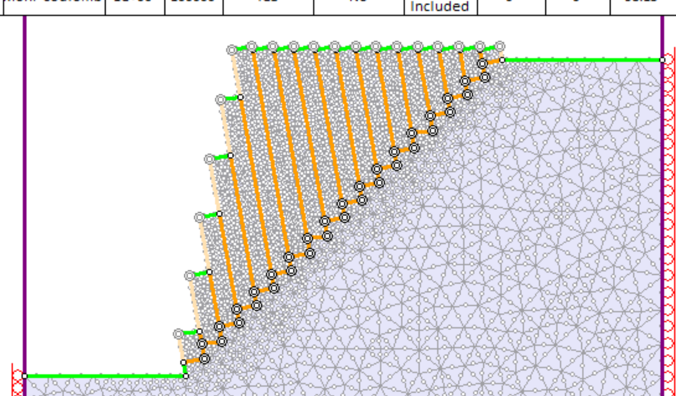


Figure 3.4.2: *RocTopple* Geometry and Block Failure Modes

3.4.4. Building a Compatible *RS2* Model

Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	1e+06	100000	Yes	No	Not Included	0	0	38.15	No	No



Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Unsaturated Shear Strength Angle (degrees)	Material Behaviour
Material 1		Body Force Only	0.025	Isotropic	0.3	1e+06	Mohr-Coulomb	Elastic	0	35	10.5	0	Drained

Figure 3.4.3: *RS2* Geometry and Properties

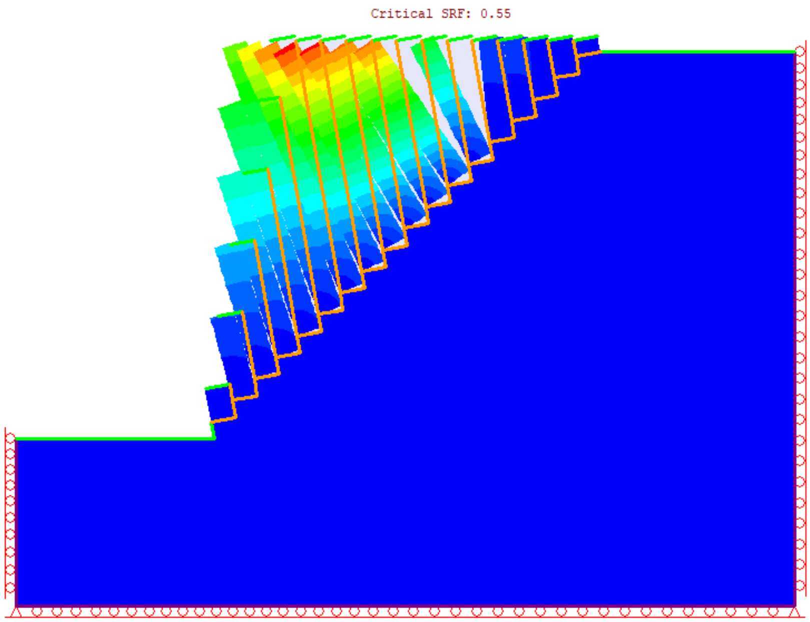


Figure 3.4.4: *RS2* Displacement Contours

3.4.5. Results

Table 3.4.2: Factors of Safety

RocSlope2	*RocTopple*	*RS2*	*UDEC*
0.59	0.59	0.55	0.59

3.5. *RocSlope2* Block Toppling Verification Problem #5

[RocSlope2 Build 1.005]

3.5.1. Problem Description

This verification problem examines the case of sliding blocks on a slope.

A block toppling model was constructed and analyzed in *RocSlope2* using geometric data given in the Table 3.5.1. The model was then verified in *RocTopple* and exported to *RS2*, in which shear strength reduction analysis was used to verify factor of safety results. Results were also verified using *RocPlane*, which uses the limit equilibrium method to predict the factor of safety for 2D planar failures. The analysis in *RocPlane* used a failure plane angle of 20°. Both *RS2* and *RocPlane* programs also generated comparable factors of safety.

Note that block width (joint spacing) of 20.0m was used in the *RocSlope2* model.

Geometry and Material Properties

Table 3.5.1: Geometry and Material Properties

Slope Height (m)	Slope Angle (deg)	Joint Angle (deg)	Overall Base Inclination (deg)	ϕ' (deg)	γ (kN/m^3)
92.5	35	70	26	30	25.0

3.5.2. *RocSlope2* Analysis

RocSlope2 predicts that blocks are sliding critical at the point of failure.

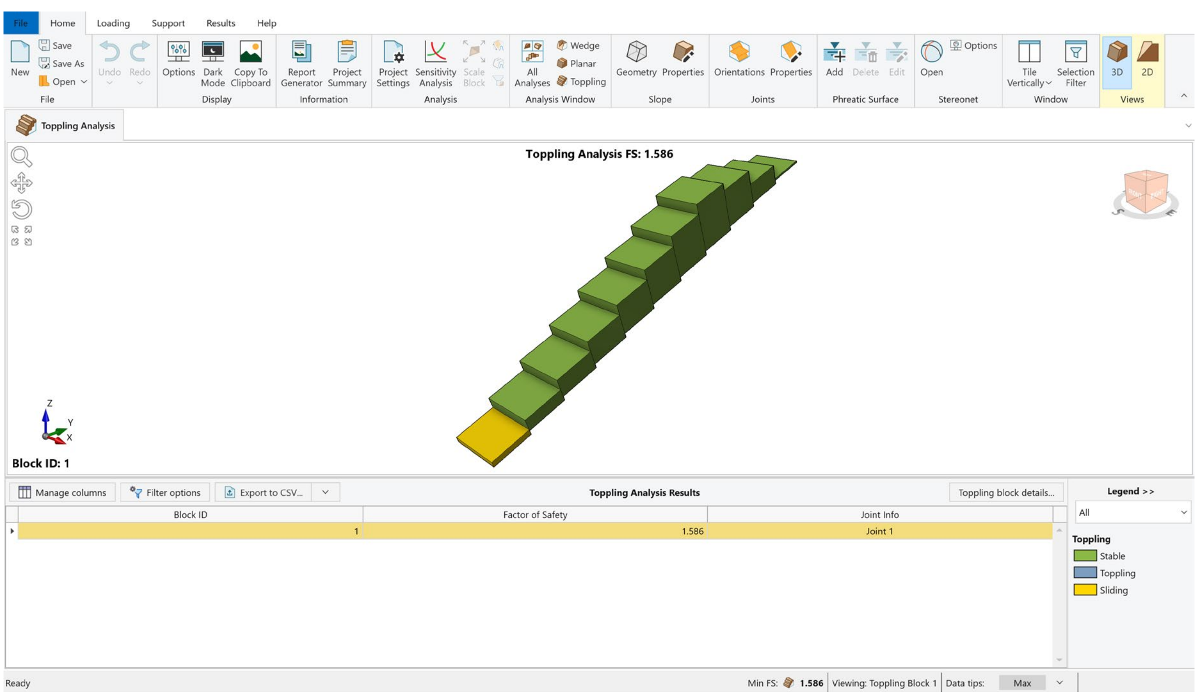


Figure 3.5.1: *RocSlope2* Geometry and Block Failure Modes

3.5.3. *RocTopple* Analysis

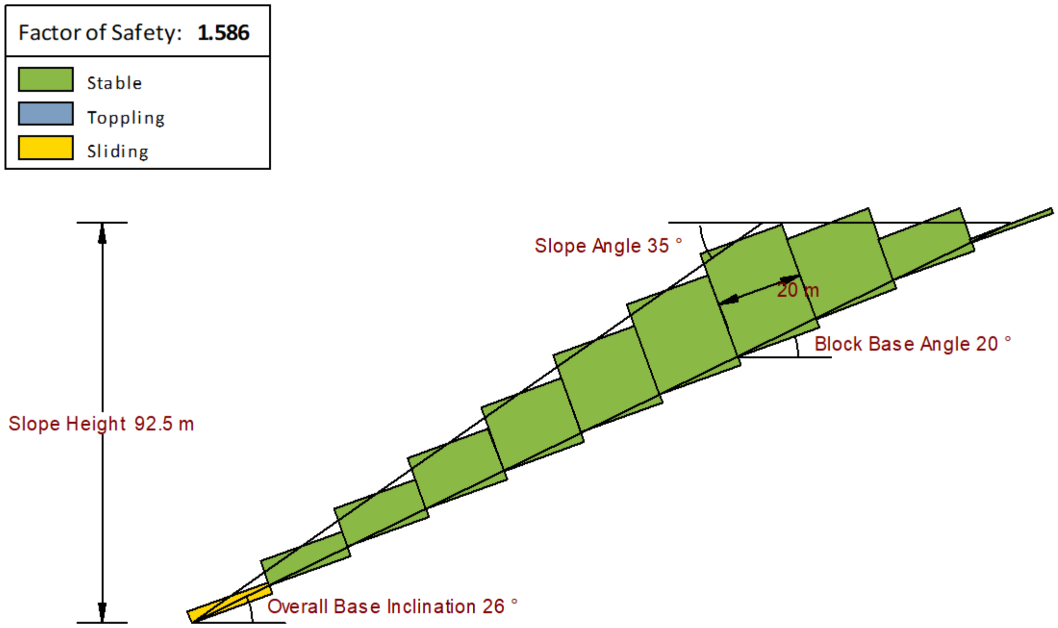
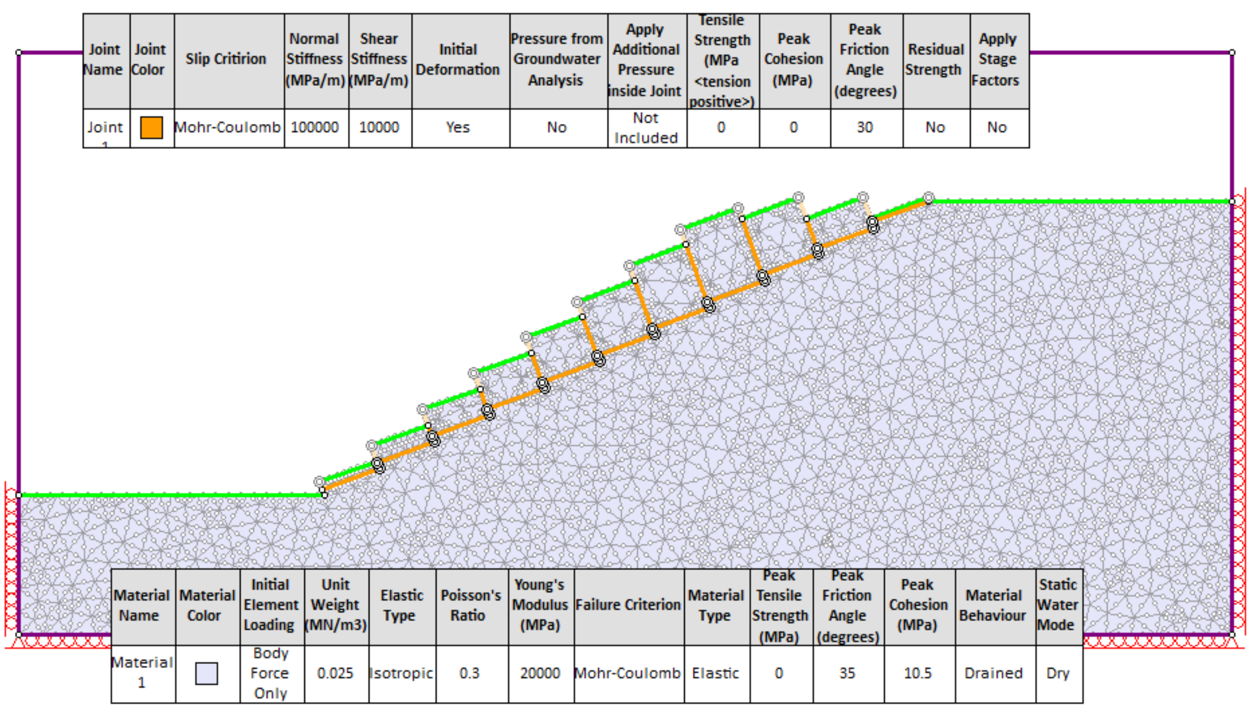


Figure 3.5.2: *RocTopple* Geometry and Block Failure Modes

3.5.4. Building a Compatible *RS2* Model



Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	100000	10000	Yes	No	Not Included	0	0	30	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Material Behaviour	Static Water Mode
Material 1		Body Force Only	0.025	Isotropic	0.3	20000	Mohr-Coulomb	Elastic	0	35	10.5	Drained	Dry

Figure 3.5.3: *RS2* Geometry and Properties

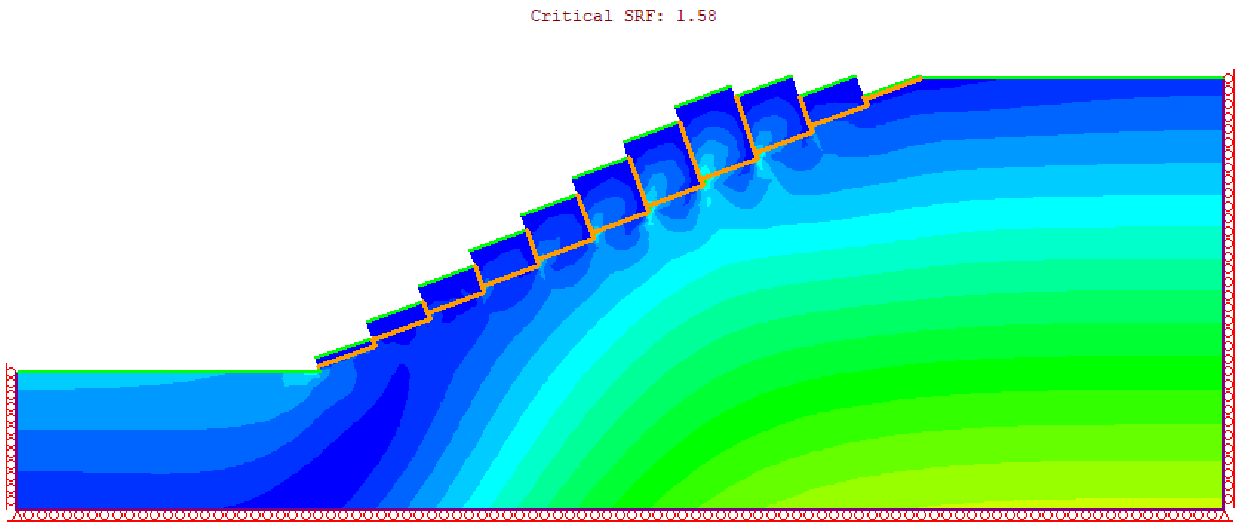


Figure 3.5.4: *RS2* Displacement Contours

3.5.5. Results

Table 3.5.2: Factors of Safety

RocSlope2	*RocTopple*	*RS2*	*RocPlane*
1.59	1.59	1.58	1.59

3.6. *RocSlope2* Block Toppling Verification Problem #6

[RocSlope2 Build 1.005]

3.6.1. Problem Description

This verification problem examines the Barton-Bandis Joint Shear Strength model.

Three different block toppling models were constructed and analyzed in *RocSlope2* using geometric data given in the Table 3.6.1 and joint strength data given in Table 3.6.2. Models were then verified in *RocTopple* and exported to *RS2*, in which shear strength reduction analysis was used to verify factor of safety results.

The joint strength parameters could not be divided by the factor of safety values in finding a shear strength reduction factor because the Barton Bandis model is non-linear. Instead, normal and shear stress data at the given shear strength model had to be exported to *Excel* from *RocData*, where the shear stresses were manually adjusted for different factors of safety (shear stress/FS). The normal stress and new shear stress values were imported back into *RocData*, which uses the Levenberg-Marquardt algorithm to fit the stress values to a set of Barton Bandis parameters. Finally, the slope stability was evaluated using stress analysis in *RS2* given the adjusted parameters. A discrepancy is seen in one of the factors of safety because the parameters did not give a perfect fit to the stress data. As seen in Table 3.6.3, factors of safety between *RocSlope2* and *RS2* do not agree when there are large residuals in the parameter fitting process.

Note that block width (joint spacing) of 10.0m was used in the *RocSlope2* model.

Table 3.6.1: Geometry and Material Properties

Slope Height (m)	Slope Angle (deg)	Upper Slope Angle (deg)	Joint Angle (deg)	Overall Base Inclination (deg)	γ (kN/m^3)
92.5	56.6	4	60	35.8	25.0

Table 3.6.2: Joint Strength Properties

	Joints		
	JRC	JCS (kPa)	PhiR
A	10	10000	30°
B	8	7000	20°
C	5	5000	15°

3.6.2. *RocSlope2* Analysis

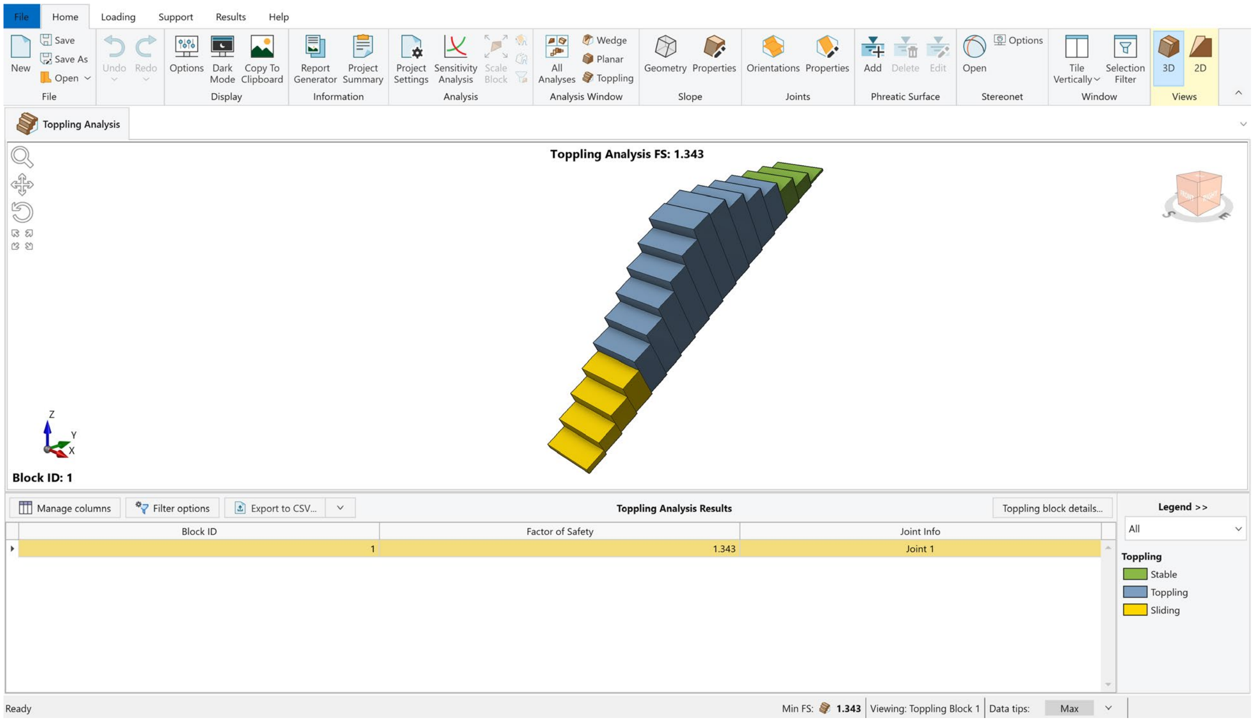


Figure 3.6.1: *RocSlope2* Geometry of Example 6a and Block Failure Modes

3.6.3. *RocTopple* Analysis

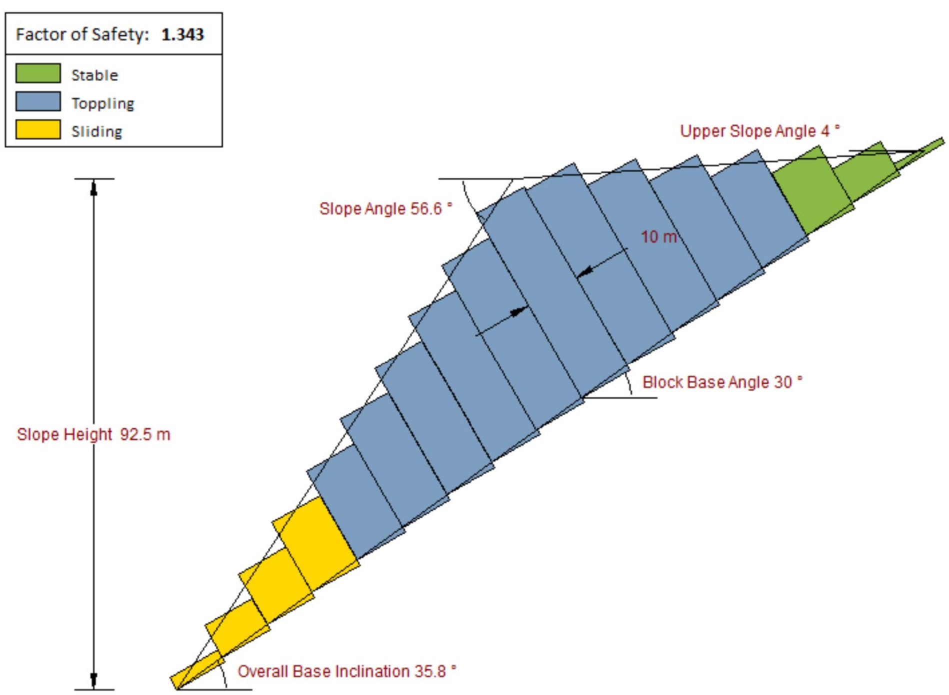
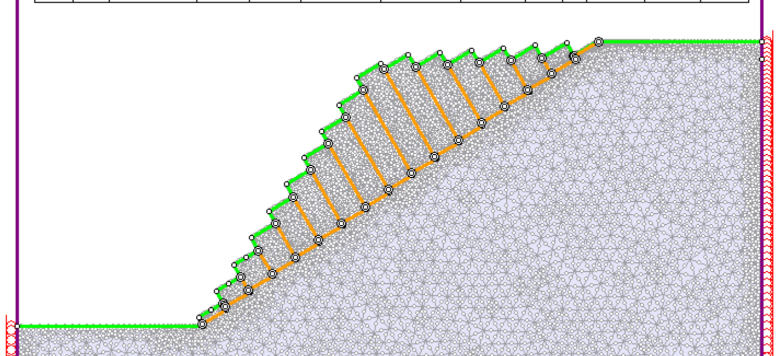


Figure 3.6.2: *RocTopple* Geometry of Example 6a and Block Failure Modes

3.6.4. Building a Compatible *RS2* Model

Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	JCS (MPa)	JRC	Residual Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joints		Barton-Bandis	100000	10000	Yes	No	Not Included	37.219	10	30	No	No



Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Unsaturated Shear Strength Angle (degrees)	Air Entry Value	Material Behaviour	Static Water Mode	Ru Value
Material 1		Body Force Only	0.025	Isotropic	0.3	50000	Mohr-Coulomb	Elastic	0	38.15	0	0	0	Drained	Ru	0

Figure 3.6.3: *RS2* Geometry and Properties for Example 6a

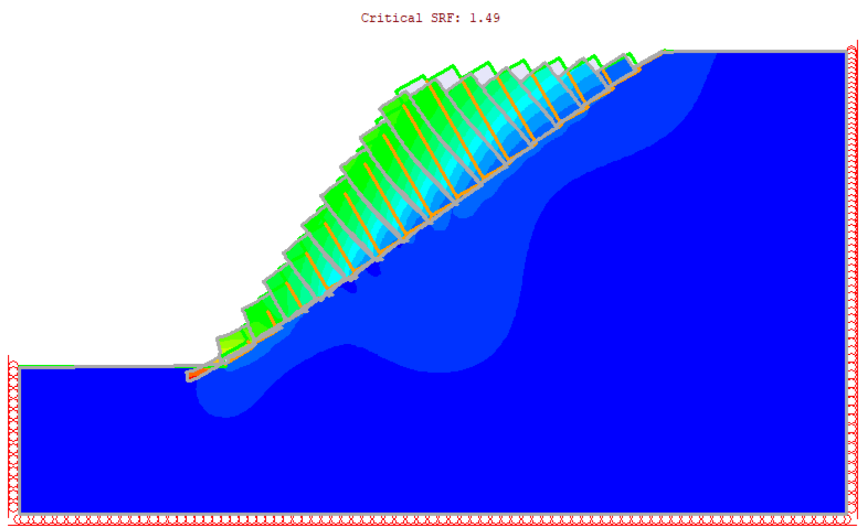


Figure 3.6.4: *RS2* Displacement Contours for Example 6a

3.6.5. Results

Table 3.6.3: Factors of Safety

	Factors of Safety			*RocData* Residuals (Fit at *RS2* FS)
	RocSlope2	*RocTopple*	*RS2*	
A	1.34	1.34	1.49	17.964
B	0.79	0.79	0.96	0.020
C	0.51	0.51	0.57	4.414

3.7. *RocSlope2* Block Toppling Verification Problem #7

[RocSlope2 Build 1.005]

3.7.1. Problem Description

This verification problem examines the application of bolts and line loads.

