# *RocPlane*

Planar sliding stability analysis for rock slopes

**Verification Manual**

## Table of Contents

**INTRODUCTION** 3

**ROCPLANE VERIFICATION PROBLEM #1** 4
Tension crack present and not present, sensitivity analysis on three parameters.

**ROCPLANE VERIFICATION PROBLEM #2** 15
Sensitivity analysis on bench dip with varying percent filled TC.

**ROCPLANE VERIFICATION PROBLEM #3** 17
Graphing factor of safety vs. tension crack depth, varying cohesion

**ROCPLANE VERIFICATION PROBLEM #4** 19
Seismic loading, varying perent filled tension crack.

**ROCPLANE VERIFICATION PROBLEM #5** 23
Waviness factor, different strength models (JRC, power curve, linear)

**ROCPLANE VERIFICATION PROBLEM #6** 25
Sensitivity plot with four parameters, exact reproduction of plot.

**ROCPLANE VERIFICATION PROBLEM #7** 27
Bolt reinforcement

**ROCPLANE VERIFICATION PROBLEM #8** 29
Imperial unit analysis

**REFERENCES** 31

# INTRODUCTION

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

The examples presented here, are taken from articles, technical notes and papers written in the field of Geotechnical Engineering.

The results produced by RocPlane, as documented in this paper, agree very well with the examples from these sources, and confirm the reliability of results produced by RocPlane.

## 1.1 Introduction:

Here we begin a stability assessment to verify that the ROCPLANE program written by Rocscience Inc. computes values using the correct equations. The equations we will use to verify the results produced by ROCPLANE, were originally presented by Dr. Evert Hoek (ref. [1]). In the following example problem, a rock slope on Sau Mau Ping Road in Kowloon, Hong Kong was analyzed. The geometry of the slope is illustrated in Figure 1. The overall slope angle is 50$^o$ and the individual bench faces are inclined at 70$^o$ to the horizontal. A failure plane dips at 35$^o$. Tension cracks are frequently observed behind the crests of slopes. However, in this case, it can't be determined whether or not tension cracks are present. Therefore, two sets of analysis will be carried out for both with tension cracks and without tension cracks.

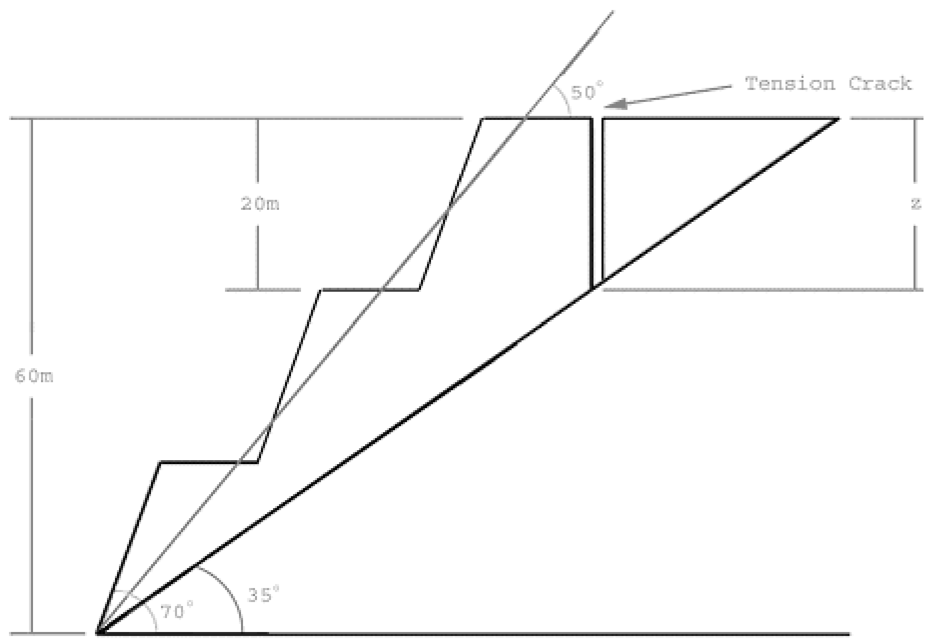



**Figure 1.1: Geometry of Hoek's slope**

**Equations:**

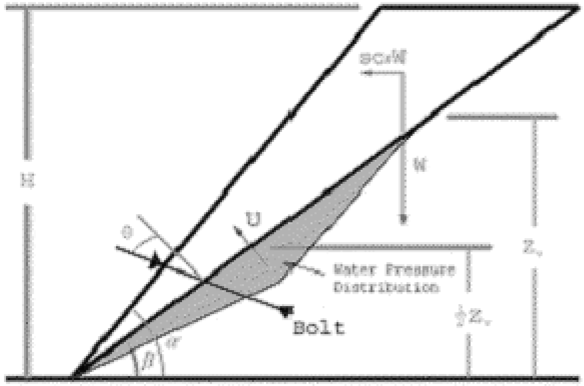
Without Tension Crack (Figure 2):

$$F.S. = \frac{cA + \left(W\left(\cos\alpha - sc\times\sin\alpha\right) - U + T\cos\theta\right)\tan\phi}{W\left(\sin\alpha + sc\times\cos\alpha\right) - T\sin\theta} \tag{1}$$

$$A = \frac{H}{\sin\alpha} \tag{2}$$

$$W = \frac{\gamma_r H^2}{2}\left(\cot\alpha - \cot\beta\right) \tag{3}$$

$$U = \frac{\gamma_w H^2}{4\sin\alpha} \tag{4}$$



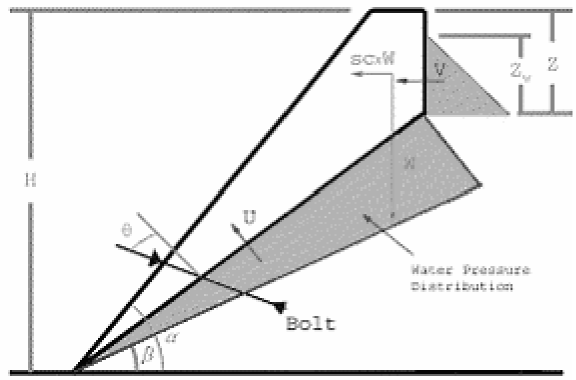




**Figure 1.2: Slope without Tension Crack**

**Figure 1.3: Slope with Tension Crack**

<u>With Tension Crack (Figure 3):</u>

$$F.S.=\frac{cA+\left(W\left(\cos\alpha-sc\times\sin\alpha\right)-U-V\sin\alpha+T\cos\theta\right)\tan\phi}{W\left(\sin\alpha+sc\times\cos\alpha\right)+V\cos\alpha-T\sin\theta} \tag{1}$$

$$z=H\left(1-\sqrt{\cot\beta\tan\alpha}\right) \tag{2}$$

$$A=\frac{H-z}{\sin\alpha} \tag{3}$$

$$W=\frac{\gamma_r H^2}{2}\left(\left(1-\left(\frac{z}{H}\right)^2\right)\cot\alpha-\cot\beta\right) \tag{4}$$

$$U=\frac{\gamma_w z_w A}{2} \tag{5}$$

$$V=\frac{\gamma_w z_w^2}{2} \tag{6}$$

**H** is the slope height. **α** is slope angle. **β** is the failure plane angle. $\gamma_r$ is the unit weight of rock and $\gamma_w$ 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. **sc** 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 and $\phi$ 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. **F.S.** is the factor of safety.

## Example Verification:

Here we use the data and equations supplied to calculate the factor of safety in both the cases of with tension crack and without tension crack. A comparison is then made with the results from the ROCPLANE program.

Without Tension Crack:

Input Data:

| | | | |
|---|---|---|---|
| Height (H) | 60 m | Unit Weight of Water ($\gamma_w$) | 0.01 MN/m$^3$ |
| Slope Angle (β) | 50$^o$ | Cohesion (c) | 0.1 MN/m$^2$ |
| Failure Plane Angle (α) | 35$^o$ | Friction Angle ( $\phi$ ) | 35$^o$ |
| Seismic Coefficient (sc) | 0.08g | Bolt Force (T) | 0 MN |
| Unit Weight of Rock ($\gamma_r$) | 0.027 MN/m$^3$ | Bolt Plunge (θ) | 0$^o$ |

Calculated Values:
Weight of Rock Wedge (W) →

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

Base Area of Wedge (A) → $A = \frac{H}{\sin\alpha} = \frac{60}{\sin 35°} = 104.6068m^2$

Water FP Pressure Force (U) → $U = \frac{\gamma_w H^2}{4\sin\alpha} = \frac{0.01 \times 60^2}{4 \times \sin 35°} = 15.6910MN$

Factor of Safety (F.S.) → $F.S. = \frac{cA + (W(\cos\alpha - sc \times \sin\alpha) - U + T\cos\theta)\tan\phi}{W(\sin\alpha + sc \times \cos\alpha) - T\sin\theta}$

$$= \frac{0.1 \times 104.6068 + (28.6278(\cos 35° - 0.08 \times \sin 35°) - 15.6910 + 0)\tan 35°}{28.6278(\sin 35° + 0.08 \times \cos 35°) - 0} = 0.8184254$$

The factor of safety calculated using the input data and equations supplied by Dr. Evert Hoek [1] is 0.8184254. All we have to do now is to enter all the input data in the ROCPLANE program and see if we can get the same result.

