rocscience

RocPlane

Planar Sliding Stability Analysis for Rock Slopes

Verification Manual

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1. *RocPlane* Geometry Verification

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

The examples presented in this section, are taken from articles, technical notes and papers written in the field of Geotechnical Engineering. The results produced by *RocPlane*, as documented in this section, agree very well with the examples from these sources, and confirm the reliability of results produced by *RocPlane*.

1.1. *RocPlane* Verification Problem #1

[*RocPlane Build 4.001*]

1.1.1. Problem Description

A stability assessment is conducted to verify that *RocPlane* computes values using the correct equations. The equations used to verify the results produced by *RocPlane* were originally presented by Dr. Evert Hoek [1].

In this verification example, a rock slope on Sau Mau Ping Road in Kowloon, Hong Kong is analyzed. The geometry of the slope is illustrated in Figure 1-1.

Geometry and Properties

The overall slope angle is 50° and the individual bench faces are inclined at 70° to the horizontal. A failure plane dips at 35°. Tension cracks are observed behind the crests of slopes. In this case, it cannot be determined if tension cracks are present. Therefore, two sets of analysis are carried out for both cases: with tension cracks and without tension cracks.

Table 1.1.1: Slope and Plane Geometry

Geometry Parameter	Value
Height ($\boldsymbol{H}$)	60 m
Slope Angle ($\boldsymbol{\beta}$)	50°
Failure Plane Angle ($\boldsymbol{\alpha}$)	35°
Upper Face Angle ($\boldsymbol{\psi}$)	0°

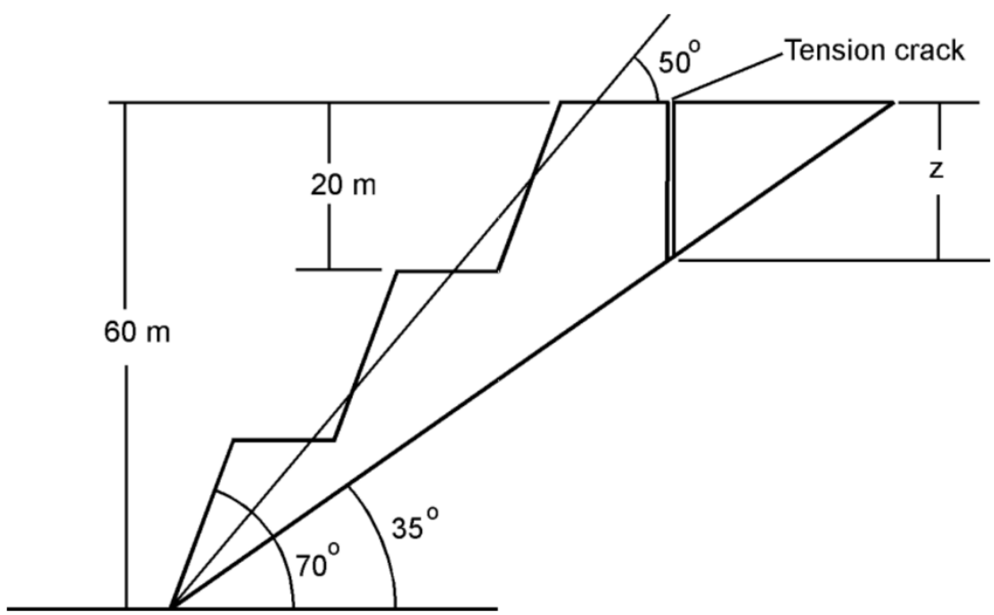


Figure 1.1.1: Geometry Assumed for the Two-Dimensional Analysis of the Sau Mau Ping Road Slope [1]

Table 1.1.2: Material Properties

Parameter	Value
Unit Weight of Water (γ_w)	0.01 MN/m^3
Unit Weight of Rock (γ_r)	0.027 MN/m^3
Cohesion (c)	0.10 MN/m^2
Friction Angle (ϕ)	35°

Table 1.1.3: Force Parameters

Parameter	Value
Seismic Coefficient (s_c)	0.08g
Bolt Force (T)	0 MN
Bolt Plunge (θ)	0°
Depth of Water in TC (Z_w)	90% z *

* Applicable only to case with tension crack only

1.1.2. Analytical Solution

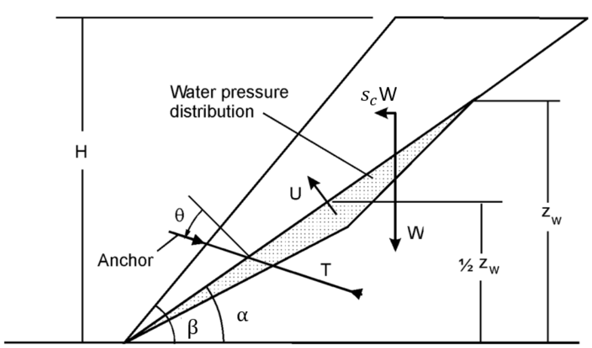


Figure 1.1.2: Slope without Tension Crack [1]

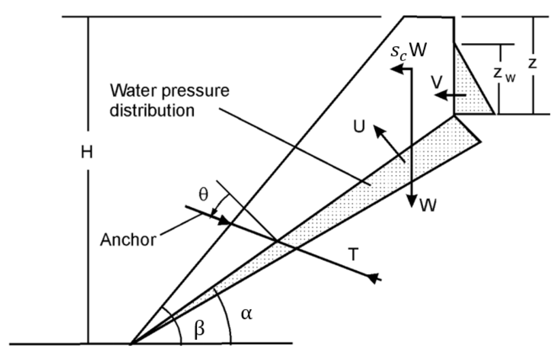


Figure 1.1.3: Slope with Tension Crack [1]

Equations

Without Tension Crack (Figure 1.1.2):

$$FS = \frac{cA + [W(\cos\alpha - s_c \sin\alpha) - U + T\cos\theta]\tan\phi}{W(\sin\alpha + s_c\cos\alpha) - T\sin\theta} \quad \textbf{(1.1.1)}$$

$$A = \frac{H}{\sin\alpha} \quad \textbf{(1.1.2)}$$

$$W = \frac{\gamma_r H^2}{2}(\cot\alpha - \cot\beta) \quad \textbf{(1.1.3)}$$

$$U = \frac{\gamma_w H^2}{4\sin\alpha} \quad \textbf{(1.1.4)}$$

With Tension Crack (Figure 1.1.3):

$$FS = \frac{cA + [W(\cos\alpha - s_c\sin\alpha) - U - V\sin\alpha + T\cos\theta]\tan\phi}{W(\sin\alpha + s_c\cos\alpha) + V\cos\alpha - T\sin\theta} \quad \textbf{(1.2.1)}$$

$$z = H\left(1 - \sqrt{\cot\beta\tan\alpha}\right) \quad \textbf{(1.2.2)}$$

$$A = \frac{H - z}{\sin\alpha} \quad \textbf{(1.2.3)}$$

$$W = \frac{\gamma_r H^2}{2}\left\{\left[1 - \left(\frac{z}{H}\right)^2\right]\cot\alpha - \cot\beta\right\} \quad \textbf{(1.2.4)}$$

$$U = \frac{\gamma_w z_w A}{2} \quad \textbf{(1.2.5)}$$

$$V = \frac{\gamma_w z_w^2}{2} \quad \textbf{(1.2.6)}$$

Where:

H	is the slope height
α	is slope angle
β	is the failure plane angle
$\boldsymbol{\gamma_r}$	is the unit weight of rock
$\boldsymbol{\gamma_w}$	is the unit weight of water
z	is the depth of tension crack
z_w	is the depth of water in tension crack or on failure surface
s_c	is the horizontal seismic coefficient
W	is the weight of rock wedge resting on failure surface
A	is the base area of wedge

U	is the uplift force due to water failure plane pressure
V	is the horizontal force due to water tension crack pressure
c	is the cohesive strength
ϕ	is the friction angle of the Mohr Coulomb Shear Strength Model
T	is the magnitude of any added bolt and **θ** is the plunge angle of the added bolt
FS	is the factor of safety

Sample Calculation

The factors of safety for both cases–without tension crack and with tension crack–are calculated using the equations and data provided by Dr. Evert Hoek.

<u>Without Tension Crack:</u>

Weight of Rock Wedge (W):

$$W = \frac{\gamma_r H^2}{2}(\cot\alpha - \cot\beta) = \frac{0.027 \times 60^2}{2}(\cot 35 - \cot 50) = 28.6278 \text{ MN}$$

Base Area of Wedge (A):

$$A = \frac{H}{\sin\alpha} = \frac{60}{\sin 35} = 104.6068 \text{ m}^2$$

Water FP Pressure Force (U):

$$\frac{\gamma_w H^2}{4\sin\alpha} = \frac{0.01 \times 60^2}{4\sin 35} = 15.6910 \text{ MN}$$

Factor of Safety (FS)

$$FS = \frac{cA + [W(\cos\alpha - s_c\sin\alpha) - U + T\cos\theta]\tan\phi}{W(\sin\alpha + s_c\cos\alpha) - T\sin\theta}$$
$$= \frac{0.1 \times 104.6068 + [28.6278(\cos 35 - 0.08\sin 35) - 15.6910 + 0]\tan 35}{28.6278(\sin 35 + 0.08\cos 35) - 0} = 0.8184254$$

The factor of safety calculated using the input data and equations supplied by Dr. Evert Hoek [1] is 0.8184254.

<u>With Tension Crack:</u>

Depth of Tension Crack (z):

$$z = H\left(1 - \sqrt{\cot\beta\tan\alpha}\right) = 60\left(1 - \sqrt{\cot 50 \tan 35}\right) = 14.0092 \text{ m}$$

Weight of Rock Wedge (W):

$$W = \frac{\gamma_r H^2}{2}\left\{\left[1 - \left(\frac{z}{H}\right)^2\right]\cot\alpha - \cot\beta\right\} = \frac{0.027 \times 60^2}{2}\left\{\left[1 - \left(\frac{14.0092}{60}\right)^2\right]\cot 35 - \cot 50\right\} = 24.8439 \text{ MN}$$

Base Area of Wedge (A):

$$A = \frac{H - z}{\sin\alpha} = \frac{60 - 14.0092}{\sin 35} = 80.1826 \text{ m}^2$$

Depth of Water in TC (z_w):

$$z_w = 0.9z = 0.9 \times 14.0092 = 16.6082 \text{ m}$$

Water FP Pressure Force (U):

$$U = \frac{\gamma_w z_w A}{2} = \frac{0.01 \times 16.6082 \times 80.1826}{2} = 4.4932 \text{ MN}$$

Water TC Pressure Force (V):

$$V = \frac{\gamma_w z_w^2}{2} = \frac{0.01 \times 16.6082^2}{2} = 0.6280 \text{ MN}$$

Factor of Safety (FS)

$$FS = \frac{cA + [W(\cos\alpha - s_c \sin\alpha) - U - V\sin\alpha + T\cos\theta]\tan\phi}{W(\sin\alpha + s_c\cos\alpha) + V\cos\alpha - T\sin\theta}$$
$$= \frac{0.01 \times 80.1826 + [24.8439(\cos 35 - 0.08\sin 35) - 4.4932 - 0.6280\sin 35 + 0]\tan 35}{24.8439(\sin 35 + 0.08\cos 35) + 0.6280\cos 35 - 0}$$
$$= 1.0654738$$

The factor of safety calculated using the input data and equations supplied by Dr. Evert Hoek [2] is 1.0654738.

1.1.3. RocPlane Analysis

Identical input data are entered in the *RocPlane* program to verify against the sample calculations.

Deterministic Analysis

Without Tension Crack:

Enter the *RocPlane* parameters as shown in Figure 1.1.4 through Figure 1.1.7:

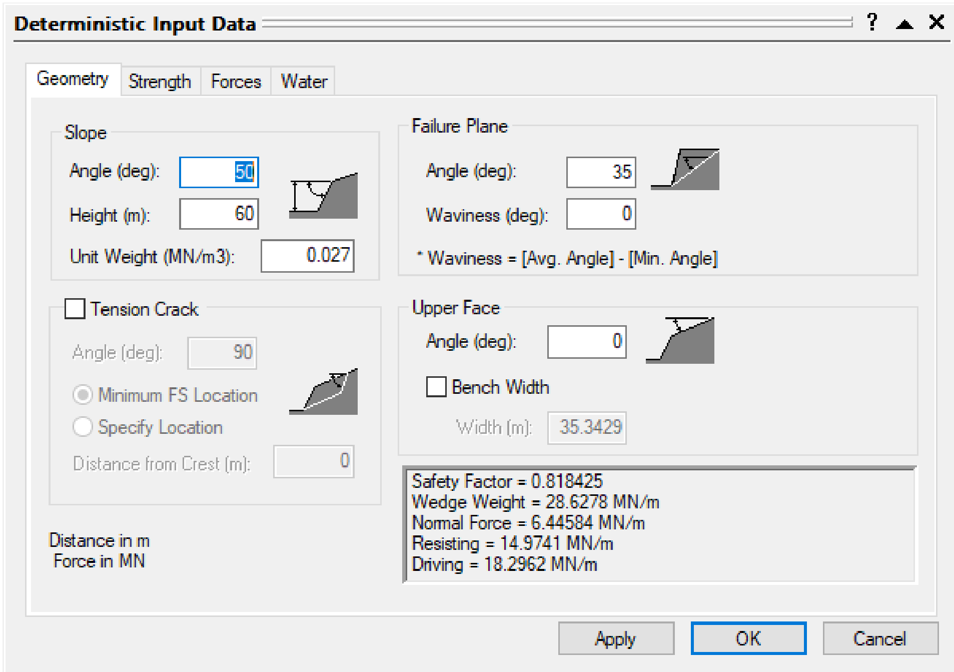


Figure 1.1.4: *RocPlane* Geometry Input Data for Slope with No Tension Crack

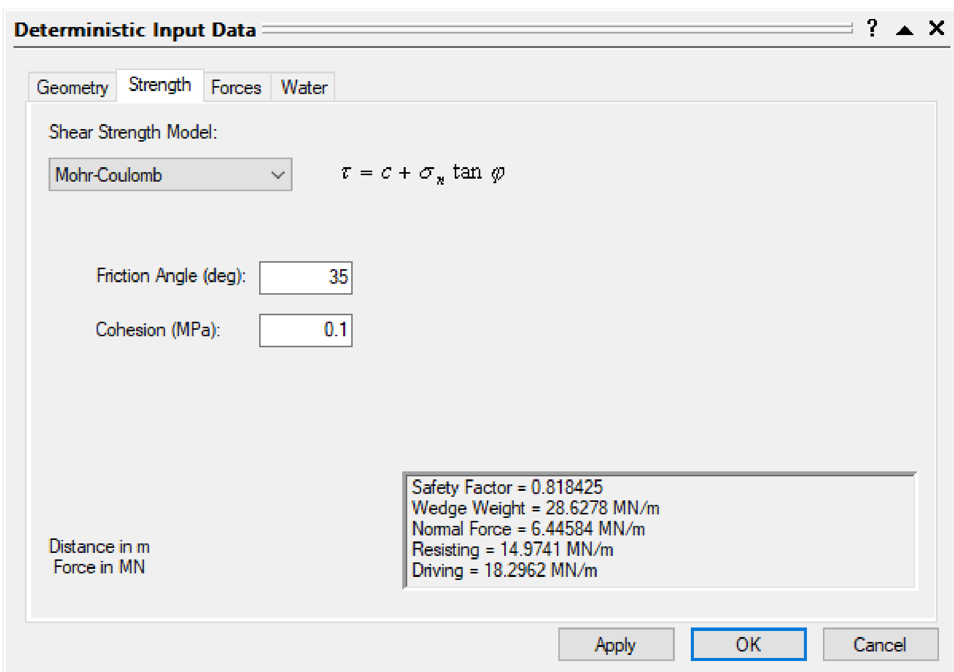


Figure 1.1.5: *RocPlane* Strength Input Data for Slope with No Tension Crack

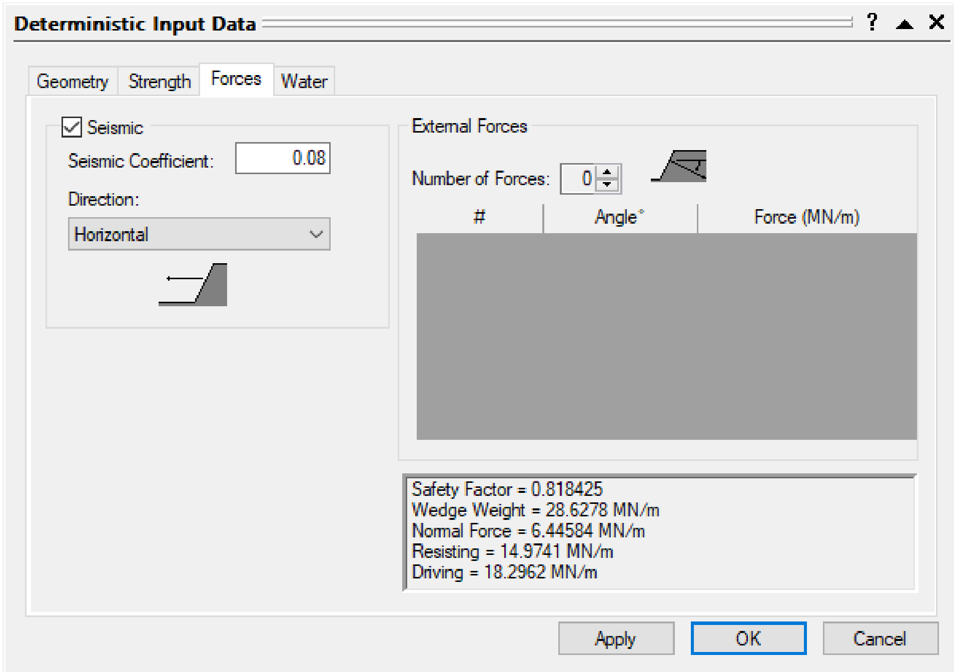


Figure 1.1.6: *RocPlane* Forces Input Data for Slope with No Tension Crack

Peak plane water pressure is assumed at mid height of the slope.

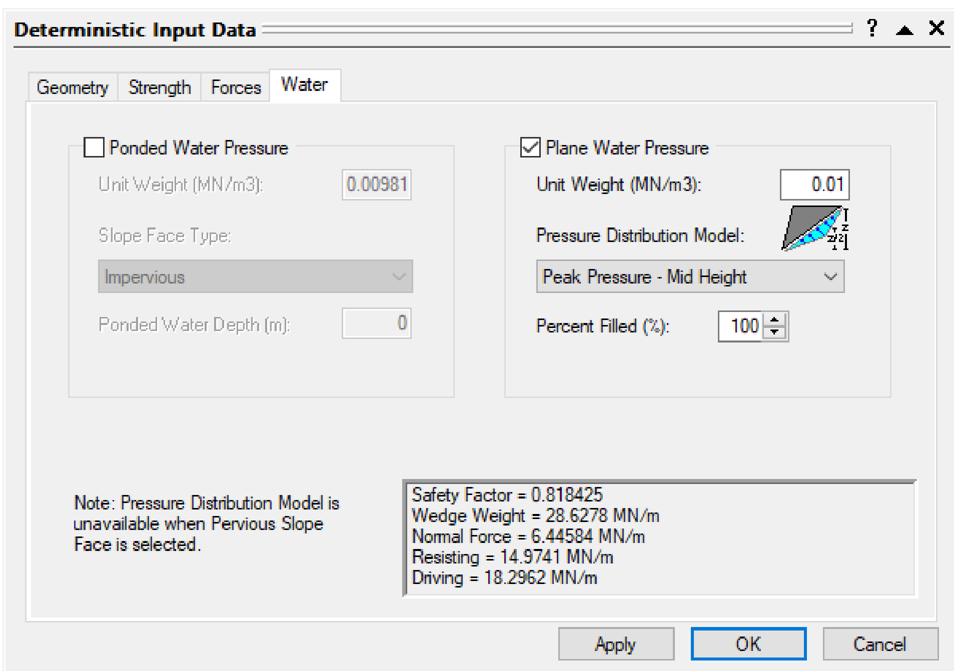


Figure 1.1.7: *RocPlane* Water Input Data for Slope with No Tension Crack

The *RocPlane* model looks like this:

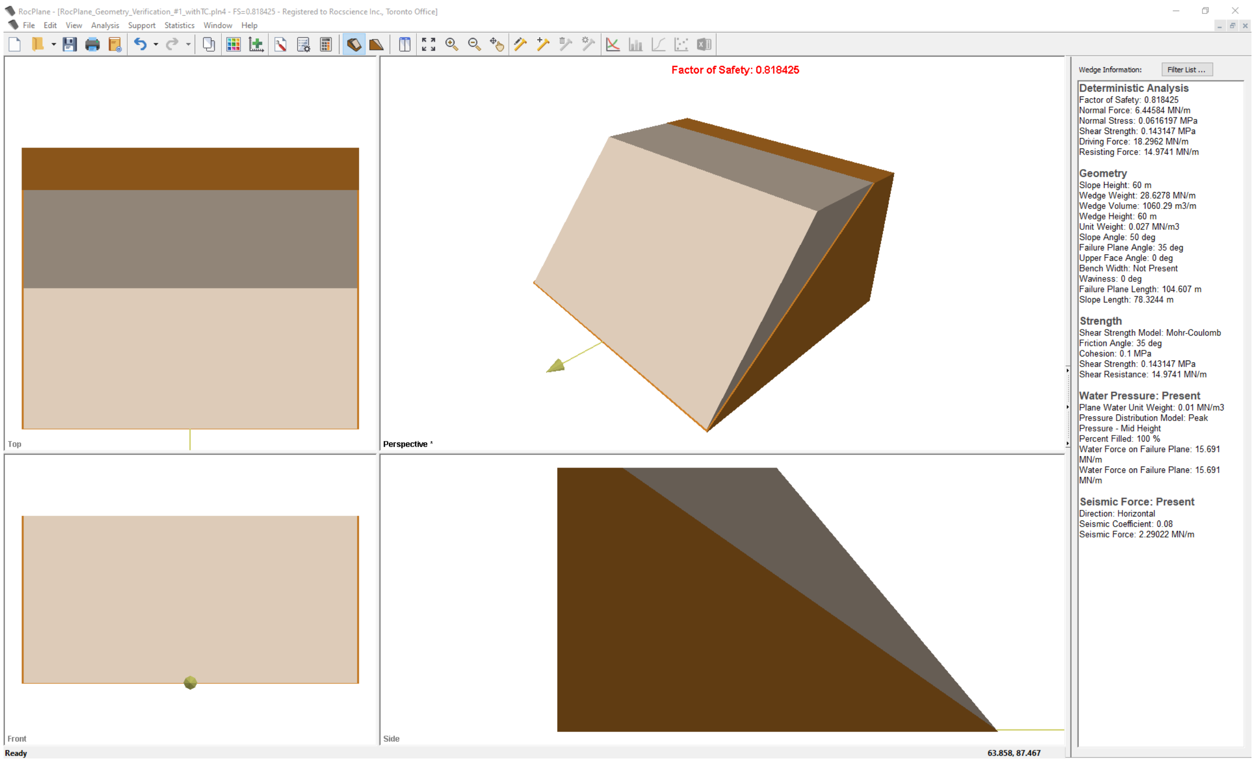


Figure 1.1.8: *RocPlane* Seismic Model without Tension Crack

<u>With Tension Crack:</u>

The distance from the tension crack to the crest of the slope must first be calculated. This can be done using simple geometry (Figure 1.1.9).