Since the formulation for end-anchored bolts consists of having two forces applied at the two ends, having a bolt that is anchored in the slope bedrock is equivalent to having a point load applied at where the bolt is installed.

Two equivalent block toppling models (one with bolts and the other with point loads) were constructed and analyzed in *RocSlope2* using geometric data given in the Table 3.7.1. Models were then verified in *RocTopple* and then *RocTopple* models are exported to *RS2*, in which shear strength reduction analysis was used to verify factor of safety results.

Note that block width (joint spacing) of 10.0m was used in the *RocSlope2* model.

Geometry and Properties

Table 3.7.1: Geometry and Material Properties

Slope Height (m)	Slope Angle (deg)	Joint Angle (deg)	Overall Base Inclination (deg)	ϕ' (deg)	γ (kN/m^3)
92.5	56.6	60	36	38.15	25.0

3.7.2. *RocSlope2* Analysis

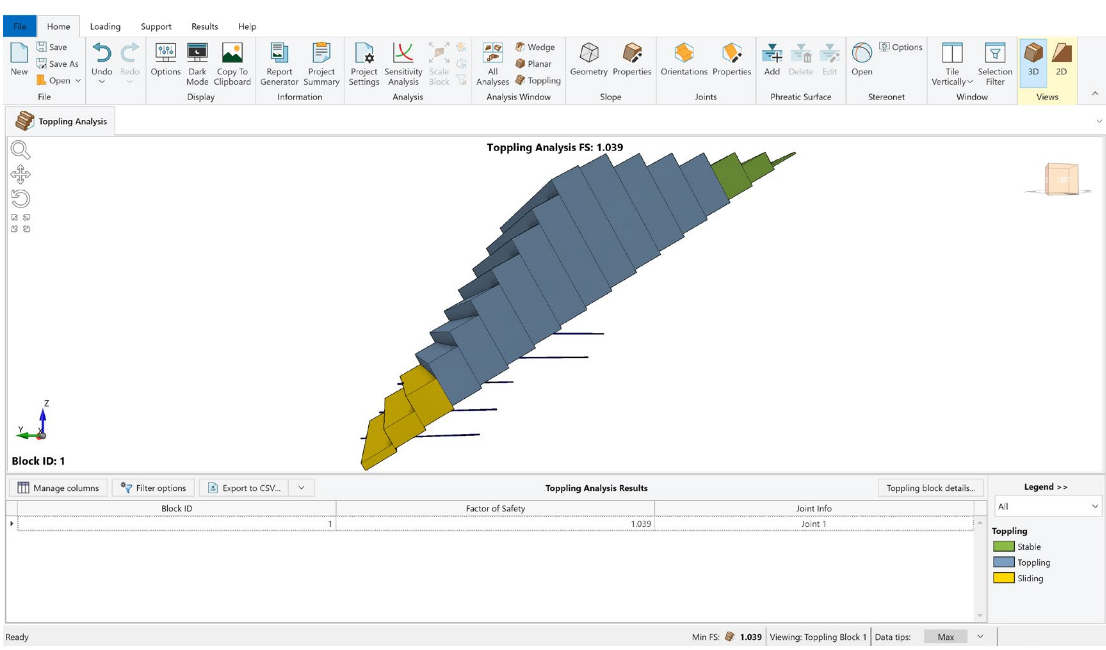


Figure 3.7.1: *RocSlope2* Geometry with Bolts

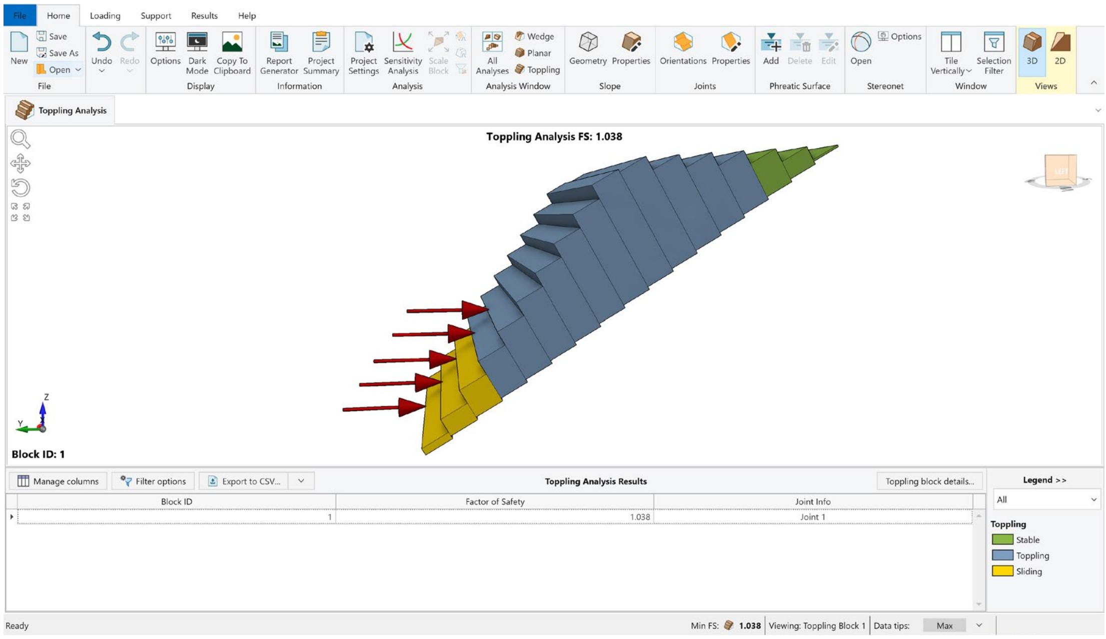


Figure 3.7.2: *RocSlope2* Geometry with Equivalent Point Loads

3.7.3. *RocTopple* Analysis

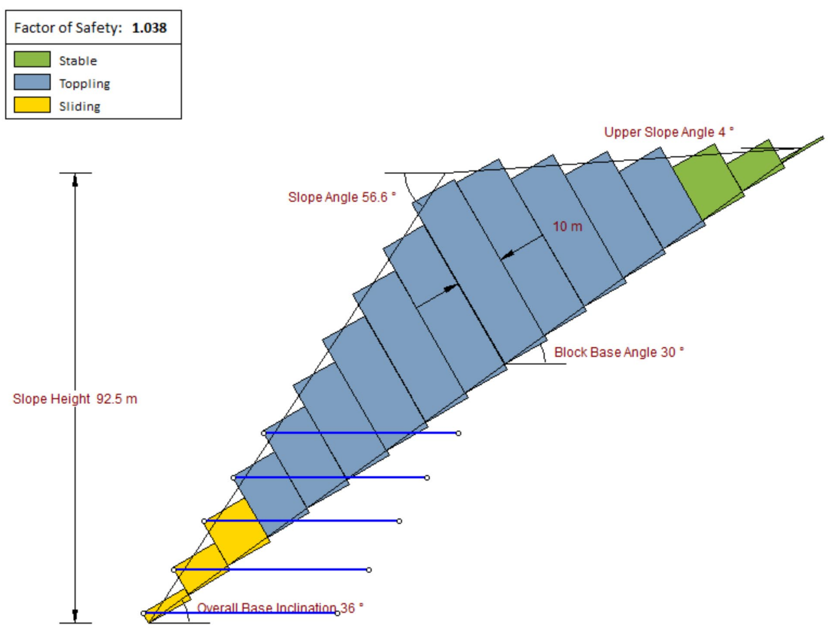


Figure 3.7.3: *RocTopple* Geometry with Bolts

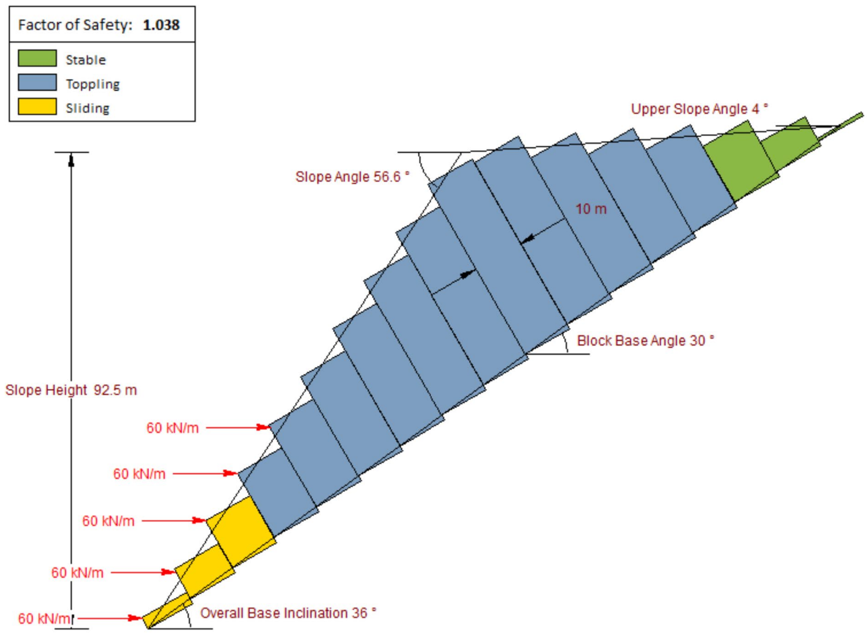
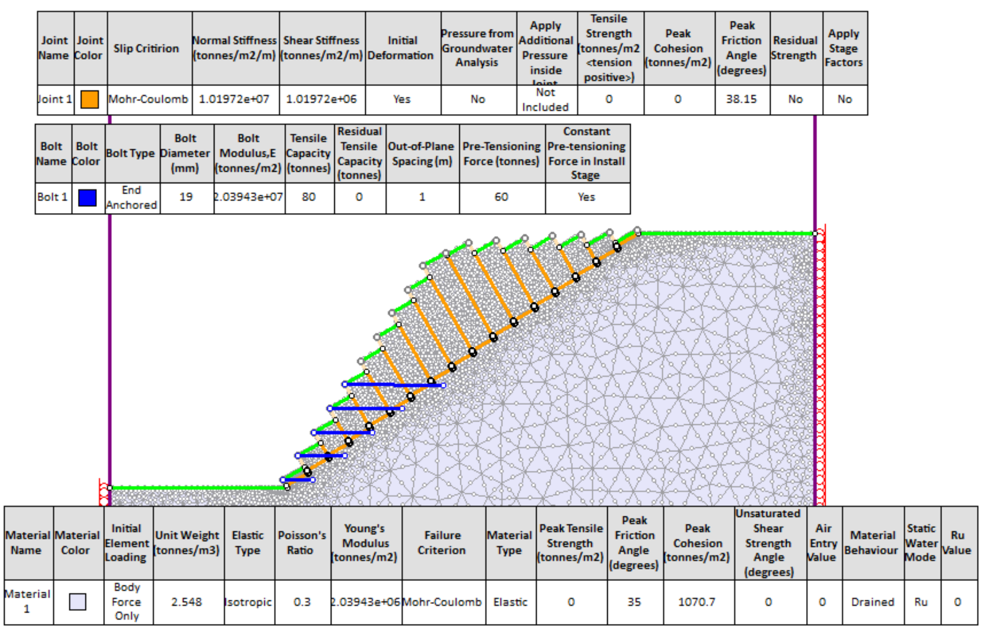


Figure 3.7.4: *RocTopple* Geometry with Equivalent Line Loads

3.7.4. Building a Compatible *RS2* Model

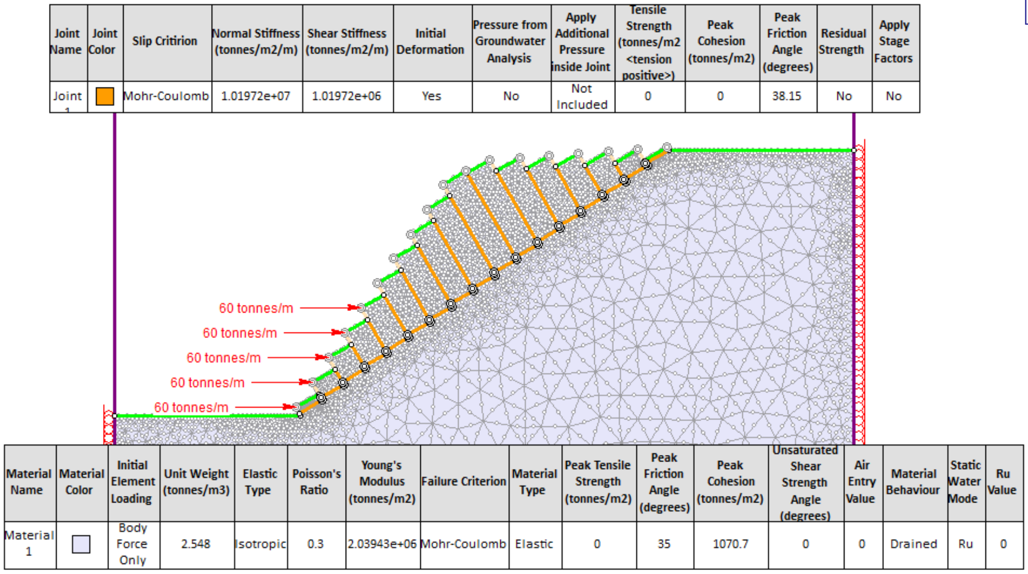


Joint Name	Joint Color	Slip Critirion	Normal Stiffness (tonnes/m2/m)	Shear Stiffness (tonnes/m2/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (tonnes/m2 <tension positive>)	Peak Cohesion (tonnes/m2)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	1.01972e+07	1.01972e+06	Yes	No	Not Included	0	0	38.15	No	No

Bolt Name	Bolt Color	Bolt Type	Bolt Diameter (mm)	Bolt Modulus,E (tonnes/m2)	Tensile Capacity (tonnes)	Residual Tensile Capacity (tonnes)	Out-of-Plane Spacing (m)	Pre-Tensioning Force (tonnes)	Constant Pre-tensioning Force in Install Stage
Bolt 1		End Anchored	19	2.03943e+07	80	0	1	60	Yes

Material Name	Material Color	Initial Element Loading	Unit Weight (tonnes/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (tonnes/m2)	Failure Criterion	Material Type	Peak Tensile Strength (tonnes/m2)	Peak Friction Angle (degrees)	Peak Cohesion (tonnes/m2)	Unsaturated Shear Strength Angle (degrees)	Air Entry Value	Material Behaviour	Static Water Mode	Ru Value
Material 1		Body Force Only	2.548	Isotropic	0.3	2.03943e+06	Mohr-Coulomb	Elastic	0	35	1070.7	0	0	Drained	Ru	0

Figure 3.7.5: *RS2* Geometry and Properties for Bolts



Joint Name	Joint Color	Slip Critirion	Normal Stiffness (tonnes/m2/m)	Shear Stiffness (tonnes/m2/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (tonnes/m2 <tension positive>)	Peak Cohesion (tonnes/m2)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	1.01972e+07	1.01972e+06	Yes	No	Not Included	0	0	38.15	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (tonnes/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (tonnes/m2)	Failure Criterion	Material Type	Peak Tensile Strength (tonnes/m2)	Peak Friction Angle (degrees)	Peak Cohesion (tonnes/m2)	Unsaturated Shear Strength Angle (degrees)	Air Entry Value	Material Behaviour	Static Water Mode	Ru Value
Material 1		Body Force Only	2.548	Isotropic	0.3	2.03943e+06	Mohr-Coulomb	Elastic	0	35	1070.7	0	0	Drained	Ru	0

Figure 3.7.6: *RS2* Geometry and Properties for Equivalent Line Loads

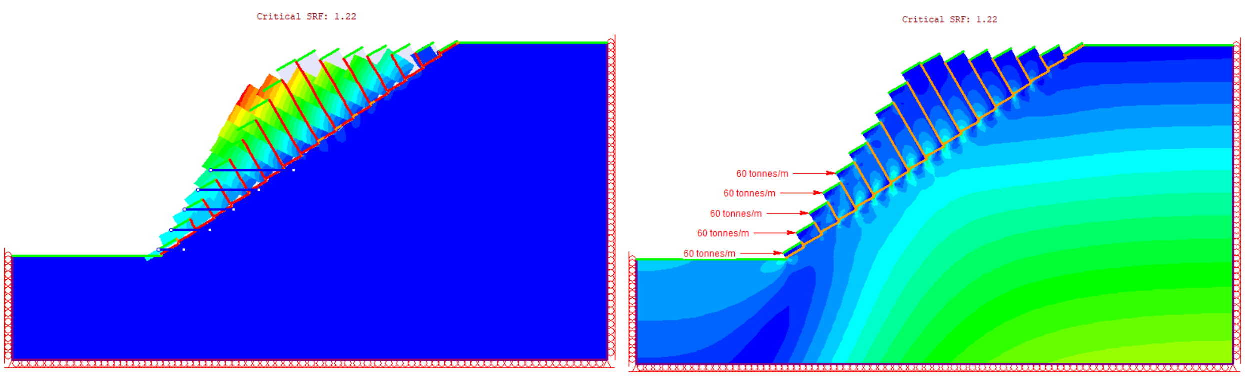


Figure 3.7.7: *RS2* Displacement Contours for Bolts (left) and Equivalent Line Loads (right)

3.7.5. Results

Table 3.7.2: Factors of Safety

Example	*RocSlope2*	*RocTopple*	*RS2*
7A with Bolts	1.04	1.04	1.22
7B with Equivalent Point/Line Loads	1.04	1.04	1.22

3.8. *RocSlope2* Block Toppling Verification Problem #8

[RocSlope2 Build 1.005]

3.8.1. Problem Description

This verification problem examines the application of distributed loads.

Four different block toppling models were constructed and analyzed in *RocSlope2* using geometric data given in the Table 3.8.1. Models were then verified in *RocTopple* and exported to *RS2*, in which shear strength reduction analysis was used to verify factor of safety results.

Note that block width (joint spacing) of 10.0m was used in the *RocSlope2* model.

Geometry and Properties

Table 3.8.1: Geometry and Material Properties

Slope Height (m)	Slope Angle (deg)	Joint Angle (deg)	Overall Base Inclination (deg)	ϕ' (deg)	γ (kN/m^3)
92.5	56.6	60	36	38.15	25.0

3.8.2. *RocSlope2* Analysis

Case 1:

Pressure loads of 11 kPa are assumed to apply on slope face.

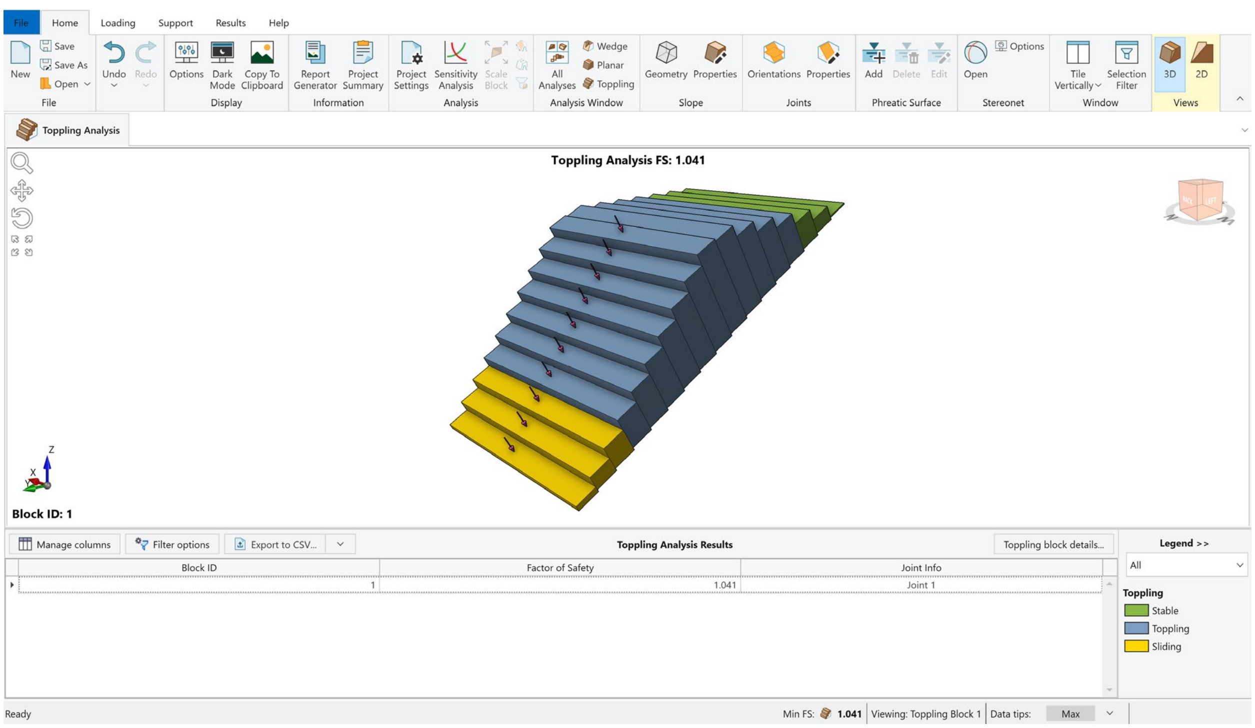


Figure 3.8.1: *RocSlope2* Slope Face Pressure of 11 kPa

This case is also modelled by applying equivalent point loads on slope face.