However, we have to first convert all the data into the unit system used in ROCPLANE. (Assume g = 10 m/s$^2$)

$\gamma_r$ = 0.027 MN/m$^3$ = 2.7x10$^4$ N/m$^3$ = 2.7x10$^3$ kg/m$^3$ = 2.7 tonnes/m$^3$

$\gamma_w$ = 0.01 MN/m$^3$ = 1x10$^4$ N/m$^3$ = 1 x10$^3$ kg/m$^3$ = 1 tonnes/m$^3$

c = 0.1 MN/m$^2$ = 1x10$^5$ N/m$^2$ = 1x10$^4$ kg/m$^2$ = 10 tonnes/m$^3$

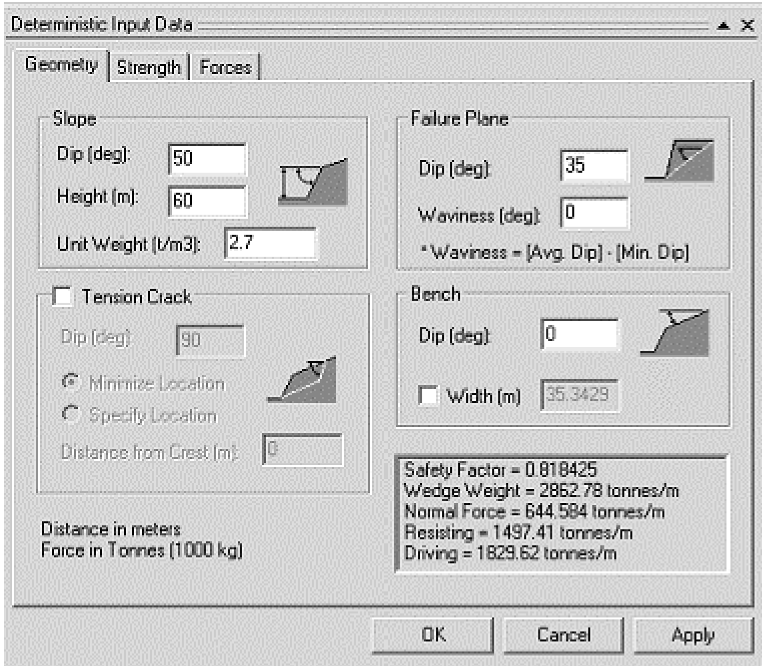



**Figure 1.4: Geometry input data for slope with no tension crack**

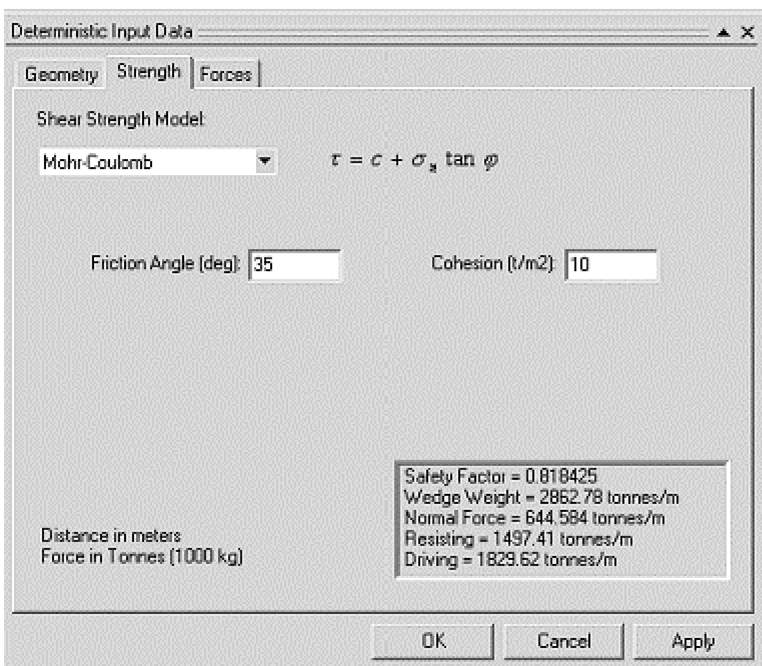



**Figure 1.5: Strength input data for slope with no tension crack**

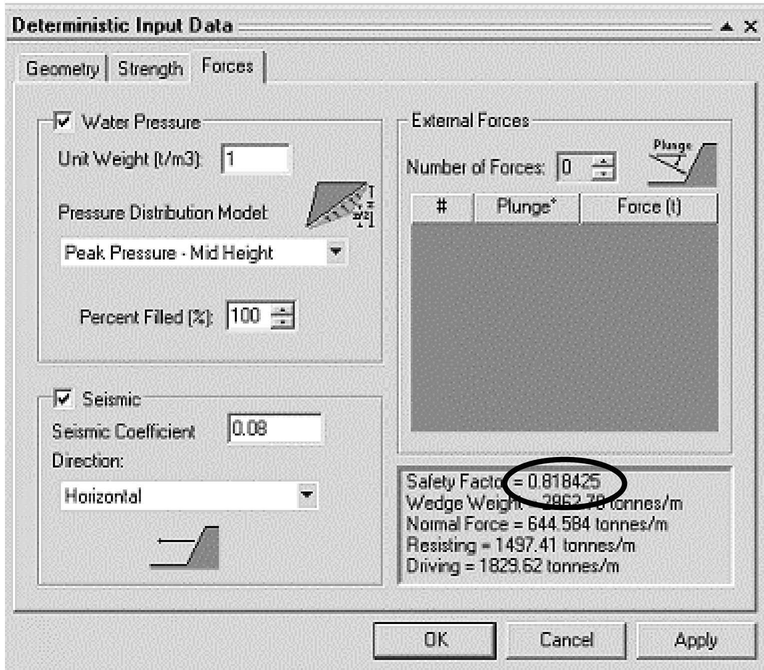



**Figure 1.6: Forces input data for slope with no tension crack**

By entering the values as shown in Figures 4-6 and pressing "Apply", the calculated factor of safety from the ROCPLANE program is also 0.818425. This is the same value as what we calculated before. Now, test out the ROCPLANE program for the case with tension crack. First we calculate the factor of safety using the equations and data provided by Dr. Evert Hoek [1].

<u>With Tension Crack:</u>

Input Data:

| | | | |
|---|---|---|---|
| Height (H) | 60 m | Depth of water in TC ($Z_w$) | 90% z |
| Slope Dip (β) | $50^o$ | Cohesion (c) | 0.1 $MN/m^2$ |
| Failure Plane Dip (α) | $35^o$ | Friction Angle ( $\phi$ ) | $35^o$ |
| Seismic Coefficient (sc) | 0.08g | Bolt Force (T) | 0 MN |
| Unit Weight of Rock ($\gamma_r$) | 0.027 $MN/m^3$ | Bolt Plunge (θ) | $0^o$ |
| Unit Weight of Water ($\gamma_w$) | 0.01 $MN/m^3$ | | |

Calculated Values:

Depth of Tension Crack (z) → $z = H\left(1-\sqrt{\cot\beta\tan\alpha}\right) = 60\left(1-\sqrt{\cot 50^\circ \tan 35^\circ}\right) = 14.0092m$

Weight of Rock Wedge (W) → $W = \frac{\gamma_r H^2}{2}\left(\left(1-\left(\frac{z}{H}\right)^2\right)\cot\alpha - \cot\beta\right)$

$$= \frac{0.027\times 60^2}{2}\left(\left(1-\left(\frac{14.0092}{60}\right)^2\right)\cot 35^\circ - \cot 50^\circ\right) = 24.8439MN$$

Base Area of Wedge (A) → $A = \frac{H-z}{\sin\alpha} = \frac{60-14.0092}{\sin 35^\circ} = 80.1826m^2$

Depth of water in TC ($z_w$) → 0.9 x z = 0.9 x 14.0092 = 16.6082 m

Water FP Pressure Force (U) → $U = \frac{\gamma_w z_w A}{2} = \frac{0.01 \times 16.6082 \times 80.1826}{2} = 4.4932MN$

Water TC Pressure Force (V) → $V = \frac{\gamma_w z_w^2}{2} = \frac{0.01 \times 16.6082^2}{2} = 0.6280MN$

Factor of Safety (F.S.) → $F.S. = \frac{cA + (W(\cos\alpha - sc \times \sin\alpha) - U - V\sin\alpha + T\cos\theta)\tan\phi}{W(\sin\alpha + sc \times \cos\alpha) + V\cos\alpha - T\sin\theta}$

$$= \frac{0.1 \times 80.1826 + (24.8439(\cos 35° - 0.08 \times \sin 35°) - 4.4932 - 0.6280 \times \sin 35° + 0)\tan 35°}{24.8439(\sin 35° + 0.08 \times \cos 35°) + 0.6280 \times \cos 35° - 0}$$

$= 1.0654738$

The factor of safety calculated using the input data and equations supplied by Dr. Evert Hoek [2] is 1.0654738. All we have to do now is to enter all the input data in the ROCPLANE program and see if we can get the same result.