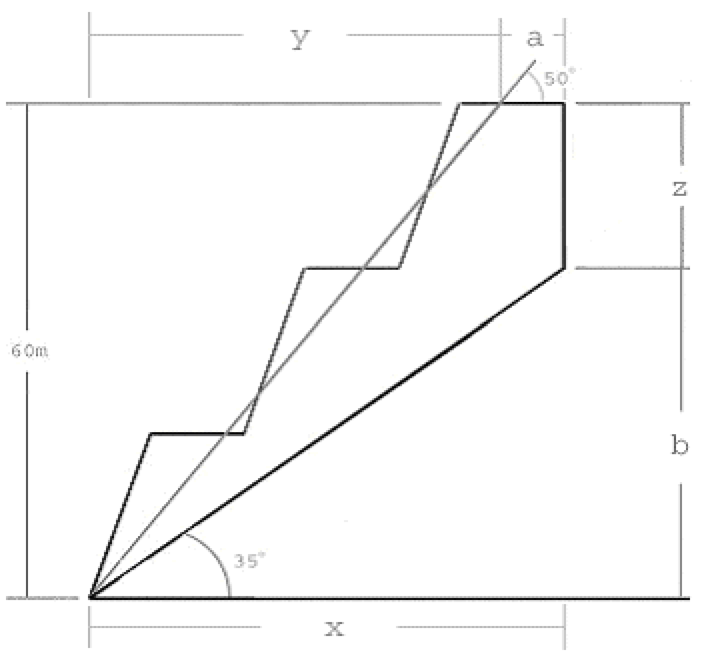


Figure 1.1.9: Geometry of the Slope with Tension Crack

$$b = 60 - z = 60 - 14.0092 = 45.9908 \text{ m}$$

$$x = \frac{b}{\tan 35} = \frac{45.9908}{0.7002} = 65.6817 \text{ m}$$

$$y = \frac{60}{\tan 50} = \frac{60}{1.1918} = 50.3460 \text{ m}$$

$$a = x - y = 65.6817 \text{ m} - 50.3460 \text{ m} = 15.3357 \text{ m}$$

Therefore, distance from crest is 15.3357 m.

Enter the *RocPlane* parameters as shown in Figure 1.1.10 through Figure 1.1.13:

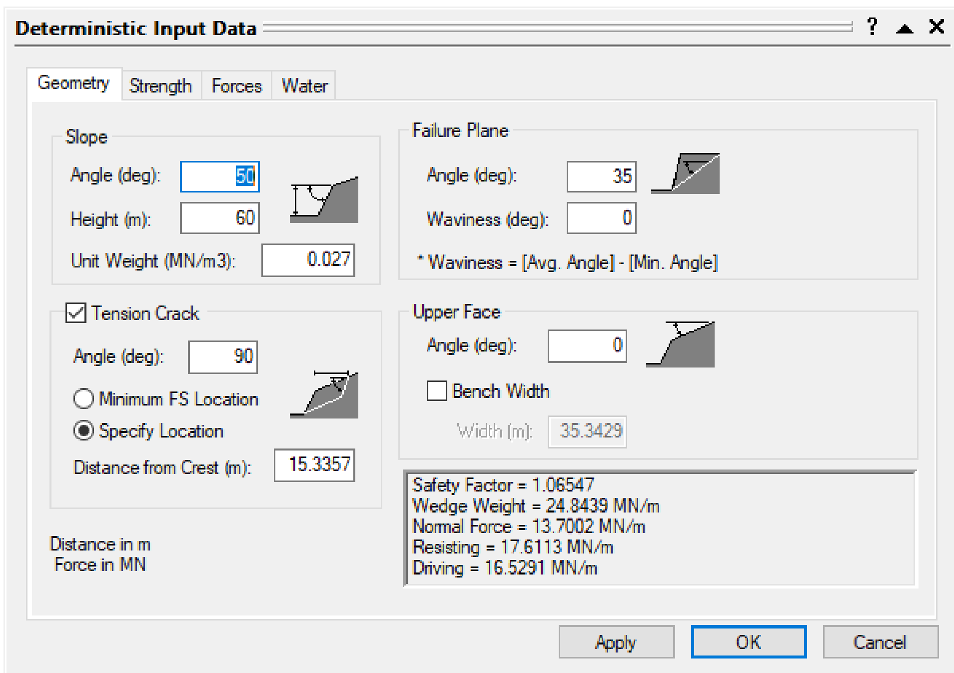


Figure 1.1.10: *RocPlane* Geometry Input Data for Slope with Tension Crack

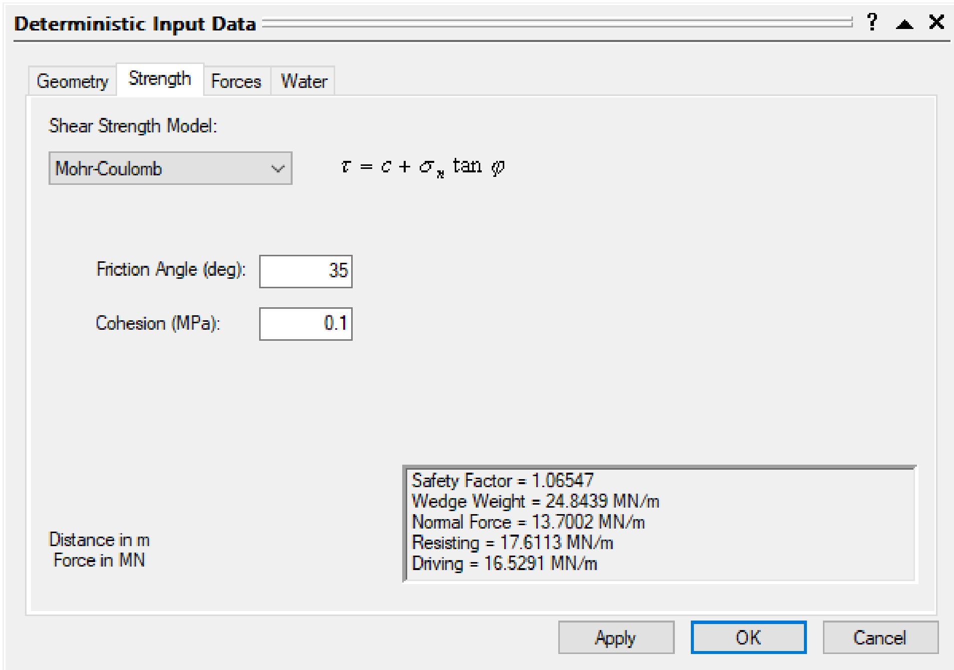


Figure 1.1.11: *RocPlane* Strength Input Data for Slope with Tension Crack

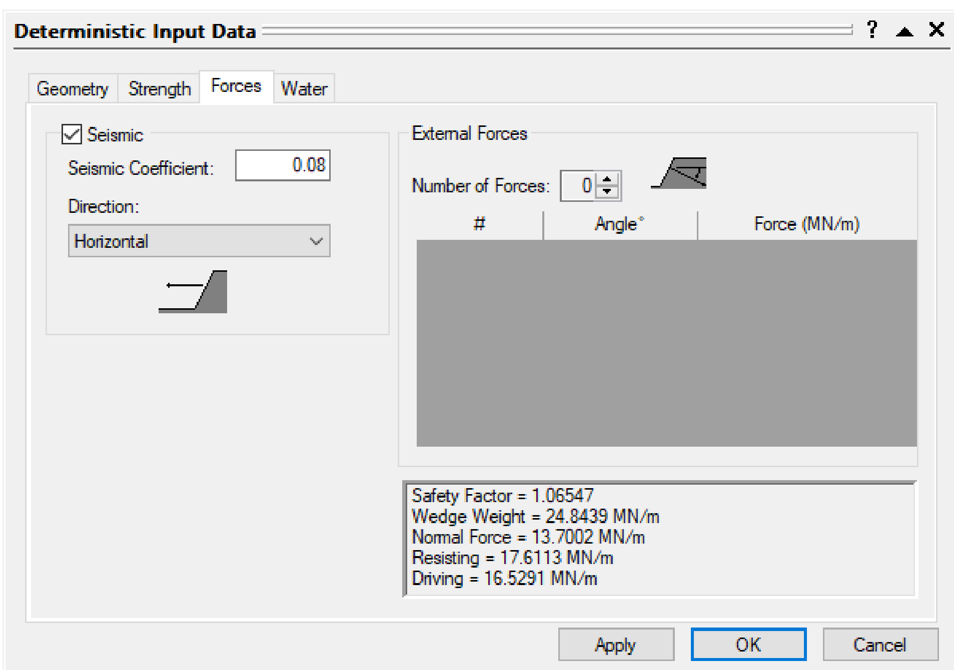


Figure 1.1.12: *RocPlane* Forces Input Data for Slope with Tension Crack

Peak plane water pressure is assumed at the base of the tension crack.

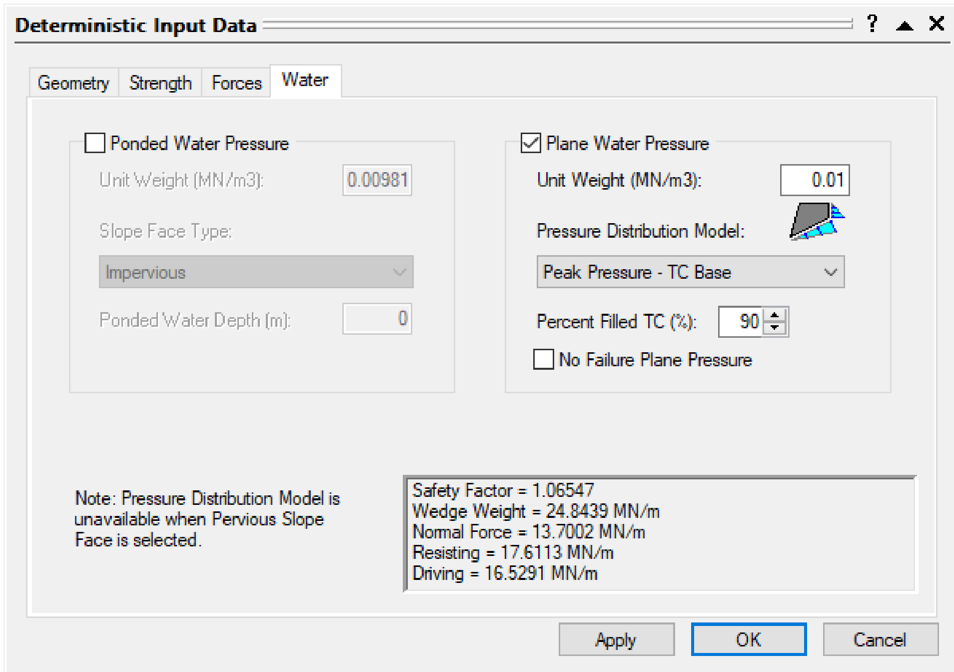


Figure 1.1.13: *RocPlane* Water Input Data for Slope with No Tension Crack

The *RocPlane* model looks like this:

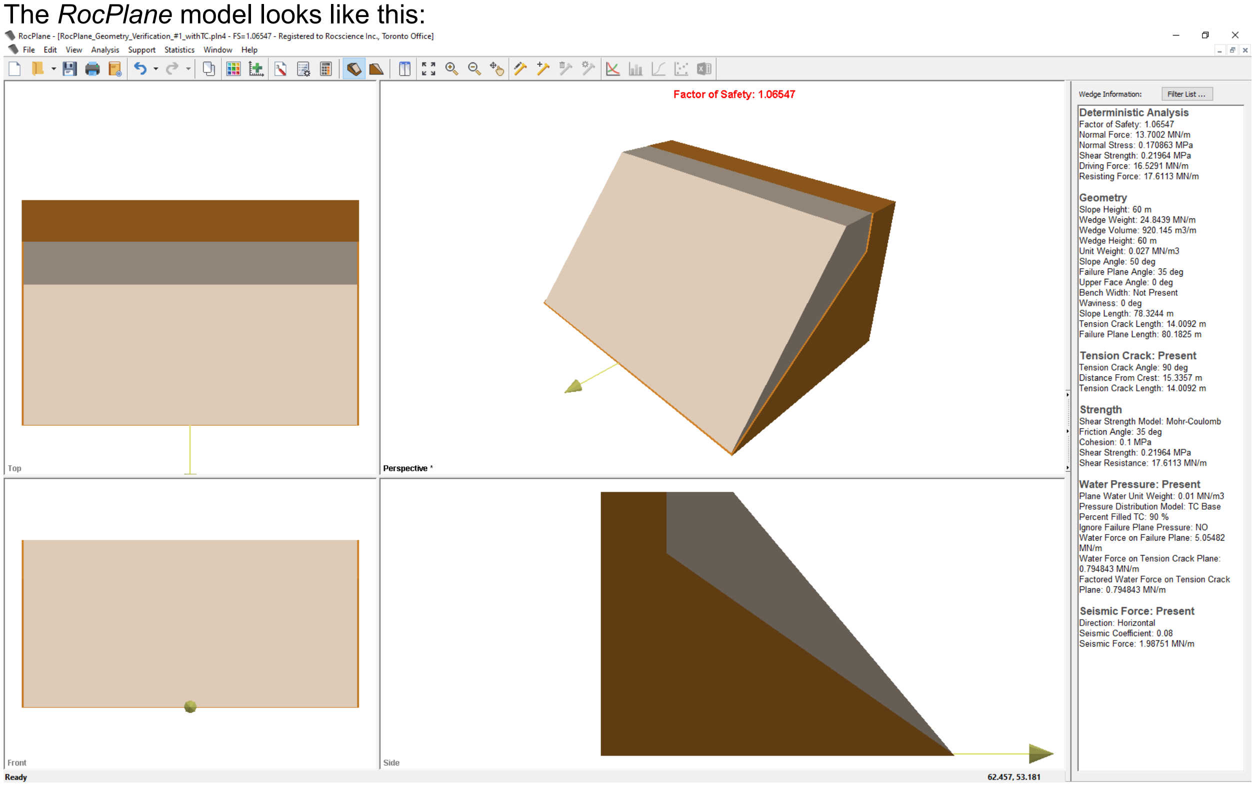


Figure 1.1.14: *RocPlane* Seismic Model with Tension Crack

Sensitivity Analysis

A sensitivity analysis is conducted in *RocPlane* to reproduce the results provided by Dr. Hoek.

Without Tension Crack:

Keeping all else the same, in the Sensitivity Input dialog, enter the *RocPlane* values as shown:

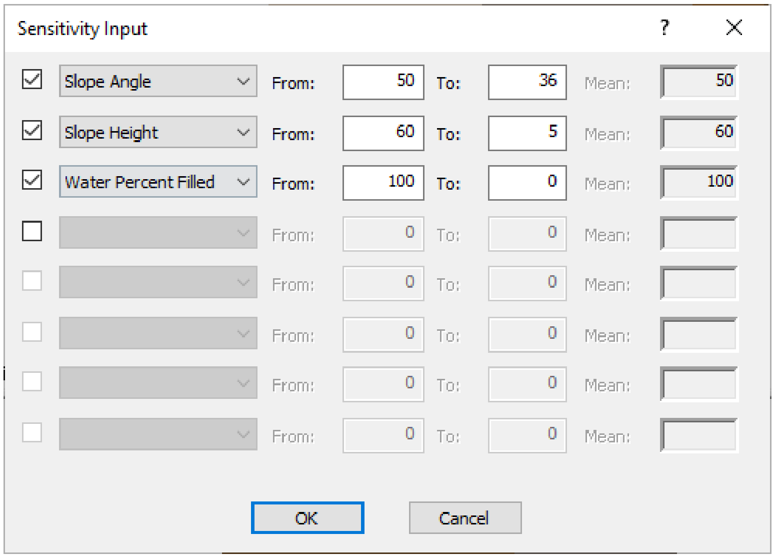


Figure 1.1.15: *RocPlane* Sensitivity Input without Tension Crack.

The *RocPlane* sensitivity plot looks like this:

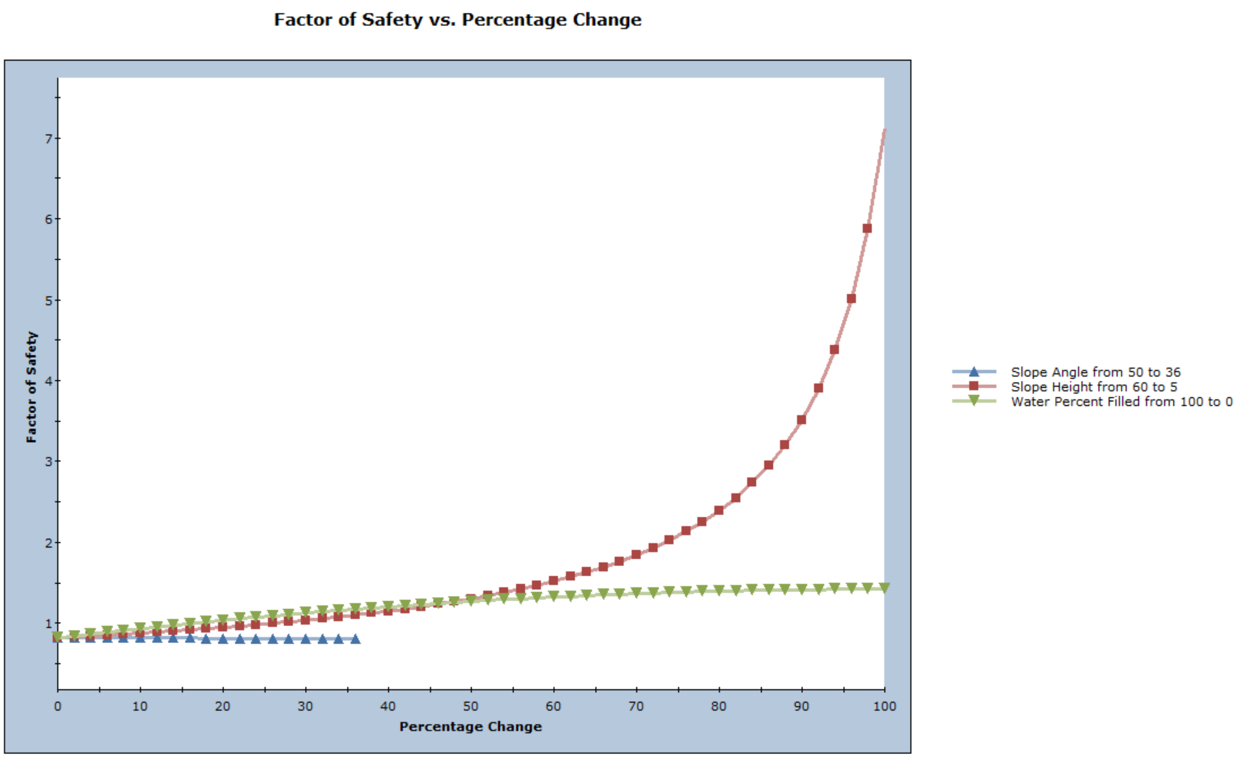


Figure 1.1.16: *RocPlane* Sensitivity Plot of Slope without Tension Crack

With Tension Crack:

Keeping all else the same, in the Sensitivity Input dialog, enter the *RocPlane* values as shown:

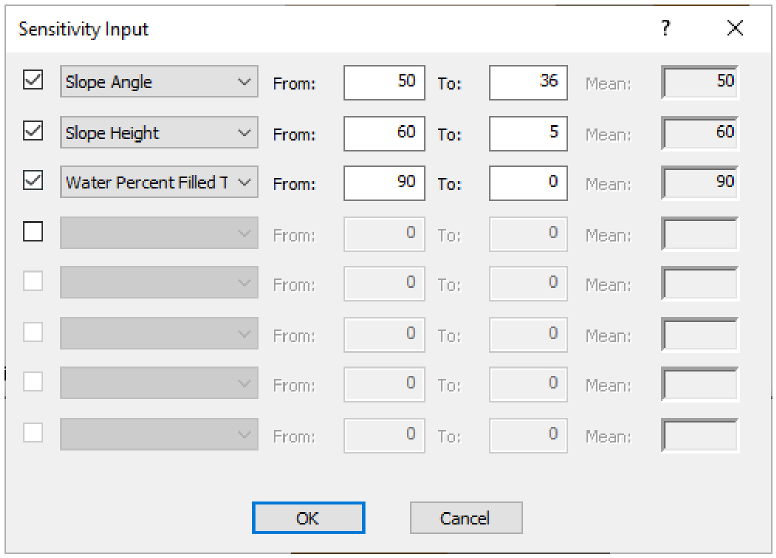


Figure 1.1.17: *RocPlane* Sensitivity Input with Tension Crack.

The *RocPlane* sensitivity plot looks like this:

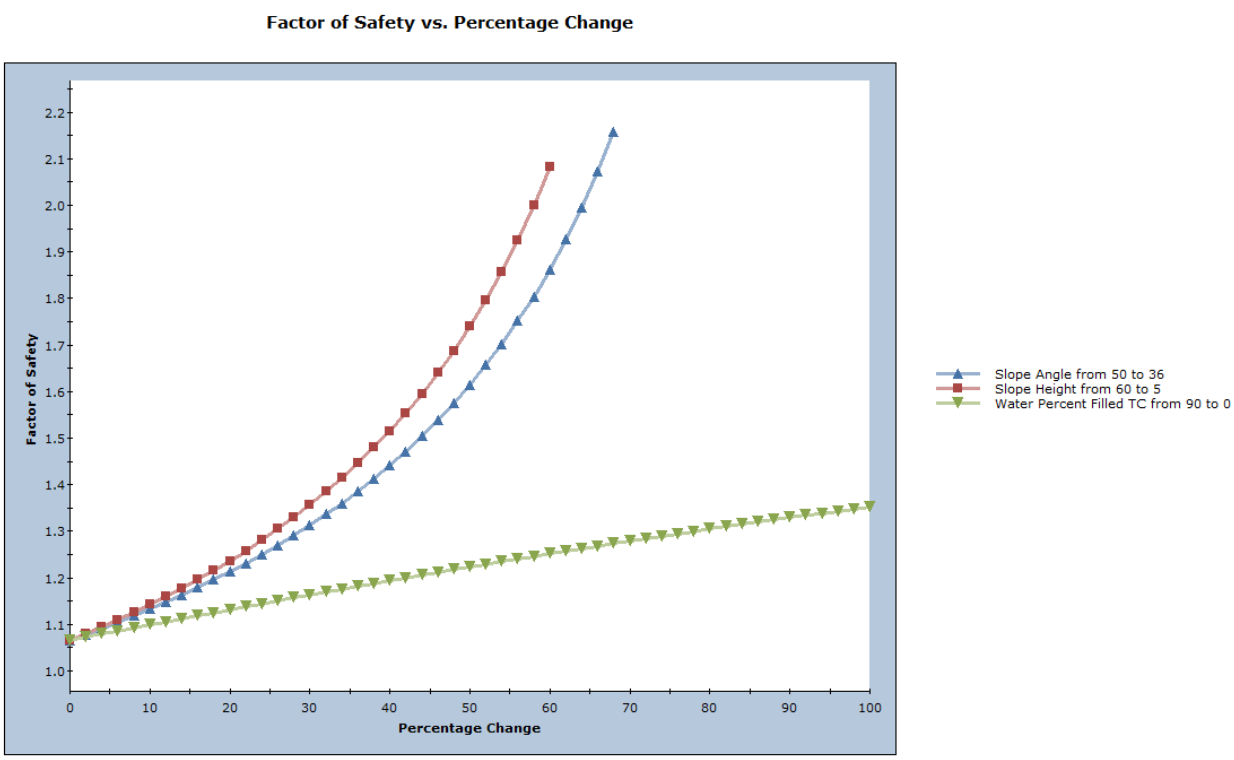


Figure 1.1.18: *RocPlane* Sensitivity Plot of Slope with Tension Crack

1.1.4. Results

In the case with no tension crack, the calculated factor of safety from the *RocPlane* program is 0.818425. This is the same value as what was calculated before.

In the case with tension crack, the calculated factor of safety from the *RocPlane* program is 1.06547. This is the same value as what was calculated before.

The two sensitivity plots from the *RocPlane* program have exactly the same shape as the diagram provided by Dr. Hoek (Figure 1.1.19).