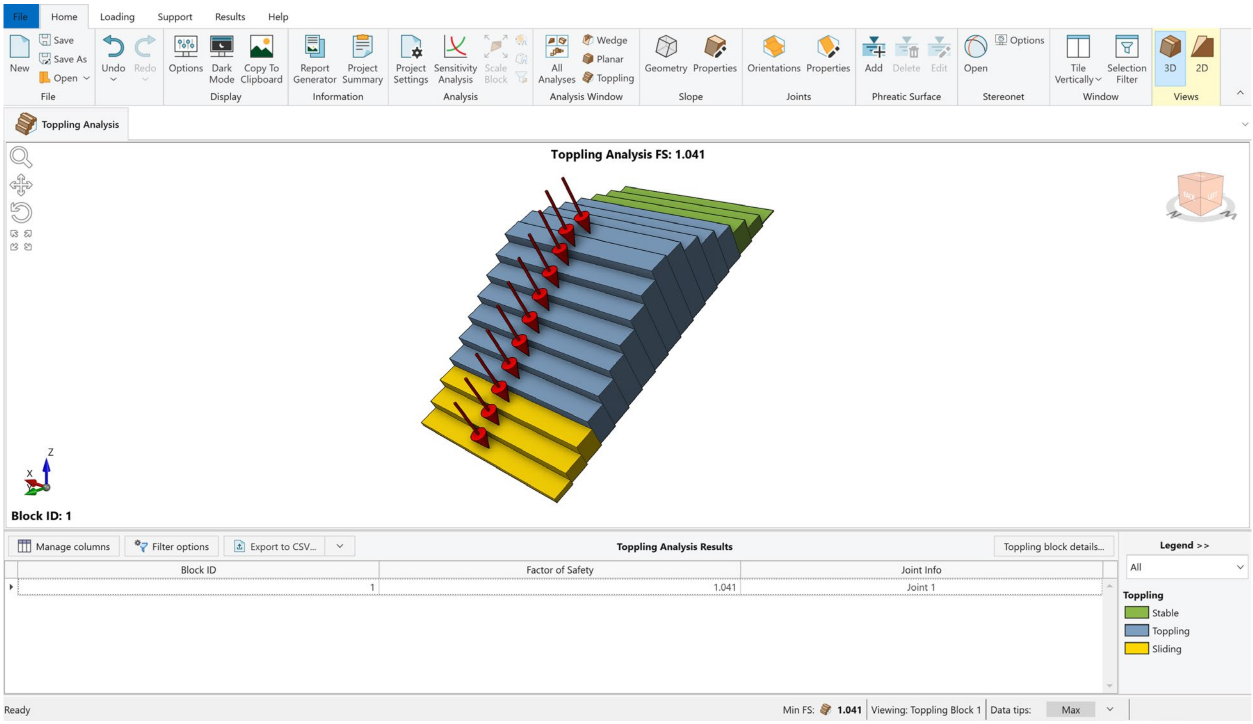


Figure 3.8.2: *RocSlope2* Model with Equivalent Point Loads

Case 2:

A similar analysis for a pressure of 90 kPa on the upper slope face is illustrated below.

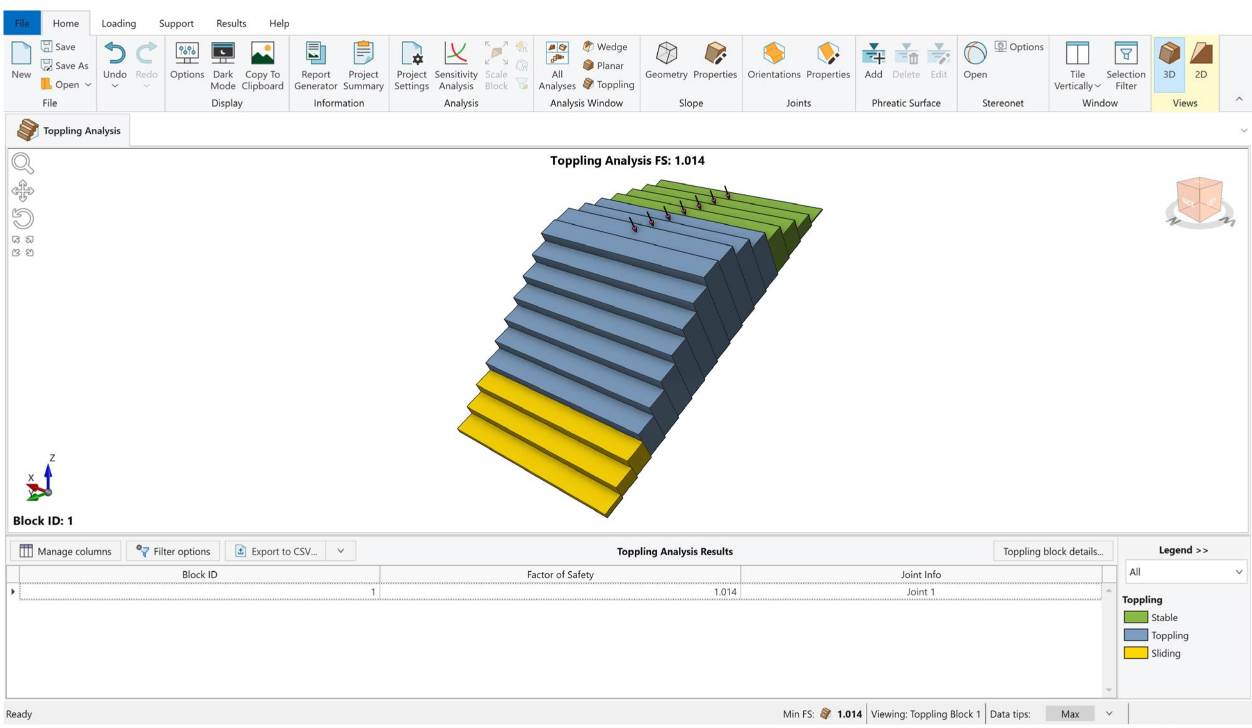


Figure 3.8.3: *RocSlope2* Upper Slope Face Pressure of 90 kPa

This case is also modelled by applying equivalent point loads on upper slope face.

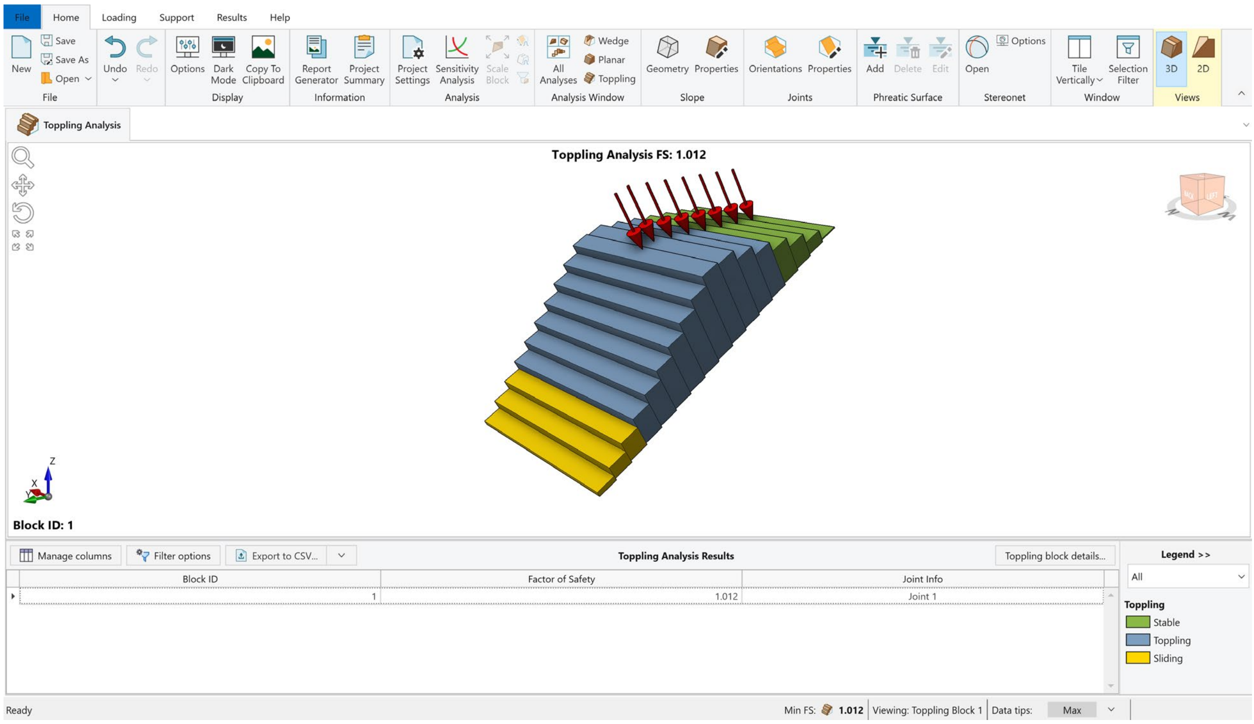


Figure 3.8.4: *RocSlope2* Model with Equivalent Point Loads

3.8.3. *RocTopple* Analysis

Case 1:

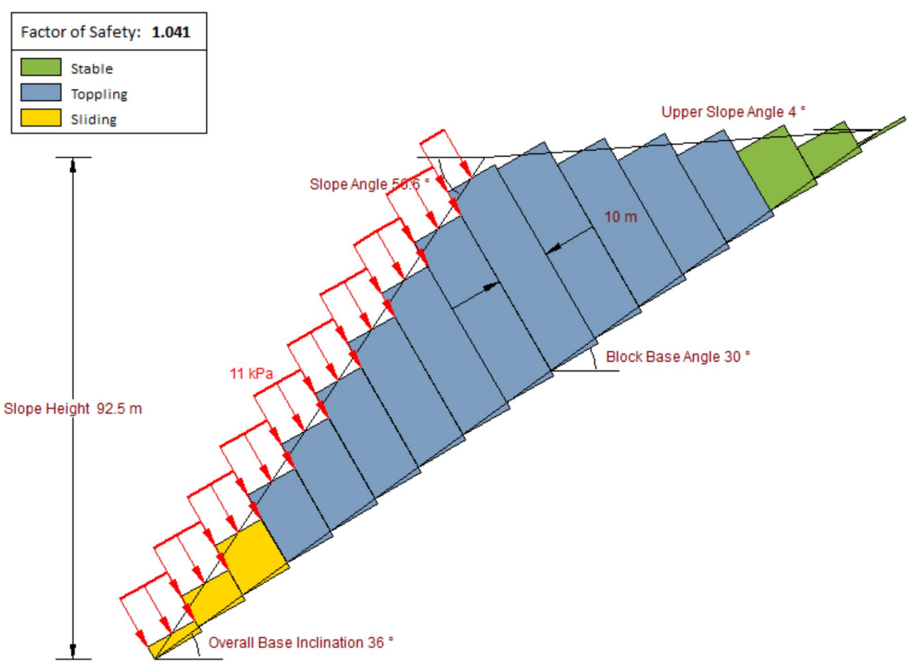


Figure 3.8.5: *RocTopple* Slope Face Distributed Load of 11 kPa

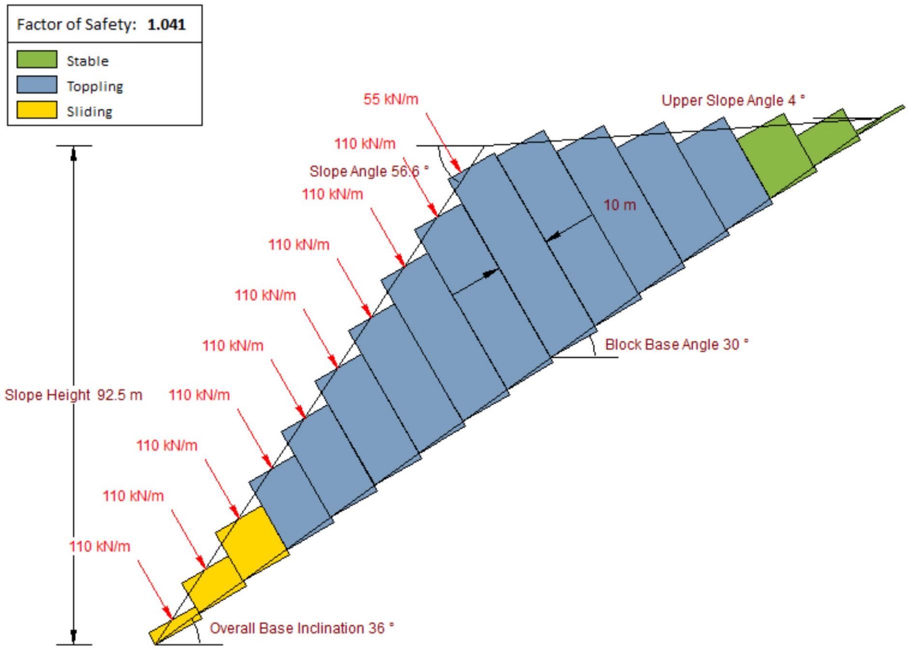


Figure 3.8.6: *RocTopple* Model with Equivalent Line Loads

Case 2:

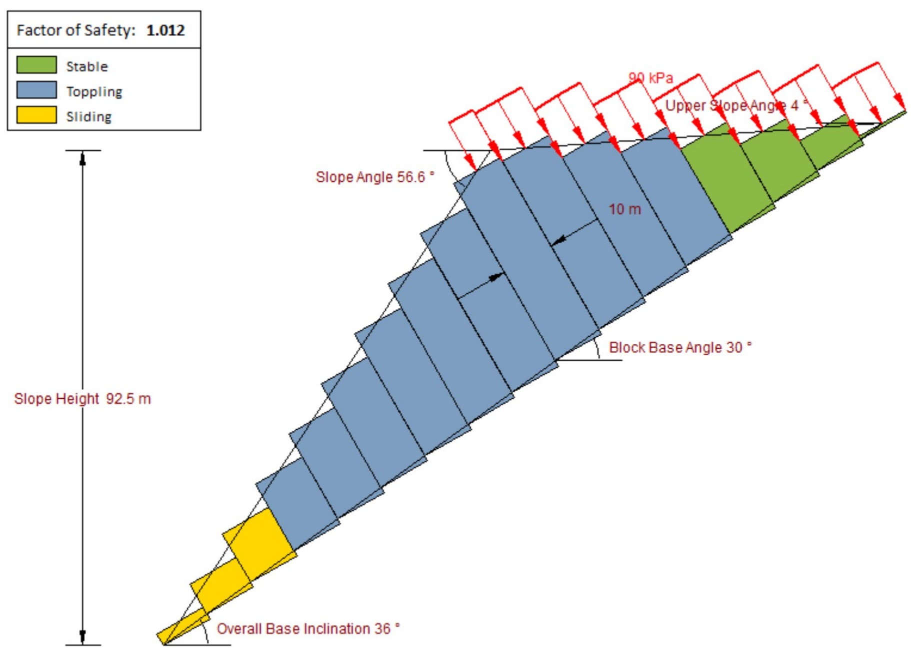


Figure 3.8.7: *RocTopple* Upper Slope Face Distributed Load of 90 kPa

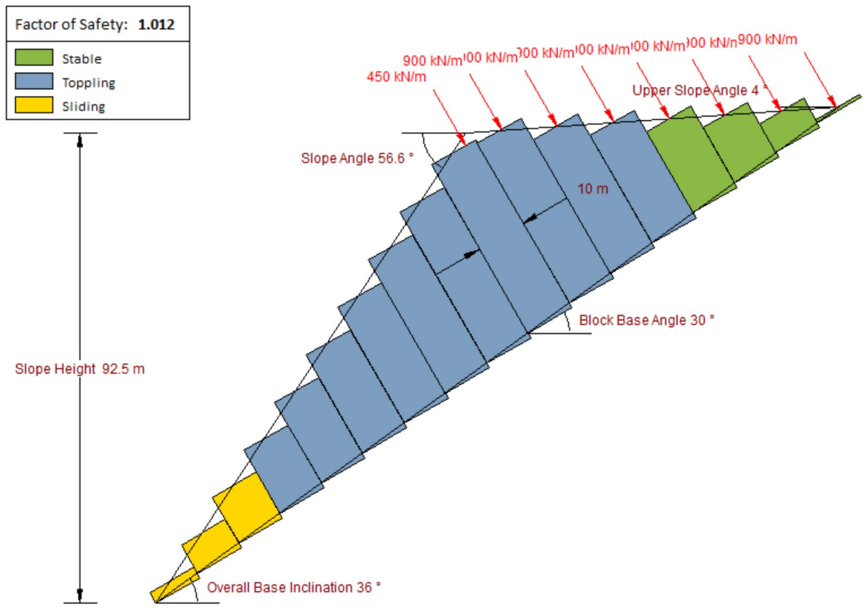


Figure 3.8.8: *RocTopple* Model with Equivalent Line Loads

3.8.4. Building a Compatible *RS2* Model

Case 1:

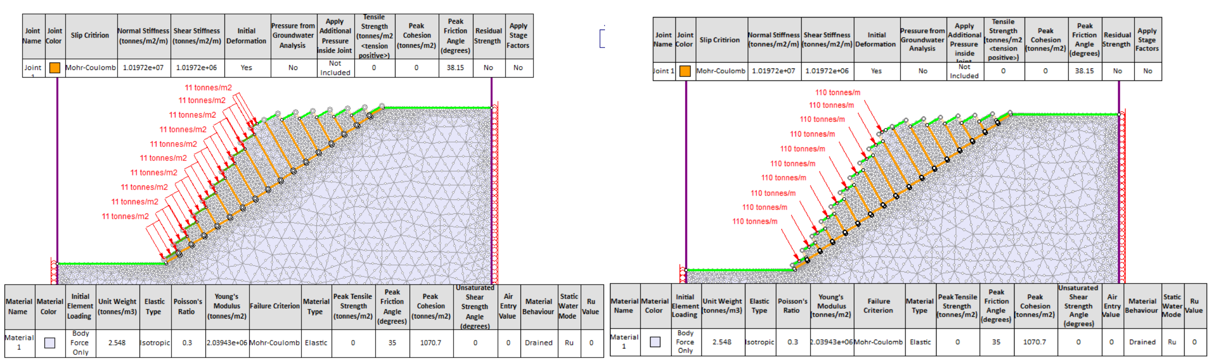


Figure 3.8.9: *RS2* Geometry and Properties for Examples 8a and 8b

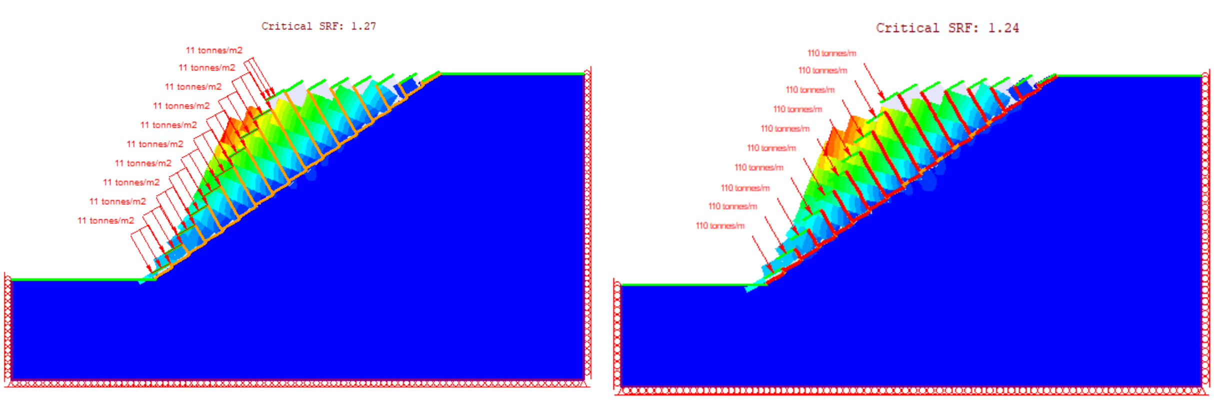


Figure 3.8.10: *RS2* Displacement Contours for Examples 8a and 8b

Case 2:

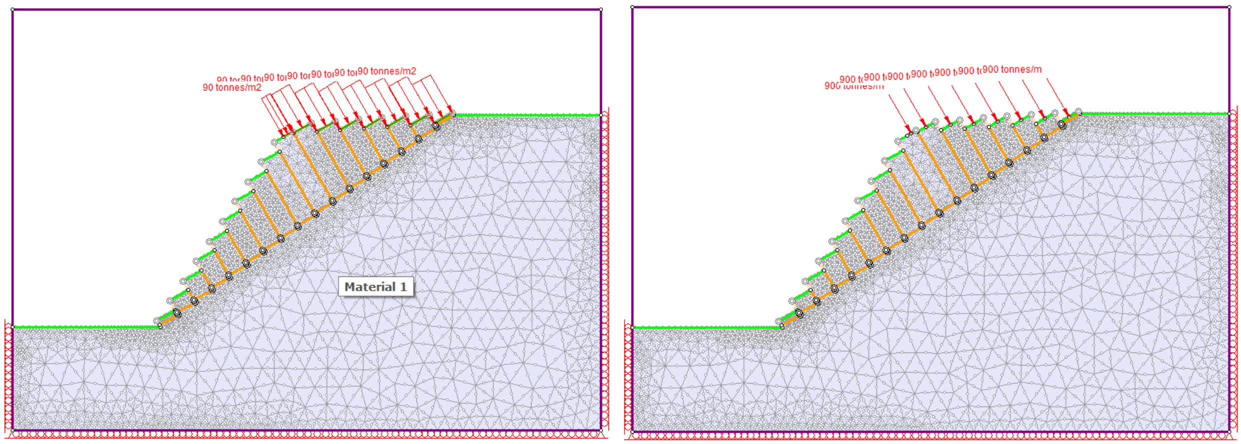


Figure 3.8.11: *RS2* Geometry for Examples 8c and 8d

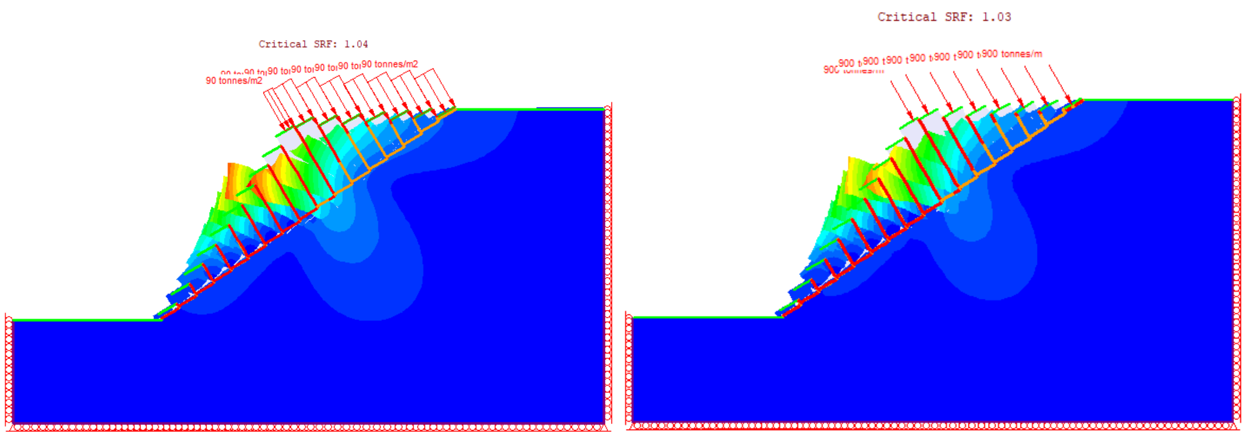


Figure 3.8.12: *RS2* Displacement Contours for Examples 8c and 8d

3.8.5. Results

Table 3.8.2: Factors of Safety for Model with Slope Face Pressure

Example	Note	*RocSlope2*	*RocTopple*	*RS2*
8a	Pressure/Distributed Load (11 kPa)	1.04	1.04	1.27
8b	Equivalent Point/Line Loads	1.04	1.04	1.24

Table 3.8.3: Factors of Safety for Model with Upper Slope Face Pressure

Example	Notes	*RocSlope2*	*RocTopple*	*RS2*
8c	Pressure/Distributed Load (90 kPa)	1.01	1.01	1.04
8d	Equivalent Point/Line Loads	1.01	1.01	1.03

3.9. *RocSlope2* Block Toppling Verification Problem #9

[RocSlope2 Build 1.005]

3.9.1. Problem Description

This verification problem examines the Mohr-Coulomb Joint Shear Strength model by varying combinations of friction angle and cohesion.