However, we first have to calculate the distance from the tension crack to the crest of the slope. This can be done using simple geometry (Figure 7).

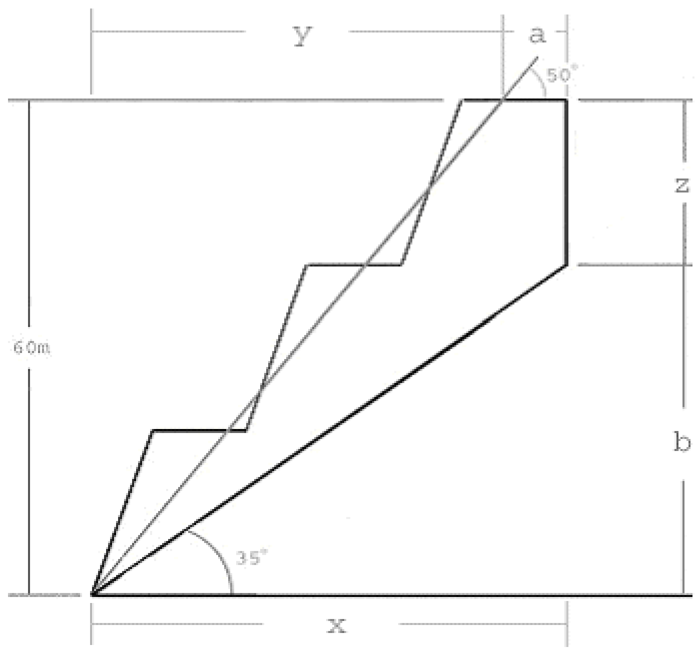



**Figure 1.7: Geometry of the slope with tension crack**

b = 60 – z = 60 – 14.0092 = 45.9908 m

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

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

a = x – y = 65.6817 m – 50.3460 m = 15.3357 m

∴ Distance from Crest = 15.3357 m

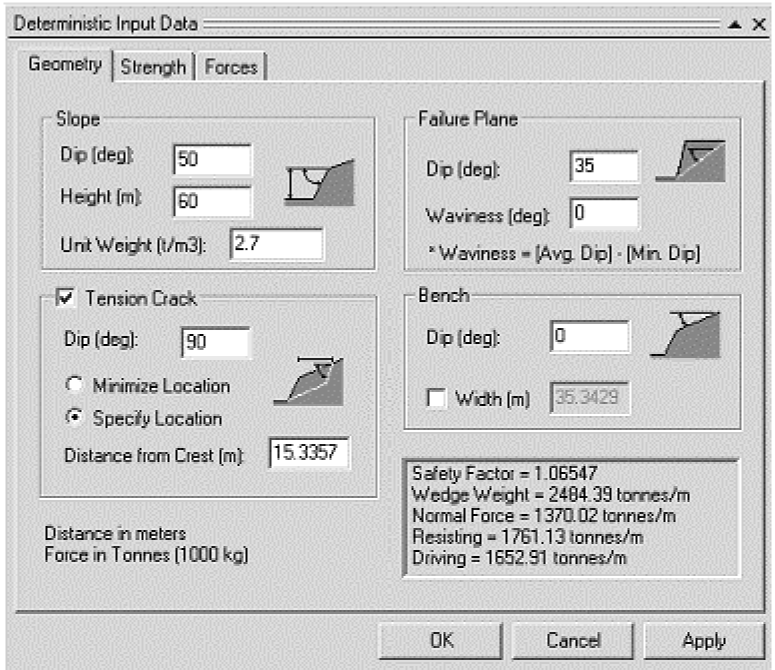



**Figure 1.8: Geometry input data for slope with tension crack**

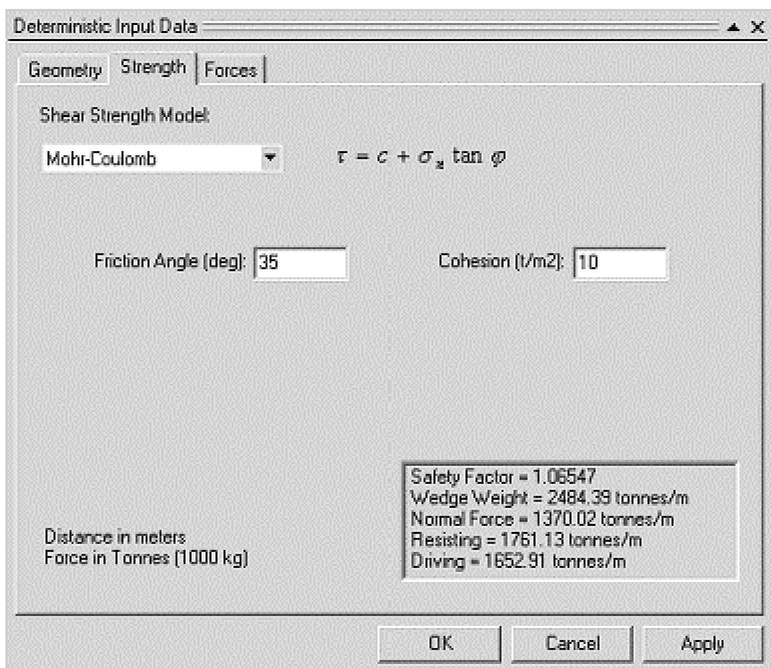



**Figure 1.9: Strength Input data for slope with tension crack**

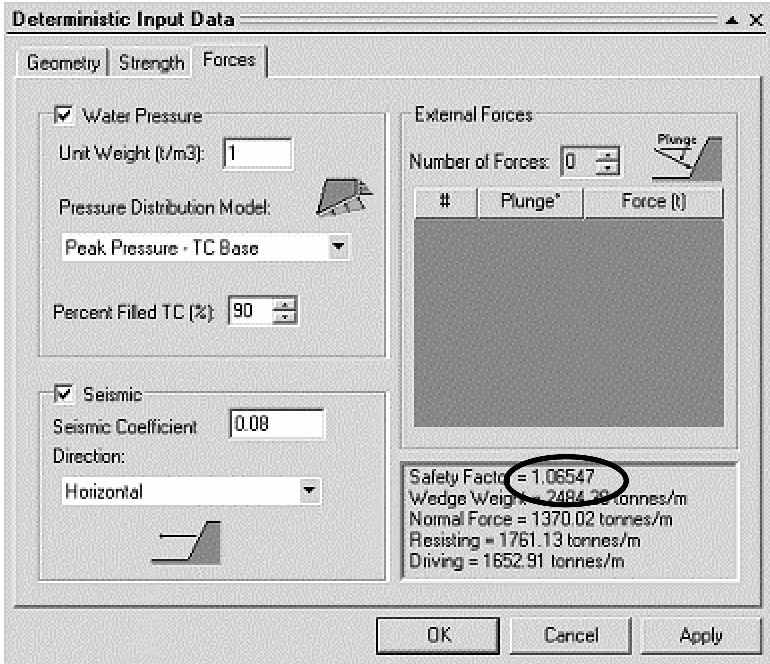



**Figure 1.10: Forces input data for slope with tension crack.**

By entering the values as shown in Figures 8-10 and pressing "Apply", the calculated factor of safety from the ROCPLANE program is also 1.06547. This is the same value as what we calculated before. Now, we will try to reproduce the same sensitivity plot provided by Dr. Hoek [1]. In the sensitivity input dialog, enter the values as shown in Figure 11 and Figure 12:

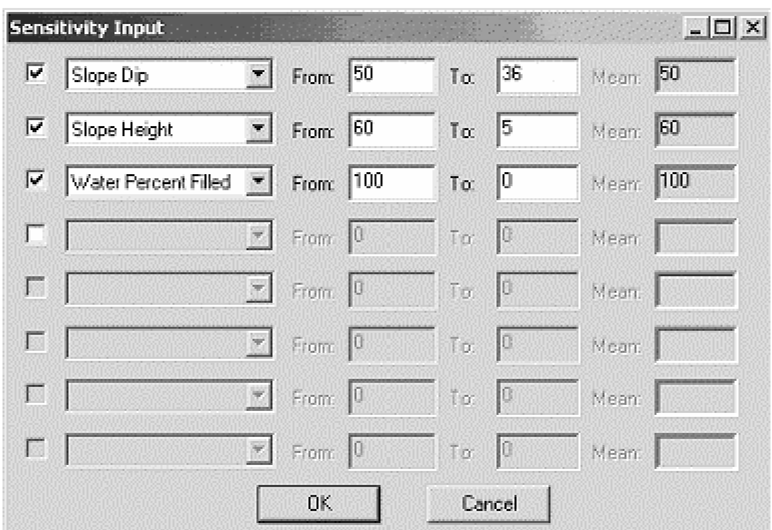



**Figure 1.11: Sensitivity Input in ROCPLANE without Tension Crack.**

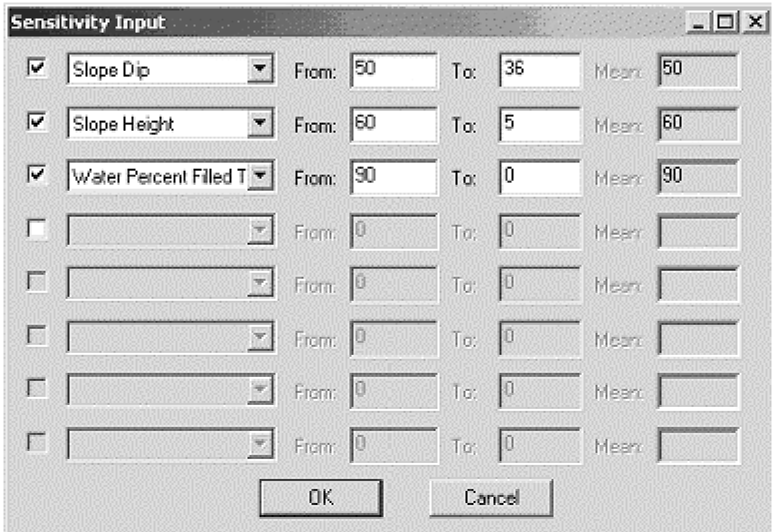



**Figure 1.12: Sensitivity Input in ROCPLANE with Tension Crack.**

We will get two plots that look like Figure 13 and Figure 14 below:

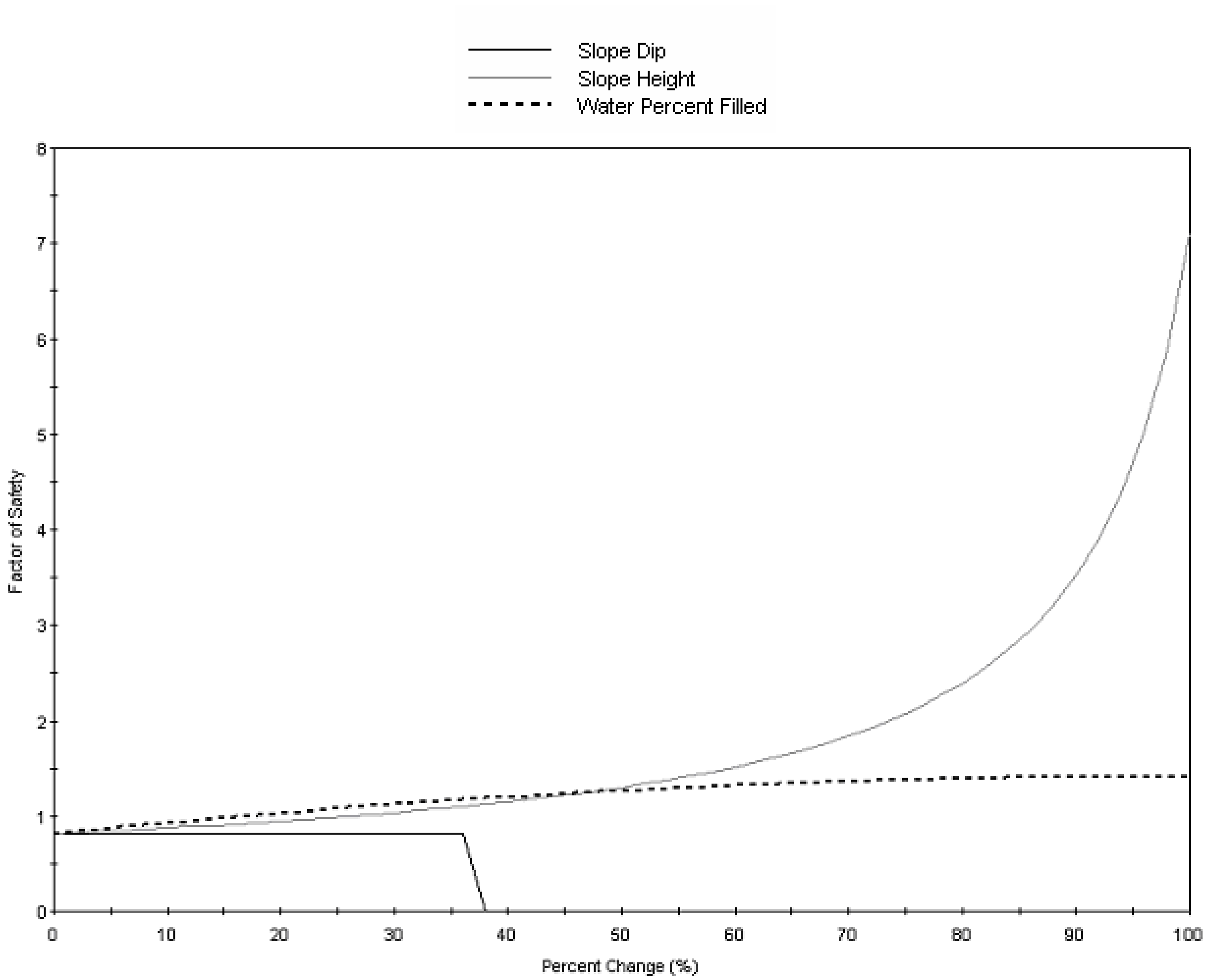



**Figure 1.13: Sensitivity Plot of slope without Tension Crack in ROCPLANE**

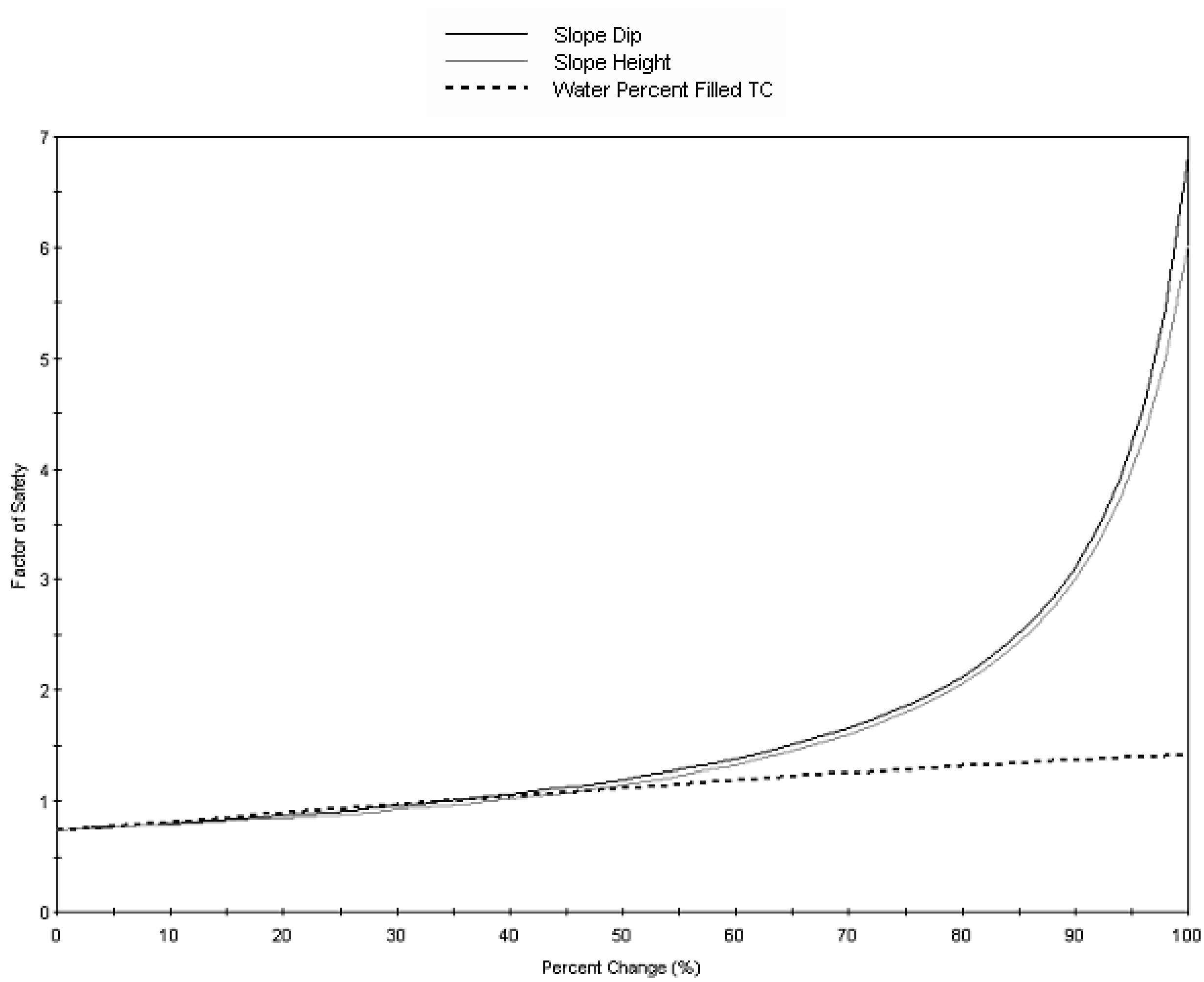



**Figure 1.14: Sensitivity Plot of Slope with Tension Crack using ROCPLANE**

The two plots we get from the ROCPLANE program have exactly the same shape as the diagram provided by Dr. Hoek.