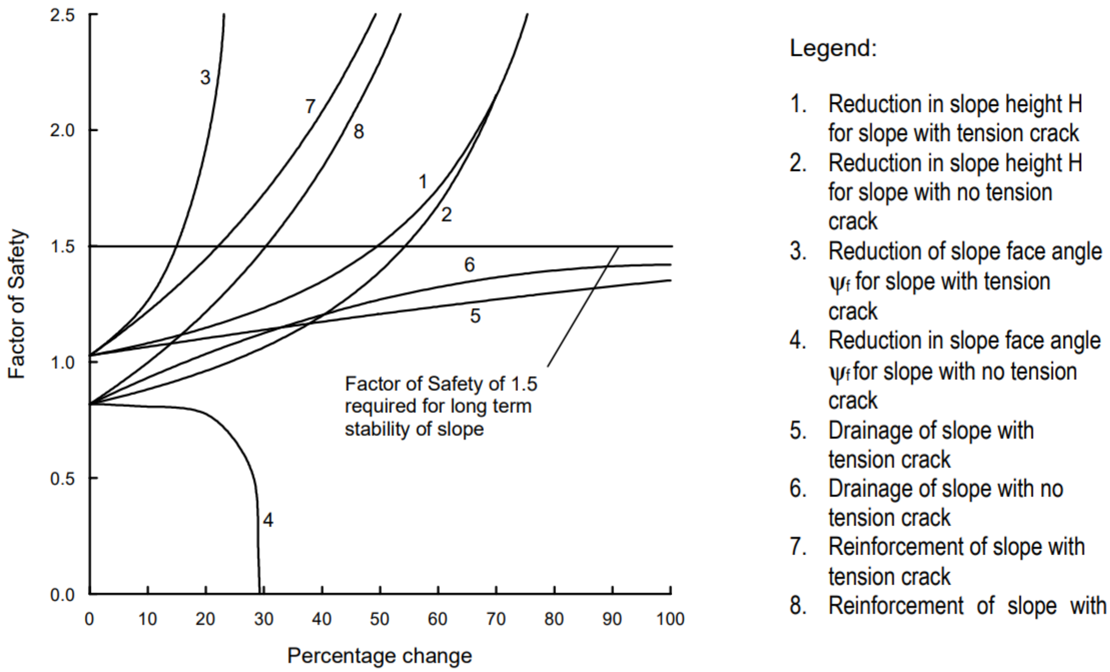


Figure 1.1.19: Evaluation of Remedial Options to Increase the Stability of the Slope by Hoek [1]

1.2. *RocPlane* Verification Problem #2

[*RocPlane Build 4.001*]

1.2.1. Problem Description

This example verification is based on the technical note by S. Sharma [2]. A hypothetical example was considered in the paper. The authors designed the slope so that the bench dip will vary from 0° to 30° and the tension crack dip will vary from vertical (90°) to 70°.

Geometry and Properties

Table 1.2.1: Slope and Plane Geometry [2]

Parameter	Value
Slope Height (H)	60 m
Failure Plane Angle (α)	35°
Slope Angle (β)	50°
Upper Face (Bench) Angle (ψ)	0° → 30°
Tension Crack Angle (θ)	90° → 70°
Height of Water Column in the Tension Crack (z_w)	14 m

Table 1.2.2: Material Properties

Parameter	Value
Slope Height (H)	60 m
Cohesion (c)	12 t/m^2
Friction Angle (ϕ)	45°
Unit Weight of Rock	2.6 t/m^3
Unit Weight of Water	1.0 t/m^3

1.2.2. *RocPlane* Analysis

Deterministic Analysis

Enter the *RocPlane* geometry and material parameters from Table 1.2.1 and Table 1.2.2.

The distance from the tension crack to the crest and the water percent filled in the tension crack must be calculated. Using the provided equations:

$$TC\ distance = H\left(\sqrt{\cot\beta\cot\alpha} - \cot\beta\right)$$

$$percent\ filled = \frac{z_w}{z}$$

$$z = \frac{H\sin\theta\left(1 - \frac{\cot\beta}{\cot\alpha} + \sqrt{\frac{\cot\beta}{\cot\alpha}} \times \frac{\cot\alpha}{\cot\psi - 1}\right)}{\sin\theta - \tan\alpha\cos\theta}$$

The distance from tension crack to the crest is 15.33576 m. The water percent filled value depends on the tension crack length in each case. Peak plane water pressure is assumed at the base of the tension crack.

The *RocPlane* models look like this:

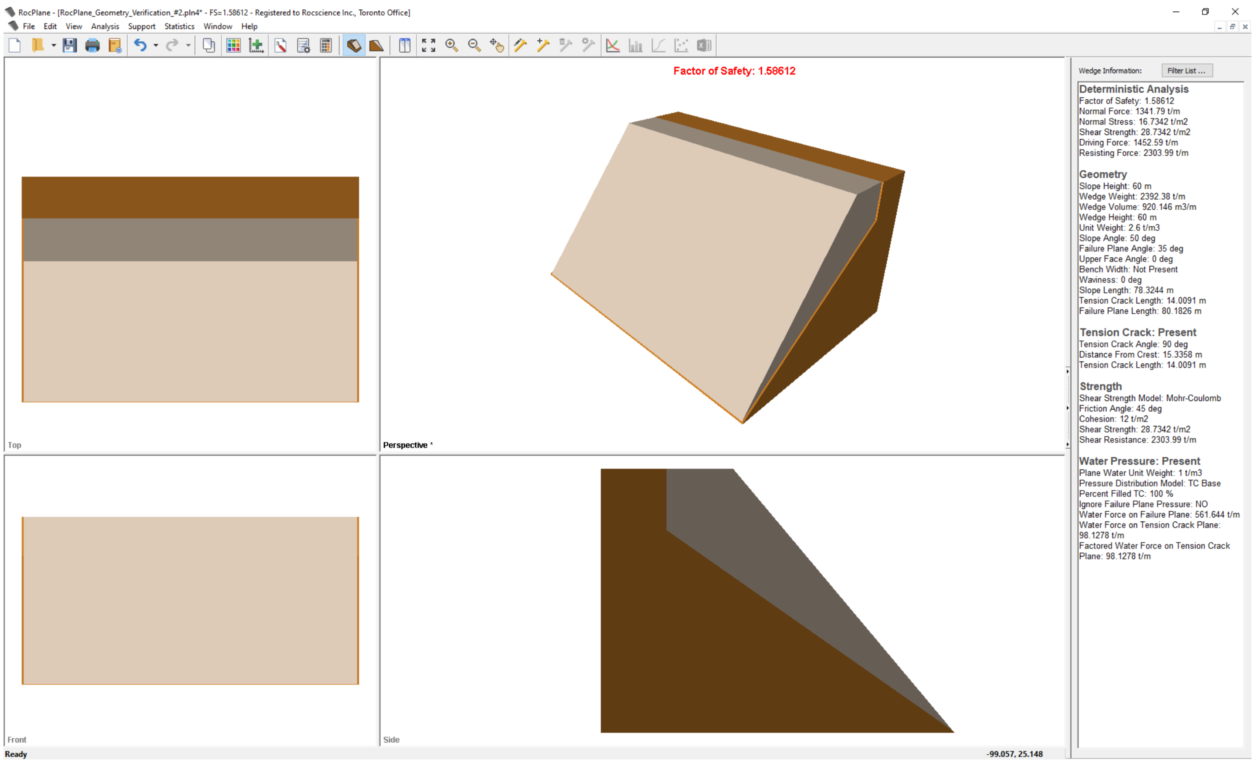


Figure 1.2.1: *RocPlane* Model with Tension Crack (ψ = 0°, θ = 90°, 100% Filled Plane Water)

1.2.3. Results

Analysis results provided by Sharma [2] are shown in Table 1.2.3.

Table 1.2.3: Stability Analysis Provided by Sharma [2]

Bench Angle (°)	Tension Crack Angle (°)	Weight (kN)	Factor of Safety
0	70	2267.68	1.60
10	70	3317.43	1.54
15	70	4433.85	1.51
20	70	6715.23	1.48
25	70	12998.24	1.45
30	70	71425.55	1.43
0	80	2340.37	1.58
10	80	3456.77	1.53
15	80	4636.49	1.50
20	80	7032.68	1.48
25	80	13465.16	1.45
30	80	46627.40	1.43
0	90	2391.03	1.58
10	90	3558.34	1.53
15	90	4785.03	1.50
20	90	7254.02	1.48
25	90	13932.64	1.45
30	90	47526.01	1.43

Analysis results obtained from *RocPlane* are listed in Table 1.2.4.

Table 1.2.4: Factor of Safety using *RocPlane*

Bench Angle (°)	Tension Crack Angle (°)	Weight (t)	Percent Filled (%)	Factor of Safety
0	70	2267.76	74	1.57049
10	70	2268.91	62	1.56472
15	70	2265.85	58	1.55308
20	70	2259.95	53	1.55761
25	70	2250.62	49	1.55549
30	70	2236.97	46	1.54370
0	80	2341.05	87	1.58310
10	80	2373.24	73	1.57812
15	80	2388.45	68	1.56995
20	80	2403.29	63	1.56679
25	80	2417.85	58	1.56812
30	80	2432.20	54	1.56231
0	90	2392.38	100	1.58612
10	90	2446.29	84	1.58148
15	90	2474.30	77	1.58373
20	90	2503.66	71	1.58382
25	90	2534.95	66	1.57957
30	90	2568.90	61	1.57849

By comparing the factors of safety, we observe that only the values at 0° bench dip are the same. The program is studied, and we found that the equation provided in ref. [2] for calculating the wedge weights is incorrect in the paper.

For reference, the equation is supplied below:

$$W = \frac{1}{2}\gamma[(H + a)X - D \times z_L]$$

Where:

γ is the unit weight of rock

H is the slope height

a is the bench height

X is the whole bench length

D is the distance from the top of the bench to the tension crack

z_L is the vertical depth of the tension crack

This formula is incorrect except when the bench dip is 0°. Since the weights are wrong, the factor of safety provided by the paper is not dependable.

1.3. *RocPlane* Verification Problem #3

[*RocPlane Build 4.001*]

1.3.1. Problem Description

In this verification example, *RocPlane* is tested against the Hoek & Bray's formulae for the stability assessment of plane failures. The accuracy of *RocPlane* is verified against the plot of tension crack depth versus factor of safety (Figure 1.3.3), provided by Froldi P. [3].

Geometry and Properties

The geometry for the unstable slope is shown in Figure 1.3.1. The information we have now is listed in Table 1.3.1.

Table 1.3.1: Slope and Plane Geometry

Parameter	Value
Slope Height (H)	1 m
Slope Angle (β)	70°
Failure Plane Angle (α)	35°
Upper Face (Bench) Angle (ψ)	0°
Tension Crack Angle	90°
Water Percent Filled TC	100%

Peak plane water pressure is assumed at the base of the tension crack.

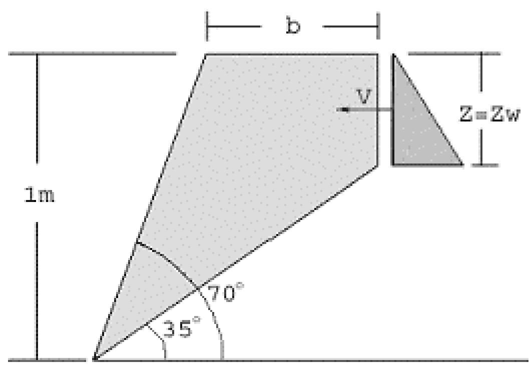


Figure 1.3.1: Plane Geometry of the Unstable Slope

Table 1.3.2: Material Properties

Parameter	Value
Unit Weight of Slope (γ)	2.6 t/m^3
Unit Weight of Water (γ_w)	1.0 t/m^3
Cohesion (c)	0 t/m^2 → 1.0 t/m^2
Friction Angle (ϕ)	30°

1.3.2. *RocPlane* Analysis

Deterministic Analysis

Enter the *RocPlane* geometry and material parameters from Table 1.3.1 and Table 1.3.3.

The distance from the tension crack to the crest of the slope (b) is calculated using the following formula:

$$b = \frac{\left(1 - \frac{z}{H}\right)H}{\tan\alpha} - \frac{H}{\tan\beta}$$

The *RocPlane* models look like this:

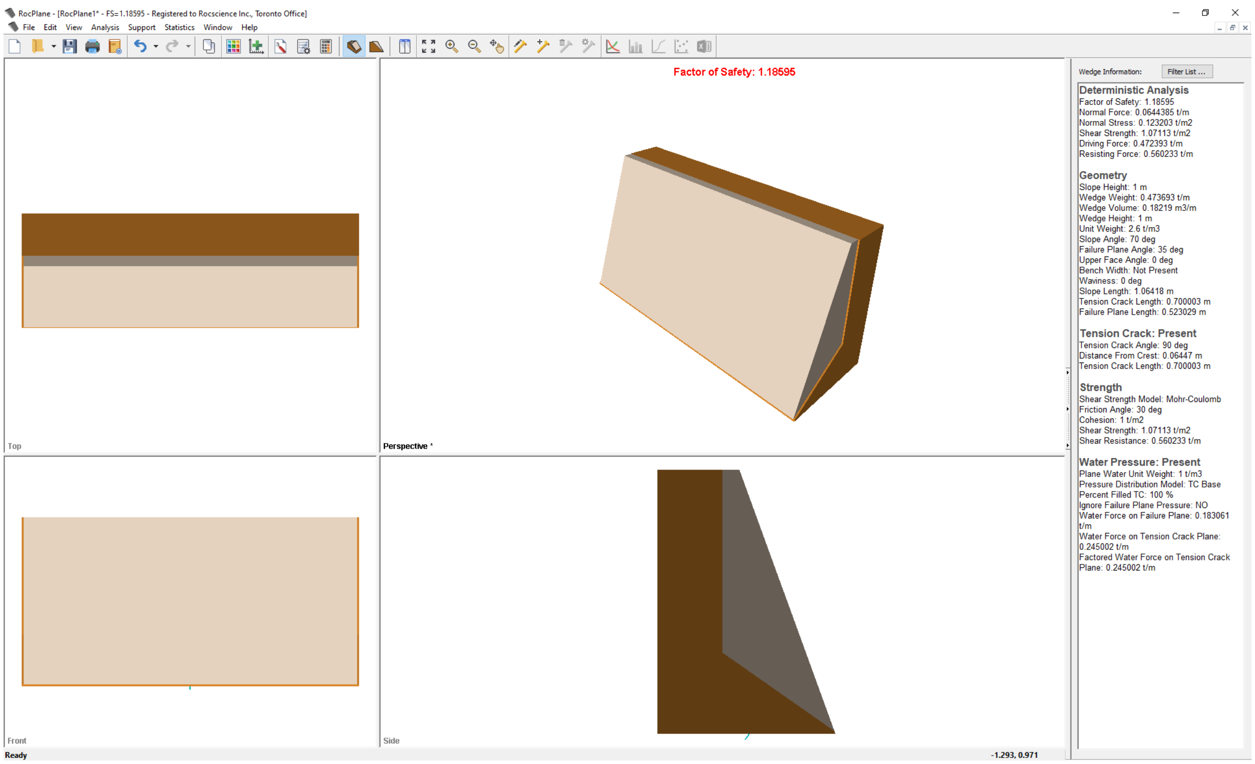


Figure 1.3.2: *RocPlane* Model with Tension Crack ($\boldsymbol{b}$ = 0.06447 m, $\boldsymbol{c}$ = 1 t/m^2)

1.3.3. Results

RocPlane results are listed in Table 1.3.3, and the plot created by Microsoft Excel in Figure 3-4.

Table 1.3.3: Calculated Factor of Safety for the Slope at Different Cohesion Using *RocPlane*

z/H	b	Factor of Safety					
		c = 1 t/m^2	c = 0.8 t/m^2	c = 0.6 t/m^2	c = 0.4 t/m^2	c = 0.2 t/m^2	c = 0 t/m^2
0	1.06418	3.02169	2.58226	2.14283	1.7034	1.26397	0.824542
0.05	0.99277	2.88437	2.46605	2.04773	1.62941	1.21109	0.792763
0.1	0.92136	2.75449	2.35571	1.95693	1.55815	1.15937	0.760587
0.15	0.84996	2.63054	2.24995	1.86936	1.48878	1.10819	0.727601
0.2	0.77855	2.51112	2.14757	1.78402	1.42046	1.05691	0.693355
0.25	0.70714	2.39489	2.04738	1.69988	1.35237	1.00486	0.657346
0.3	0.63573	2.28048	1.94818	1.61588	1.28358	0.951284	0.618984
0.35	0.56433	2.16646	1.84868	1.5309	1.21312	0.895342	0.577563
0.4	0.49292	2.05122	1.74741	1.44361	1.13981	0.83601	0.532208
0.45	0.42151	1.93292	1.64269	1.35247	1.06225	0.772028	0.481805
0.5	0.35010	1.8093	1.53242	1.25554	0.97866	0.701779	0.424898
0.55	0.27870	1.6775	1.41391	1.15031	0.886717	0.623121	0.359526
0.6	0.20729	1.53368	1.28354	1.03339	0.783252	0.533111	0.28297
0.65	0.13588	1.37245	1.13623	0.900003	0.663777	0.427551	0.191326
0.7	0.06447	1.18595	0.964518	0.743079	0.521641	0.300202	0.078763

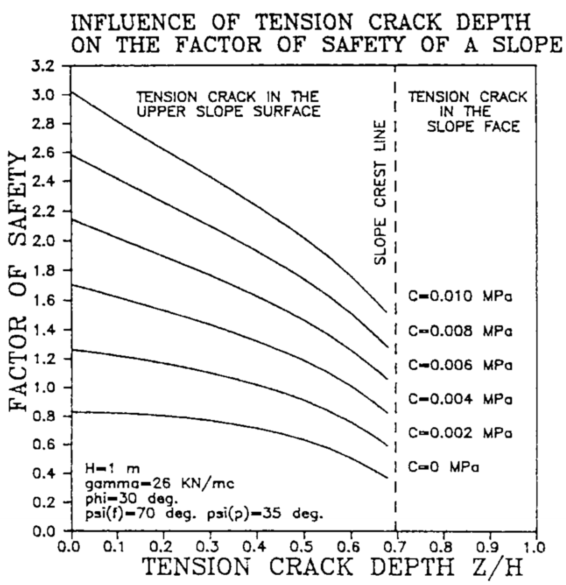


Figure 1.3.3: F.S. vs. Z/H from Froldi [3].

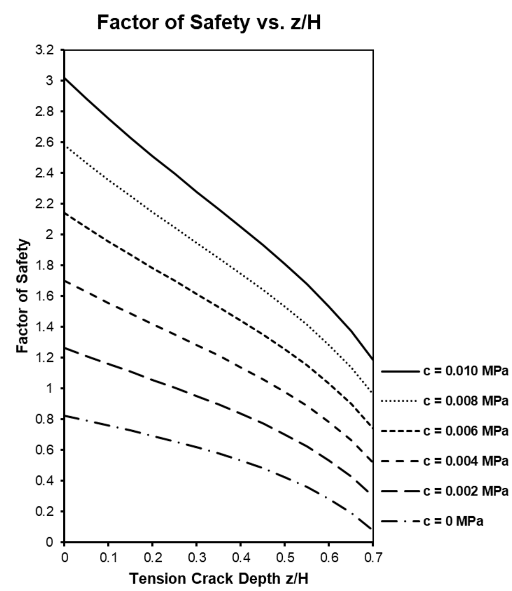


Figure 1.3.4: Factor of Safety vs. Z/H with Values Calculated Using *RocPlane*

The plots provided by Froldi P. [3] and generated by *RocPlane* results have the same shape and similar data points, with slight discrepancies as the tension crack depth (Z/H) values get closer to 0.7 (the tension crack is in the slope face if Z/H exceeds 0.7). Hence, *RocPlane* is verified for this example.

1.4. *RocPlane* Verification Problem #4

[*RocPlane Build 4.001*]

1.4.1. Problem Description

In this verification example, the slope stability along the side of the River Yamun in Garhwal Himalaya, India, where the Lakhwar Dam is located, is analyzed. The results produced by *RocPlane* are compared against the data provided S. Sharma [4]. A series of sensitivity analysis is also conducted with various heights to the release joint.

Geometry and Properties

Table 1.4.1: Geometry Parameters for the Slope

Parameter	Value
Slope Angle	58°
Failure Plane Angle	53°
Tension Crack Angle	134°
Distance from TC to Crest	0 m
Slope Height	20 m → 160 m

Table 1.4.2: Material Properties

Parameter	Value
Unit Weight of Slope	2.75 t/m^3
Unit Weight of Water	1.0 t/m^3
Cohesion	10 t/m^2
Friction Angle	40°

Table 1.4.3: Force Parameters

Parameter	Value
Water Percent Filled TC	0%, 50%, 100%
Seismic Coefficient	0 or 0.15

Peak plane water pressure is assumed at the base of the tension crack.

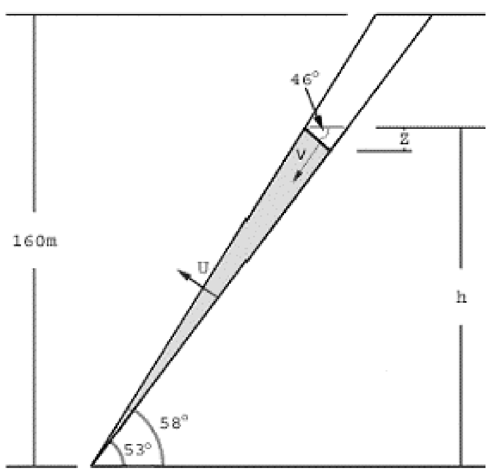


Figure 1.4.1: Geometry of Slope

1.4.2. RocPlane Analysis

Enter the *RocPlane* geometry, material, and force parameters from Table 1.4.1 through Table 1.4.3.

The *RocPlane* model looks like this:

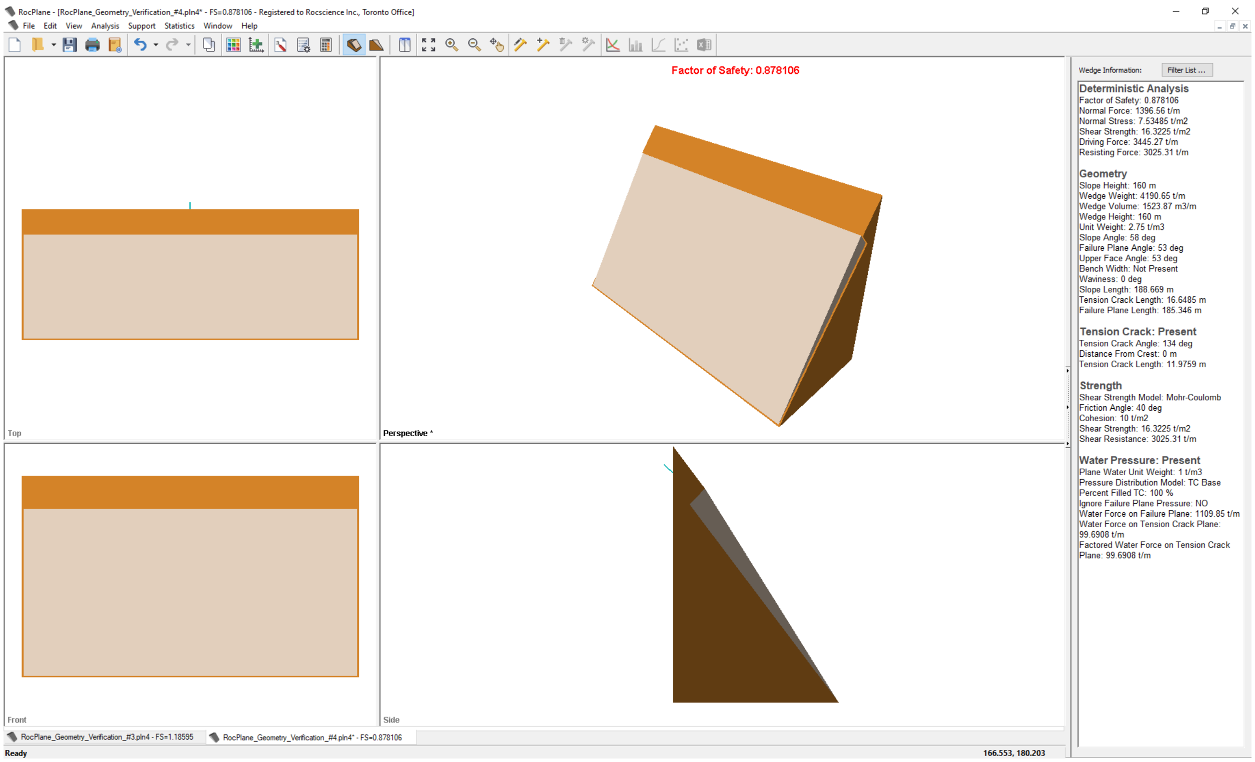


Figure 1.4.2: *RocPlane* Model with Tension Crack (c = 10 t/m^2, H = 160 m, 100% Filled TC)

Sensitivity Analysis

A series of sensitivity analysis is also carried out with varying slope height, cohesion, friction angle, water pressure, tension crack dip, and failure plane dip. The plots generated with the sensitivity data in Microsoft Excel is shown in Figure 1.4.4 and Figure 1.4.5. The parameters for the sensitivity analysis are listed in Table 1.4.4.