Five different block toppling models were constructed and analyzed in *RocSlope2* using geometric data given in the Table 3.9.1 and joint strength data given in Table 3.9.2. Models were then verified in *RocTopple* and exported to *RS2*, in which shear strength reduction analysis was used to verify factor of safety results.

Note that block width (joint spacing) of 15.0m was used in the *RocSlope2* model.

Geometry and Properties

Table 3.9.1: Geometry and Material Properties

Slope Height (m)	Slope Angle (deg)	Upper Slope Angle (deg)	Joint Angle (deg)	Overall Base Inclination (deg)	γ (kN/m^3)
92.5	70	-20	70	36	25.0

Table 3.9.2: Joint Strength Properties

Example	Joints	
	ϕ (°)	Cohesion (kPa)
a	38.15	0
b	30	10
c	25	25
d	10	40
e	0	50

3.9.2. *RocSlope2* Analysis

Results for a series of analyses using Mohr-Coulomb shear strength are shown below.

Example a:

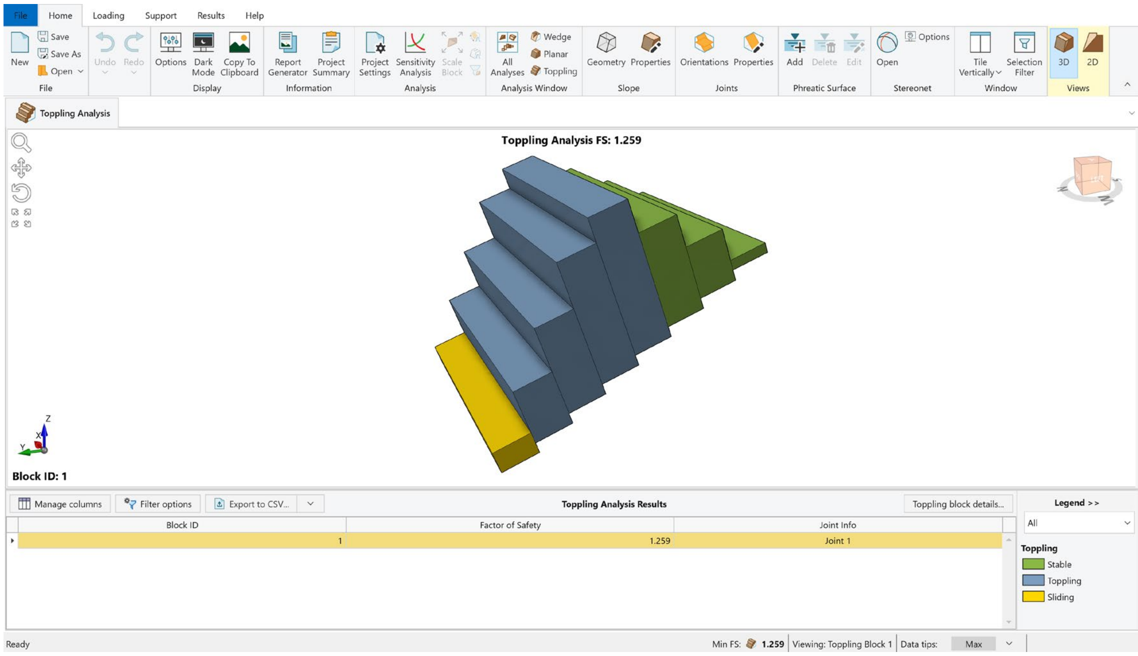


Figure 3.9.1: *RocSlope2* Geometry of Example 9a and Block Failure Modes

Example b:

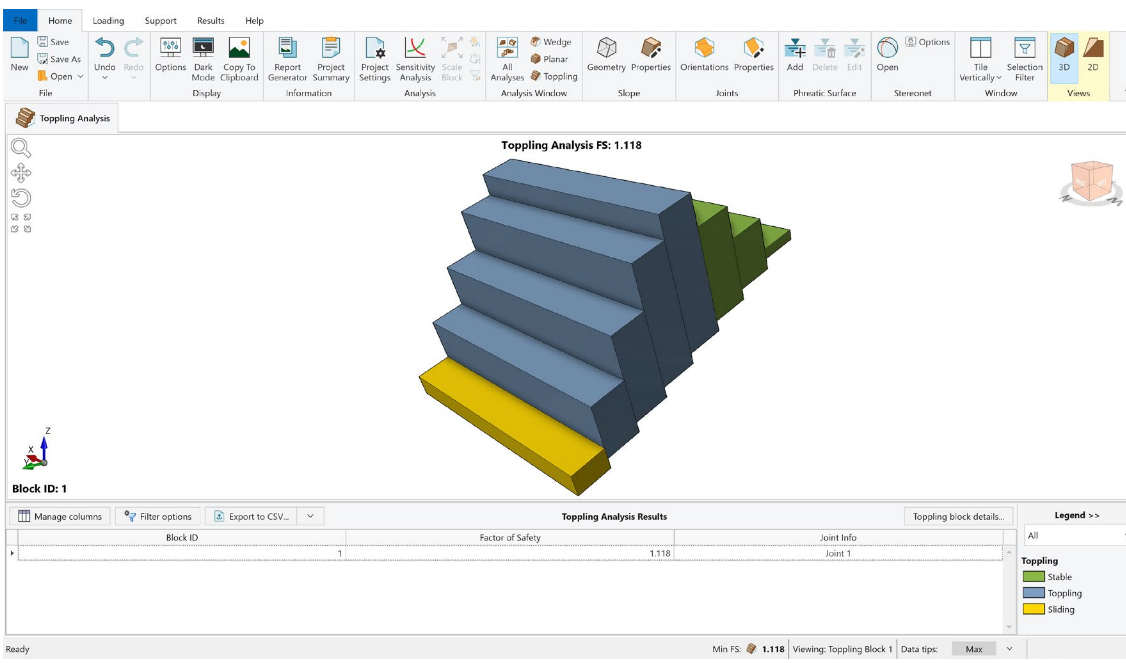


Figure 3.9.2: *RocSlope2* Geometry of Example 9b and Block Failure Modes

Example c:

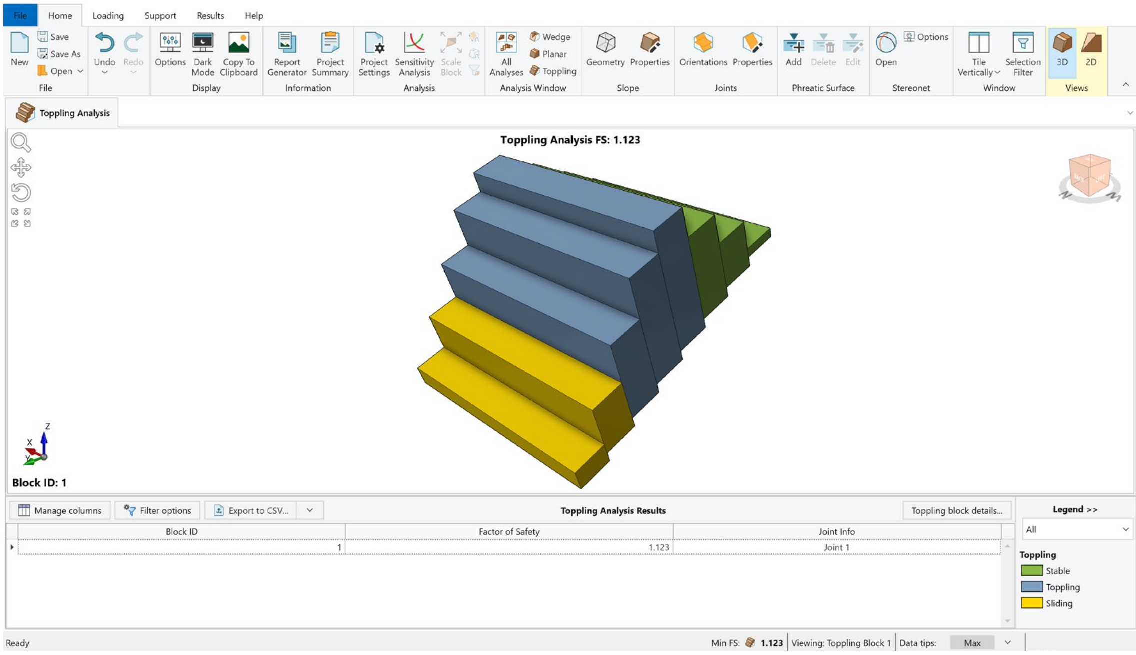


Figure 3.9.3: *RocSlope2* Geometry of Example 9c and Block Failure Modes

Example d:

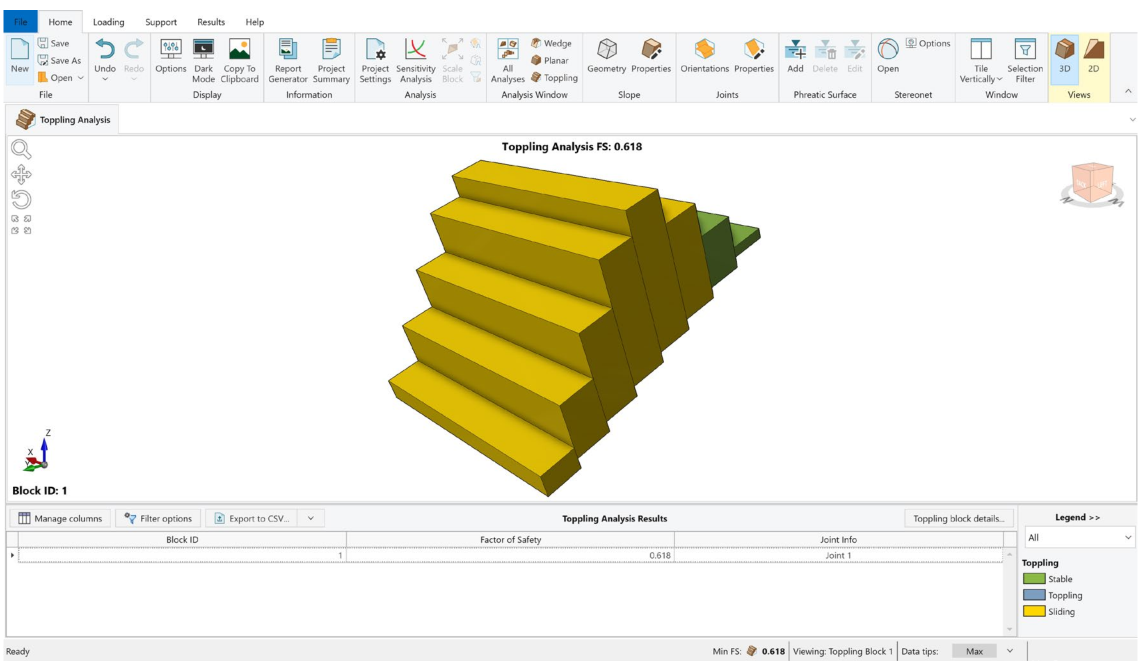


Figure 3.9.4: *RocSlope2* Geometry of Example 9d and Block Failure Modes

Example e:

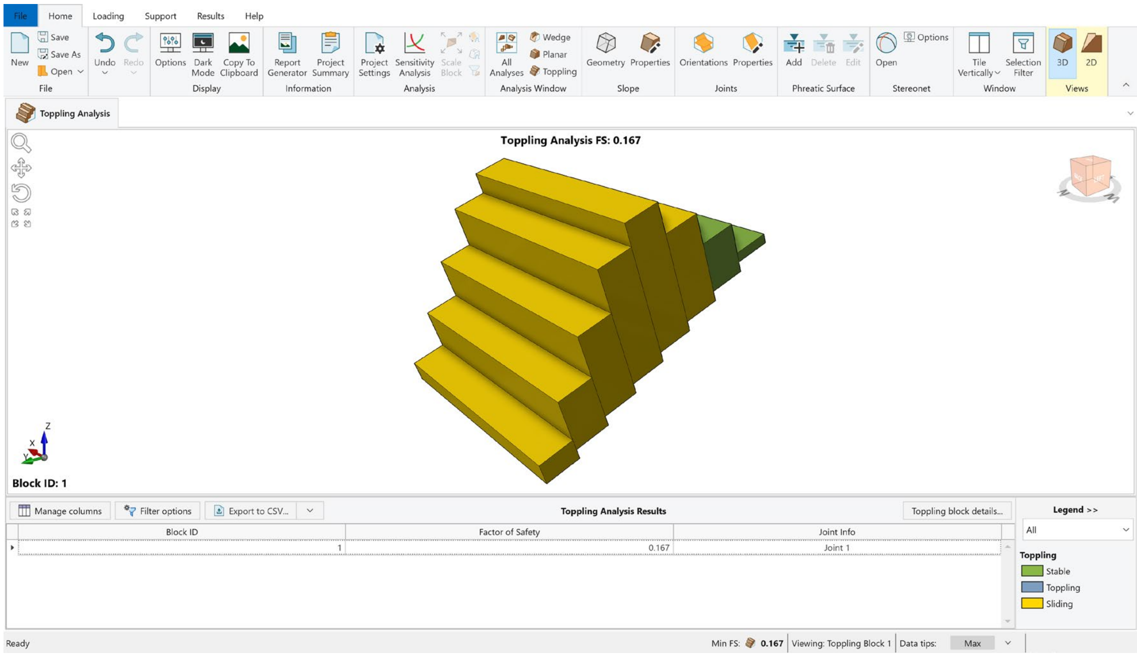


Figure 3.9.5: *RocSlope2* Geometry of Example 9e and Block Failure Modes

3.9.3. *RocTopple* Analysis

Example a:

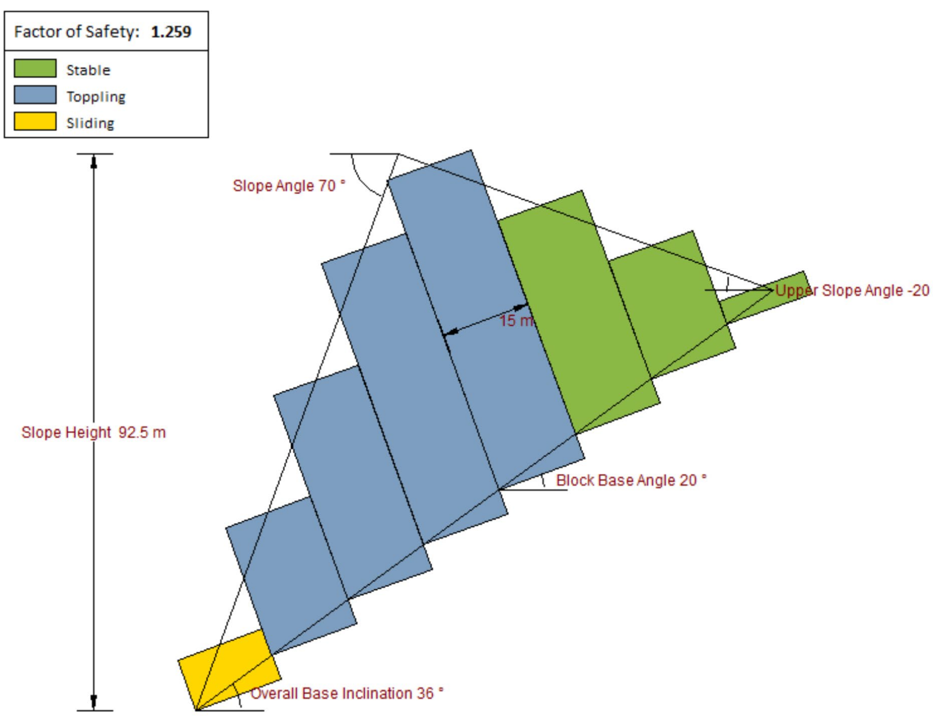


Figure 3.9.6: *RocTopple* Geometry of Example 9a and Block Failure Modes

Example b:

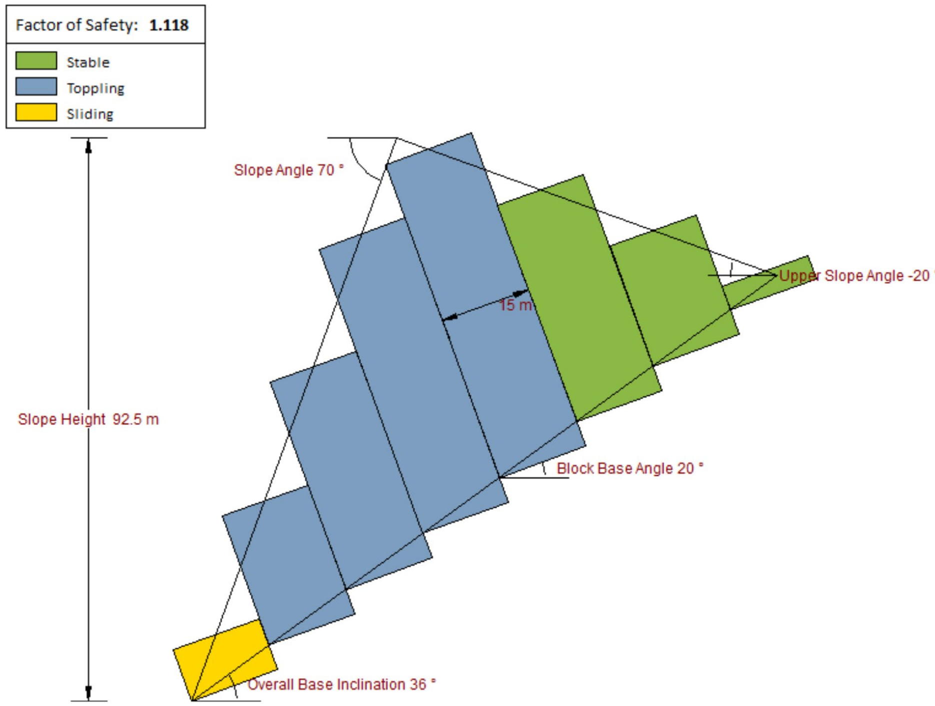


Figure 3.9.7: *RocTopple* Geometry of Example 9b and Block Failure Modes

Example c:

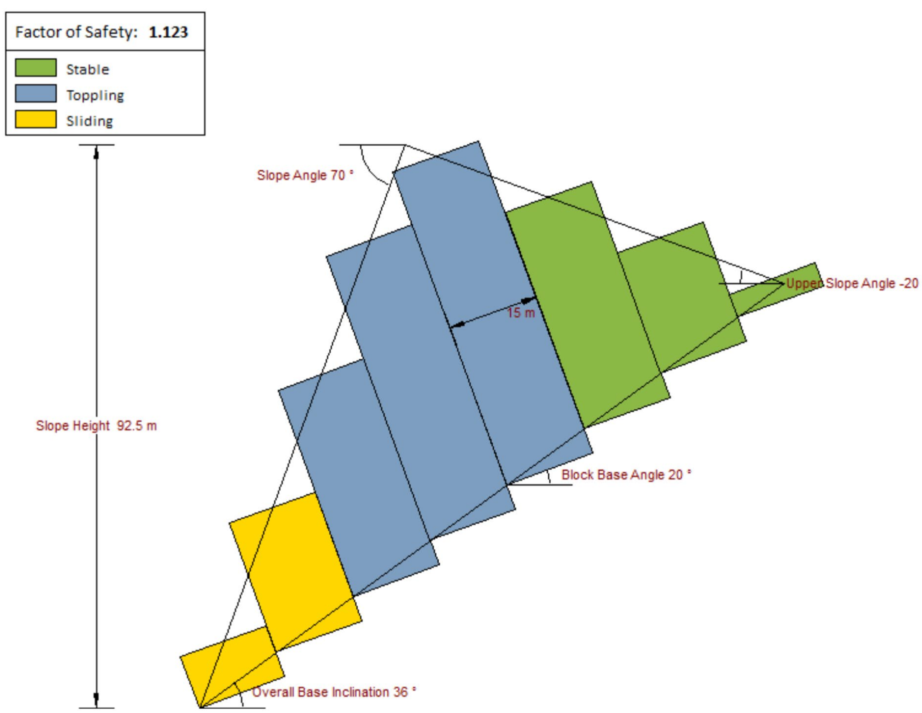


Figure 3.9.8: *RocTopple* Geometry of Example 9c and Block Failure Modes

Example d:

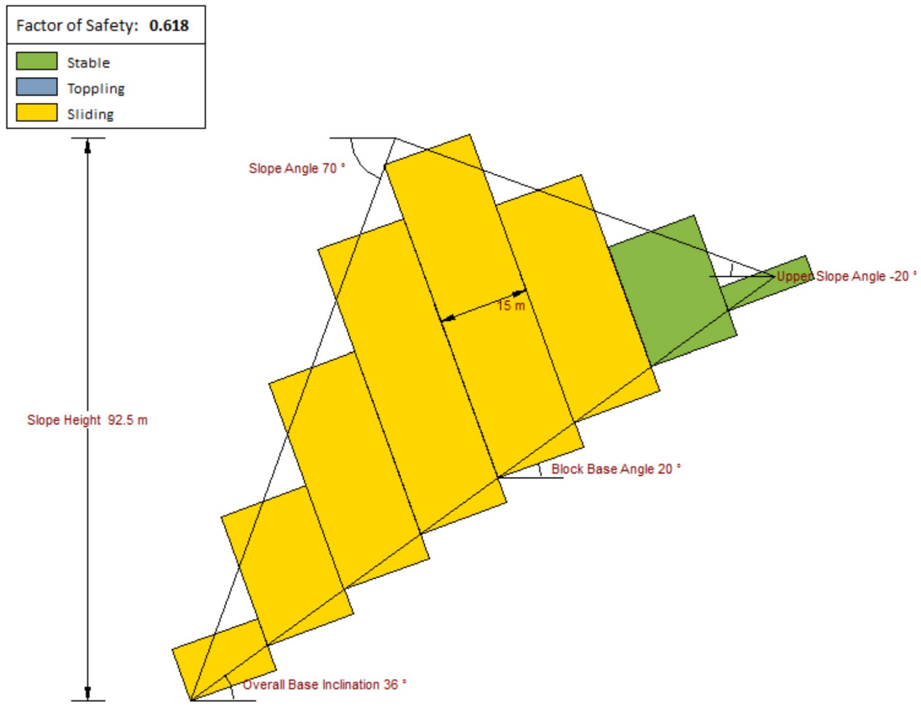


Figure 3.9.9: *RocTopple* Geometry of Example 9d and Block Failure Modes

Example e:

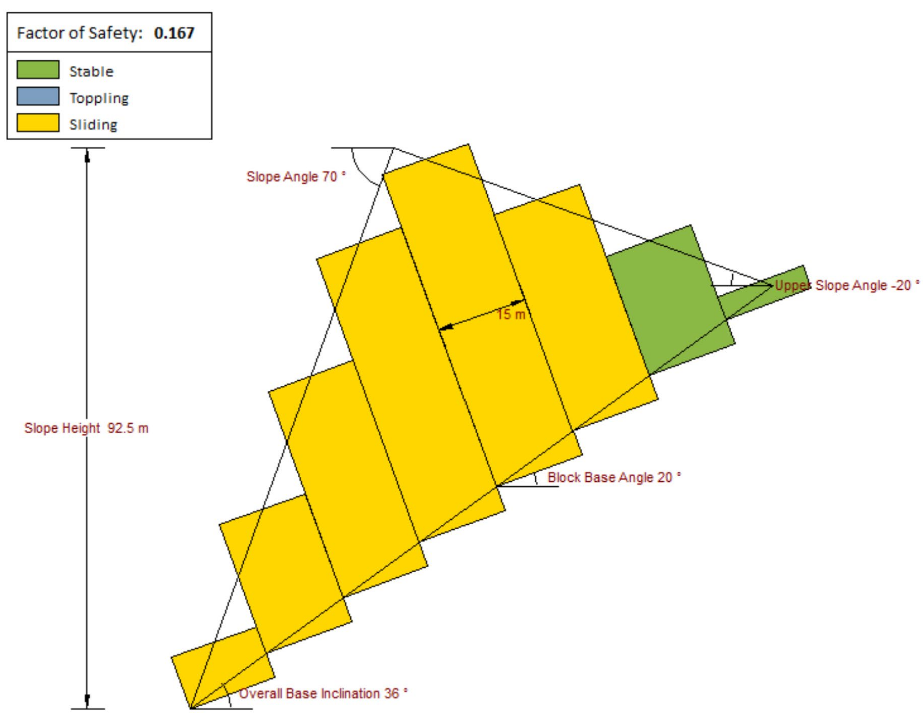
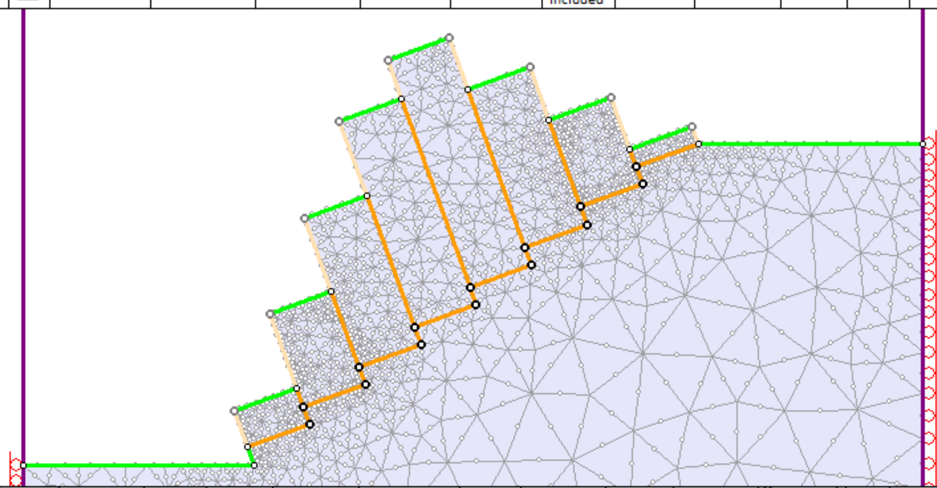


Figure 3.9.10: *RocSlope2* Geometry of Example 9e and Block Failure Modes

3.9.4. Building a Compatible *RS2* Model

Joint Name	Joint Color	Slip Critirion	Normal Stiffness (tonnes/m2/m)	Shear Stiffness (tonnes/m2/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure nside Joint	Tensile Strength (tonnes/m2 <tension positive>)	Peak Cohesion (tonnes/m2)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	5e+09	5e+08	Yes	No	Not Included	0	0	38.15	No	No



Material Name	Material Color	Initial Element Loading	Unit Weight (tonnes/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (tonnes/m2)	Failure Criterion	Material Type	Peak Tensile Strength (tonnes/m2)	Peak Friction Angle (degrees)	Peak Cohesion (tonnes/m2)	Unsaturated Shear Strength Angle (degrees)	Air Entry Value	Material Behaviour	Static Water Mode	Ru Value
Material 1		Body Force Only	2.548	Isotropic	0	1e+13	Mohr-Coulomb	Elastic	0	35	1070.7	0	0	Drained	Ru	0

Figure 3.9.11: *RS2* Geometry and Properties for Example 9a

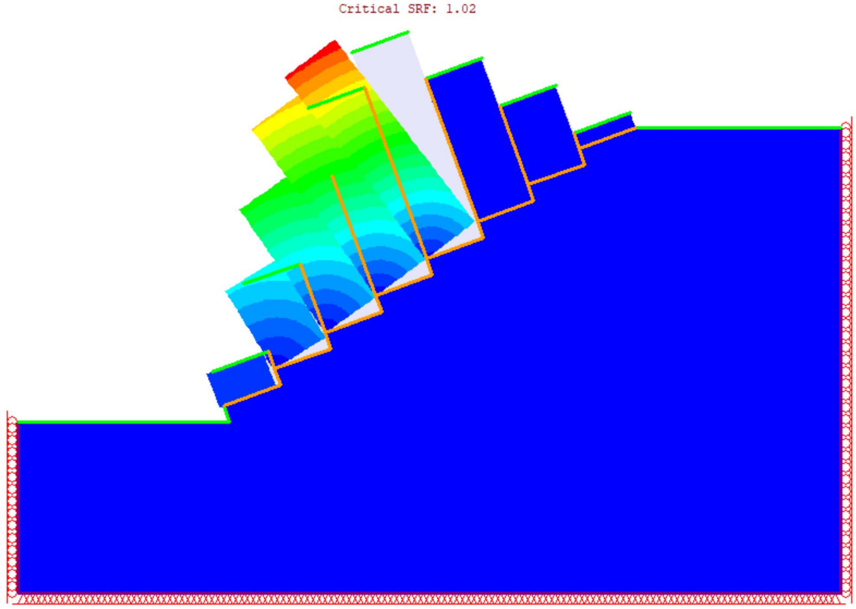


Figure 3.9.12: *RS2* Deformation and Yielded Joints for Example 9a

3.9.5. Results

Table 3.9.3: Factor of Safety

Example	ϕ (°)	Cohesion (kPa)	*RocSlope2*	*RocTopple*	*RS2*
a	38.15	0	1.259	1.259	1.02
b	30	10	1.118	1.118	0.98
c	25	25	1.123	1.123	1.11
d	10	40	0.618	0.618	0.62
e	0	50	0.167	0.167	0.16

3.10. *RocSlope2* Block Toppling Verification Problem #10

[RocSlope2 Build 1.005]

3.10.1.Problem Description

This verification problem examines the application of seismic loads.

A shallow slope with all sliding critical blocks at the point of failure, is now exhibiting toppling failure under a large seismic load. The block toppling model was constructed and analyzed in *RocSlope2* using geometric data given in the Table 3.10.1. The model was then verified in *RocTopple* and exported to *RS2*, in which shear strength reduction analysis was used to verify factor of safety results.

Note that block width (joint spacing) of 20m was used in the *RocSlope2* model.

Geometry and Properties

Table 3.10.1: Geometry and Material Properties

Slope Height (m)	Slope Angle (deg)	Joint Angle (deg)	Overall Base Inclination (deg)	ϕ' (deg)	γ (kN/m^3)
92.5	35	70	26	30	25.0

3.10.2.*RocSlope2* Analysis

The same slope from Verification Example #5 now exhibits toppling behavior under a horizontal seismic loading coefficient of 0.4.

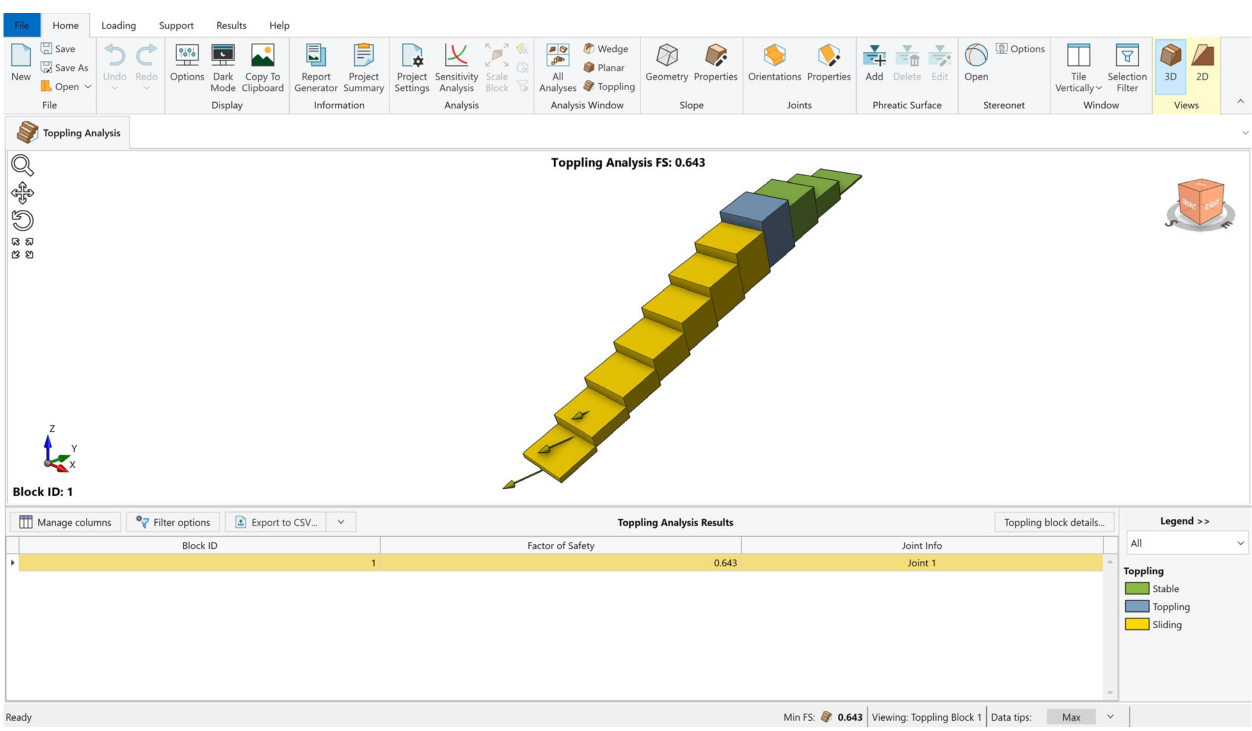


Figure 3.10.1: *RocSlope2* Geometry with Seismic Loading

3.10.3. *RocTopple* Analysis

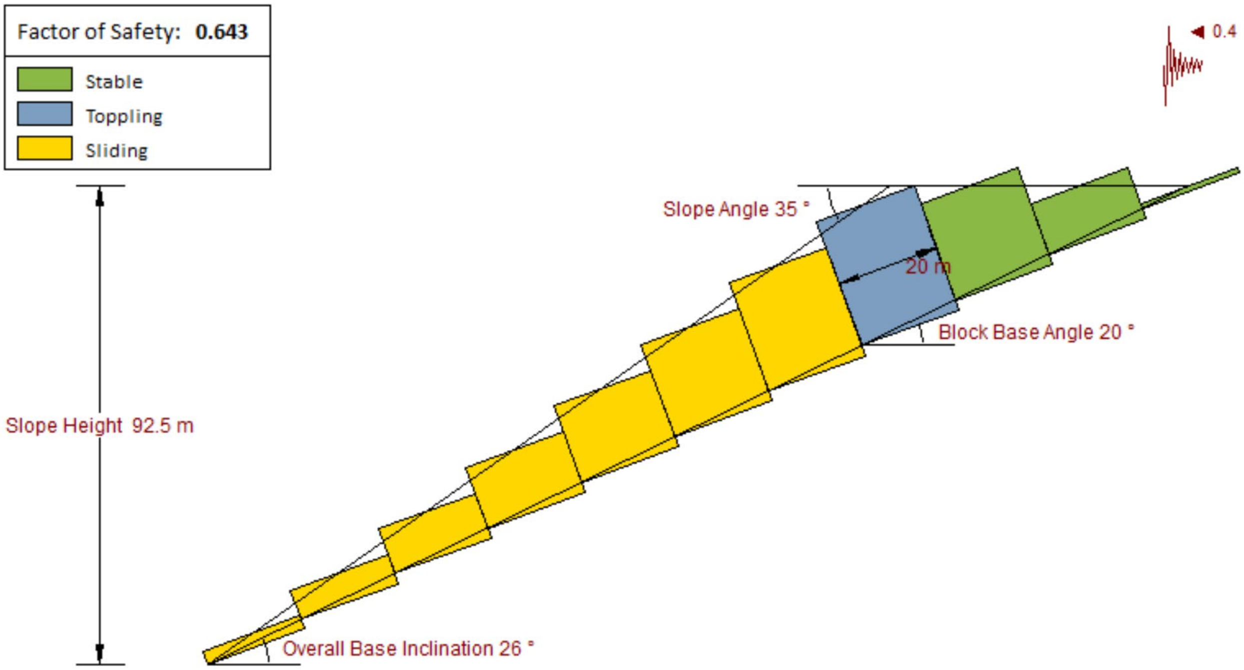


Figure 3.10.2: *RocTopple* Geometry with Seismic Loading

3.10.4. Building a Compatible *RS2* Model

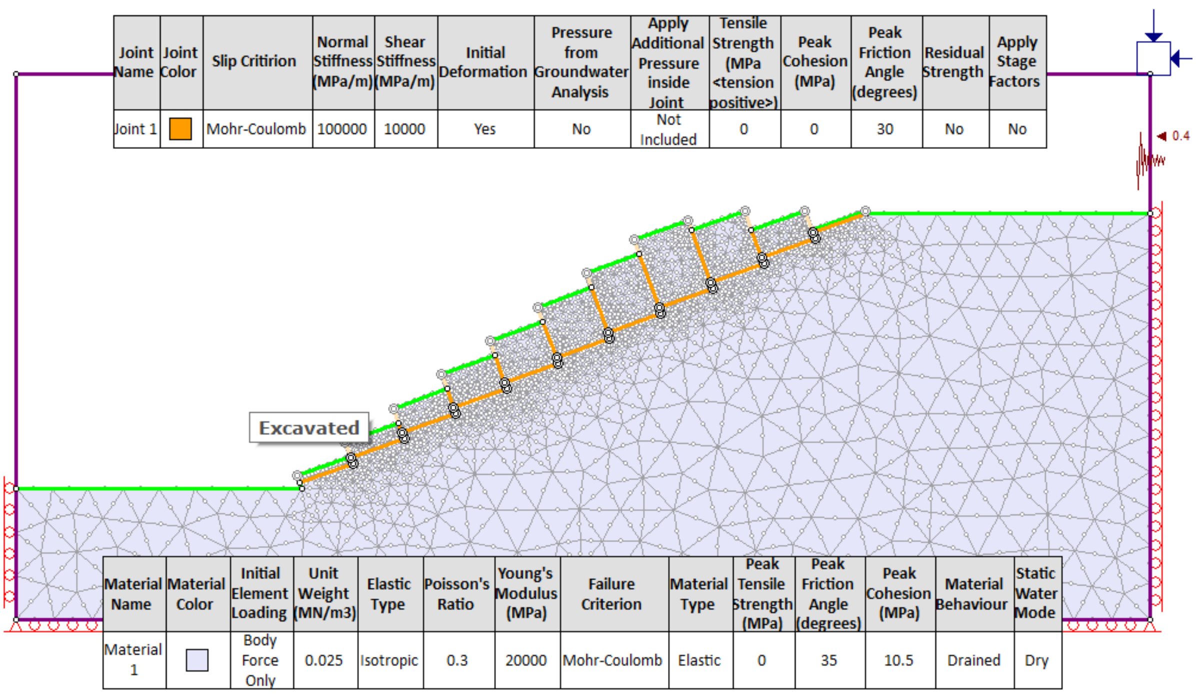


Figure 3.10.3: *RS2* Geometry and Properties

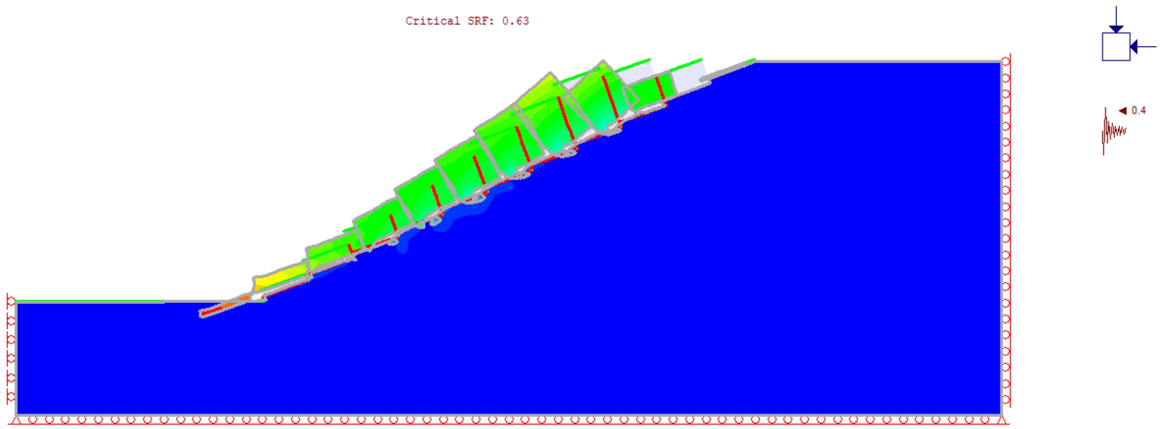


Figure 3.10.4: *RS2* Deformation and Yielded Joints

3.10.5.Results

Table 3.10.2: Factors of Safety

RocSlope2	*RocTopple*	*RS2*
0.643	0.643	0.63

3.11. *RocSlope2* Block Toppling Verification Problem #11

[RocSlope2 Build 1.005]

3.11.1.Problem Description

This verification problem examines the application of water pressure. The example is modified from the slope in Verification Example #1.

A slope with joints completely filled with water is modelled in *RocSlope2* using a phreatic surface that fully spans across the joints. The model was then verified in *RocTopple* by modelling a slope with 100% fill joints.

Note that block width (joint spacing) of 10m was used in the *RocSlope2* model.

Geometry and Properties

Table 3.11.1: Geometry and Material Properties

Slope Height (m)	Slope Angle (deg)	Joint Angle (deg)	Overall Base Inclination (deg)	ϕ' (deg)	γ (kN/m^3)
92.5	56.6	60	35.8	38.15	25.0

3.11.2.*RocSlope2* Analysis

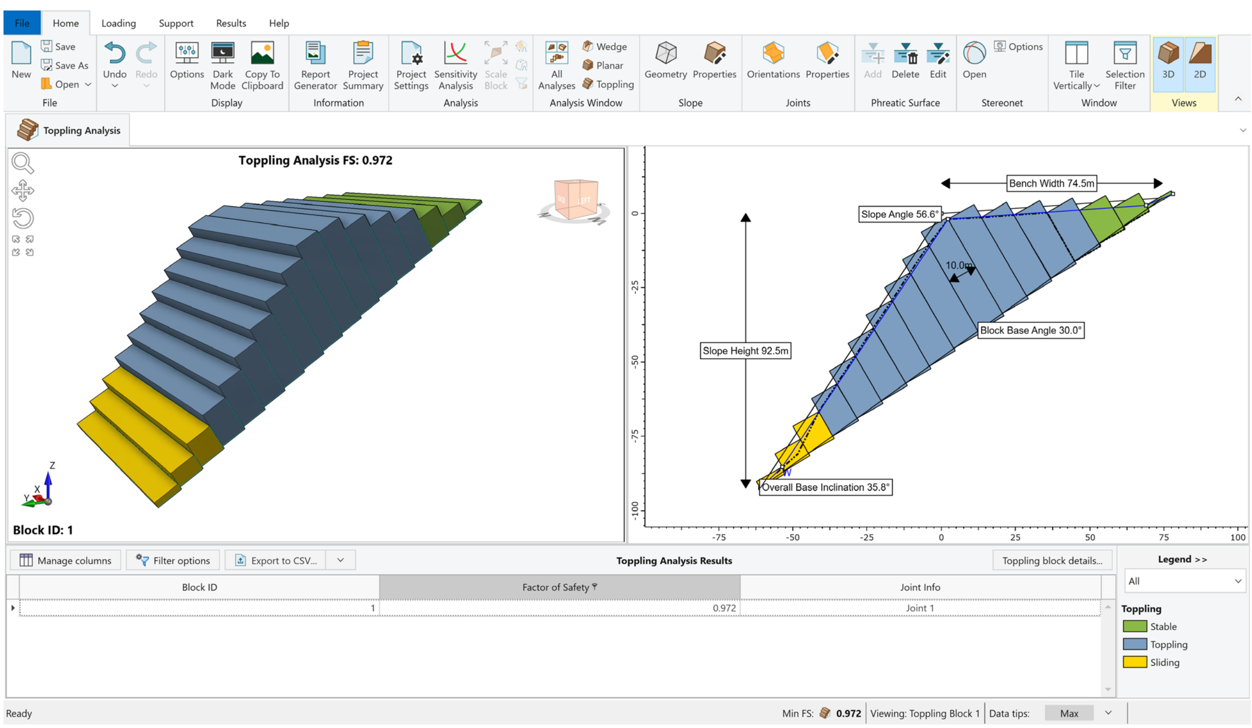


Figure 3.11.1: *RocSlope2* model with Phreatic Surface

3.11.3. *RocTopple* Analysis

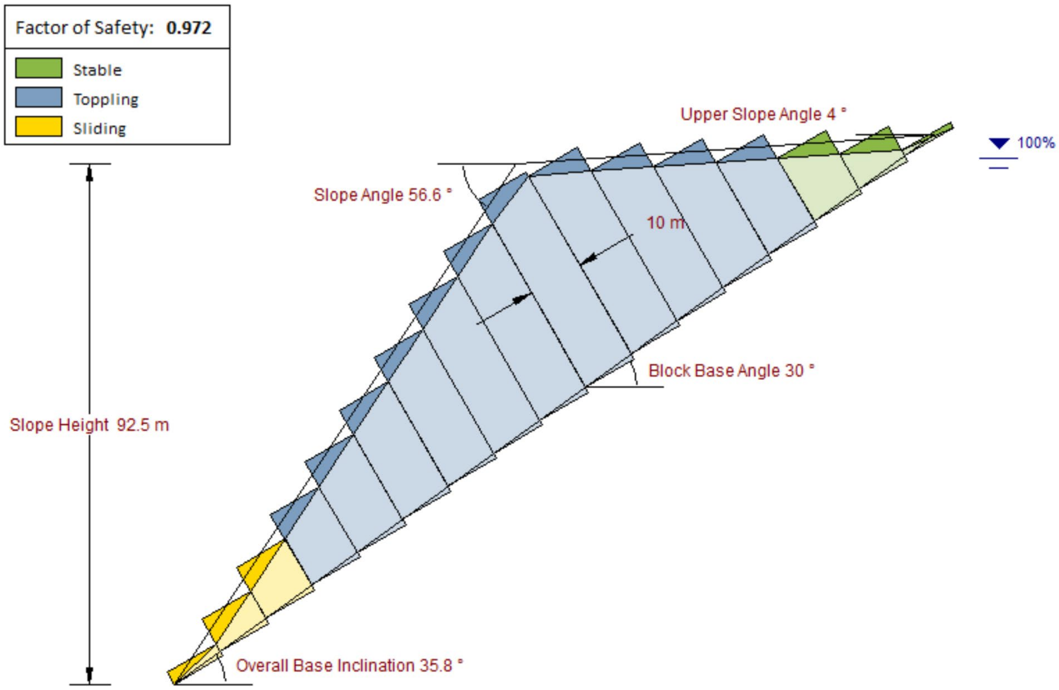


Figure 3.11.2: *RocTopple* model with 100% Filled Joints

3.11.4. Results

Table 3.11.2: Factors of Safety

RocSlope2	***RocTopple***
0.972	0.972

3.12. *RocSlope2* Block Toppling Verification Problem #12

[RocSlope2 Build 1.005]

3.12.1. Problem Description

This verification problem examines the case of upslope toppling blocks.