### 2.1 Introduction

This example verification is based on the technical note by S.Sharma (ref. [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 to 70°. Their analysis yielded the results as shown in Table 1. In the following, we will verify that ROCPLANE will give the same output.

| Bench Dip (°) | Tension Crack Dip (°) | 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 |

**Table 2.1: Stability analysis provided by Sharma [2]**

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Failure Plane Angle (α) | 35° | Slope Height (h) | 60 m |
| Slope Angle (β) | 50° | Cohesion (c) | 12 t/m² |
| Bench Dip ($\varphi$) | 0° → 30° | Friction Angle | 45° |
| Tension Crack Angle ($\phi$) | 90° → 70° | Unit Weight of Rock | 2.6 t/m³ |
| Height of water column in the tension crack (Zw) | 14 m | Unit Weight of Water | 1.0 t/m³ |

**Table 2.2: Geometry parameters for the hypothetical slope**

Now, we have to calculate the distance from the tension crack to the crest and the water percent filled in the tension crack. We can use the provided equations to get these two values.

### 2.2 Equations

$$TCDist. = h\left(\sqrt{\cot\beta \times \cot\alpha} - \cot\beta\right)$$

$$PercentFilled = \frac{Zw}{Z}$$

$$Z = \frac{h \times \sin\phi\left(1 - \dfrac{\cot\beta}{\cot\alpha} + \sqrt{\dfrac{\cot\beta}{\cot\alpha} \times \dfrac{\cot\alpha}{\cot\varphi - 1}}\right)}{\sin\phi - \tan\alpha \times \cos\phi}$$

The distance from tension crack to the crest is 15.33576m and the water percent filled value depends on the tension crack length in each case.

### 2.3 Conclusion

The results obtained from ROCPLANE program are listed in Table 3.

| Bench Dip (°) | 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 |

**Table 2.3: Factor of Safety using ROCPLANE**

By comparing the factors of safety, we observe that only the values at $0^o$ 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 $\gamma$ is the unit weight of rock, 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, and $Z_L$ is the vertical depth of the tension crack. This formula is incorrect except when the bench dip is $0^o$. Since the weights are wrong, the factor of safety provided by the paper is not dependable.

### 3.1 Introduction

In this example, we are going to test the ROCPLANE program against the Hoek & Bray's formulae for the assessment of the stability in case of plane failure. We will verify the accuracy of the ROCPLANE program by reproducing the plot of the influence of tension crack depth on the factor of safety (Figure 16) provided by Froldi P. (ref. [3]).

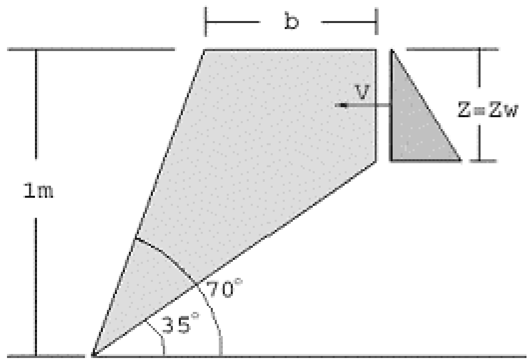



**Figure 3.1: Plane geometry of the unstable slope**

The geometry for this unstable slope is shown in Figure 15. We will transform the provided data into the format that the ROCPLANE program uses. The information we have now is listed in Table 4.

| | | | |
|---|---|---|---|
| Slope Angle (β) | 70° | Unit Weight of Slope (γ) | 2.6 t/m³ |
| Failure Plane Angle (α) | 35° | Unit Weight of Water ($\gamma_w$) | 1.0 t/m³ |
| Bench Dip (Ψ) | 0° | Slope Height (H) | 1 m |
| Tension Crack Angle | 90° | Cohesion (c) | 0 t/m² → 1.0 t/m² |
| Water Percent Filled TC | 100% | Friction Angle (Φ) | 30° |

**Table 3.1: Geometry information for the slope**

All we need to do is to find the distance from the tension crack to the crest of the slope (b), which can be calculated using the following formula:

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

After acquiring all the necessary input data, the obtained results are listed in Table 5, and the plot created by Microsoft Excel in Figure 17.

| 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 | 1.18596 | 0.964518 | 0.743079 | 0.521641 | 0.300202 | 0.078763 |

**Table 3.2: Calculated Factor of Safety for the slope at different cohesion using ROCPLANE**

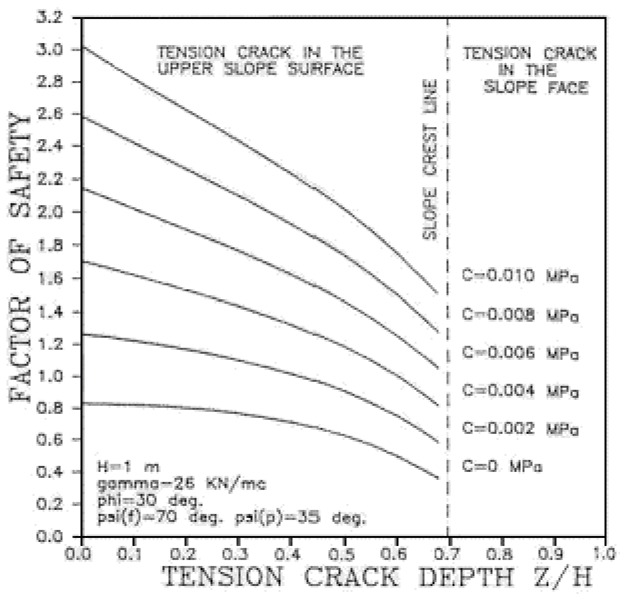



**Figure 3.2: F.S. vs. Z/H from Froldi [3].**

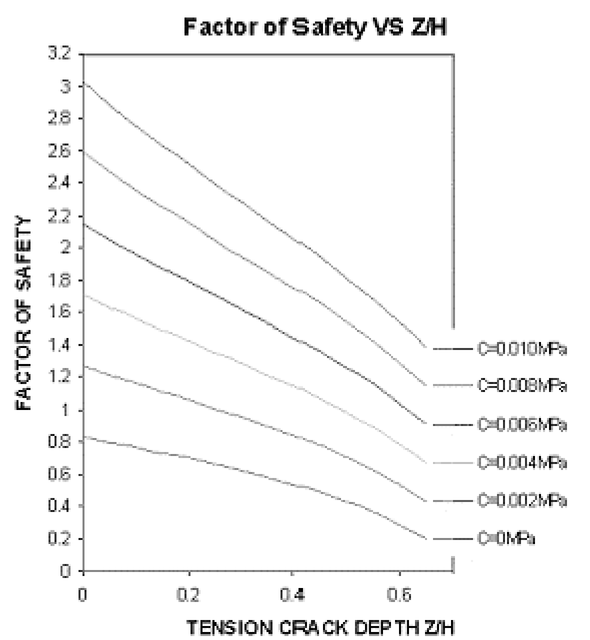



**Figure 3.3: Factor of Safety vs. Z/H with values calculated using ROCPLANE**

### 3.2 Conclusion

By comparing the plots provided by Froldi P. [3] and the ROCPLANE program, we can find that the two plots have the same shape and similar data points, with slight discrepancies as the tension crack depth (Z/H) values get closer to 0.7 since the tension crack will be in the slope face if Z/H exceeds 0.7. Hence, the ROCPLANE program is verified to work for this specific example.

### 4.1 Introduction

In this example, the slope stability along the side of the River Yamun in Garhwal Himalaya, India, where the Lakhwar Dam is located, will be analyzed. We will verify the ROCPLANE program by comparing the results produced by the ROCPLANE program with the data provided S.Sharma in ref. [4]. We will also carry out a series of sensitivity analysis with various heights to the release joint.

### 4.2 Description and Geometry

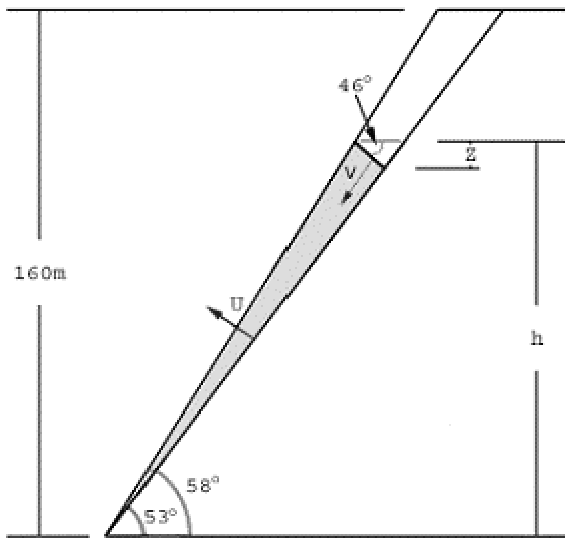



**Figure 4.1: Geometry of slope**

Input Data:

| | | | |
|---|---|---|---|
| Slope Angle | 58° | Unit Weight of Slope | 2.75 t/m$^3$ |
| Failure Plane Angle | 53° | Unit Weight of Water | 1.0 t/m$^3$ |
| Tension Crack Angle | 134° | Cohesion | 10 t/m$^2$ |
| Distance from TC to Crest | 0 m | Friction Angle | 40° |
| Slope Height | 20 m → 160 m | | |
| Water Percent Filled TC | 0%, 50%, 100% | Seismic Coefficient | 0 or 0.15 |

**Example Verification**

Here we enter the supplied data in the ROCPLANE program to calculate the factor of safety. The analysis by S. Sharma [4] is listed in Table 6, and the results calculated by ROCPLANE are displayed in Table 7.

| 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 4.1: 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 | 4.64392 | 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 |

**Table 4.2: Stability analysis for plane failure with ROCPLANE**

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 20 and Figure 21. The parameters for the sensitivity analysis are listed in Table 8.