Table 1.4.4: Parameters for Sensitivity Analysis

Parameter	Value
Slope Height	20 → 160 m
Cohesion	0 → 20 t/m^2
Friction Angle	30° → 50°
Tension Crack Angle	128° → 140°
Failure Plane Angle	49° → 57°
Water Percent Filled TC	0% → 100%

1.4.3. Results

The analysis by S. Sharma [4] is listed in Table 1.4.5, and the results calculated by *RocPlane* are displayed in Table 1.4.6.

Table 1.4.5: Stability Analysis for Plane Failure from S. Sharma [4]

Slope Height (m)	Factor of Safety					
	Without Seismic Loading			With Seismic Loading		
	100% Filled	50% Filled	0% Filled	100% Filled	50% Filled	0% Filled
20	4.81	4.95	5.06	4.21	4.33	4.43
40	2.62	2.74	2.84	2.24	2.35	2.44
60	1.89	2.00	2.11	1.58	1.68	1.78
80	1.52	1.63	1.74	1.25	1.35	1.45
100	1.30	1.41	1.52	1.06	1.15	1.25
120	1.15	1.26	1.37	0.93	1.02	1.12
140	1.05	1.16	1.26	0.83	0.93	1.02
160	0.97	1.08	1.18	0.76	0.86	0.95

Table 1.4.6: Stability Analysis for Plane Failure with *RocPlane*

Slope Height (m)	Factor of Safety					
	Without Seismic Loading			With Seismic Loading		
	100% Filled	50% Filled	0% Filled	100% Filled	50% Filled	0% Filled
20	4.64392	4.88666	5.06271	4.07428	4.28132	4.43549
40	2.49203	2.68763	2.84751	2.1353	2.30415	2.44525
60	1.77473	1.95463	2.10911	1.48897	1.64509	1.78184
80	1.41608	1.58812	1.73991	1.1658	1.31556	1.45013
100	1.20089	1.36822	1.51839	0.971904	1.11784	1.25111
120	1.05743	1.22162	1.37071	0.842639	0.98603	1.11842
140	0.954959	1.1169	1.26522	0.750306	0.891879	1.02365
160	0.878106	1.03836	1.18611	0.681056	0.821266	0.95257

By comparing the calculated and supplied factor of safety, it can be concluded that with no water force, the results are the same. With 50% and 100% water filled tension crack, there are slight differences in the calculated data. The discrepancies may come from the different equations Sharma [4] used for the factor of safety calculations.

The equations Sharma [4] used are:

With tension crack dip between 10° and 60°:

$$FS = cA + \frac{(W\cos\alpha - U)\tan\phi}{W\sin\alpha + V}$$

With tension crack dip between 61° and 90°:

$$FS = cA + \frac{(W\cos\alpha - U - V\sin\alpha)\tan\phi}{W\sin\alpha + V\cos\alpha}$$

The above equations are quite different from the standard Hoek & Bray equations.

On the other hand, *RocPlane* produced the same sensitivity plots as Sharma's [4] (Figure 1.4.3). *RocPlane* verifies this example.

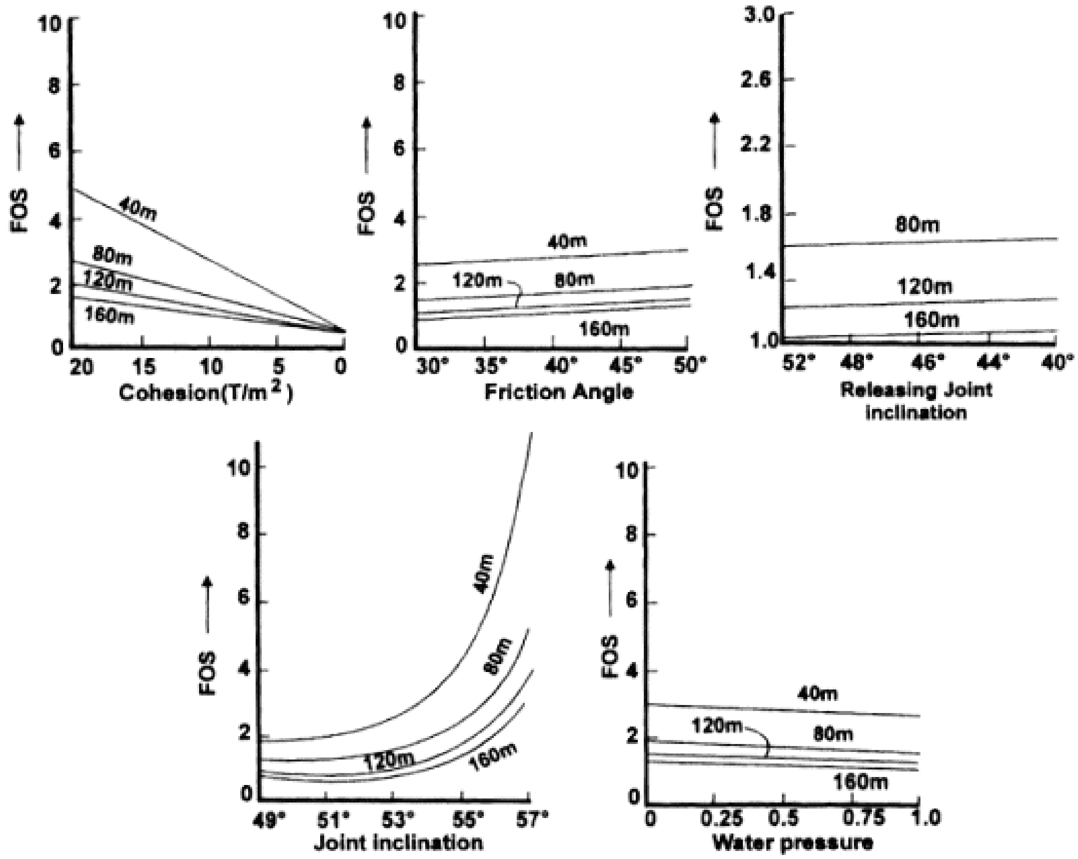


Figure 1.4.3: Sensitivity of FS to Various Factors Causing Instability of the Failure Plane by Sharma [4]

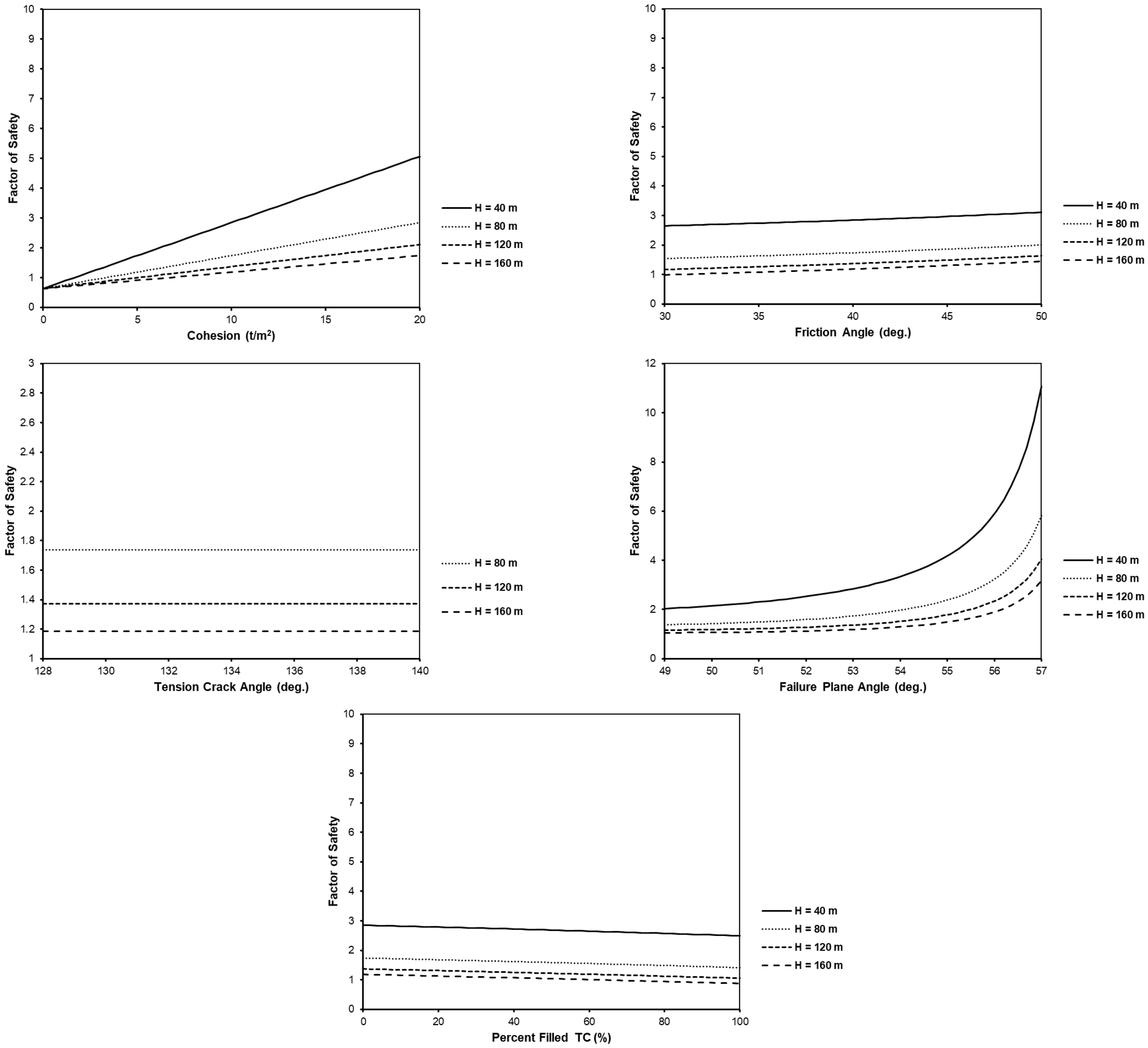


Figure 1.4.4: Sensitivity of Factor of Safety to Various Factors Causing Instability of the Failure Plane, with 0% Water Filled Tension Crack and No Seismic Loading

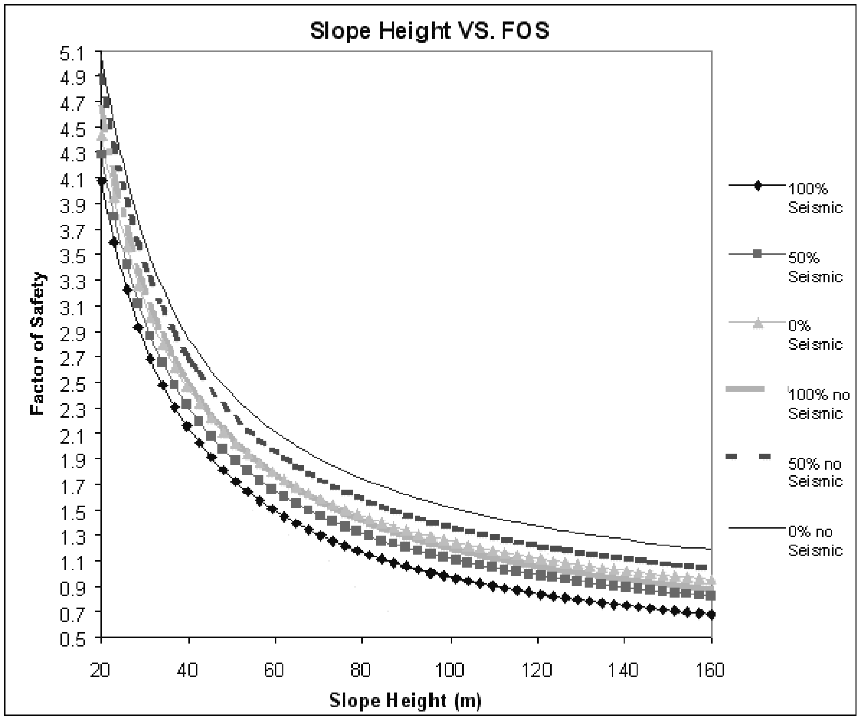


Figure 1.4.5: *RocPlane* Sensitivity Analysis with Slope Height Varied From 20 m to 160 m

1.5. *RocPlane* Verification Problem #5

[*RocPlane Build 4.001*]

1.5.1. 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 1.5.1: 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 1.5.2: 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.

1.5.2. *RocPlane* Analysis

Enter the *RocPlane* geometry and shear strength parameters from Table 1.5.1 through Table 1.5.2.

The *RocPlane* model looks like this:

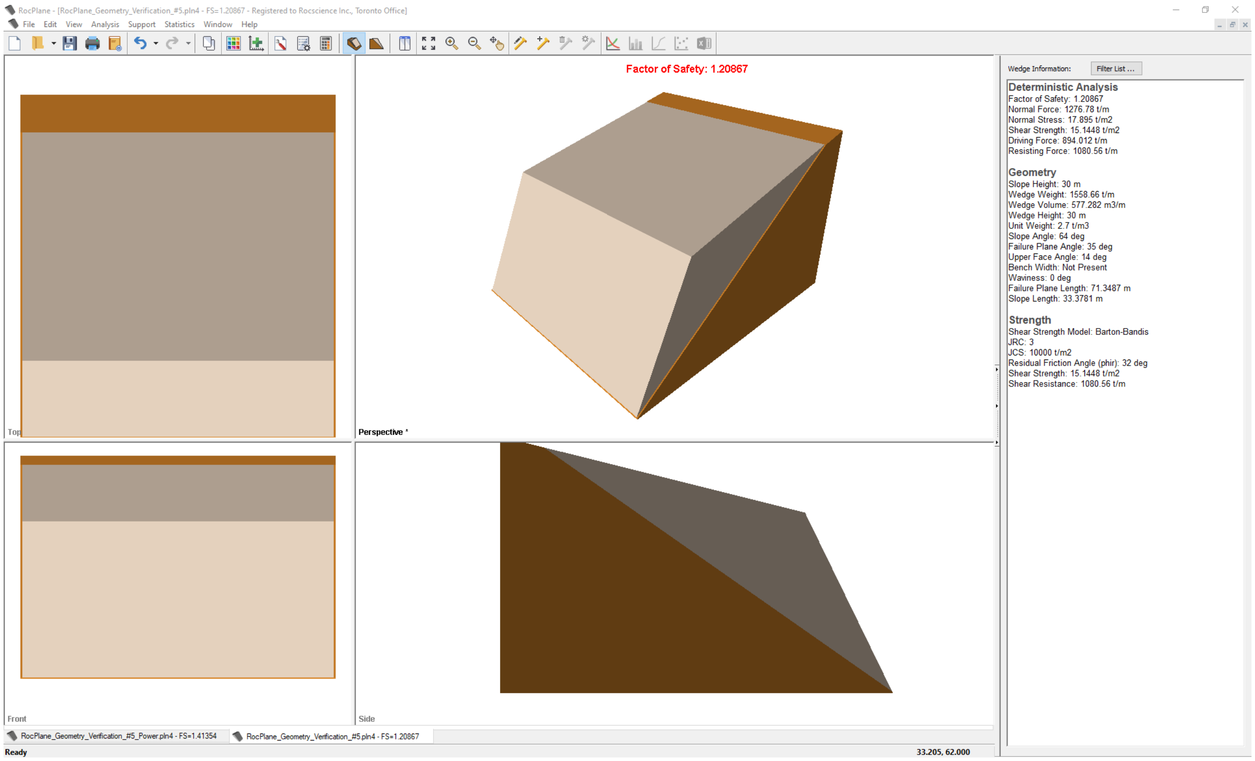


Figure 1.5.1: *RocPlane* Model

1.5.3. Results

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 1.5.3, and the results produced by *RocPlane* are listed in Table 1.5.4.

Table 1.5.3: 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: JRC = 3 Wav. = 3°	30	1.27	0.87	1.27	0.82	1.21	0.93	1.21	0.74
	15	1.42	0.97	1.35	0.93	1.45	1.29	1.25	0.76
	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: JRC = 7 Wav. = 11°	30	1.47	0.98	1.47	0.93	1.41	1.05	1.78	1.16
	15	1.62	1.09	1.55	1.05	1.65	1.41	1.92	1.26
	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: JRC = 11 Wav. = 20°	30	1.72	1.13	1.71	1.08	1.65	1.19	2.72	1.96
	15	1.86	1.23	1.79	1.19	1.89	1.55	3.15	2.32
	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 1.5.4: Factor of Safety Computed by *RocPlane* 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	1.125	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 1.5.2. A similar graph generated with Microsoft Excel with factor of safety data generated by *RocPlane* is shown in Figure 1.5.3.

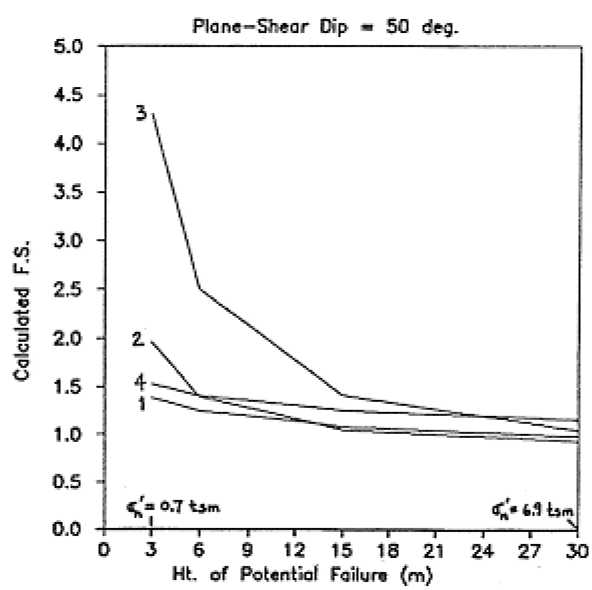


Figure 1.5.2: Sensitivity Plot of FS vs. Slope Height by Miller

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

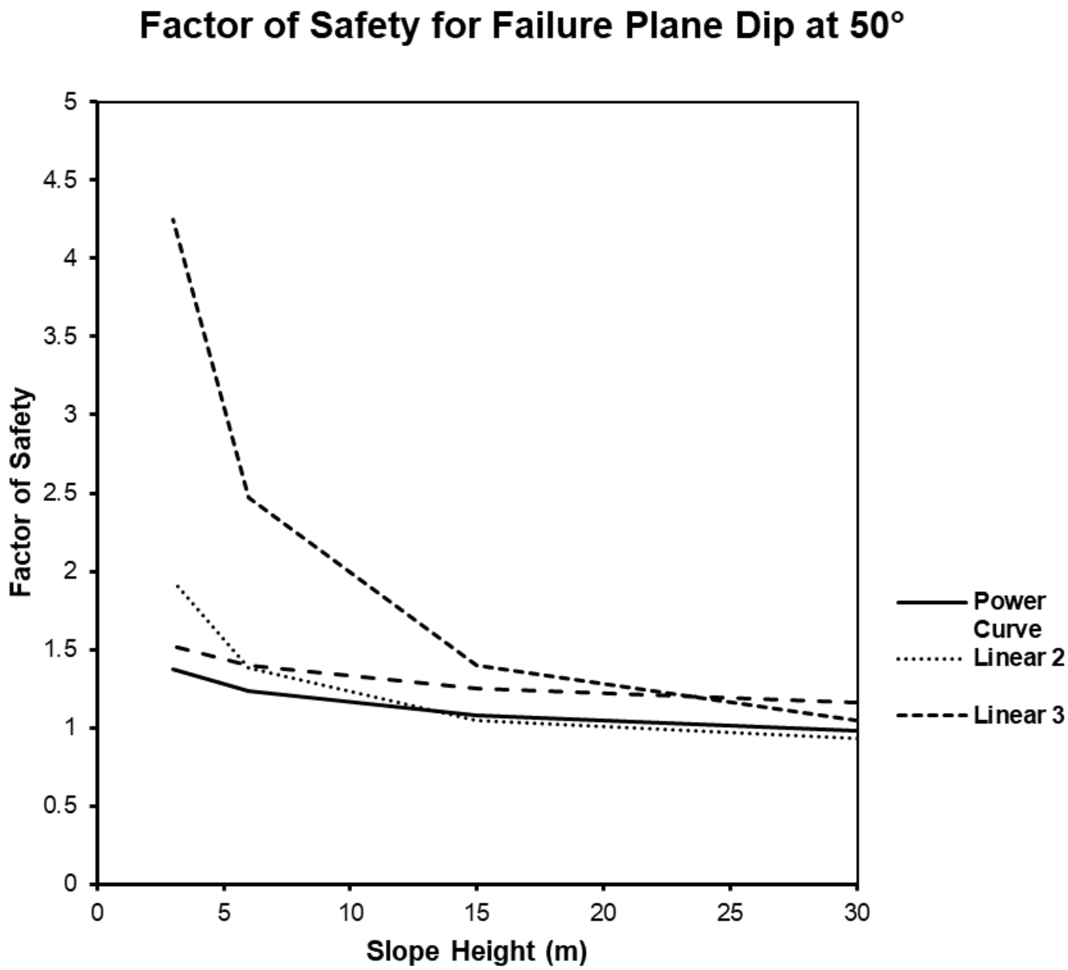


Figure 1.5.3: Sensitivity Plot of FS vs. Slope Height by *RocPlane*

By comparison of the data in Table 1.5.3 with Table 1.5.4 and Figure 1.5.2 with Figure 1.5.3, the results are either the same or within a difference of 1.5%. Therefore, *RocPlane* verifies the results provided by Miller [5].

1.6. *RocPlane* Verification Problem #6

[*RocPlane Build 4.001*]

1.6.1. Problem Description

This problem was taken from Priest (1993) and involves the analysis of rigid blocks, and the sensitivity of various parameters.

This verification problem analyzes a slope undergoing planar failure (Figure 1.6.1). The slope has a tension crack at the crest 15 m deep. A water table is also present, filling the tension crack 25% at the line of failure. No seismic forces are present. The factor of safety for the block is required. A sensitivity analysis is performed varying cohesion, friction angle, failure plane angle, and percent TC filled (Figure 1.6.3).

Geometry and Properties

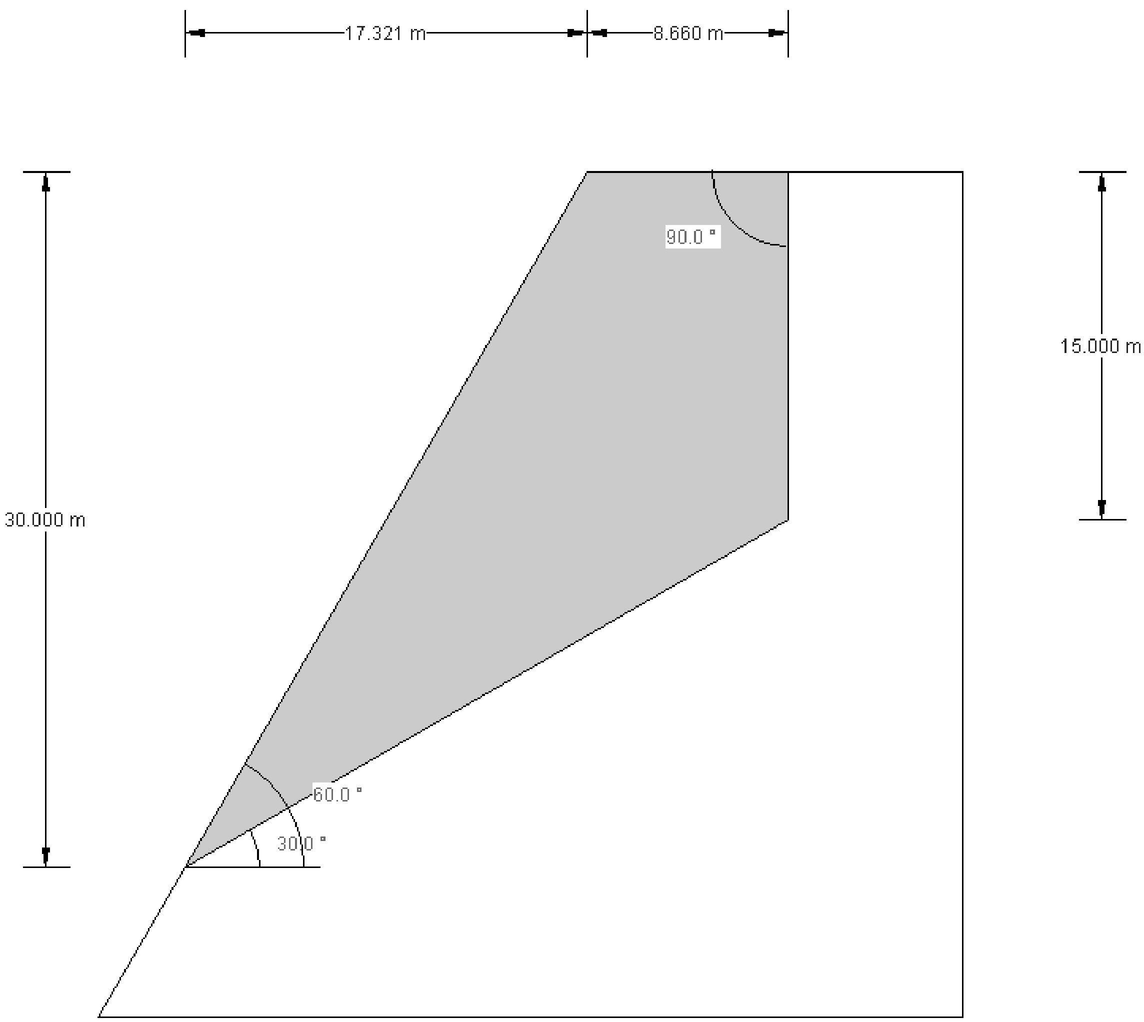


Figure 1.6.1: Slope Geometry

Table 1.6.1: Slope and Failure Plane Geometry

Parameter	Mean Value	Range
Failure Plane Angle (deg.)	30	28 to 36
Slope Height (m)	30	-
Slope Angle (deg.)	60	-
Upper Face Angle (deg.)	0	-
Tension Crack Angle (deg.)	90	-
Tension Crack Distance from Crest (m)	8.660	-

Table 1.6.2: Material Properties

Parameter	Mean Value	Range
Cohesion (t/m^2)	2	0 to 4
Friction Angle (deg.)	30	28 to 36
Unit Weight of Slope (t/m^3)	2.5	-
Unit Weight of Water (t/m^3)	0.981	-

Table 1.6.3: Force Parameters

Parameter	Mean Value	Range
Peak Pressure	TC Base	-
Percent filled TC (%)	25	0 to 100

1.6.2. RocPlane Analysis

Deterministic Analysis

Enter the mean values in Table 1.6.1 through Table 1.6.3 into *RocPlane* Deterministic Input Data.