When there are external forces, blocks may topple upslope. Note that *RocSlope2* only checks for upslope stability for group blocks (blocks that are in contact with other blocks), and for only the toppling failure mode (rotation about the upper base corner).

A block toppling model was constructed and analyzed in *RocSlope2* using geometric data given in the Table 3.12.1. The model was then verified in *RocTopple* and exported to *RS2*, in which stress analysis was used to verify the upslope toppling.

Note that block width (joint spacing) of 10m was used in the *RocSlope2* model.

Geometry and Properties

Table 3.12.1: Geometry and Material Properties

Slope Height (m)	Slope Angle (deg)	Joint Angle (deg)	Overall Base Inclination (deg)	ϕ' (deg)	γ (kN/m^3)
92	69	77	13	40	25.0

3.12.2. *RocSlope2* Analysis

The slope is stable in terms of downslope failure (factor of safety exceeding 25) but is unstable in terms of toppling upslope.

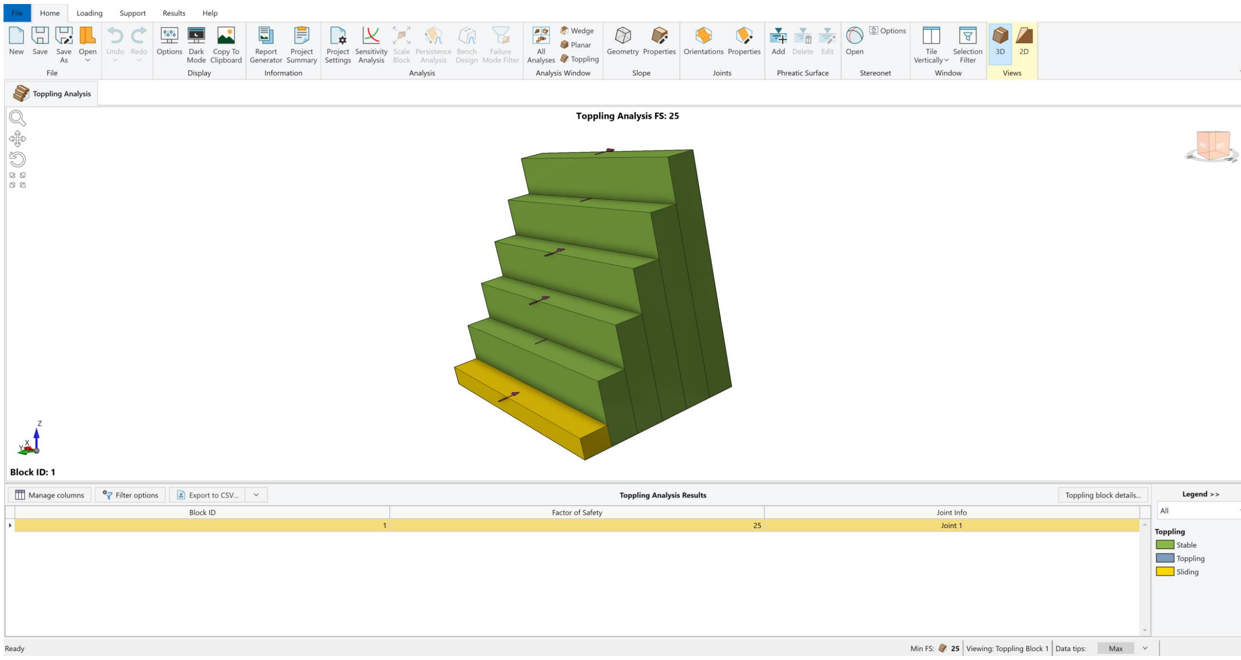


Figure 3.12.1: *RocSlope2* Geometry with a Pressure of 500kPa Supporting the Slope

3.12.3. *RocTopple* Analysis

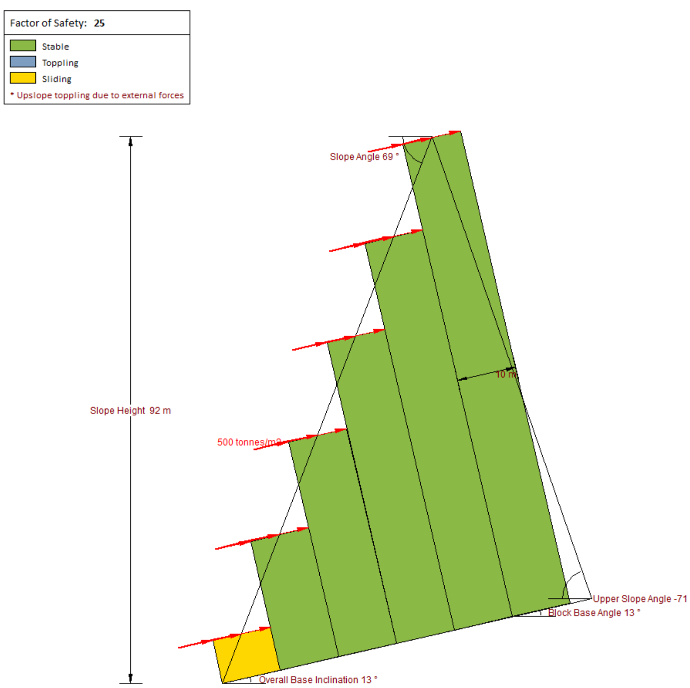


Figure 3.12.2: *RocTopple* Geometry with a Pressure of 500kPa Supporting the Slope

3.12.4. Building a Compatible *RS2* Model

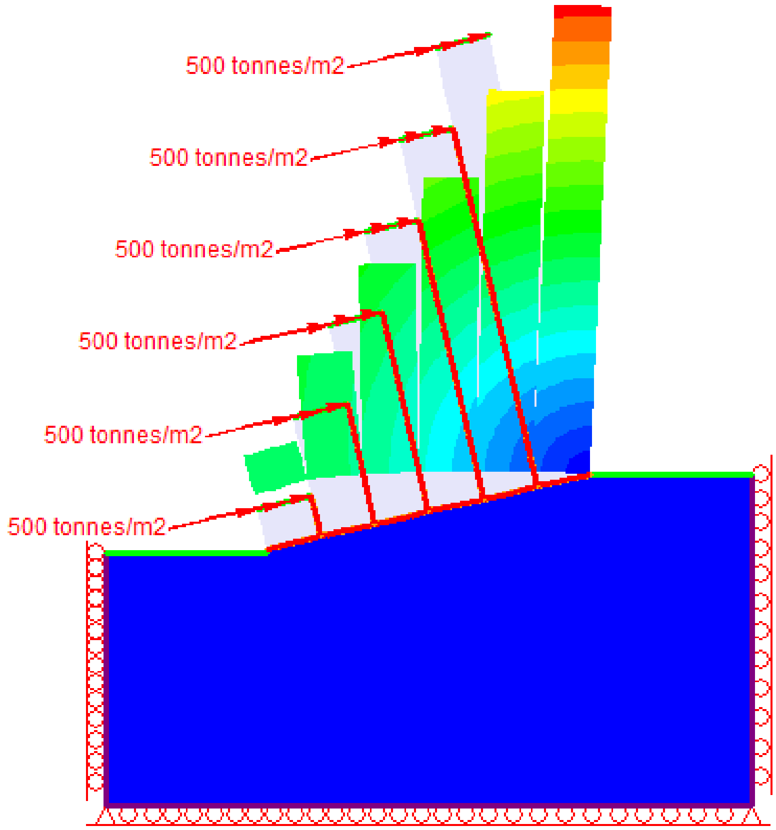


Figure 3.12.3: *RS2* Stress Analysis

RS2 stress analysis confirms that the blocks are rotating upslope.

4. *RocSlope2* Block-Flexural Toppling Verification

Analyses of block-flexure toppling were performed in *RocSlope2* and verified with *RocTopple* and Finite Element Analysis using *RS2*. FS obtained from *RocSlope2* was compared to *RocTopple* FS and the SRF obtained in *RS2*.

4.1. *RocSlope2* Block Flexural Toppling Verification Problem #1

[RocSlope2 Build 1.005]

4.1.1. Problem Description

This verification problem examines a linear plane geometry.

Geometry and Material Properties

With the given geometry below:

Table 4.1.1: Geometry

Parameter	Value
Face Slope Angle (°)	57
Height (m)	93
Joint Spacing (m)	10
Overall Base Inclination Angle (°)	30
Upper Slope Angle (°)	0
Joint Dip (°)	60
Point of Application (Sliding/Shearing Block Above) Ratio	0.75
Point of Application (Bending Block Above) Ratio	0.9

Examples 1a, 1b, 1c and 1d were investigated using the material properties listed below. The results are shown below.

Table 4.1.2: Material Properties

	Joint Friction Angle (°)	Joint Cohesion (kPa)	Joint Tensile Strength (kPa)	Rock Friction Angle (°)	Rock Cohesion (kPa)	Rock Tensile Strength (kPa)	Unit Weight (kN/m^3)
Example 1a	38	100	100	50	1000	50	27
Example 1b	26	50	50	40	1000	100	27
Example 1c	45	200	100	60	4000	100	32
Example 1d	44	160	46	56	2540	82	19

4.1.2. *RocSlope2* Analysis

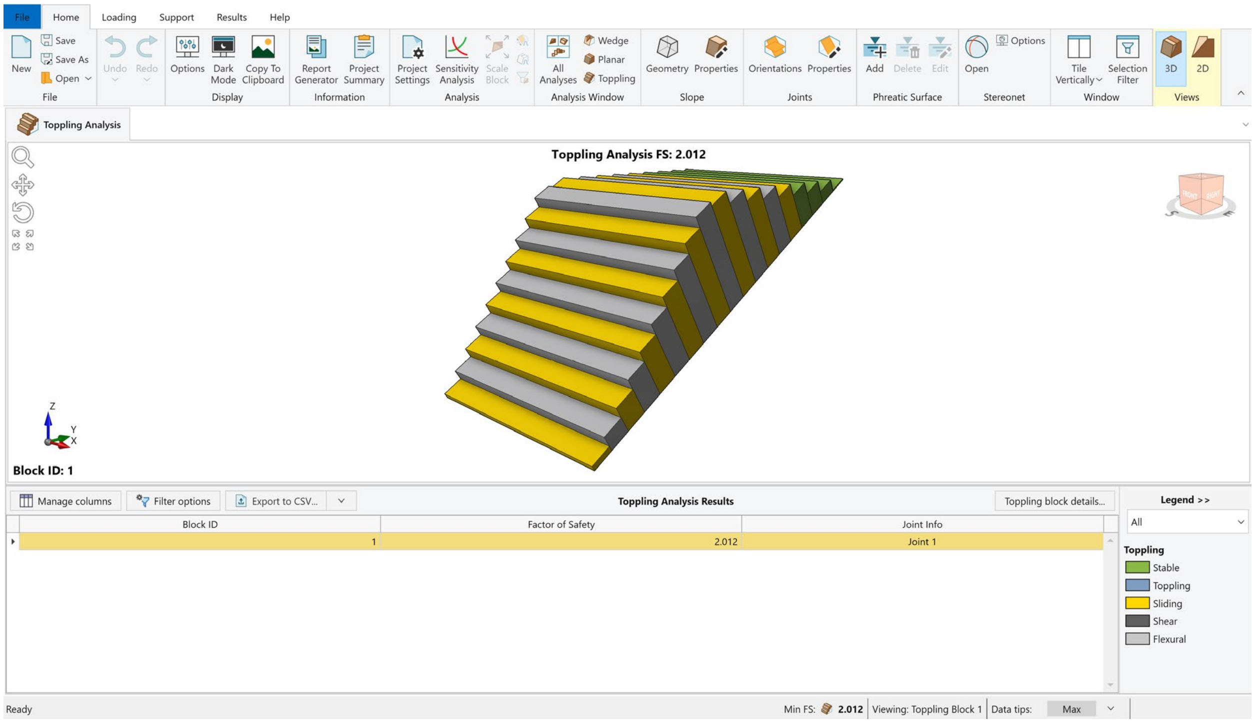


Figure 4.1.1: *RocSlope2* Model of Example 1a

4.1.3. *RocTopple* Analysis

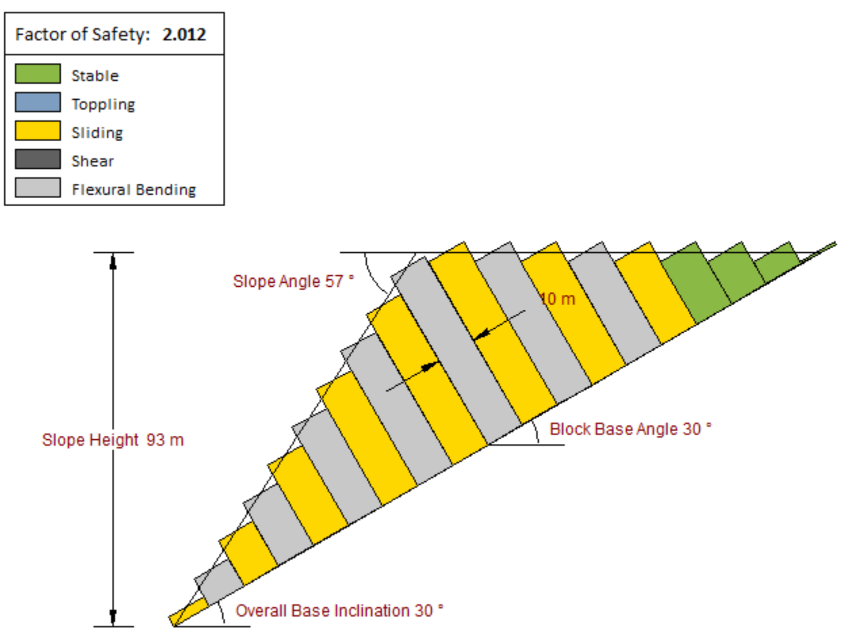


Figure 4.1.2: *RocTopple* Model of Example 1a

4.1.4. Building a Compatible *RS2* Model

RocSlope2 does not account for solids deforming in the toppling process. Therefore, when conducting *RS2* Analysis, the stiffness of the rock was assumed to be high, with a Young's Modulus of 2000 GPa, and a Poisson's ratio of 0.1.

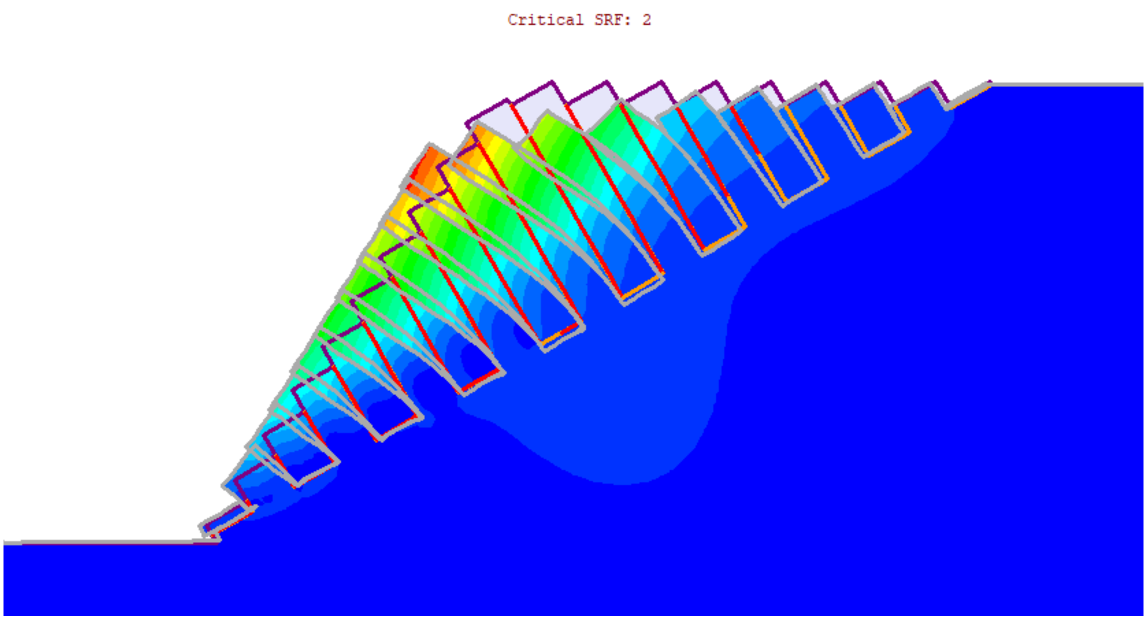


Figure 4.1.3: *RS2* Total Displacement Contours of Example 1a at Critical SRF

4.1.5. Results

Table 4.1.3: Factors of Safety

	RocSlope2	*RocTopple*	*RS2* (SRF)
Example 1a	2.01	2.01	2.00
Example 1b	1.27	1.27	1.25
Example 1c	2.78	2.78	2.85
Example 1d	3.01	3.01	3.05

4.2. *RocSlope2* Block Flexural Toppling Verification Problem #2

[RocSlope2 Build 1.005]

4.2.1. Problem Description

This verification problem examines another linear plane geometry.

Geometry and Material Properties

With the given geometry below:

Table 4.2.1: Geometry

Parameter	Value
Face Slope Angle (°)	78
Height (m)	85
Joint Spacing (m)	7.6
Upper Slope Angle (°)	0
Joint Dip Angle (°)	39
Overall Base Inclination Angle (°)	51
Point of Application (Sliding/Shearing Block Above) Ratio	0.59
Point of Application (Bending Block Above) Ratio	0.9

5 examples with varying material properties were investigated using the material properties listed below. The results are shown below.

Table 4.2.2: Material Properties

	Joint Friction Angle (°)	Joint Cohesion (kPa)	Joint Tensile Strength (kPa)	Rock Friction Angle (°)	Rock Cohesion (kPa)	Rock Tensile Strength (kPa)	Unit Weight (kN/m^3)
Example 2a	38	100	100	40	1000	100	27
Example 2b	25	50	50	54	1200	85	27
Example 2c	45	250	150	60	4000	100	33
Example 2d	30	60	40	43	800	52	23
Example 2e	Base: 30 Bedding: 50	Base: 60 Bedding: 100	Base: 40 Bedding: 100	43	800	52	23

4.2.2. *RocSlope2* Analysis

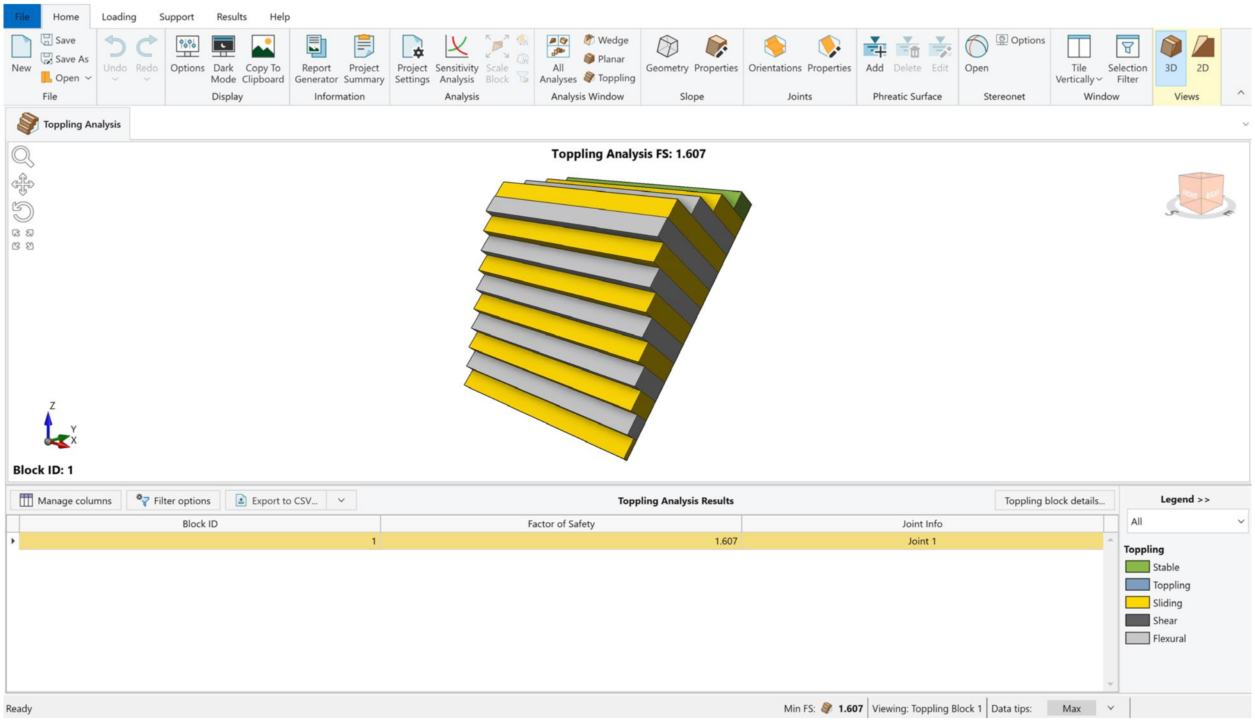


Figure 4.2.1: *RocSlope2* Model of Example 2a

4.2.3. *RocTopple* Analysis

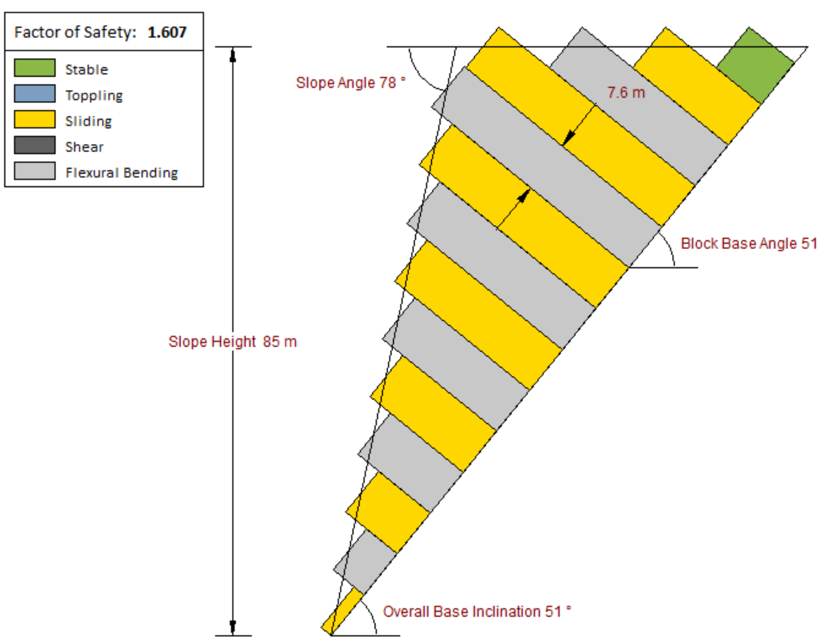


Figure 4.2.2: *RocTopple* Model of Example 2a

4.2.4. Building a Compatible *RS2* Model

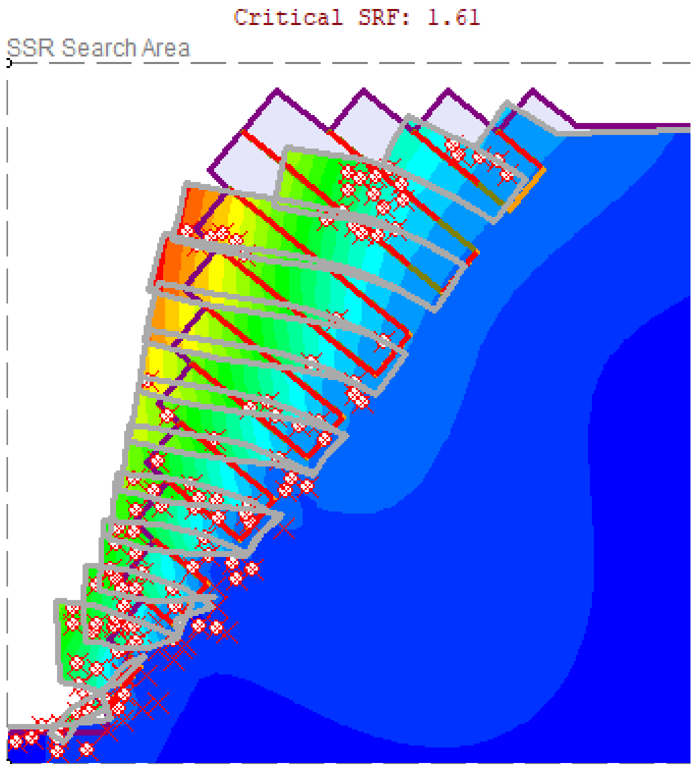


Figure 4.2.3: *RS2* Results of Example 2a at Critical SRF

4.2.5. Results

Table 4.2.3: Factors of Safety

	RocSlope2	*RocTopple*	*RS2* (SRF)
Example 2a	1.61	1.61	1.61
Example 2b	0.96	0.96	1.01
Example 2c	2.27	2.27	2.34
Example 2d	1.16	1.16	1.22
Example 2e	1.76	1.76	1.89

4.3. *RocSlope2* Block Flexural Toppling Verification Problem #3

[RocSlope2 Build 1.005]

4.3.1. Problem Description

This verification problem examines the case where shear failure occurs.