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

**Table 4.3: Functions and parameters for sensitivity analysis**

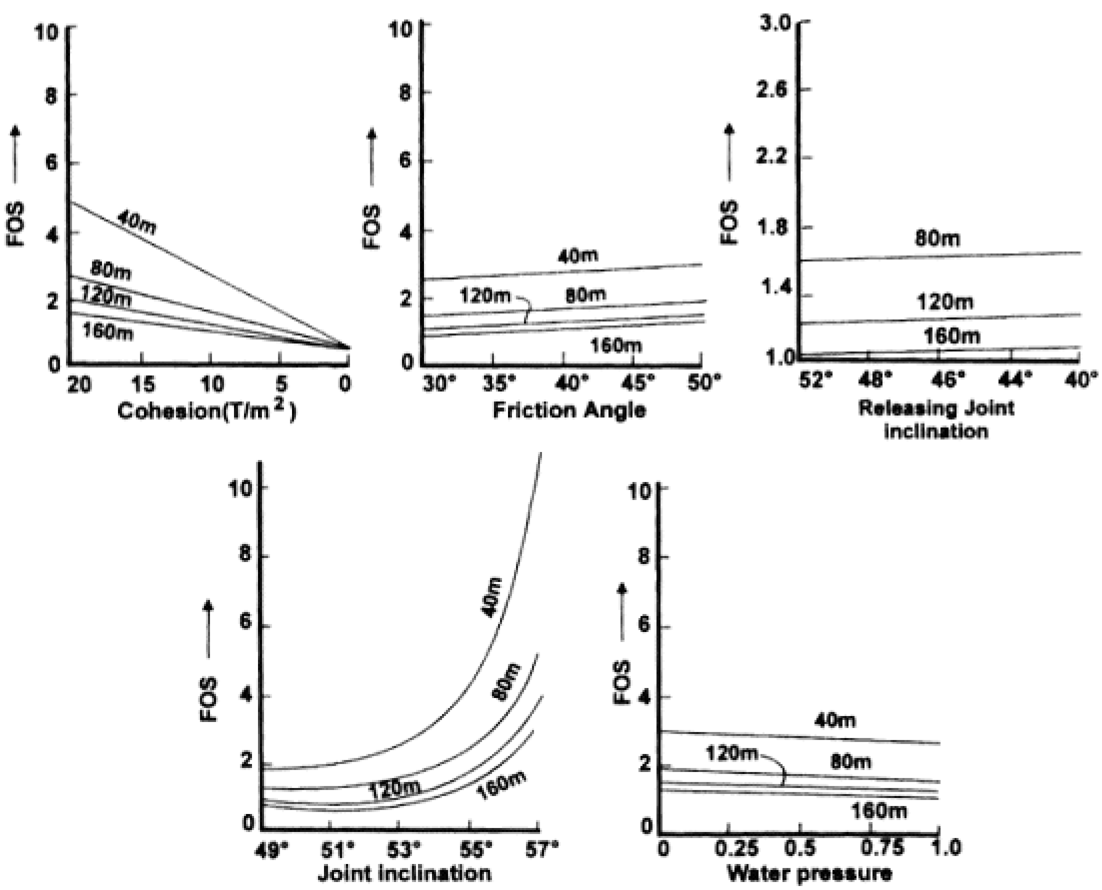



**Figure 19:Sensitivity of FOS to various factors causing instability of the failure plane by Sharma [4]**

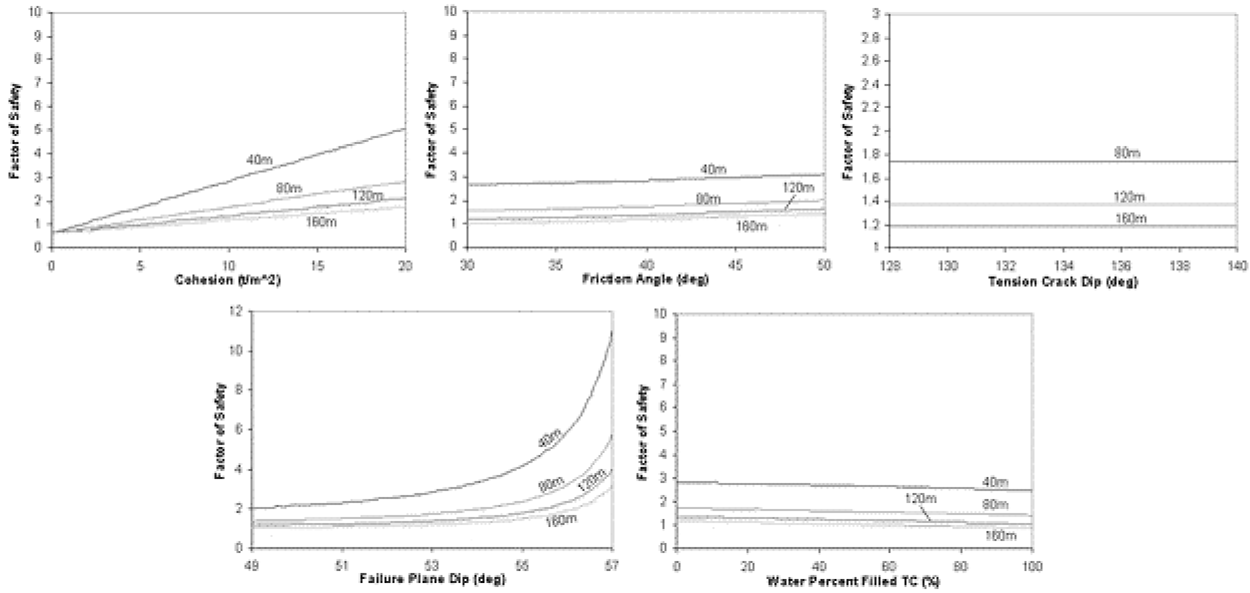



**Figure 20: Sensitivity of Factor of Safety to various factors causing instability of the failure plane, with 0% water filled tension crack and no seismic loading**