The *RocPlane* model looks like this:

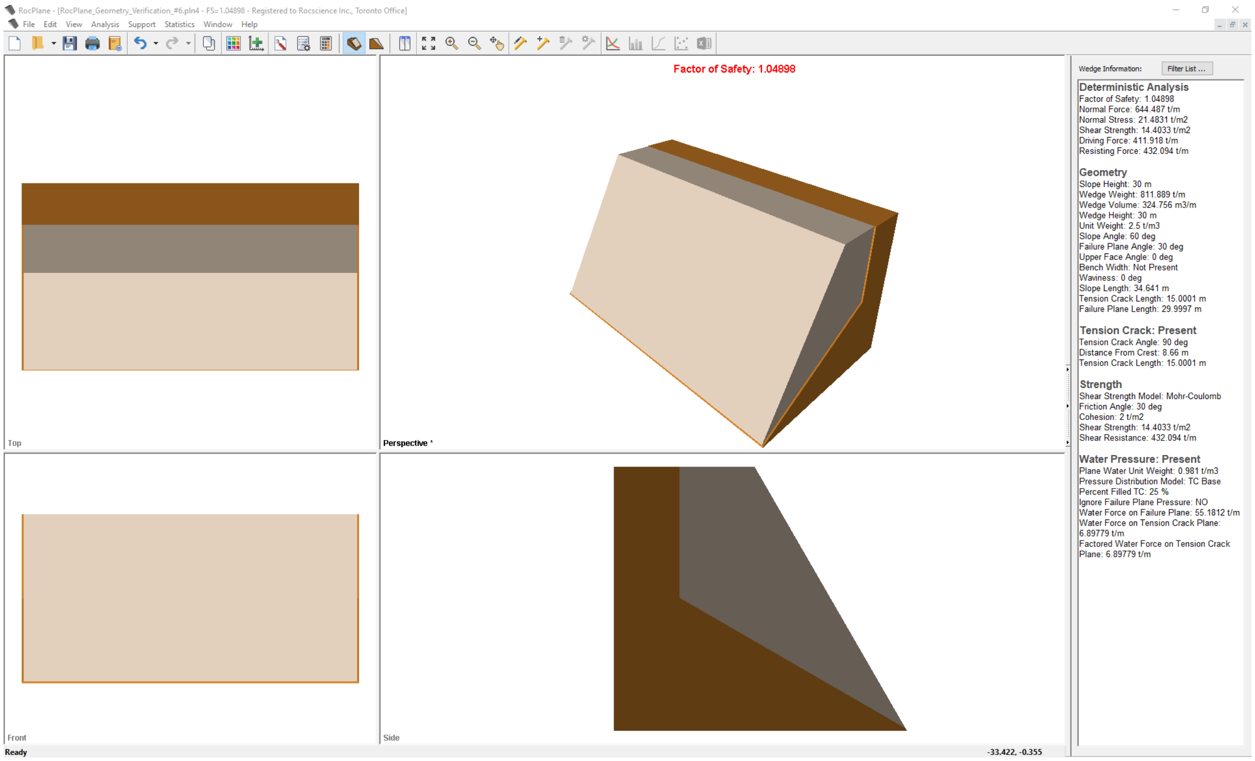


Figure 1.6.2: *RocPlane* Model with Tension Crack

Sensitivity Analysis

Enter the range of values in Table 1.6.1 through Table 1.6.3 into *RocPlane* Sensitivity Input.

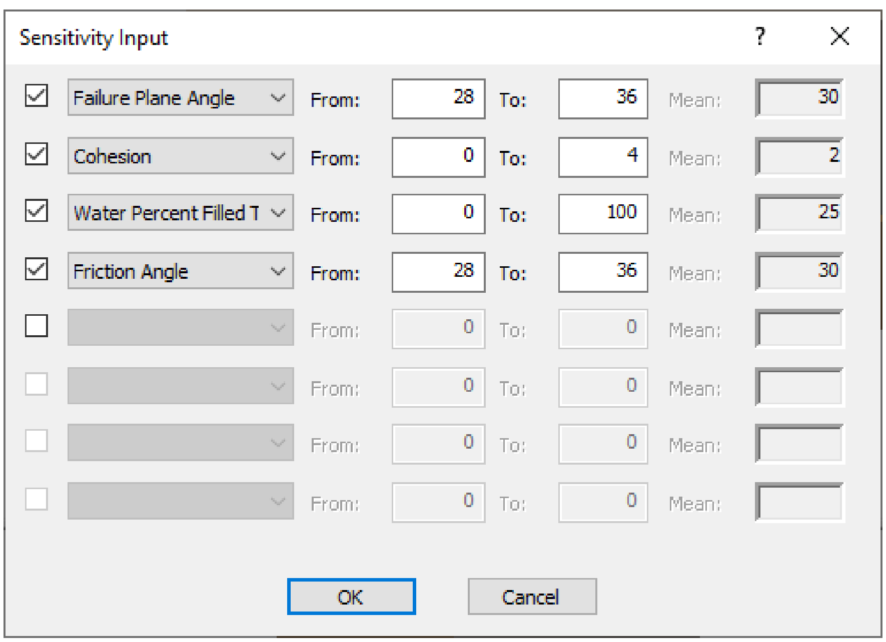


Figure 1.6.3: Sensitivity Analysis Parameters

1.6.3. Results

The deterministic analysis using RocPlane produced a factor of safety of 1.04898, matching the factor of safety provided by Priest (FS = 1.049) [6].

The sensitivity analysis plot generated by RocPlane (Figure 1.6.5) also match the plot provided by Priest (Figure 1.6.4). Therefore, *RocPlane* verifies this example.

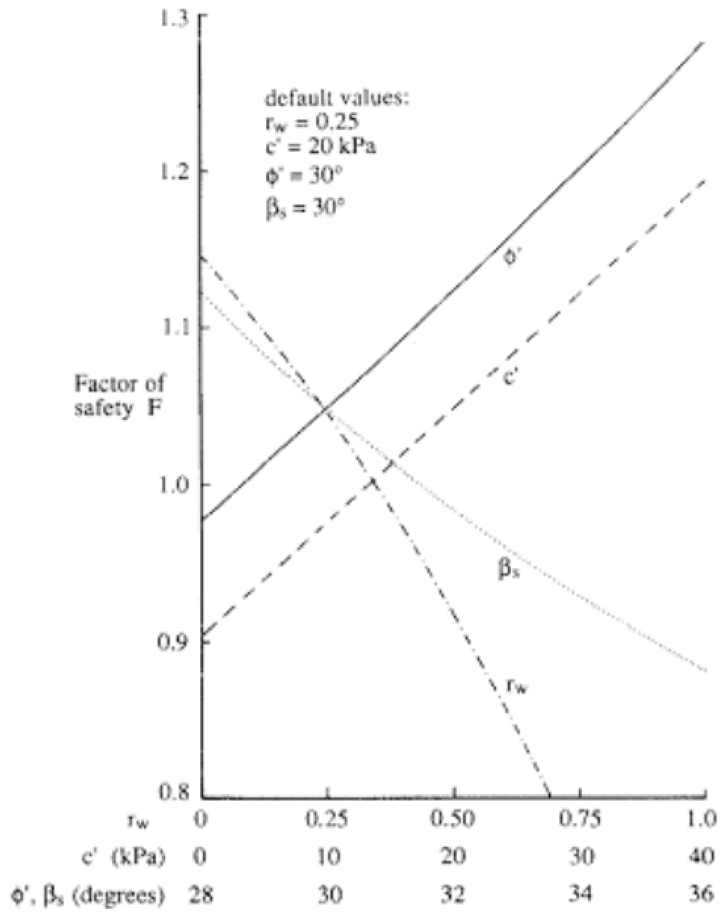


Figure 1.6.4: Sensitivity Analyses by Priest [6]

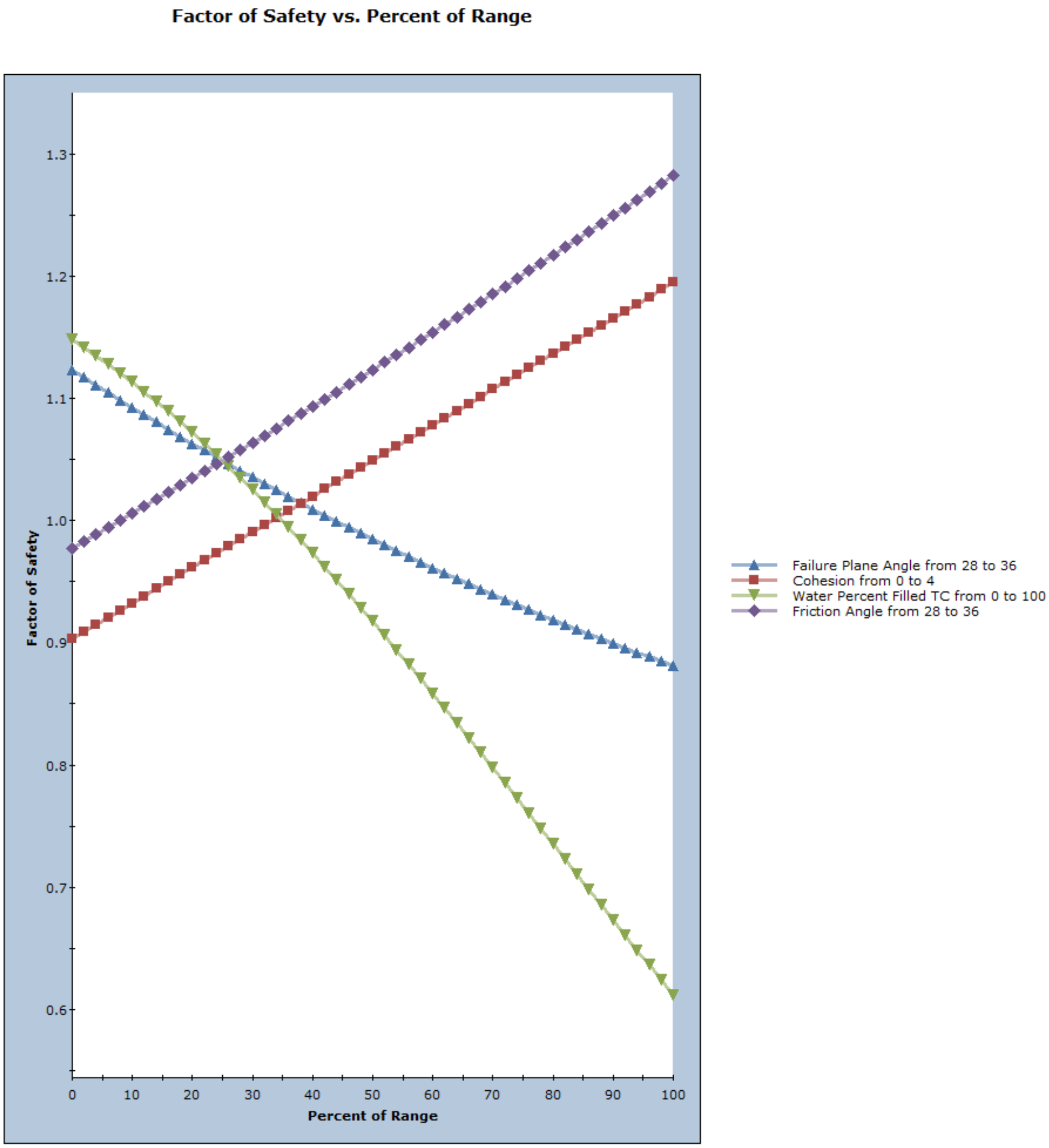


Figure 1.6.5: *RocPlane* Sensitivity Plot

1.7. *RocPlane* Verification Problem #7

[*RocPlane Build 4.001*]

1.7.1. Problem Description

This problem is taken from *Rock Slope Stability* by Kliche [7]. It is his example problem on kinematic slope stability analysis of planar failure, and it includes reinforcement requirements.

This verification problem models planar failure with a tension crack. The tension crack is 51% filled with water, and water is also observed to be leaking out of the failure plane at the slope interface. The properties of the slope are listed in Table 1.7.1. The safety factor of the unreinforced slope is required. Using the parameters for reinforcement given in Table 1.7.1, the slope is stabilized so that it has a reinforced safety factor of 1.5. The capacity of the rock bolt is then determined.

Geometry and Properties

Table 1.7.1: Slope and Plane Geometry

Parameter	Value
Slope Angle (deg.)	50
Slope Height (m)	30
Failure Plane Angle (deg.)	35
Upper Slope Angle (deg.)	0
Tension Crack Angle (deg.)	90
Tension Crack Distance from Crest (m)	9

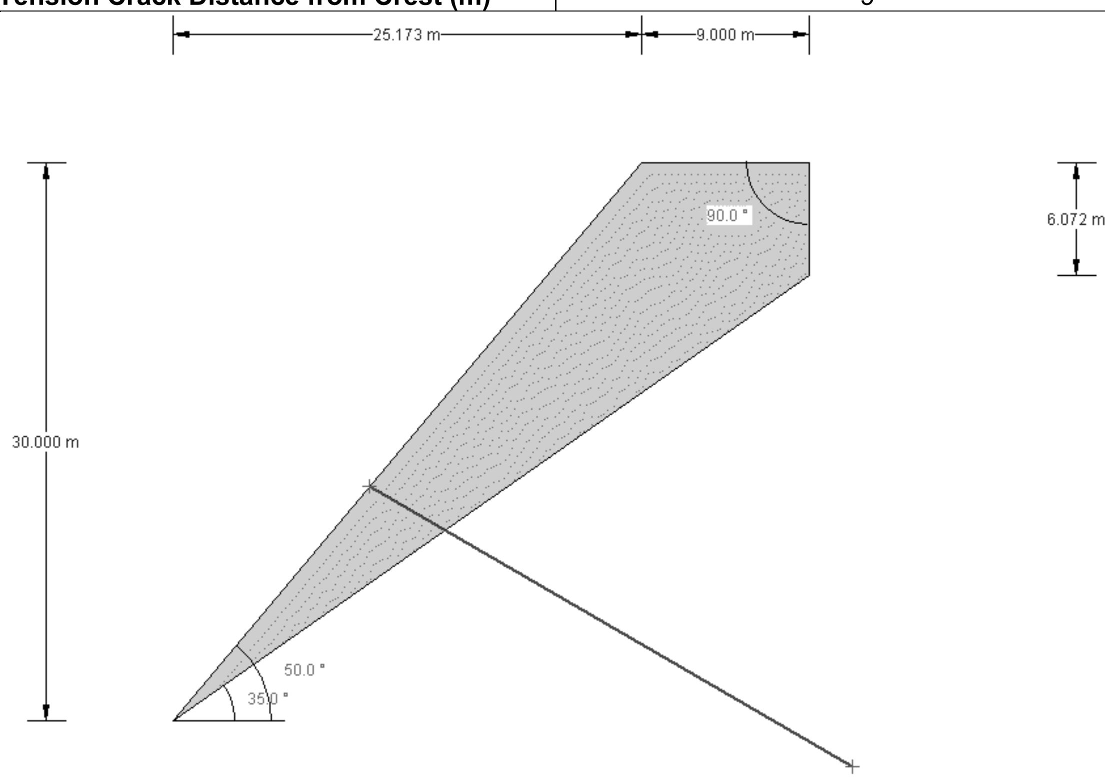


Figure 1.7.1: Slope Geometry

Table 1.7.2: Material Properties

Parameter	Value
Cohesion (t/m^2)	7
Friction Angle (deg.)	30
Unit Weight of Slope (t/m^3)	2.79
Unit Weight of Water (t/m^3)	0.981

Table 1.7.3: Force Parameters

Parameter	Value
External Force (t/m)	37
External Force Angle (deg.)	90
Seismic Acceleration	0.10 g
Peak Pressure	TC Base
Percent Filled TC (%)	51

Table 1.7.4: Bolt Parameters

Parameter	Value
Bolt Type	Active
Rock-Bolt Angle (deg.)	30
Rock-Bolt Capacity (t/m)	111

1.7.2. *RocPlane* Analysis

Deterministic Analysis

Enter the values in Table 1.7.1 through Table 1.7.3 into *RocPlane* Deterministic Input Data.

The *RocPlane* model looks like this:

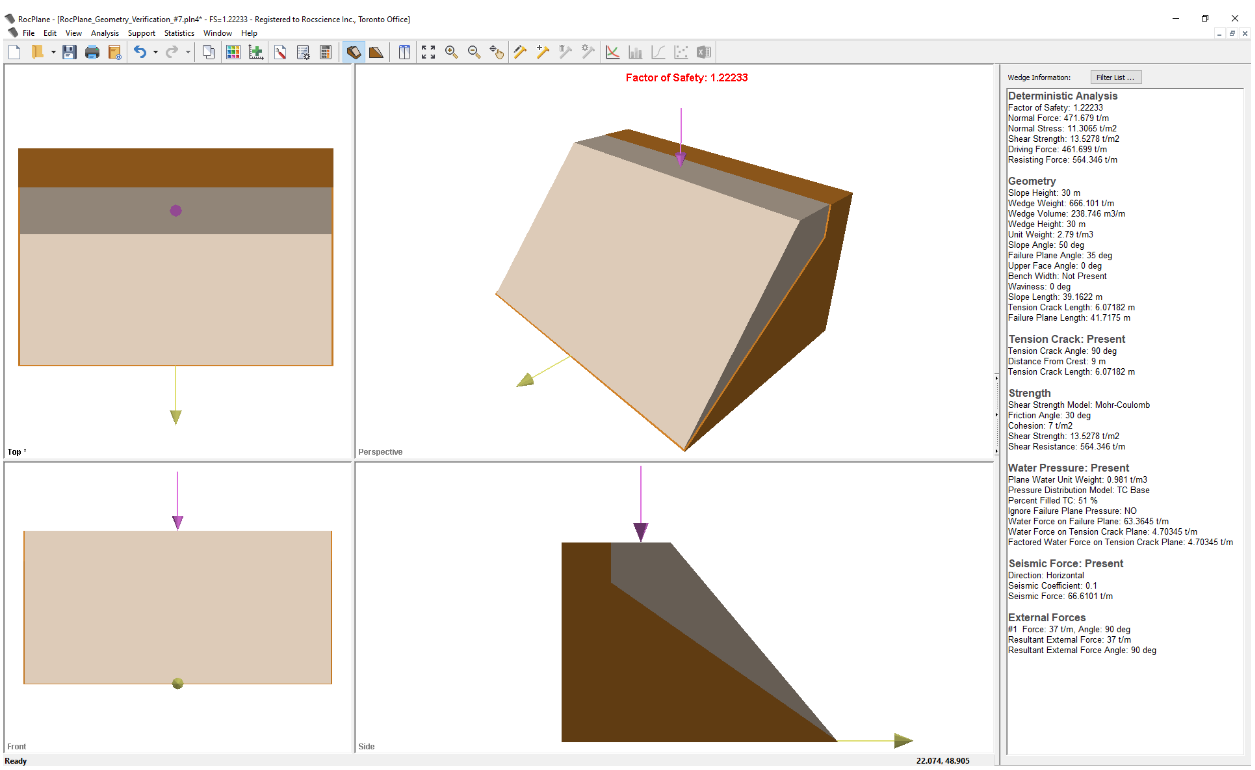


Figure 1.7.2: *RocPlane* Model with Tension Crack and No Bolt Reinforcement

Add a spot bolt reinforcement and enter the values in Table 1.7.4 into *RocPlane* Add Spot Bolt and Bolt Properties.