Geometry and Material Properties

With the given geometry below:

Table 4.3.1: Geometry

Parameter	Value
Face Slope Angle (°)	41
Height (m)	93
Joint Spacing (m)	13
Upper Slope Angle (°)	0
Joint Dip Angle (°)	60
Overall Base Inclination Angle (°)	30
Point of Application (Sliding/Shearing Block Above) Ratio	0.75
Point of Application (Bending Block Above) Ratio	0.9

3 examples with varying material properties were investigated using the material properties listed in the table below, followed by the results.

Table 4.3.2: Material Properties

	Joint Friction Angle (°)	Joint Cohesion (kPa)	Joint Tensile Strength (kPa)	Rock Friction Angle (°)	Rock Cohesion (kPa)	Rock Tensile Strength (kPa)	Unit Weight (kN/m^3)
Example 3a	30	50	50	34	400	50	40
Example 3b	25	45	40	30	300	60	40
Example 3c	36	85	80	60	600	130	35

4.3.2. *RocSlope2* Analysis

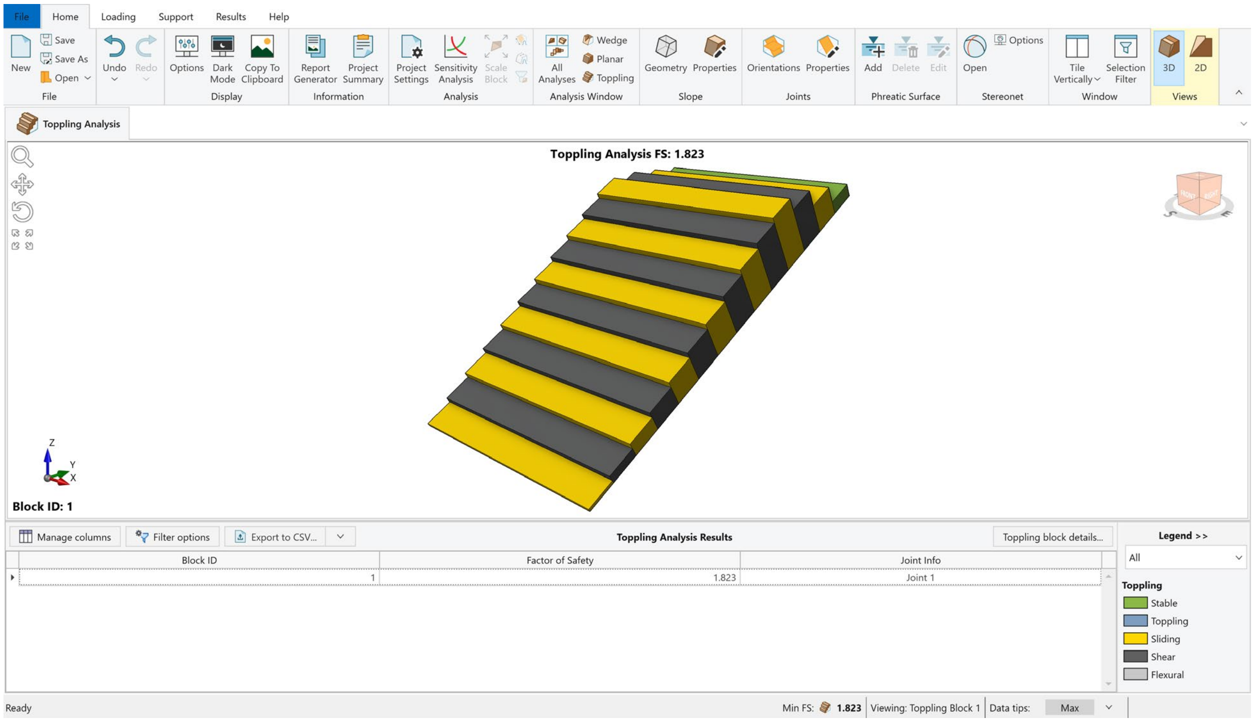


Figure 4.3.1: *RocSlope2* Model of Example 3a

4.3.3. *RocTopple* Analysis

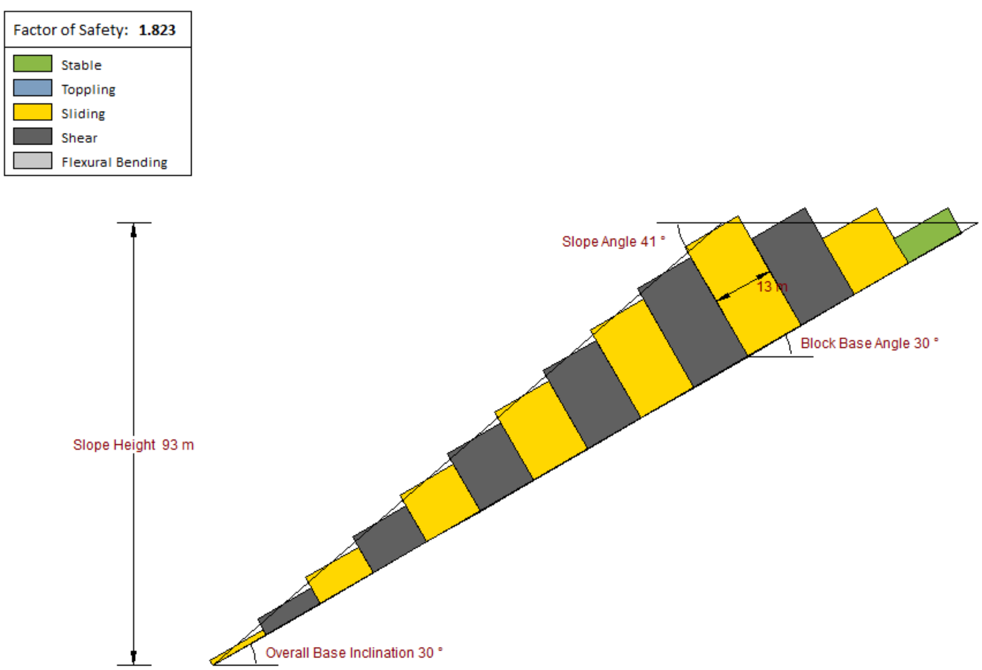


Figure 4.3.2: *RocTopple* Model of Example 3a

4.3.4. Building a Compatible *RS2* Model

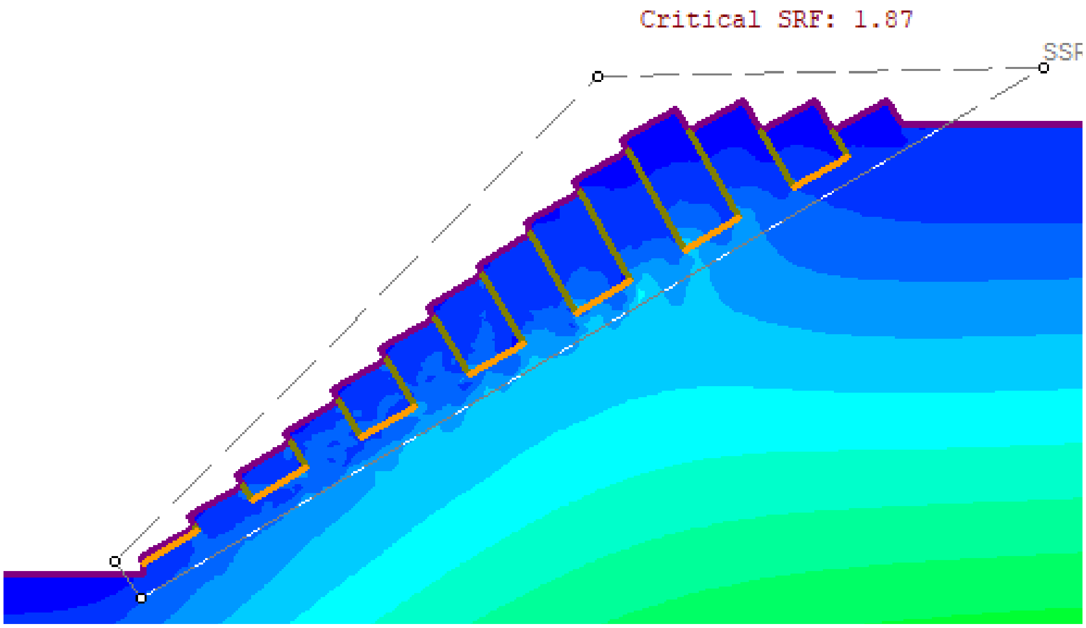


Figure 4.3.3: *RS2* Results of Example 3a at Critical SRF

4.3.5. Results

Table 4.3.3: Factors of Safety

	RocSlope2	*RocTopple*	*RS2* (SRF)
Example 3a	1.82	1.82	1.87
Example 3b	1.47	1.47	1.50
Example 3c	3.45	3.45	3.60

4.4. *RocSlope2* Block Flexural Toppling Verification Problem #4

[RocSlope2 Build 1.005]

4.4.1. Problem Description

This verification problem examines the Barton-Bandis Joint Shear Strength model.

Geometry and Material Properties

The geometry is identical to Block Flexural Toppling Verification Example #1.

3 examples with varying Barton-Bandis (BB) shear strength models were investigated.

Table 4.4.1: Material Properties

	JRC	JCS (kPa)	PhiR	Rock Friction Angle (°)	Rock Cohesion (kPa)	Rock Tensile Strength (kPa)	Unit Weight (kN/m^3)
Example 4a	10	10000	30°				32
Example 4b	8	7000	20°	45	800	50	19
Example 4c	5	500	15°				32

Examples with equivalent Mohr-Coulomb (MC) setup were also investigated for comparison.

Table 4.4.2: Mohr-Coulomb Shear Strength Properties

	Cohesion (kPa)	Friction Angle (°)
Example 4a	79.5	36.6
Example 4b	39.5	24.7
Example 4c	17.2	12.6

4.4.2. *RocSlope2* Analysis

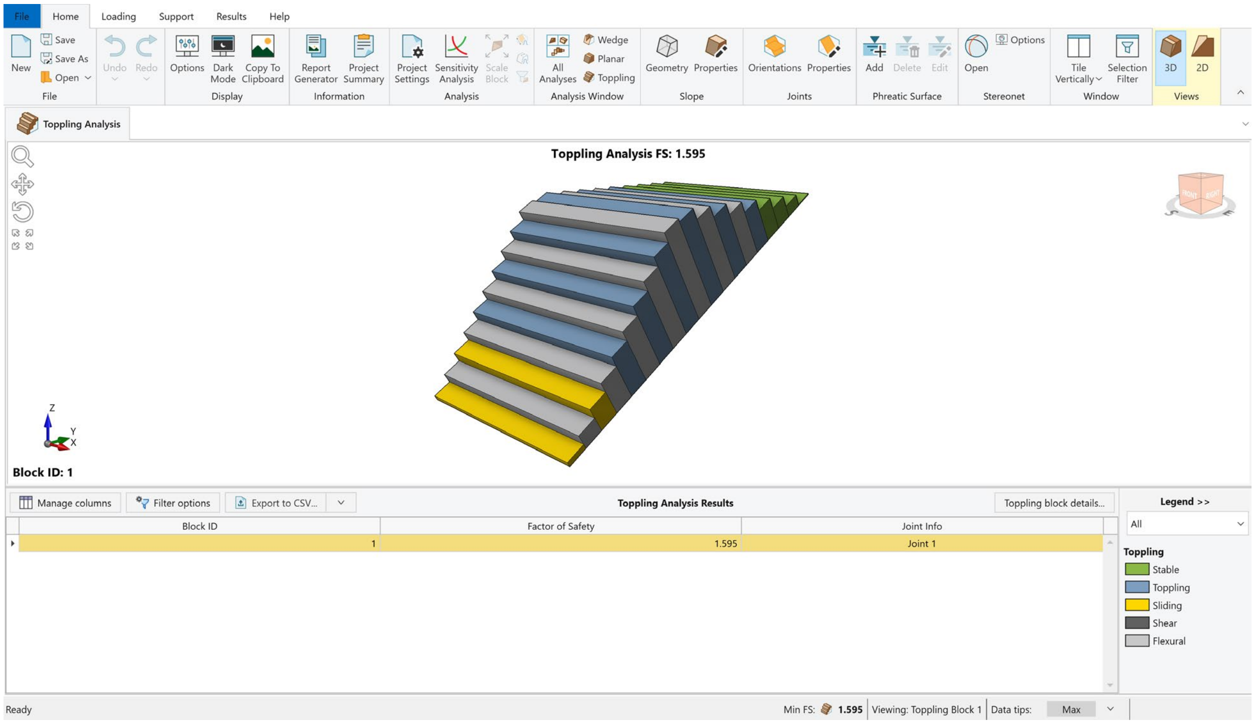


Figure 4.4.1: *RocSlope2* Model of Example 4a Barton-Bandis

4.4.3. *RocTopple* Analysis

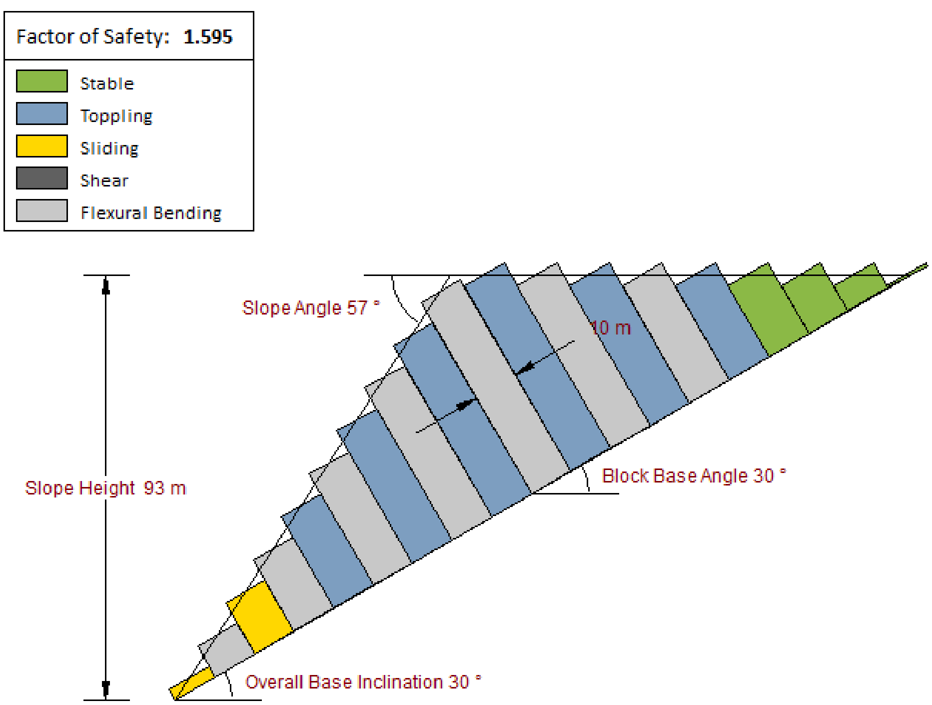


Figure 4.4.2: *RocTopple* Model of Example 4a Barton-Bandis

4.4.4. Building a Compatible *RS2* Model

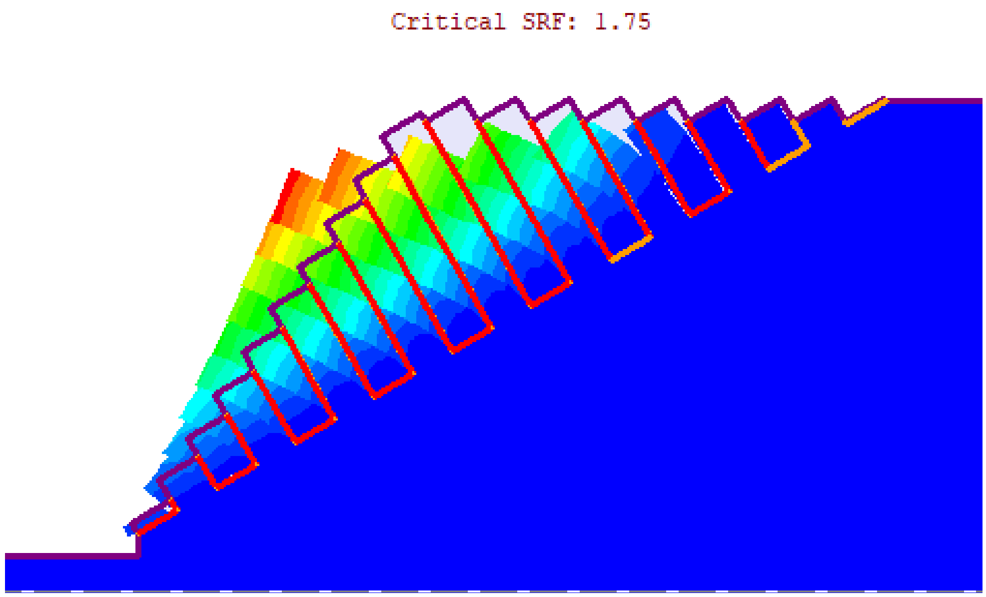


Figure 4.4.3: *RS2* Results of Example 4a

4.4.5. Results

Table 4.4.3: Factors of Safety

	RocSlope2 BB	*RocSlope2* MC	*RocTopple* BB	*RocTopple* MC	*RS2* (SRF)
Example 4a	1.60	1.67	1.60	1.67	1.75
Example 4b	1.10	1.21	1.10	1.21	1.25
Example 4c	0.52	0.51	0.52	0.51	0.55

4.5. *RocSlope2* Block Flexural Toppling Verification Problem #5

[RocSlope2 Build 1.005]

4.5.1. Problem Description

This verification problem examines the application of bolts and point loads.

Geometry and Material Properties

The geometry and strength properties are given in Example 1a and 1b, Example 5a and 5b; bolts and point loads are installed, respectively.