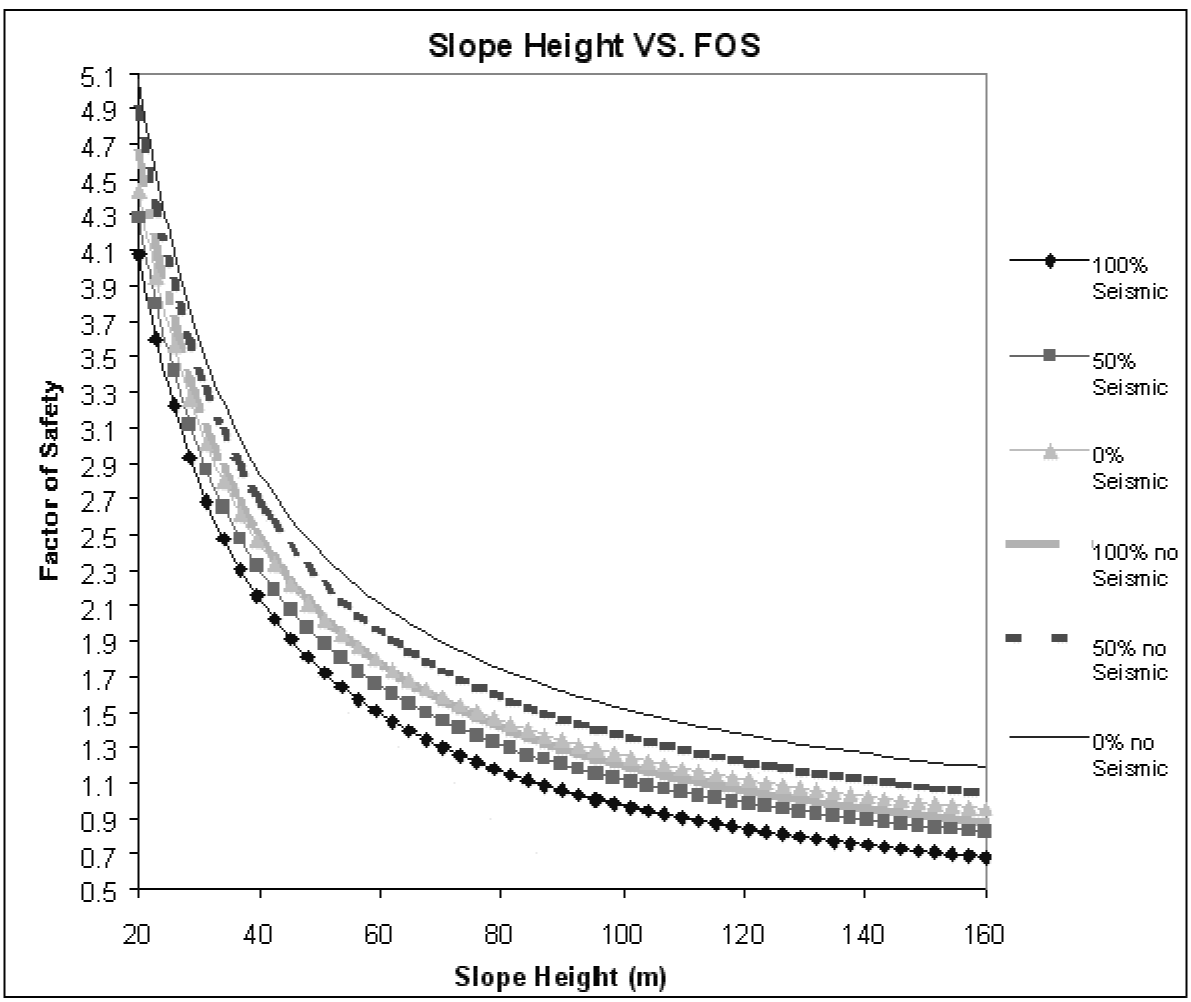



**Figure 21: Sensitivity Analysis in ROCPLANE with Slope Height varied from 20 m to 160 m**

### 4.3 Conclusion

By comparing the calculated and supplied factor of safety, we find that with no water force, the results are exactly the same. With 50% and 100% water filled tension crack, we find that there are slight differences in the calculated data. By examining the supplied equations, we conclude that 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 $10^o$ and $60^o$:

$$F.S. = CA + \frac{(W\cos\alpha - U)\tan\phi}{W\sin\alpha + V}$$

With tension crack dip between $61^o$ and $90^o$:

$$F.S. = CA + \frac{(W\cos\alpha - U - V\sin\alpha)\tan\phi}{W\sin\alpha + V\cos\alpha}$$

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

On the other hand, the ROCPLANE program generated the same sensitivity plots as Sharma's [4] (Figure 19). The ROCPLANE program verifies this example.

## 5.1 Introduction

This example is based on the reference article on modeling shear strength by S.M.Miller in ref. [5]. In this example, both linear and curved relationships between the shear strength and normal stress for rock failure planes are analyzed here. Two types of shear strength models will be examined: the Barton-Bandis Model, which is based on JRC (joint roughness coefficient), basic friction angle, and JCS (joint-wall compressive strength), and the Power Curve Model. As for the Power Curve Model analysis, both linear and curved models will be used. A linear model (Linear 2) that is fitted to three data points and another linear model (Linear 3) that is fitted to five shear data points will be considered.

## 5.2 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: $$\tau = 2.978 + 0.624\sigma_n$$

## 5.3 Geometry and Properties

| | | | |
|---|---|---|---|
| Slope Angle | $64^o$ | Bench Angle | $14^o$ |
| Slope Height | 30, 15, 6 and 3 m | JCS* | 10000 $t/m^2$ |
| Unit Weight | 2.7 $t/m^3$ | Basic Friction Angle* | $32^o$ |
| Failure Plane Angle | $35^o$ and $50^o$ | JRC* | 3, 7 and 11 |
| Waviness** | $3^o$, $11^o$ and $20^o$ | | |

**Table 5.1: Conditions of the slope in stability analysis.**

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

## 5.4 Results

Many 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 10, and the results produced by ROCPLANE are listed in Table 5.2.

| | 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 |

**Table 5.2: Safety factor values computed by M.Miller [5] for example plane-shear failure The left column shows data with failure plane dip of 35° and the right column shows data with failure plane dip of 50°.**

| | Failure Height (m) | Factor of Safety: Power | | Linear 2 | | Linear 3 | | JRC | |
|---|---|---|---|---|---|---|---|---|---|
| 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 |

**Table 5.3: Factor of safety computed by ROCPLANE for plane-shear failure with failure plane dips at 35° and 50°**

Also, 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 5.1. The similar graph generated with Microsoft Excel with factor of safety data generated with the ROCPLANE program is shown in Figure 5.2.

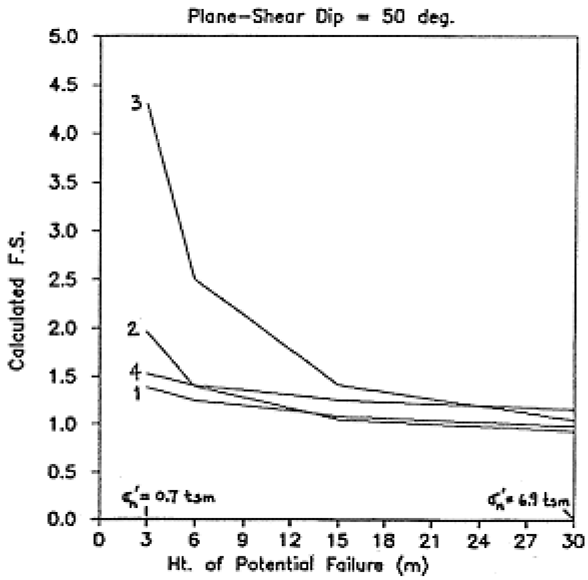



**Figure 5.1: Sensitivity plot of factor of safety versus slope height by Miller (1 – Power Curve Model, 2 – Linear 2, 3 – Linear 3, 4 – JRC)**

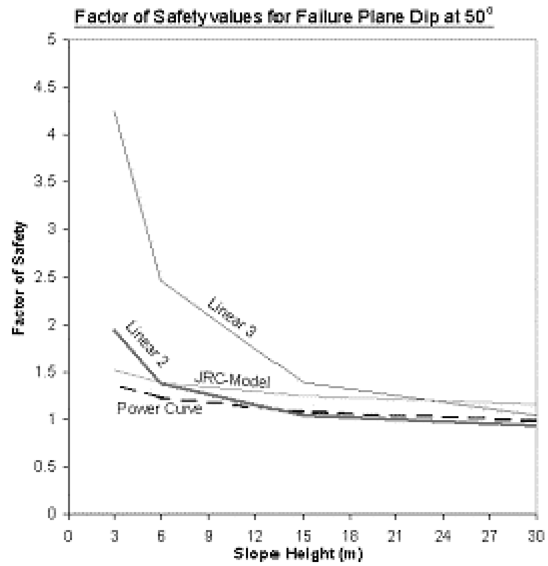



**Figure 5.2: Sensitivity plot of factor of safety versus slope height by ROCPLANE**

**5.5 Conclusion**

By comparing the data in Table 10 with Table 11 and Figure 22 with Figure 23, we find that the results are either the same or within a difference of 1.5%. Therefore, the ROCPLANE program has verified the results provided by Miller [5].

## 6.1 Introduction

This problem was taken from Priest (1993). It is his example question on the analysis of rigid blocks, and the sensitivity of various parameters.

## 6.2 Description

Verification problem 6 analyzes a slope undergoing planar failure (Figure 6.1). The slope has a tension crack at the crest 15m 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 must be performed varying cohesion, friction angle, slope angle, and percent TC filled (Figure 6.2).