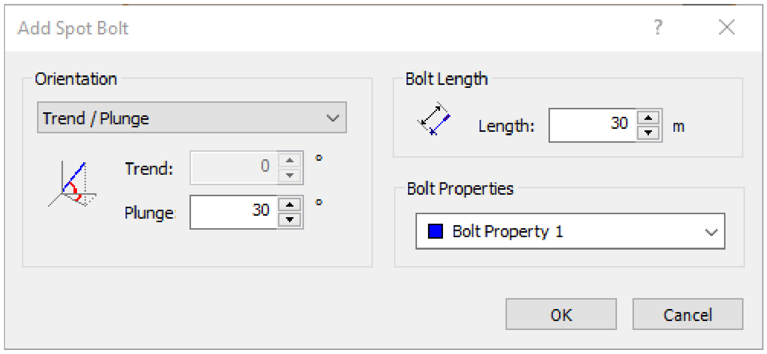


Figure 1.7.3: *RocPlane* Add Spot Bolt

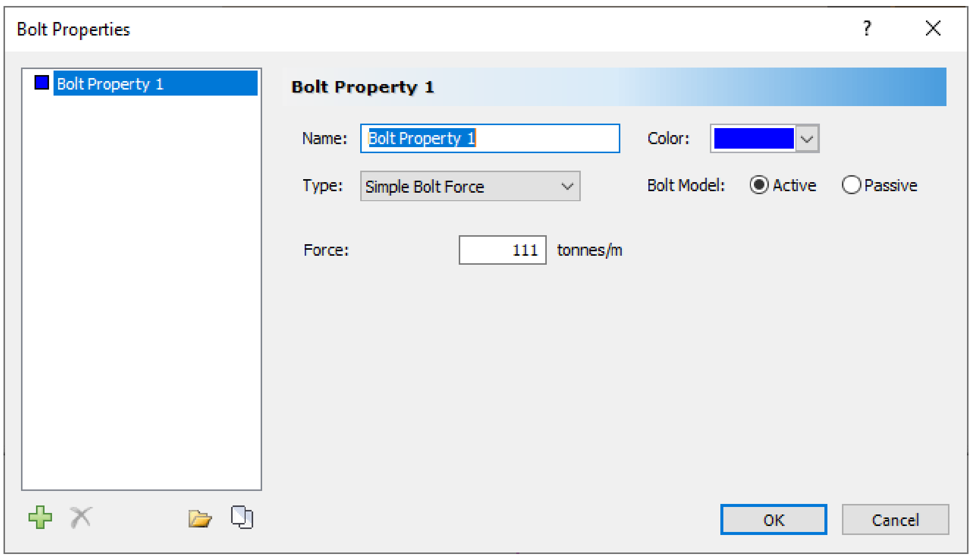


Figure 1.7.4: *RocPlane* Bolt Properties

The *RocPlane* model looks like this:

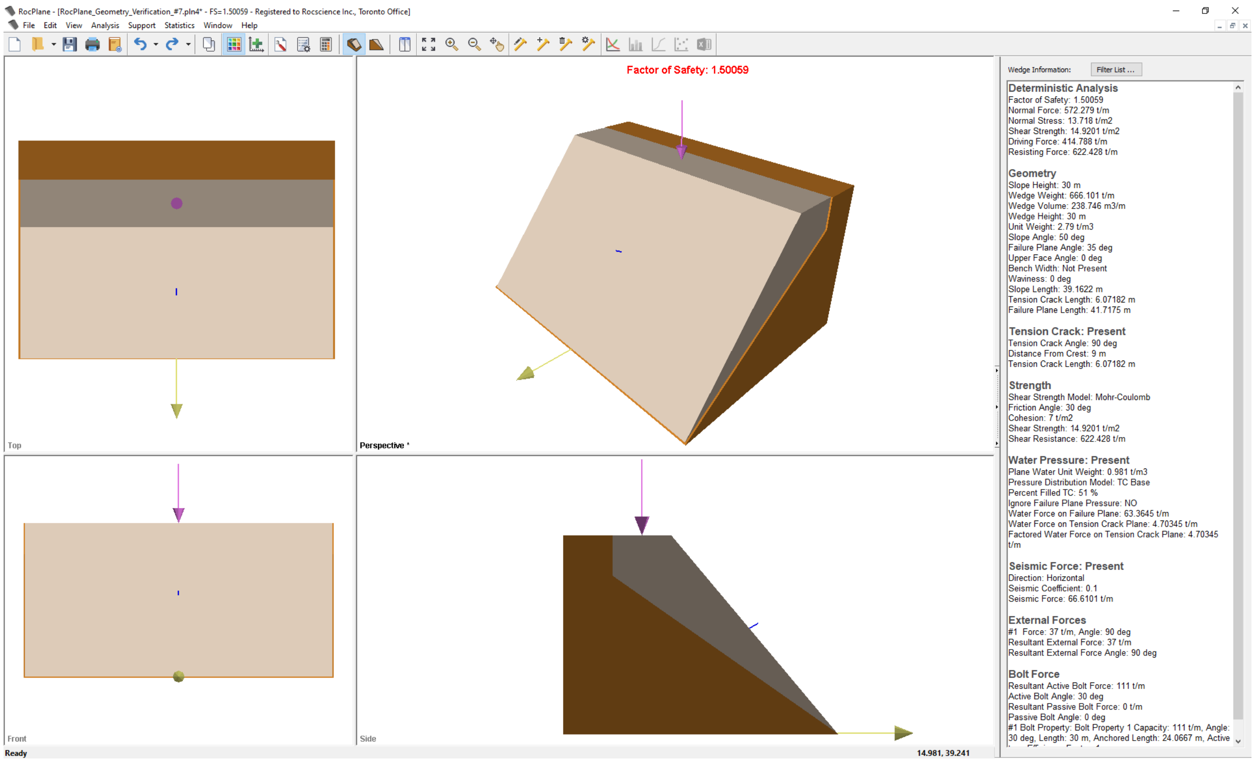
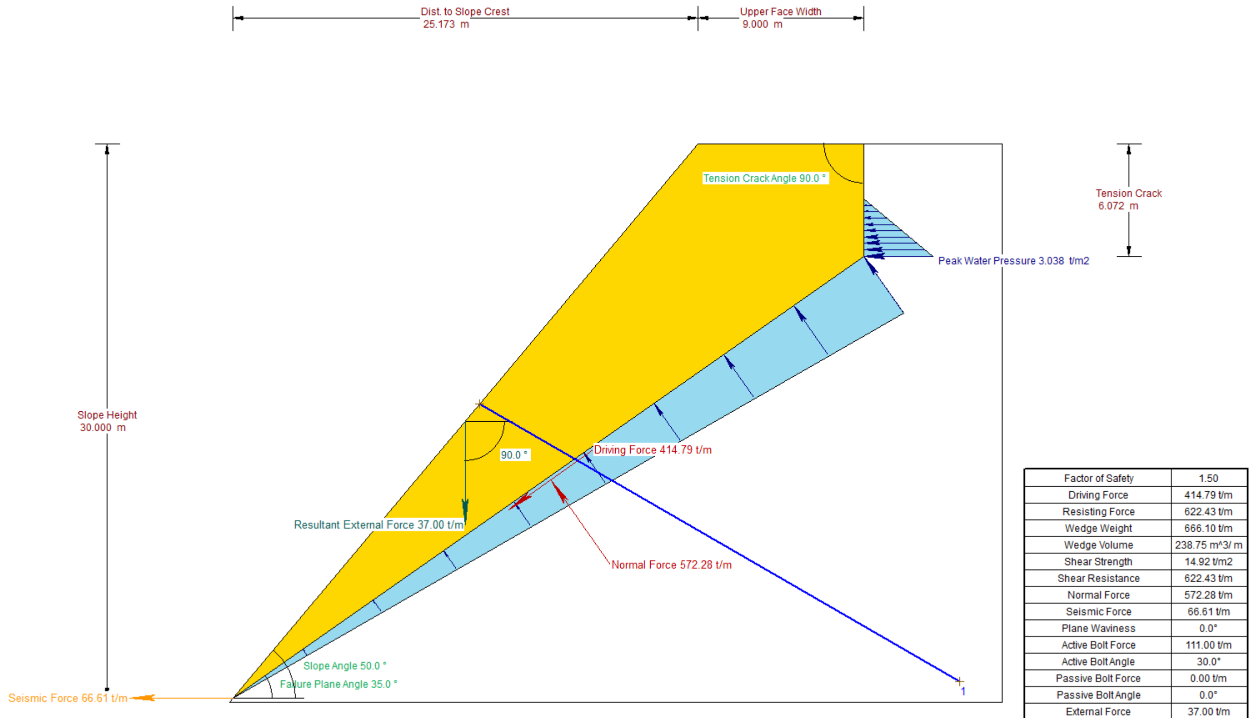


Figure 1.7.5: *RocPlane* Model with Tension Crack and with Bolt Reinforcement

1.7.3. Results

With no reinforcement, the factor of safety is 1.22233. With a rock bolt reinforcement, the factor of safety increases to 1.50059.



Bolt Definitions:

#	Angle	Capacity	Length	AnchLength	Bolt Properties	Efficiency Factor
1	30.0 °	111.00 tonnes/m	30.000 m	24.067 m	Bolt Property 1	1.000

Factor of Safety	1.50
Driving Force	414.79 t/m
Resisting Force	622.43 t/m
Wedge Weight	666.10 t/m
Wedge Volume	238.75 m^3/ m
Shear Strength	14.92 t/m2
Shear Resistance	622.43 t/m
Normal Force	572.28 t/m
Seismic Force	66.61 t/m
Plane Waviness	0.0°
Active Bolt Force	111.00 t/m
Active Bolt Angle	30.0°
Passive Bolt Force	0.00 t/m
Passive Bolt Angle	0.0°
External Force	37.00 t/m
External Force Angle	90.0°
Water Force on Failure Plane	63.36 t/m
Water Force on Tension Crack	4.70 t/m

Figure 1.7.6: *RocPlane* Reinforced Planar Wedge Analysis

These results agree with Kliche's required rock bolt capacity of 111 t/m, in order to achieve a factor of safety of 1.5.

1.8. *RocPlane* Verification Problem #8

[*RocPlane Build 4.001*]

1.8.1. 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. *RocPlane* must do the analysis in imperial units in order to use the parameters quoted by the authors.

This verification problem analyzes a simple slope with three different definitions of material properties (Table 1.8.2). There is no tension crack present, and the failure surface is dry. The upper slope is horizontal. The geometry is given in Figure 1.8.1.

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

Table 1.8.1: Slope and Plane Geometry

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

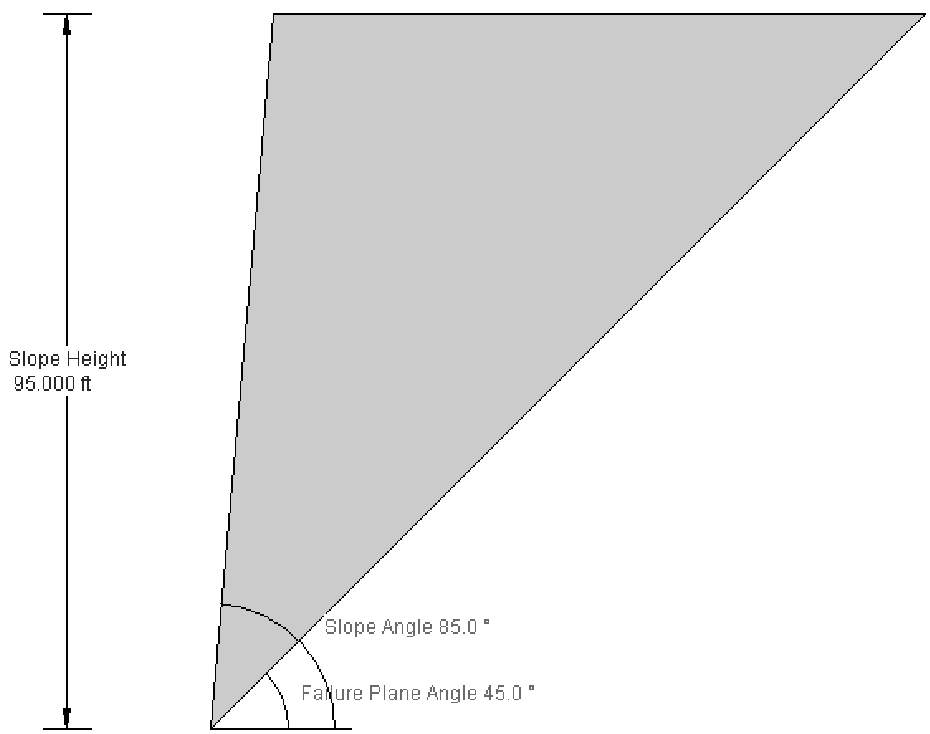


Figure 1.8.1: Geometry of Slope

Table 1.8.2: Material 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

1.8.2. RocPlane Analysis

Deterministic Analysis

Enter the values from Table 1.8.1 and Table 1.8.2 into *RocPlane*.

The *RocPlane* models look like these:

<u>Case 1:</u>

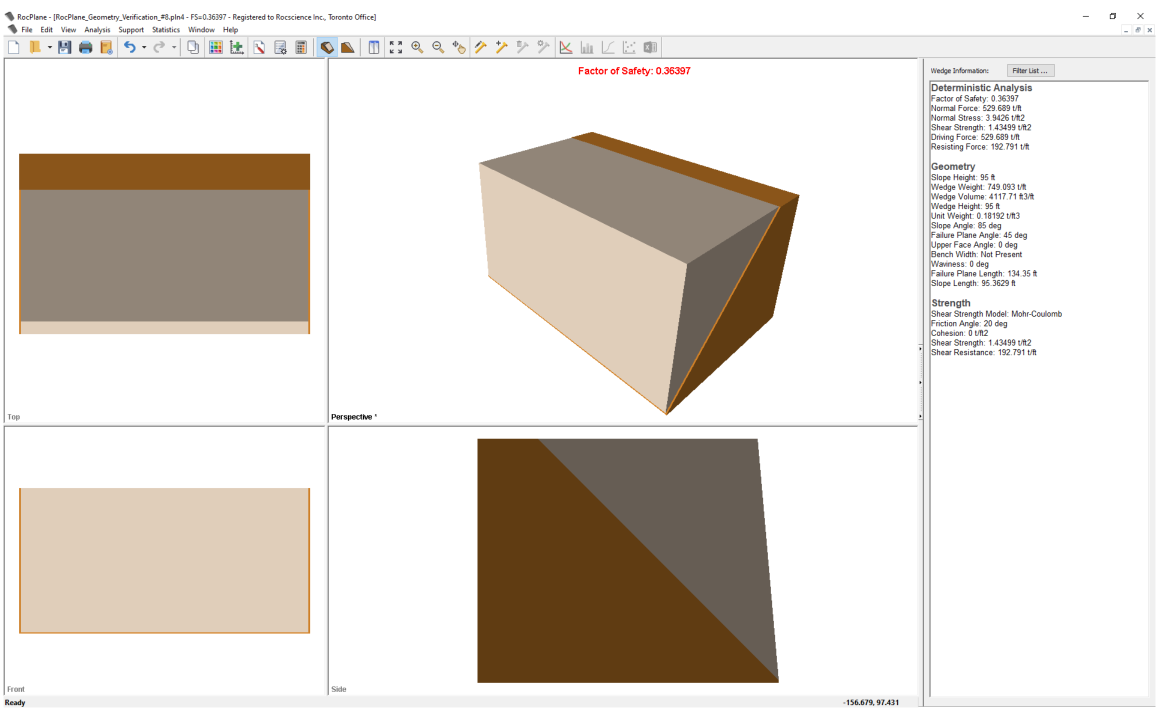


Figure 1.8.2: *RocPlane* Model (Case 1)

Case 2:

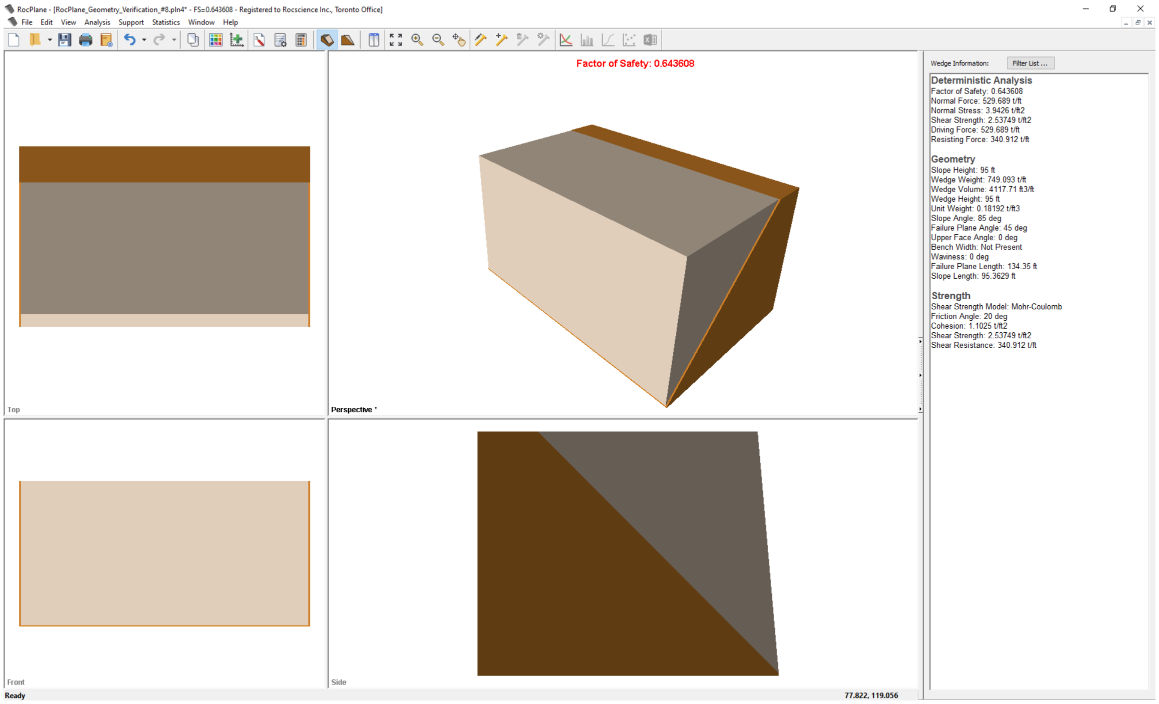


Figure 1.8.3: *RocPlane* Model (Case 2)

Case 3:

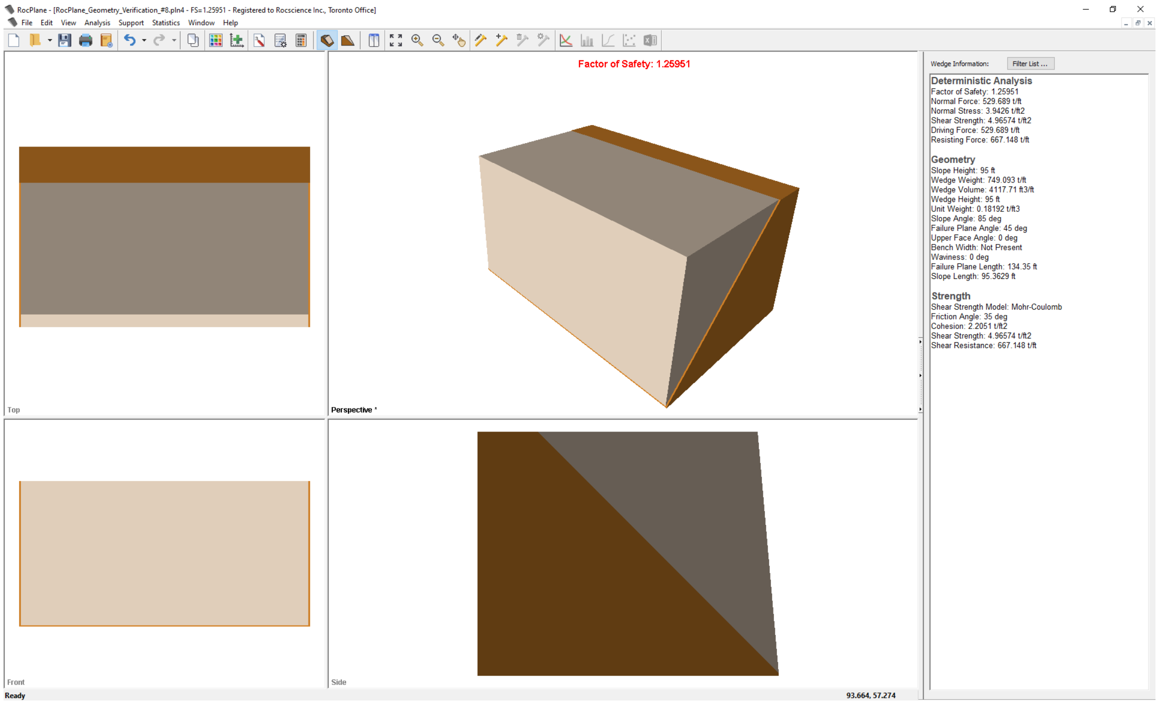


Figure 1.8.4: *RocPlane* Model (Case 3)

1.8.3. Results

Table 1.8.3: Factor of Safety Comparison

Case	*RocPlane* Factor of Safety	Watts and West Factor of Safety
1	0.36397	0.364
2	0.64361	0.644
3	1.25951	1.260