4.5.2. *RocSlope2* Analysis

Case 5a (Example 1a) – Bolts Model:

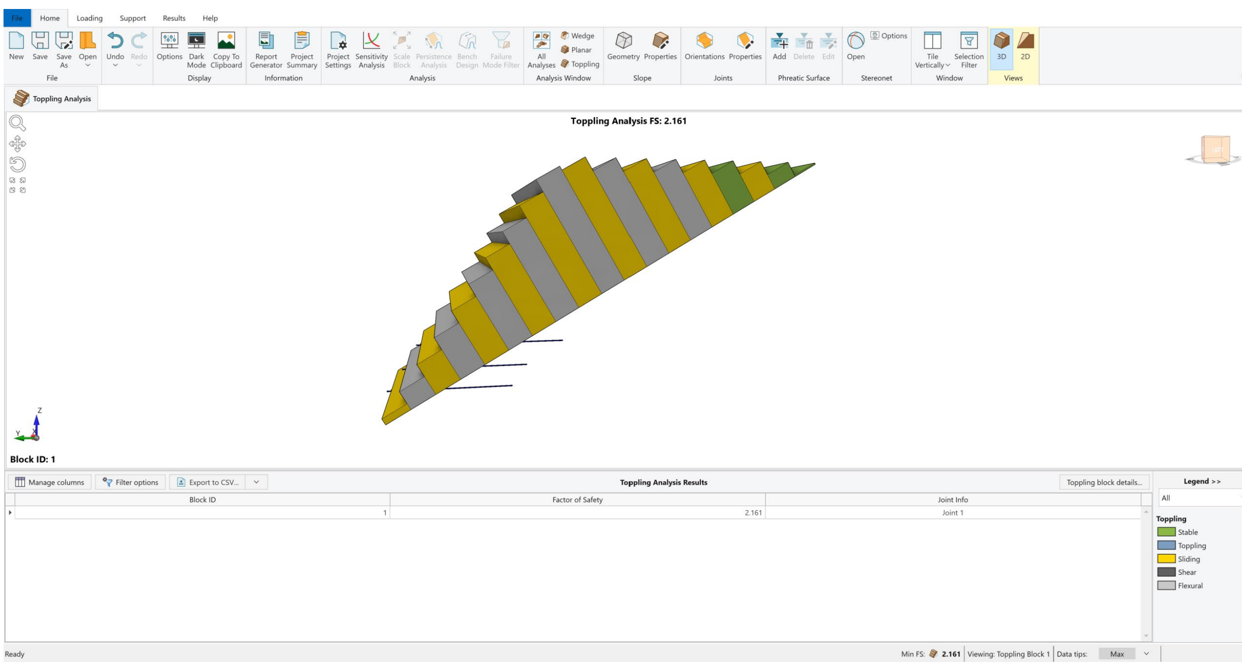


Figure 4.5.1: *RocSlope2* Model of Example 5a

Case 5b (Example 1b) – Point Loads Model:

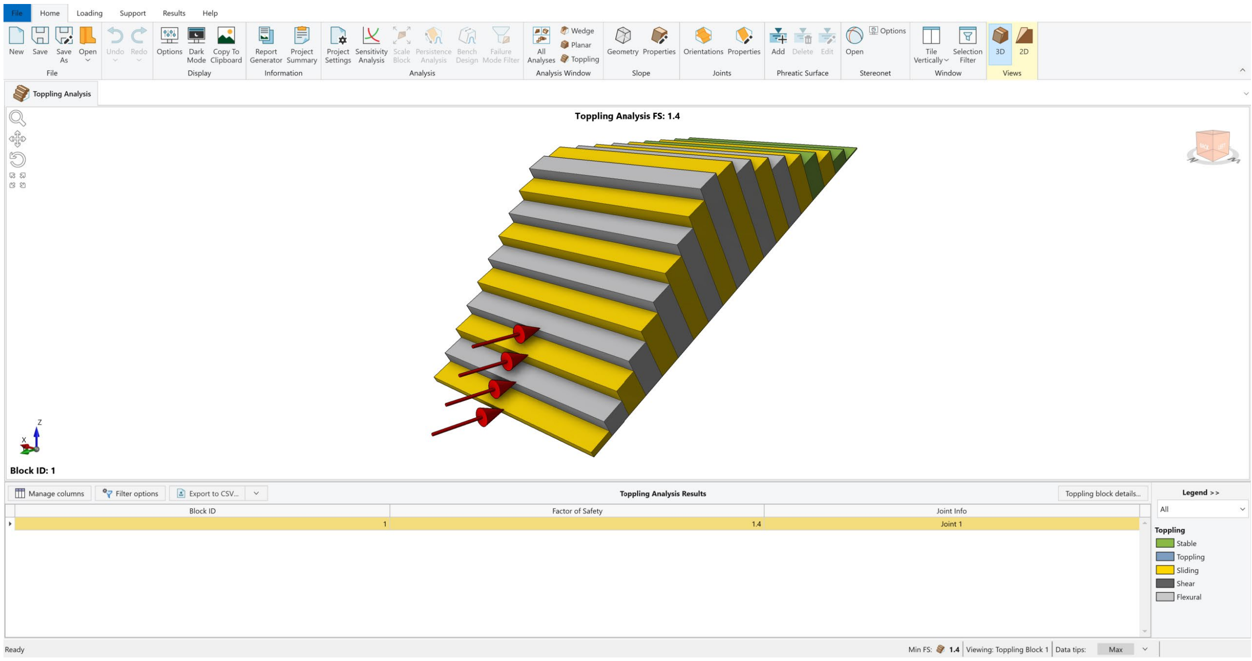


Figure 4.5.2: *RocSlope2* Model of Example 5b

4.5.3. *RocTopple* Analysis

Case 5a (Example 1a) – Bolts Model:

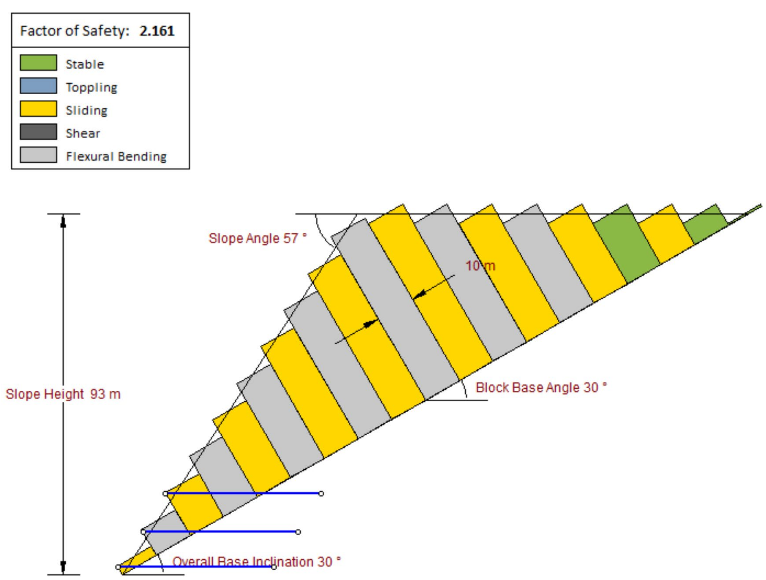


Figure 4.5.3: *RocTopple* Model of Example 5a

Case 5b (Example 1b) – Line Loads Model:

This case is modelled by applying equivalent line loads on slope face in *RocTopple*.

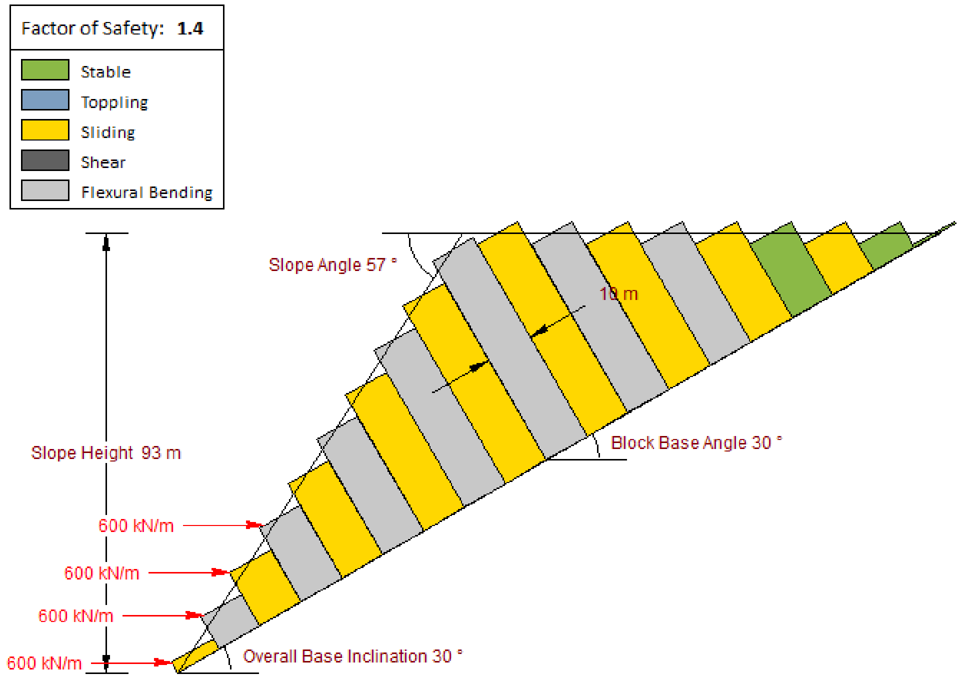


Figure 4.5.4: *RocTopple* Model of Example 5b

4.5.4. Building a Compatible *RS2* Model

Case 5a (Example 1a) – Bolts Model:

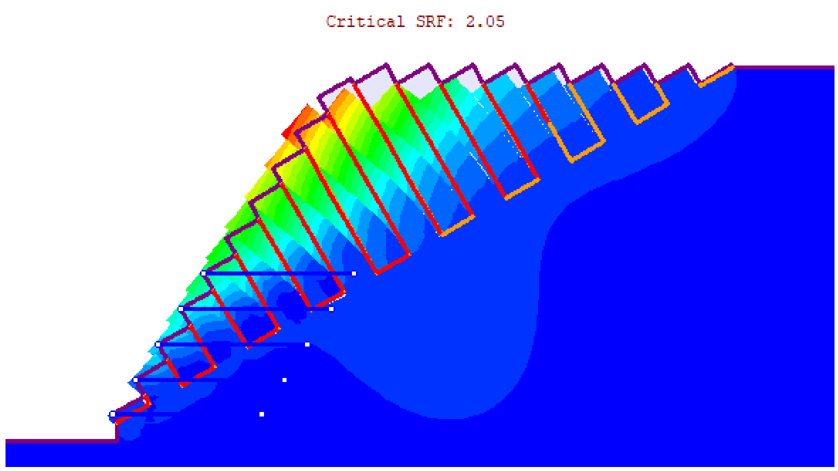


Figure 4.5.5: *RS2* Results of Example 5a

Case 5b (Example 1b) – Line Loads Model:

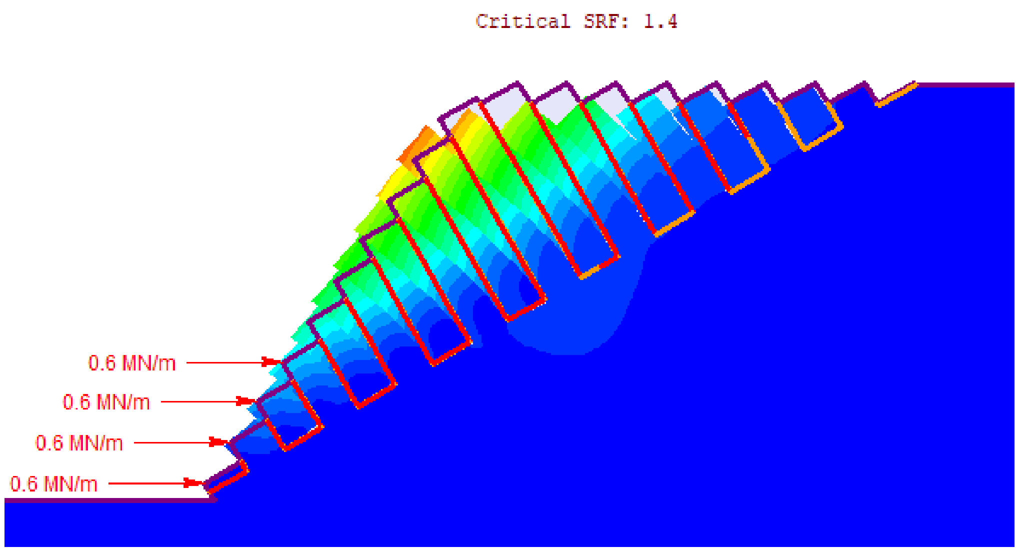


Figure 4.5.6: *RS2* Results of Example 5b

4.5.5. Results

Results are shown below.

Table 4.5.1: Factors of Safety

	RocSlope2	*RocTopple*	*RS2* (SRF)
Example 5a	2.16	2.16	2.05
Example 5b	1.40	1.40	1.40

4.6. *RocSlope2* Block Flexural Toppling Verification Problem #6

[RocSlope2 Build 1.005]

4.6.1. Problem Description

This verification problem examines the application of pressure loads.

Geometry and Material Properties

The geometry and strength properties are identical to Example 3b.

Forces

Example 6 is analyzed with 300 kPa pressure load applied on the slope face.

4.6.2. *RocSlope2* Analysis

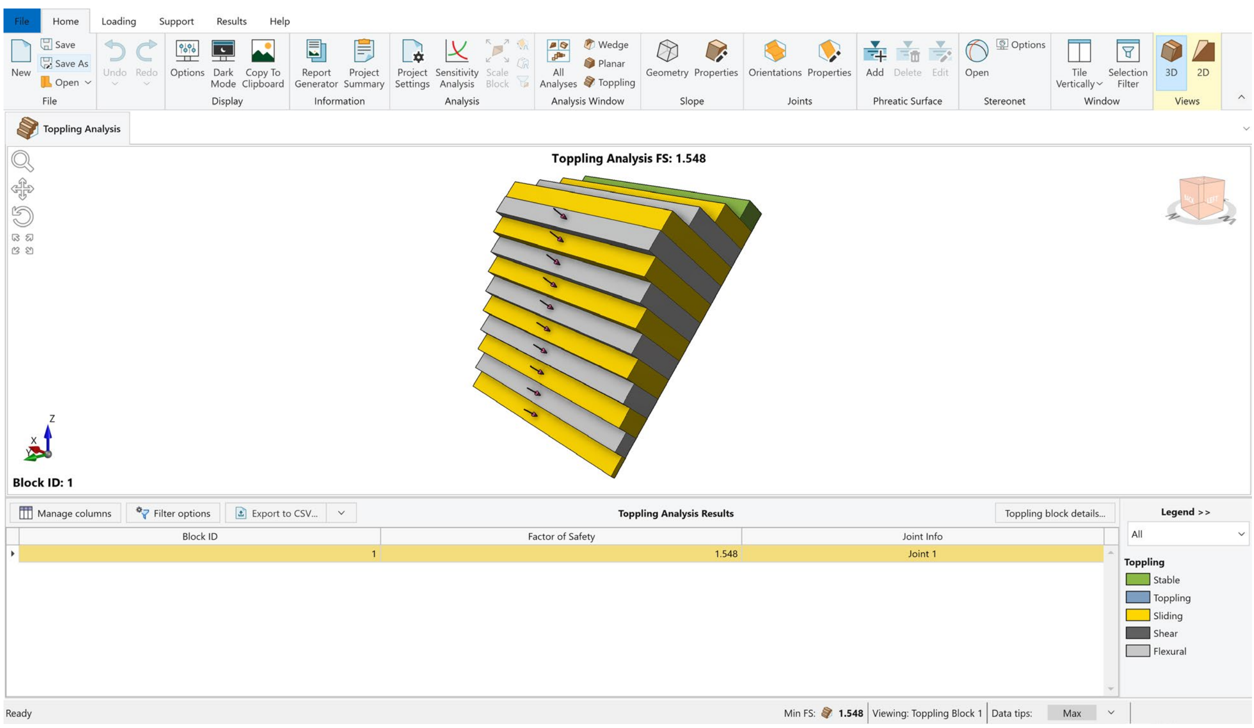


Figure 4.6.1: *RocSlope2* Model of Example 6

4.6.3. *RocTopple* Analysis

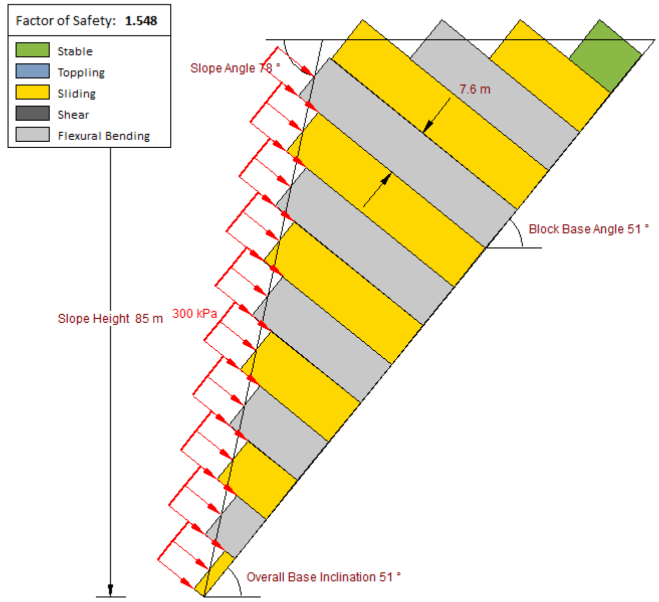


Figure 4.6.2: *RocTopple* Model of Example 6

4.6.4. Building a Compatible *RS2* Model

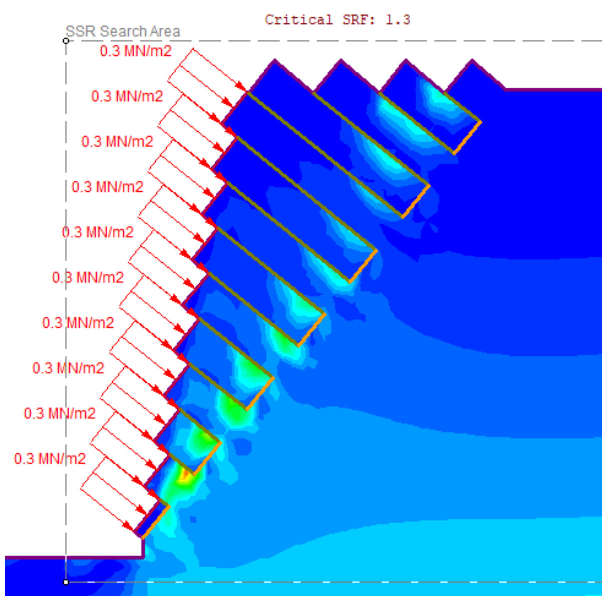


Figure 4.6.3: *RS2* Results of Example 6

4.6.5. Results

Table 4.6.1: Factors of Safety

	RocSlope2	*RocTopple*	*RS2* (SRF)
Example 6	1.55	1.55	1.30

4.7. *RocSlope2* Block Flexural Toppling Verification Problem #7

[RocSlope2 Build 1.005]

4.7.1. Problem Description

This verification problem examines the application of seismic loads.

Geometry and Material Properties

With the geometry and strength properties given in Example 3c, apply the following for Example 7.

Forces

Table 4.7.1: Seismic Coefficient

	Seismic Coefficient
Example 7	Horizontal: 0.3 (to the right) Vertical: 0.15 (down)

4.7.2. *RocSlope2* Analysis

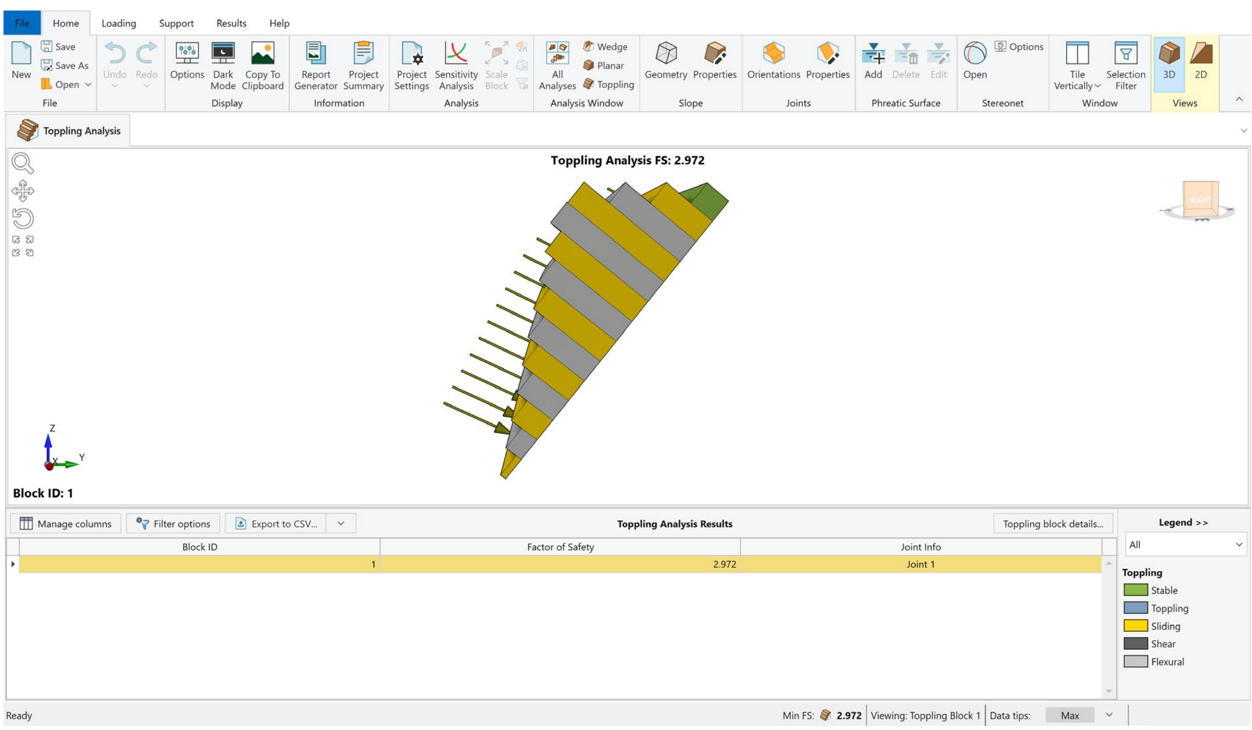


Figure 4.7.1: *RocSlope2* Model of Example 7

4.7.3. *RocTopple* Analysis

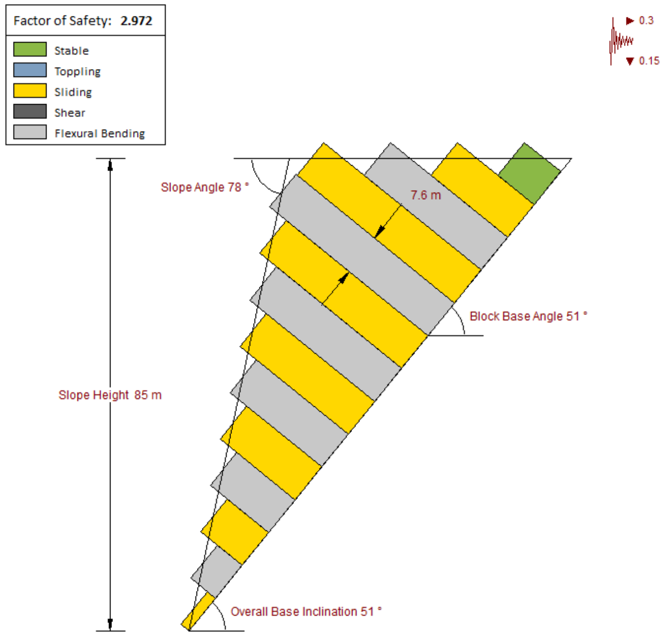


Figure 4.7.2: *RocTopple* Model of Example 7

4.7.4. Building a Compatible *RS2* Model

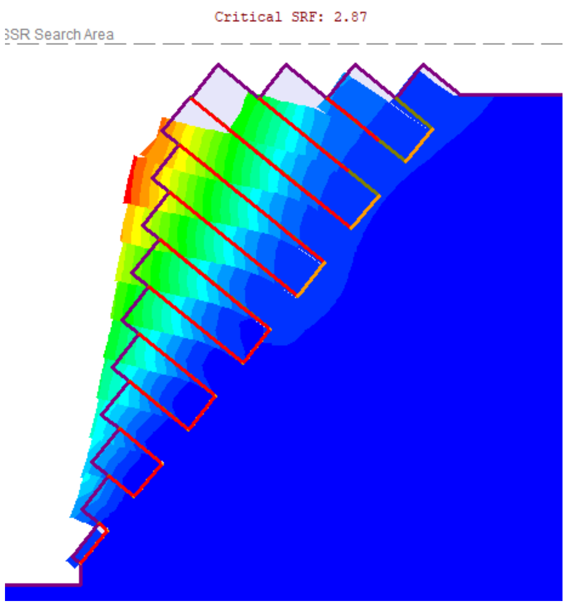


Figure 4.7.3: *RS2* Result of Example 7

4.7.5. Results

Table 4.7.2: Factors of Safety

	RocSlope2	*RocTopple*	*RS2* (SRF)
Example 7	2.97	2.97	2.87