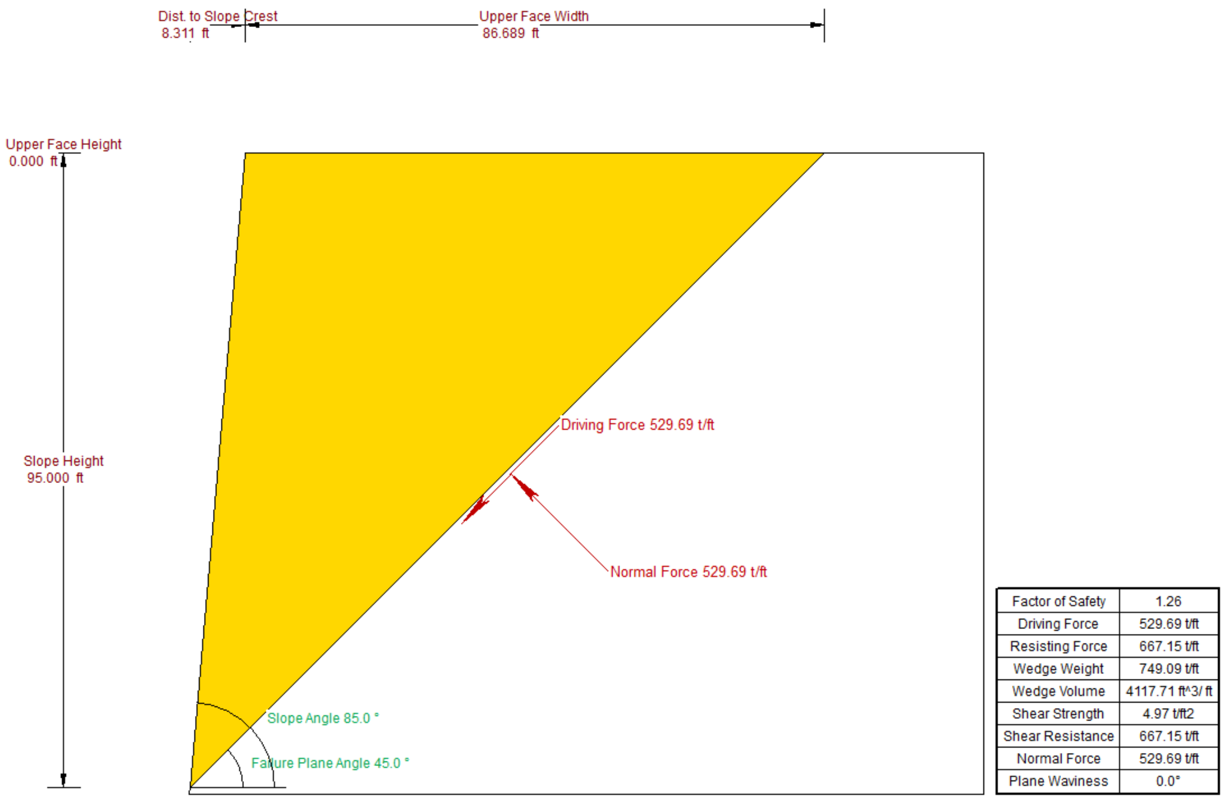


Figure 1.8.5: *RocPlane* Planar Wedge Analysis (Case 3)

```
- - - - - - - - - - - - - - - - - - - - 

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

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

1.9. References

1. **Dr. E Hoek,** 2000, “A slope stability problem in Hong Kong”, *Practical Rock Engineering***, pp.** 92-104.
2. S.Sharma, T.K. Raghuvanshi and R.Anbalagan, 1995, “Plane failure analysis of rock slopes”, *Geotechnical and Geological Engineering* , 13, pp. 105-111.
3. Froldi P., 1996, “Some Developments to Hoek & Bray’s Formulae for the Assessment of the Stability in Case of Plane Failure”, *BULLETIN of the International Association of ENGINEERING GEOLOGY*, No. 54, pp. 91-95.
4. Sanjeev Sharma, Tarun Raghuvanshi, Atul Sahai, 1993, “An Engineering geological appraisal of the Lakhwar Dam, Garhwal Himalaya, India”, *Engineering Geology*, pp. 381-398.
5. 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.
6. Priest, Steven. 1993. *Discontinuity analysis for rock engineering.* London: Chapman and Hall.
7. Kliche, C.A. 1999. *Rock Slope Stability.* Litttleton CO: Society for Mining, Metallurgy, and Exploration.
8. 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.

2. *RocPlane* Bolt Model Verification

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

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

2.1. *RocPlane* Verification Problem #1

[*RocPlane Build 4.001*]

2.1.1. *RocPlane* Analysis

Analysis in *RocPlane* Version 4.000

First, verify the *RocPlane* results against the results from the previous version. Use the default slope when opening a new file. Specify a bolt of **Type Simple Bolt Force** with a **Force** of **0.2 MN**. The results of both Active and Passive bolt models are compared.

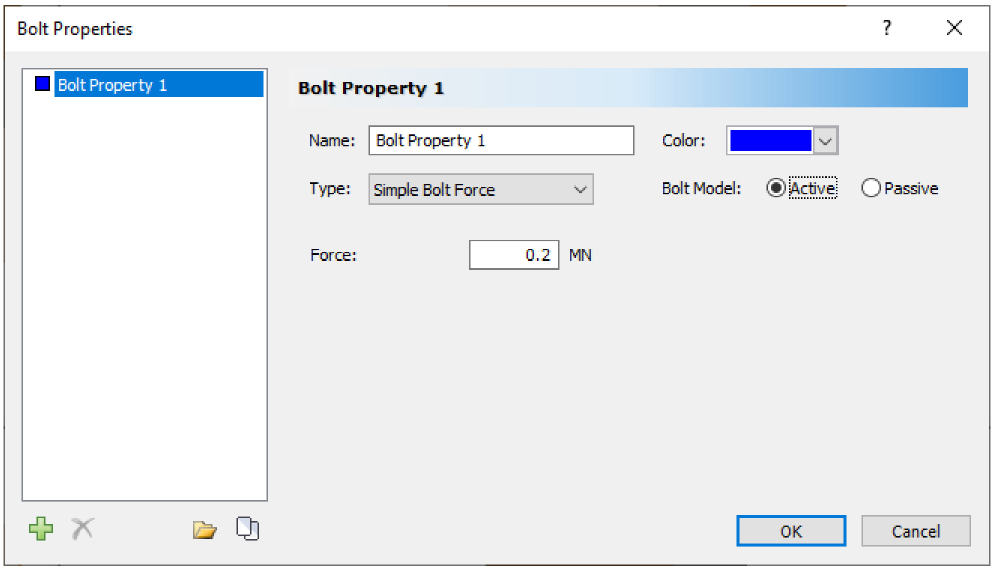


Figure 2.1.1: *RocPlane* Bolt Property [v4.000]

Add a bolt on the slope face. Specify a **plunge** angle of **40º**, normal to the slope surface, and enter a **bolt length** of **36 m**.

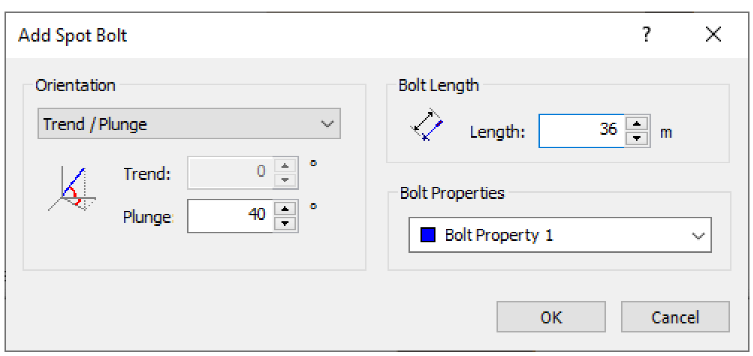


Figure 2.1.2: *RocPlane* Add Spot Bolt [v4.000]

The *RocPlane* model looks like this:

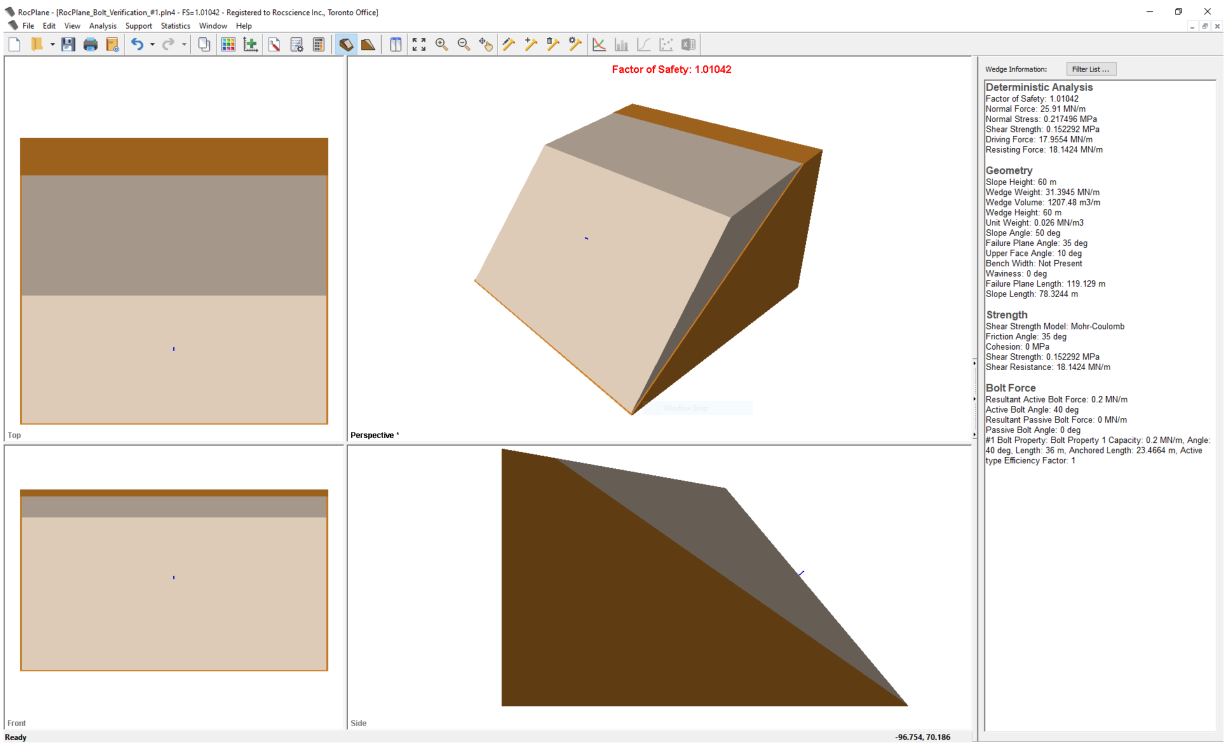


Figure 2.1.3: *RocPlane* Model with Bolt [v4.000]

Analysis in *RocPlane* Version 3.001

Add the same bolt in *RocPlane* v3:

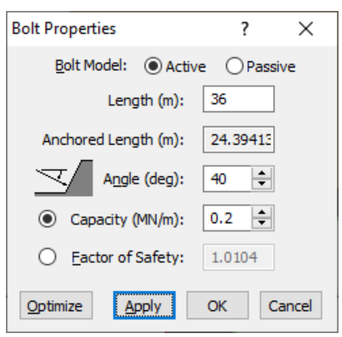


Figure 2.1.4: *RocPlane* Bolt Properties Dialog in [v3.001]

The results are summarized in Table 2.1.1.

Table 2.1.1: Comparison of RocPlane Factor of Safety

	RocPlane v4.000	*RocPlane v3.001*
FS with Active Bolt	1.01042	1.01042
FS with Passive Bolt	1.01039	1.01039

The two results are identical.

2.2. *RocPlane* Verification Problem #2

[*RocPlane Build 4.001*]

2.2.1. Problem Description

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

Geometry and Material Properties

Table 2.2.1: Slope and Plane Geometry

Parameter	Value
Slope Angle (°)	65
Height (m)	33
Failure Plane Angle (°)	55
Failure Plane Waviness (°)	0
Upper Face Angle (°)	0

Table 2.2.2: Material Properties

Parameter	Value
Shear Strength Model	Mohr-Coulomb
ϕ (°)	35
c (MPa)	0
Unit Weight (MN/m^3)	0.026

Bolt Properties

Table 2.2.3: Material Properties

Parameter	Value
Bolt Model	Active or Passive
Bolt Plunge (deg.)	25
Bolt Length (m)	36

2.2.2. RocPlane Analysis

Enter the geometry and strength parameters from Table 2.2.1 and Table 2.2.2 into *RocPlane*.

The *RocPlane* model looks like this:

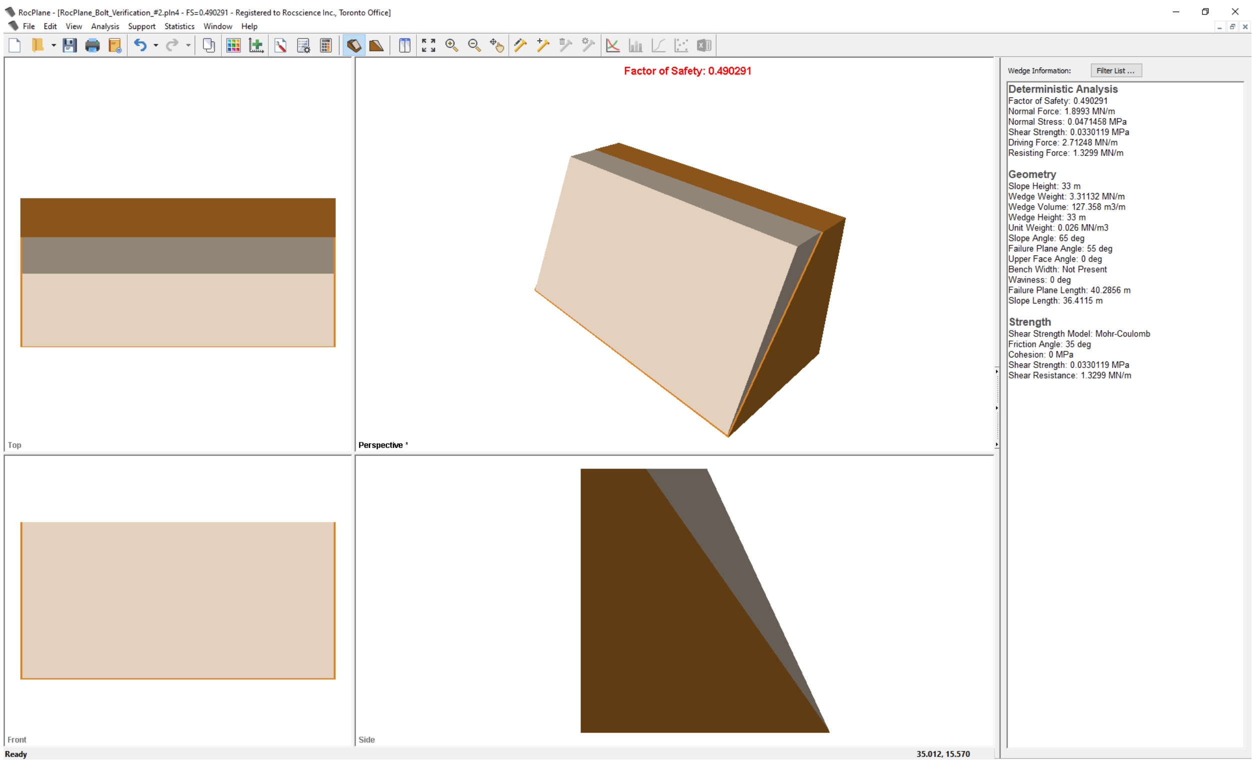


Figure 2.2.1: RocPlane Model Geometry

Bolt Properties

Add a single bolt. It doesn't matter where the bolt is located on the slope. The location of bolts has no effect on safety factor, since all forces in the slope/wedge stability analysis are assumed to pass through the centroid of the wedge.

In the Add Spot Bolt dialog, enter a **Plunge** of **25º** and a **Bolt Length** of **36 m**.

Use the default capacity values for each Bolt Type. Run analysis with each Bolt type, **Active/Passive** bolt model, with/without **Use Shear Strength** checked and with/without **Use Bolt Orientation Efficiency** checked. When enabling Use Bolt Orientation Efficiency, use the default **Cosine Tension/Shear** Method. When testing shear bolts, uncheck the Use Bolt Orientation Efficiency option.

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

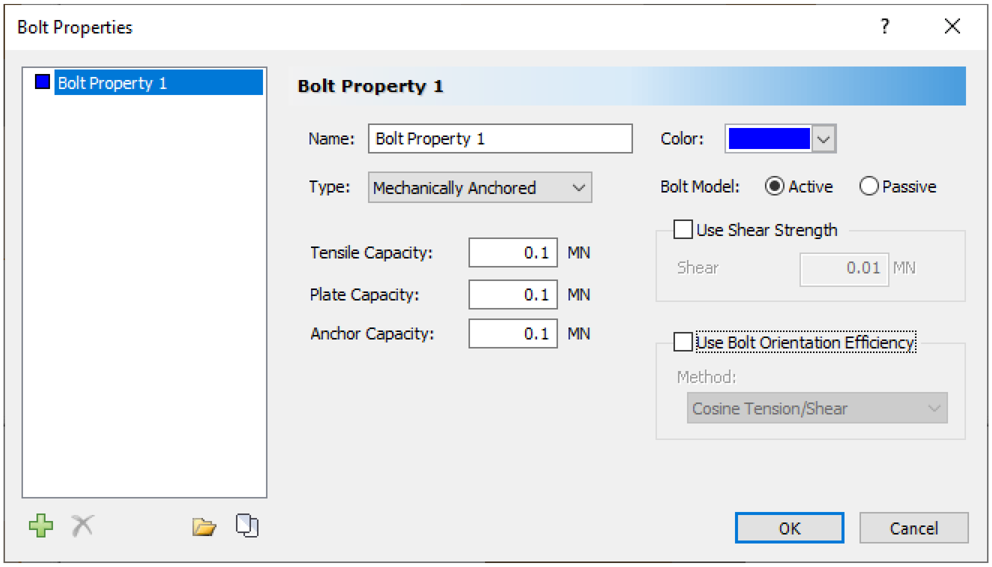


Figure 2.2.2: *RocPlane* Bolt Properties of Active Bolt Model without Bolt Orientation Efficiency

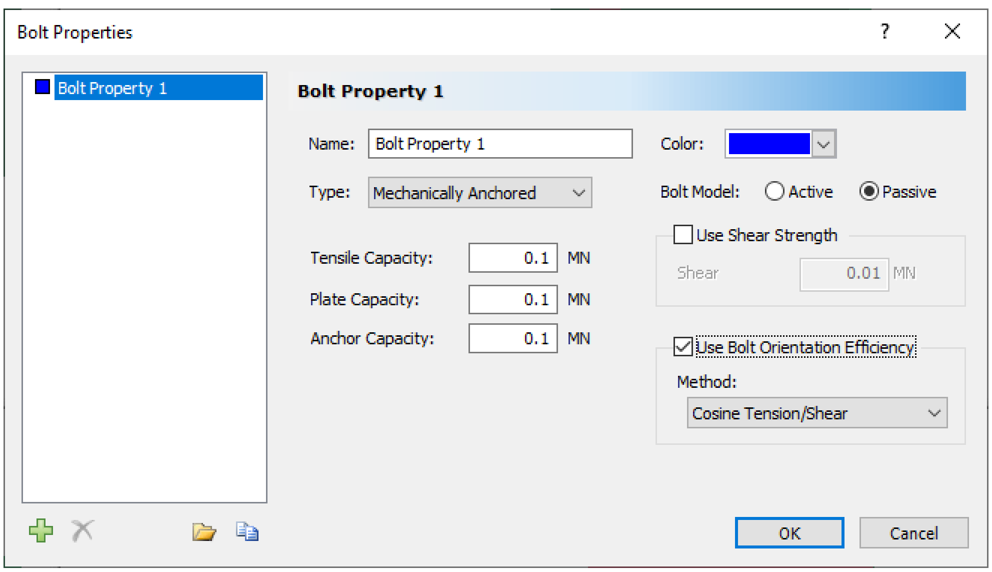


Figure 2.2.3: *RocPlane* Bolt Properties of Passive Bolt Model with Bolt Orientation Efficiency

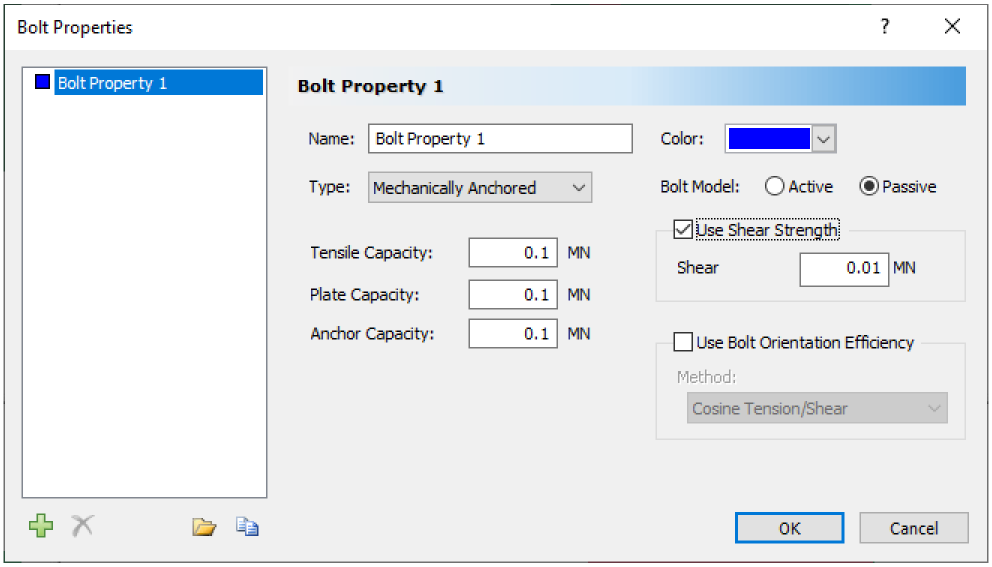


Figure 2.2.4: *RocPlane* Bolt Properties using Shear Strength

2.2.3. Building a Compatible *SWedge* Model

Enter *SWedge* geometry as below:

Slope Input Data	
Slope Dip Angle (°)	65
Dip Direction (°)	180
Height (m)	33
Upper Face Dip Angle (°)	0
Upper Face Dip Direction (°)	180
Rock Unit Weight (MN/m^3)	0.026
Joint 1 Input Data	
Dip Angle (°)	90
Dip Direction (°)	90
Waviness (°)	0
Shear Strength Model	Mohr-Coulomb
Phi (°)	0
c (MPa)	0
Joint 2 Input Data	
Dip Angle (°)	90
Dip Direction (°)	90

Waviness (°)	0
Shear Strength Model	Mohr-Coulomb
Phi (°)	0
c (MPa)	0
Basal Plane	
Dip Angle (°)	55
Dip Direction (°)	180
Waviness (°)	0
Shear Strength Model	Mohr-Coulomb
Phi (°)	35
c (MPa)	0

The *SWedge* model looks like this:

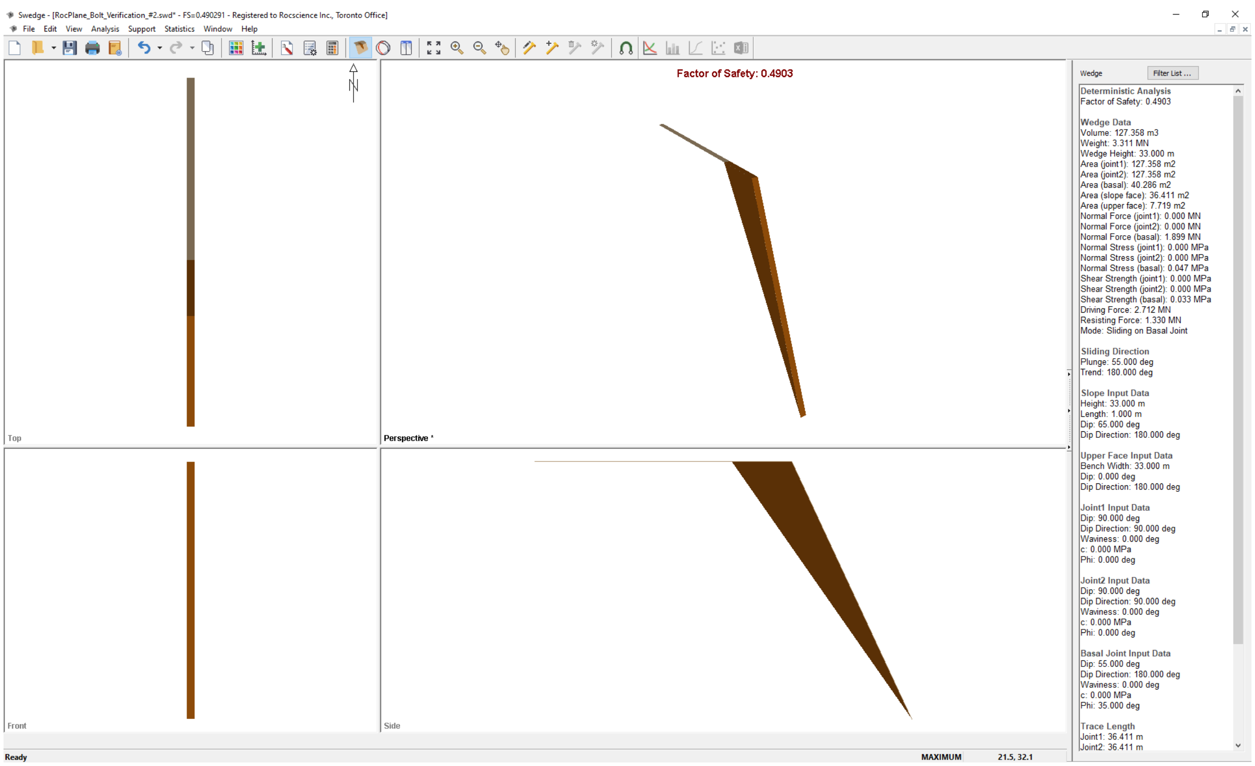


Figure 2.2.5: *SWedge* Model Geometry

Bolt Properties

In the Add Spot Bolt dialog, enter a **Trend** of **0º** (in *SWedge* only), a **Plunge** of **25º** and a **Bolt Length** of **36 m**.

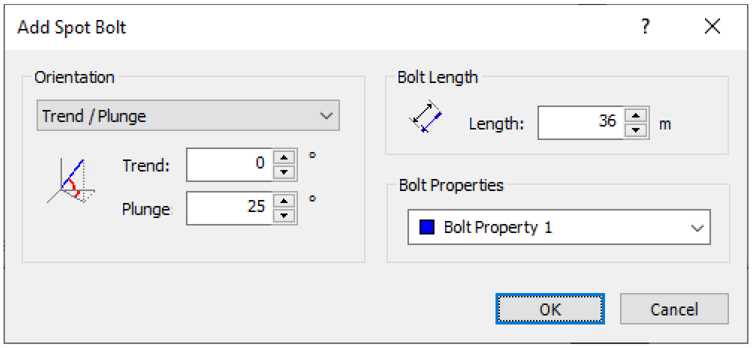


Figure 2.2.6: *SWedge* Add Spot Bolt

2.2.4. Results

With no supports, the slopes in *SWedge* and *RocPlane* have the same factor of safety of 0.4903.

The FS from both *SWedge* and *RocPlane* bolt models are listed below:

Bolt Type	Bolt Model	Use Shear Strength	Use Bolt Orientation Efficiency	FS	
				SWedge	*RocPlane*
Mechanically Anchored	Passive	No	No	0.5221	0.5221
	Passive	No	Yes	0.4958	0.4958
	Passive	Yes	No	0.4940	0.4940
	Active	No	No	0.5190	0.5190
	Active	No	Yes	0.4953	0.4953
	Active	Yes	No	0.4921	0.4921
Grouted Dowel with 100% Bond Length	Passive	No	No	0.5667	0.5667
	Passive	No	Yes	0.5036	0.5036
	Passive	Yes	No	0.4977	0.4977
	Active	No	No	0.5599	0.5599
	Active	No	Yes	0.5022	0.5022
	Active	Yes	No	0.4939	0.4939
Grouted Dowel with 8m Bond Length	Passive	No	No	0.5221	0.5221
	Passive	No	Yes	0.4958	0.4958
	Active	No	No	0.5190	0.5190
	Active	No	Yes	0.4953	0.4953
Cable Bolt	Passive	No	No	0.5539	0.5539

	Passive	No	Yes	0.5013	0.5013
	Passive	Yes	No	0.4977	0.4977
	Active	No	No	0.5482	0.5482
	Active	No	Yes	0.5002	0.5002
	Active	Yes	No	0.4939	0.4939
Split Set	Passive	No	No	0.5221	0.5221
	Passive	No	Yes	0.4958	0.4958
	Passive	Yes	No	0.4940	0.4940
	Active	No	No	0.5190	0.5190
	Active	No	Yes	0.4953	0.4953
	Active	Yes	No	0.4921	0.4921
Swellex	Passive	No	No	0.5221	0.5221
	Passive	No	Yes	0.4958	0.4958
	Passive	Yes	No	0.4940	0.4940
	Active	No	No	0.5190	0.5190
	Active	No	Yes	0.4953	0.4953
	Active	Yes	No	0.4921	0.4921
Simple Bolt Force of 0.1MN	Passive	N/A	N/A	0.5221	0.5221
	Active	N/A	N/A	0.5190	0.5190

The results produced by *RocPlane* with *SWedge* and confirm the reliability of the *RocPlane* bolt model.

3. *RocPlane* Ponded Water Pressure Model Verification

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

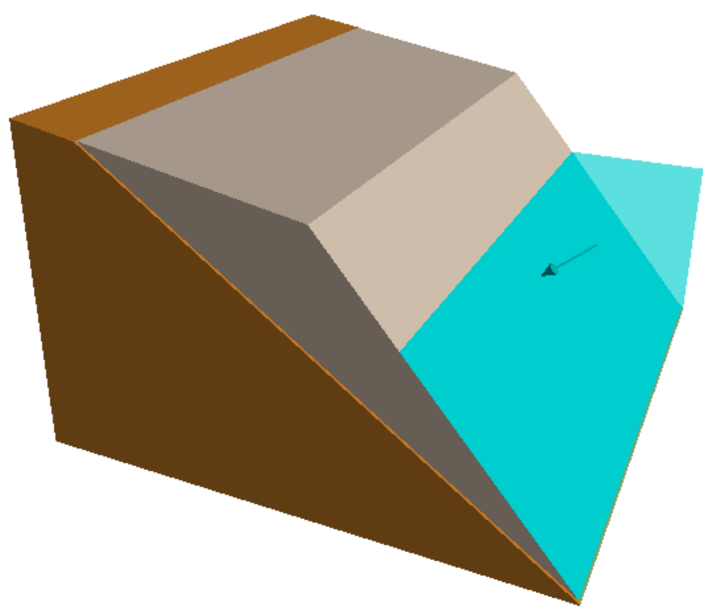
Two types of water pressures can be modelled in *RocPlane*:

- Ponded Water Pressure – water pressure which acts on the slope and/or upper face
  and
- Plane Water Pressure (formerly Water Pressure) – water pressure which acts on the internal failure plane and/or tension crack.

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

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

Analyses of the Ponded Water Pressure model were performed in *RocPlane* and verified by analytical solution, which confirms the reliability of *RocPlane* results.



3.1. *RocPlane* Verification Problem #1

[*RocPlane Build 4.001*]

3.1.1. Problem Description

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

Geometry and Material Properties

Table 3.1.1: Slope and Plane Geometry

Geometry Parameter	Value
Slope Height (H) (m)	60
Slope Angle (β) (deg.)	50°
Failure Plane Angle (α) (deg.)	35°
Upper Face Angle (ψ) (deg.)	0°

Table 3.1.2: Material Properties

Parameter	Value
Unit Weight of Rock (γ_r) (MN/m^3)	0.026
Cohesion (c) (MN/m^2)	0.10
Friction Angle (ϕ) (deg.)	35°

Water Pressure

Table 3.1.3: Ponded Water and Plane Water

Ponded Water	
Unit Weight (MN/m^3)	0.00981
Slope Face Type	Impervious
Ponded Water Depth (m)	30
Joint Water	
Unit Weight (MN/m^3)	0.00981
Pressure Distribution Type	N/A
Percent Filled (%)	100

3.1.2. RocPlane Analysis

Enter the geometry and material values from Table 3.1.1 and Table 3.1.2 into *RocPlane*.

The *RocPlane* model looks like this:

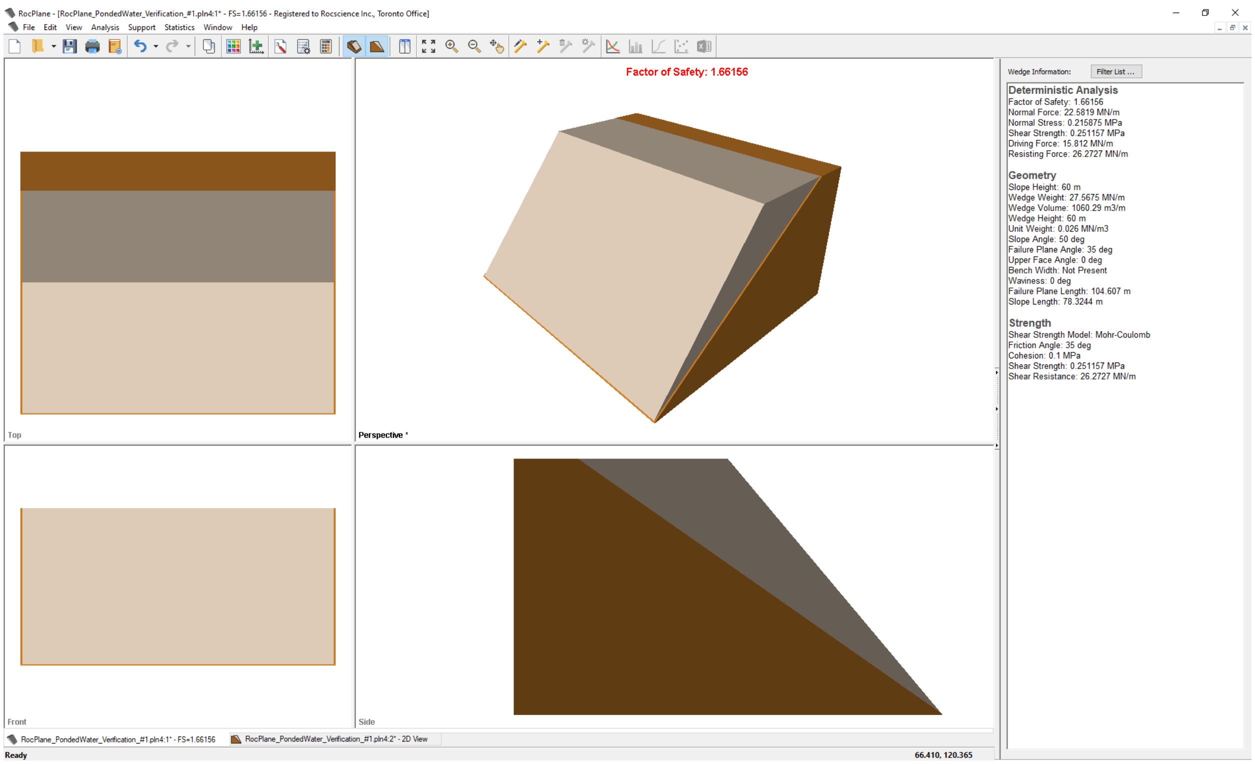


Figure 3.1.1: RocPlane Model with No Water

Water Pressure

Enter the water parameter values from Table 3.1.3 into *RocPlane*.

The analysis is run with both **Ponded Water Pressure** and **Plane Water Pressure** checked. Use the default unit weight values for ponded water. Set the **Ponded Water Depth** to **30** m and the Slope Face Type to **Pervious**.

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

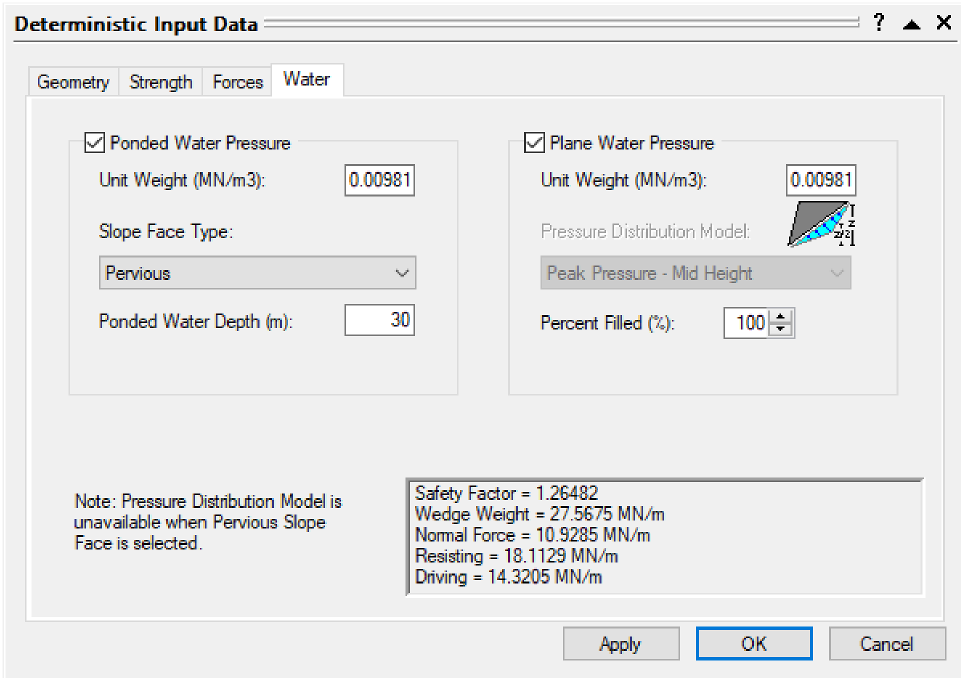


Figure 3.1.2: *RocPlane* Water Deterministic Input Data with Ponded Water Pressure and Plane Water Pressure

The *RocPlane* model looks like this:

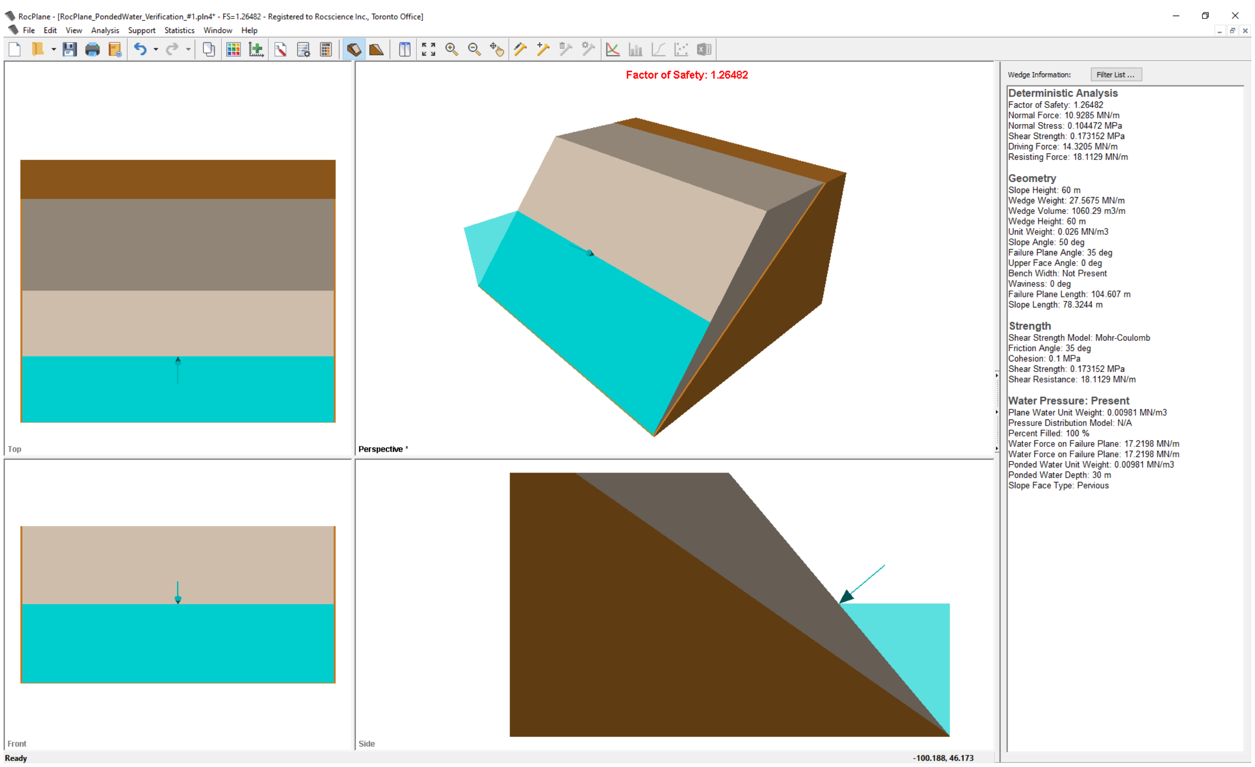


Figure 3.1.3: *RocPlane* Model with Partially Ponded Slope

3.1.3. Analytical Solution

The water table is defined by a combination of the upper face, part of the slope (to the ponded water surface), and the ponded water surface.

Water pressure is computed as:

$$U = \gamma_w z$$

Where:

γ_w is the unit weight of water (same for ponded water and plane water)

z is the distance from the water table

Sample Calculations

Ponded Water Pressure:

Ponded Water Pressure at the Free Ponded Surface:

$$P_1 = \left(0.00981 \frac{\mathrm{MN}}{\mathrm{m}^3}\right)(0 \mathrm{~m}) = 0 \mathrm{~MPa}$$

Ponded Water Pressure at the Bottom of the Slope:

$$P_2 = \left(0.00981 \frac{\mathrm{MN}}{\mathrm{m}^3}\right)(30 \mathrm{~m}) = 0.2943 \mathrm{~MPa}$$

Ponded Water Force (acting into and perpendicular to the slope face):

$$U_{ponded} = \frac{P_1 + P_2}{2} L_{12} = \frac{0 \mathrm{~MPa} + 0.2943 \mathrm{~MPa}}{2}\left(\frac{30 \mathrm{~m}}{\sin 50}\right) = 5.7627 \frac{\mathrm{MN}}{\mathrm{m}}$$

The resisting force calculations are impacted by the component of the ponded water force acting perpendicular to the failure plane. This is due to the effect of the normal force on the calculation of shear resistance.

$$\begin{aligned} U_{ponded} \perp &= U_{ponded} \sin\beta \sin\alpha + U_{ponded} \cos\beta \cos\alpha \\ &= \left(5.7627 \frac{\mathrm{MN}}{\mathrm{m}}\right) \sin 50 \sin 35 + \left(5.7627 \frac{\mathrm{MN}}{\mathrm{m}}\right) \cos 50 \cos 35 \\ &= 5.5663 \ \frac{\mathrm{MN}}{\mathrm{m}} \end{aligned}$$

The active force calculations are impacted by the component of the ponded water force acting parallel to the failure plane.

$$\begin{aligned} U_{ponded} \parallel &= U_{ponded} \sin\beta \cos\alpha + U_{ponded} \cos\beta \sin\alpha \\ &= -\left(5.7627 \frac{\mathrm{MN}}{\mathrm{m}}\right) \sin 50 \cos 35 \left(5.7627 \frac{\mathrm{MN}}{\mathrm{m}}\right) \cos 50 \sin 35 \\ &= -1.4915 \ \frac{\mathrm{MN}}{\mathrm{m}} \end{aligned}$$

Plane Water Pressure:

The water pressure is computed where a discontinuity occurs.

Plane Water Pressure at the Top of the Failure Plane:

$$P_3 = \left(0.00981 \frac{\mathrm{MN}}{\mathrm{m}^3}\right)(0\ \mathrm{m}) = 0\ \mathrm{MPa}$$

Plane Water Pressure Below the Crest on the Failure Plane:

$$P_4 = \left(0.00981 \frac{\mathrm{MN}}{\mathrm{m}^3}\right)\left(60\ \mathrm{m} - \frac{(60\ \mathrm{m}) \tan 35}{\tan 50}\right) = 0.2428\ \mathrm{MPa}$$

Plane Water Pressure Below Ponded Slope on the Failure Plane:

$$P_5 = \left(0.00981 \frac{\mathrm{MN}}{\mathrm{m}^3}\right)\left(30\ \mathrm{m} - \frac{(30\ \mathrm{m}) \tan 35}{\tan 50}\right) = 0.1214\ \mathrm{MPa}$$

Plane Water Pressure at the Toe of the Failure Plane:

$$P_6 = \left(0.00981 \frac{\mathrm{MN}}{\mathrm{m}^3}\right)(30\ \mathrm{m}) = 0.2943\ \mathrm{MPa}$$

Plane Water Force (acting into and perpendicular to the slope face):

$$\begin{aligned} U = \frac{P_3 + P_4}{2} L_{34} + \frac{P_4 + P_3}{2} L_{45} + \frac{P_5 + P_6}{2} L_{56} \\ &= \frac{0\ \mathrm{MPa} + 0.2428\ \mathrm{MPa}}{2}\left(\frac{60\ \mathrm{m}}{\sin 35} - \frac{(60\ \mathrm{m}) \sec 35}{\tan 50}\right) \\ &+ \frac{0.2428\ \mathrm{MPa} + 0.1214\ \mathrm{MPa}}{2}\left(\frac{(60\ \mathrm{m}) \sec 35}{\tan 50} - \frac{(30\ \mathrm{m}) \sec 35}{\tan 50}\right) \\ &+ \frac{0.1214\ \mathrm{MPa} + 0.2943\ \mathrm{MPa}}{2}\left(\frac{(30\ \mathrm{m}) \sec 35}{\tan 50}\right) \\ &= 5.2379 \frac{\mathrm{MN}}{\mathrm{m}} + 5.5960 \frac{\mathrm{MN}}{\mathrm{m}} + 6.3873 \frac{\mathrm{MN}}{\mathrm{m}} \\ &= 17.2212 \frac{\mathrm{MN}}{\mathrm{m}} \end{aligned}$$

The resisting force calculations are impacted by plane water force acting on the failure plane. This is due to the effect of the normal force (N) on the calculation of shear resistance.

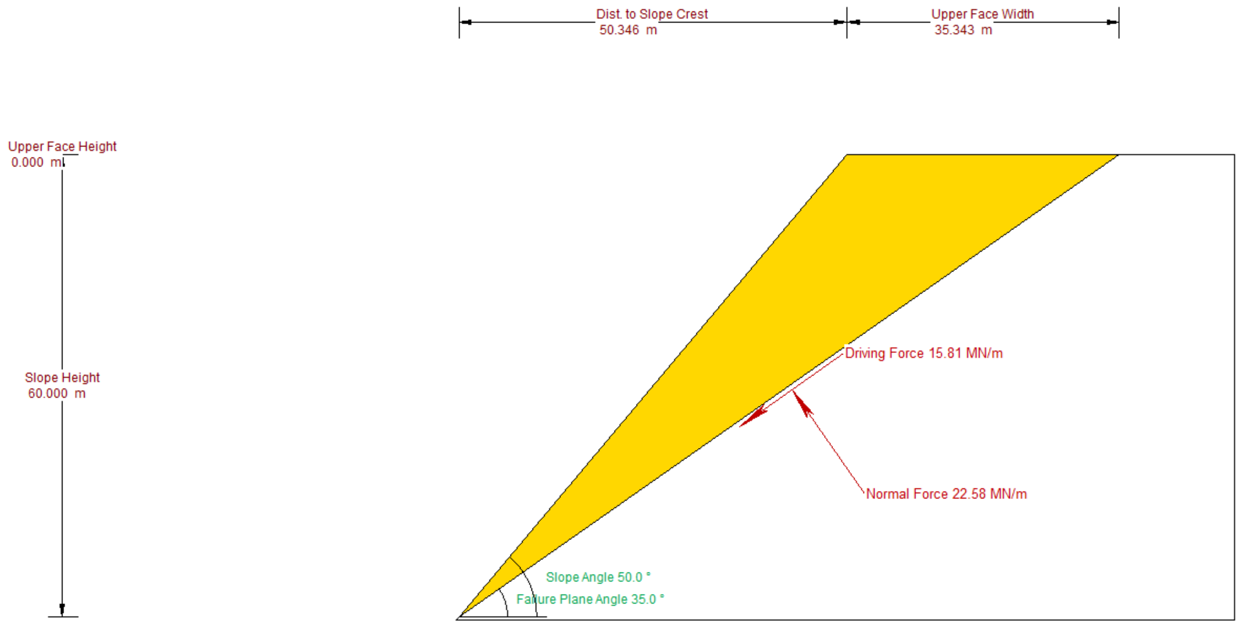
The change in resisting force and driving force are:

$$\Delta\, resisting\ force = \Delta N \tan \phi = \left(5.5663\ \frac{\mathrm{MN}}{\mathrm{m}} - 17.2212 \frac{\mathrm{MN}}{\mathrm{m}}\right) \tan 35 = -8.1608 \frac{\mathrm{MN}}{\mathrm{m}}$$

$$\Delta\, driving\ force = -1.4915\ \frac{\mathrm{MN}}{\mathrm{m}}$$

3.1.4. Results

Comparing *RocPlane* results:



Factor of Safety	1.66
Driving Force	15.81 MN/m
Resisting Force	26.27 MN/m
Wedge Weight	27.57 MN/m
Wedge Volume	1060.29 m^3/ m
Shear Strength	0.25 MPa
Shear Resistance	26.27 MN/m
Normal Force	22.58 MN/m
Plane Waviness	0.0°

Figure 3.1.4: *RocPlane* Planar Wedge Stability Analysis Results with No Water

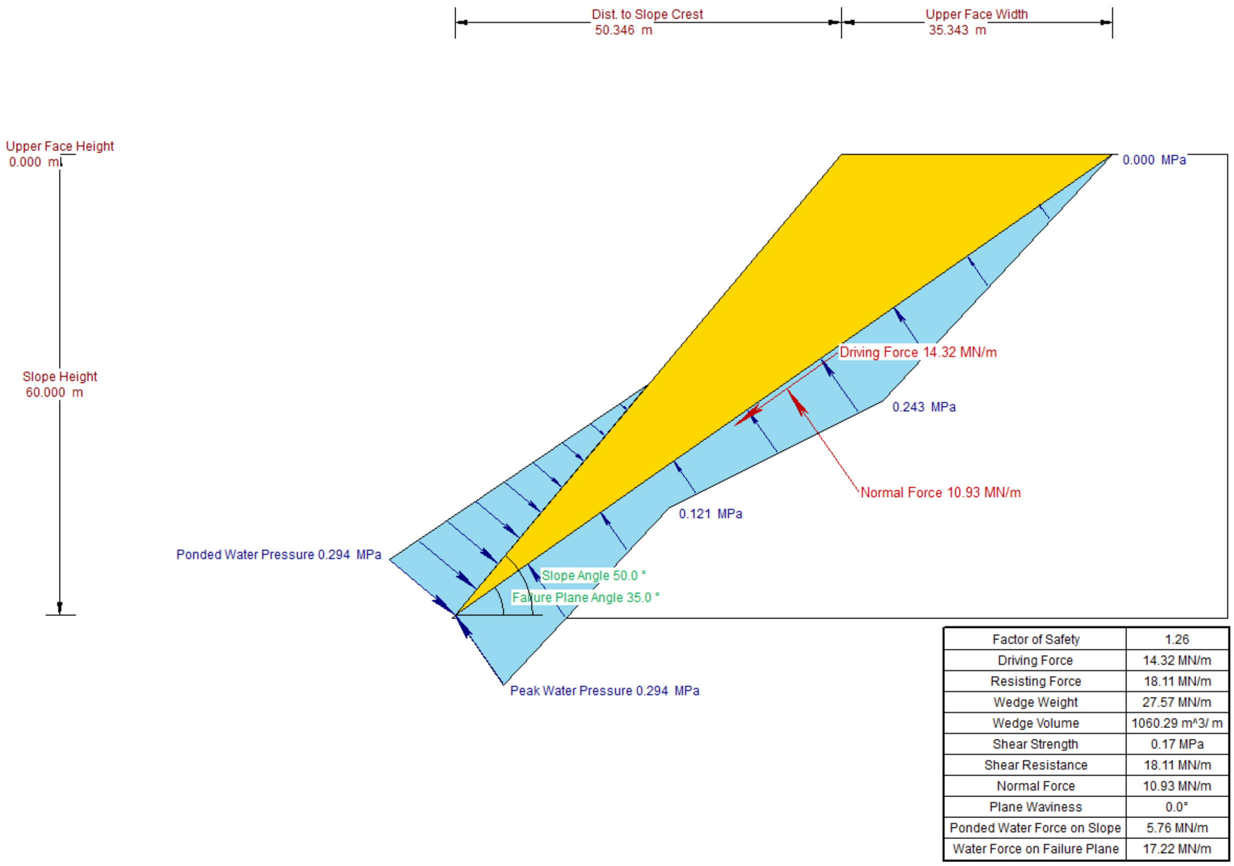


Figure 3.1.5: *RocPlane* Planar Wedge Stability Analysis Results with Ponded Water and Plane Water

The ponded water and plane water pressures and forces computed in *RocPlane* are consistent with the sample calculations.

Table 3.1.4: *RocPlane* Force and Factor of Safety Comparisons

Ponded Water Depth (m)	Plane Water Percent Filled (%)	Driving Force (MN/m)	Resisting Force (MN/m)	Factor of Safety
0	0	14.32	18.11	1.26
30	100	15.81	26.27	1.66

The difference in Driving Force computed in *RocPlane* before and after water is applied is 15.81 MN/m – 14.32 MN/m = 1.49 MN/m. The difference in Resisting Force computed in *RocPlane* before and after water is applied is 26.27 MN/m – 18.11 MN/m = 18.16 MN/m. The sample calculation is consistent with the change in driving and resisting forces computed in *RocPlane*.