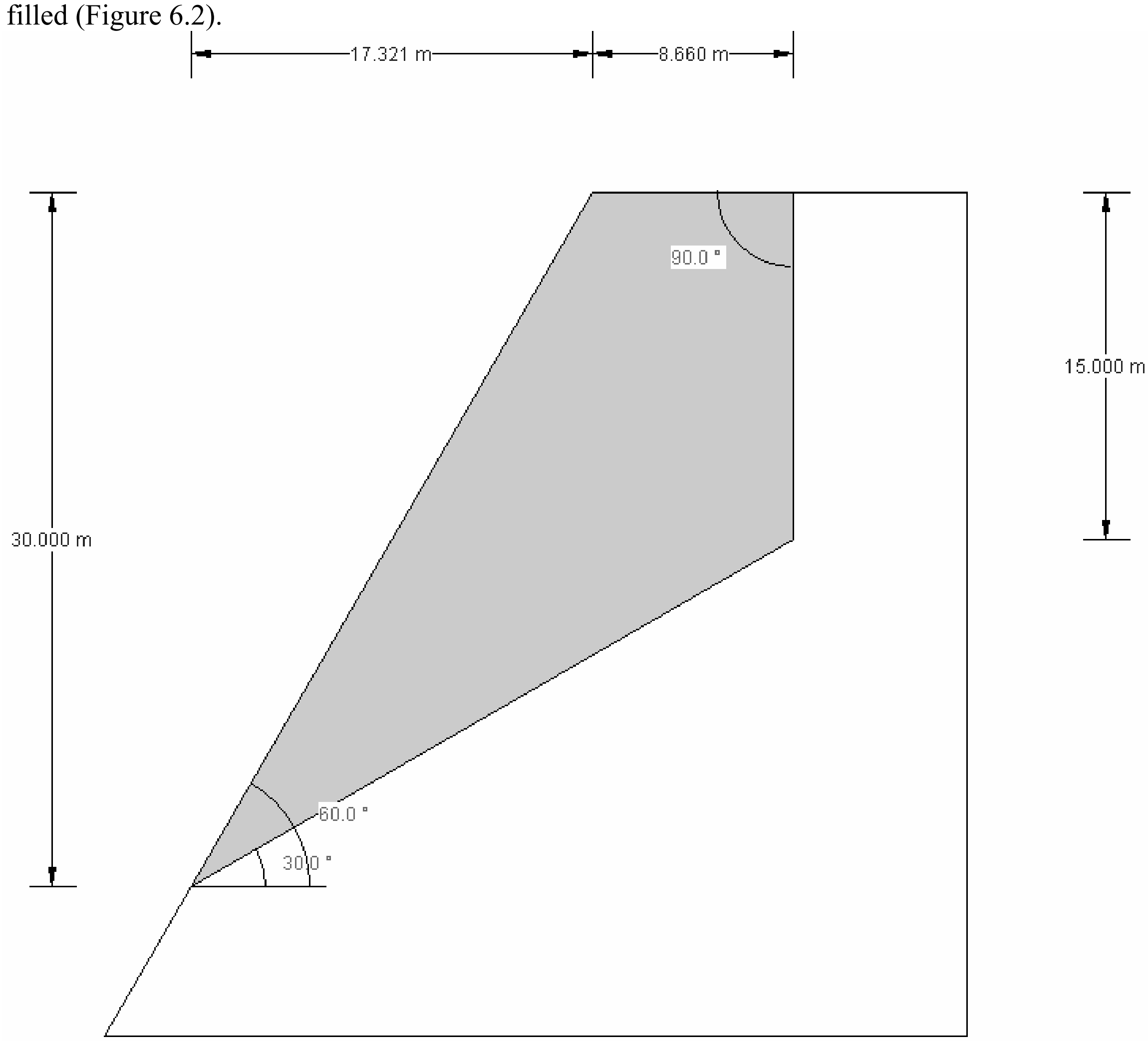



**Figure 6.1 – Slope geometry**

**Table 6.1: Properties**

| | | | |
|---|---|---|---|
| Cohesion (t/m$^{2)}$ | 2 | Percent filled TC (%) | 25 |
| Friction Angle (deg.) | 30 | Peak Pressure | TC Base |
| Unit Weight (t/m$^{3)}$ | 2.5 | Unit Weight of Water (t/m$^3$) | 0.981 |
| Cohesion Variation | 0 to 4 | Friction Angle Variation | 28 to 36 |
| Failure Plane Angle Var. | 28 to 36 | Water Percent filled TC | 0 to 100 |

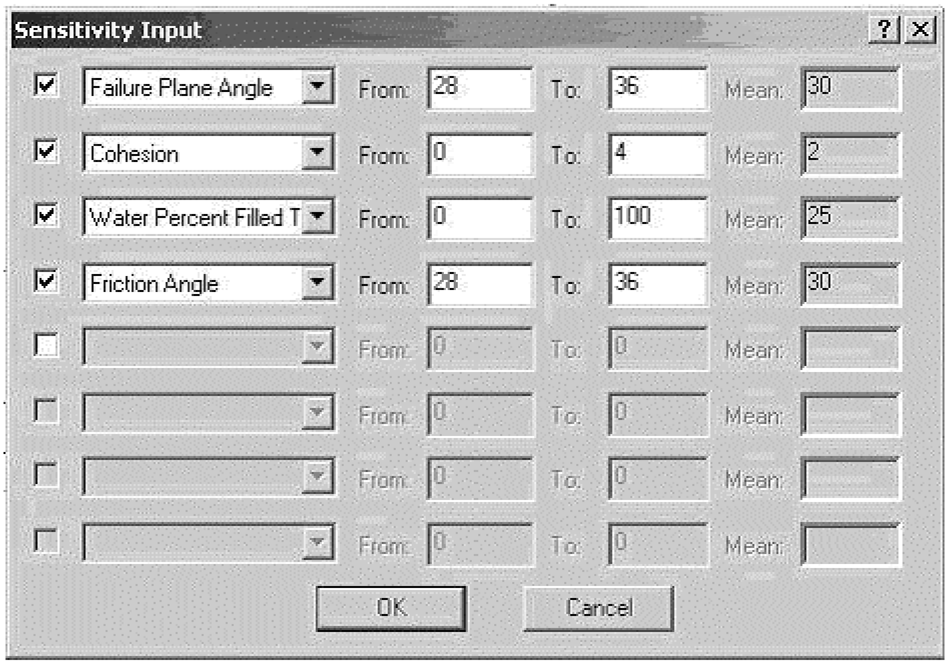



**Figure 6.2 – Sensitivity analysis parameters**

**6.3 Results**

ROCPLANE Factor of Safety = 1.049

Priest's Factor of Safety = 1.049

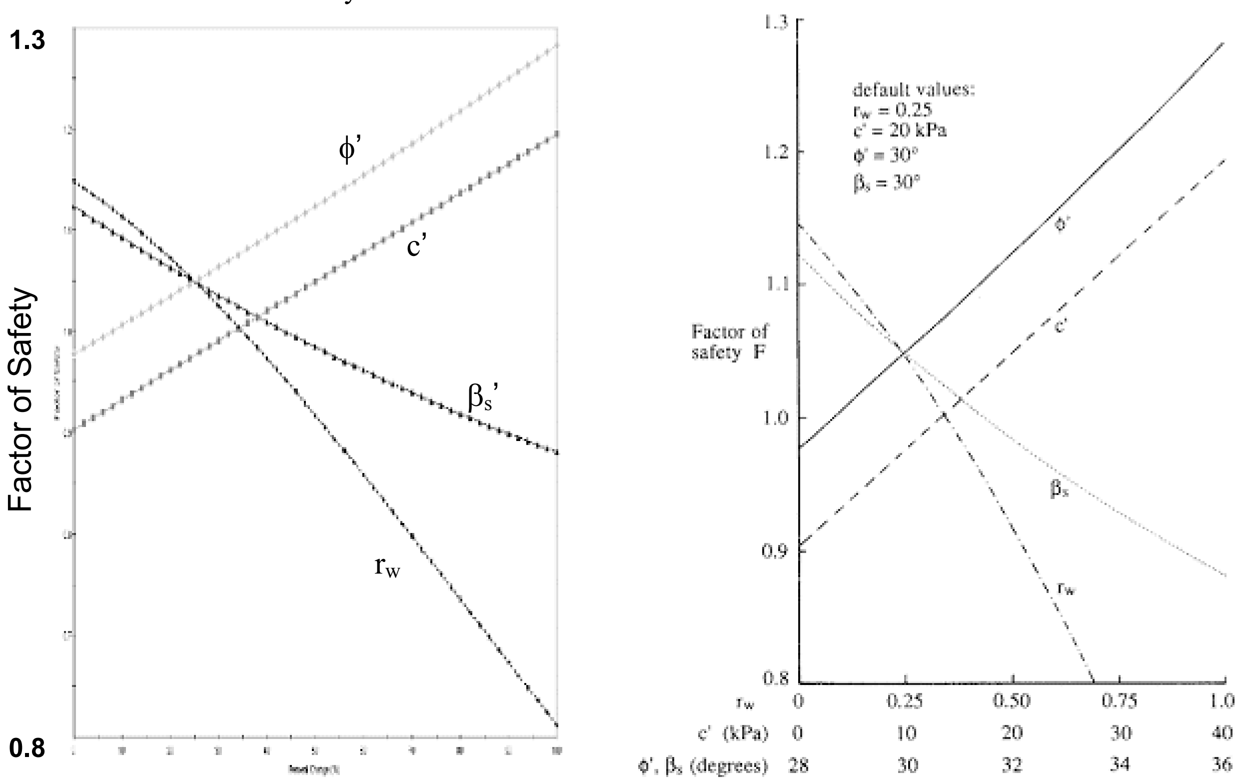



**Figure 6.3 – Sensitivity Analyses of ROCPLANE and Priest compared**

**7.1 Introduction**

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

**7.2 Description**

This 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 7.1. The safety factor of the unreinforced slope is required. Then, using the parameters for reinforcement given in Table 7.1, stabilize the slope so that it has a reinforced safety factor of 1.5. Determine the capacity of the rock bolt.

**7.3 Geometry and Properties**

**Table 7.1: Slope properties**

| | | | |
|---|---|---|---|
| Cohesion (t/m$^2$) | 7 | Percent filled TC (%) | 51 |
| Friction Angle (deg.) | 30 | Peak Pressure | TC Base |
| Unit Weight (t/m$^3$) | 2.79 | Unit Weight of Water (t/m$^3$) | 0.981 |
| Rock-bolt angle (deg.) | 30 | Bolt type | active |
| External Force (t/m) | 37 | Failure plane angle (deg.) | 35 |
| Slope angle (deg.) | 50 | Slope height (m) | 30 |
| TC distance from crest (m) | 9 | Seismic acceleration | 0.10g |

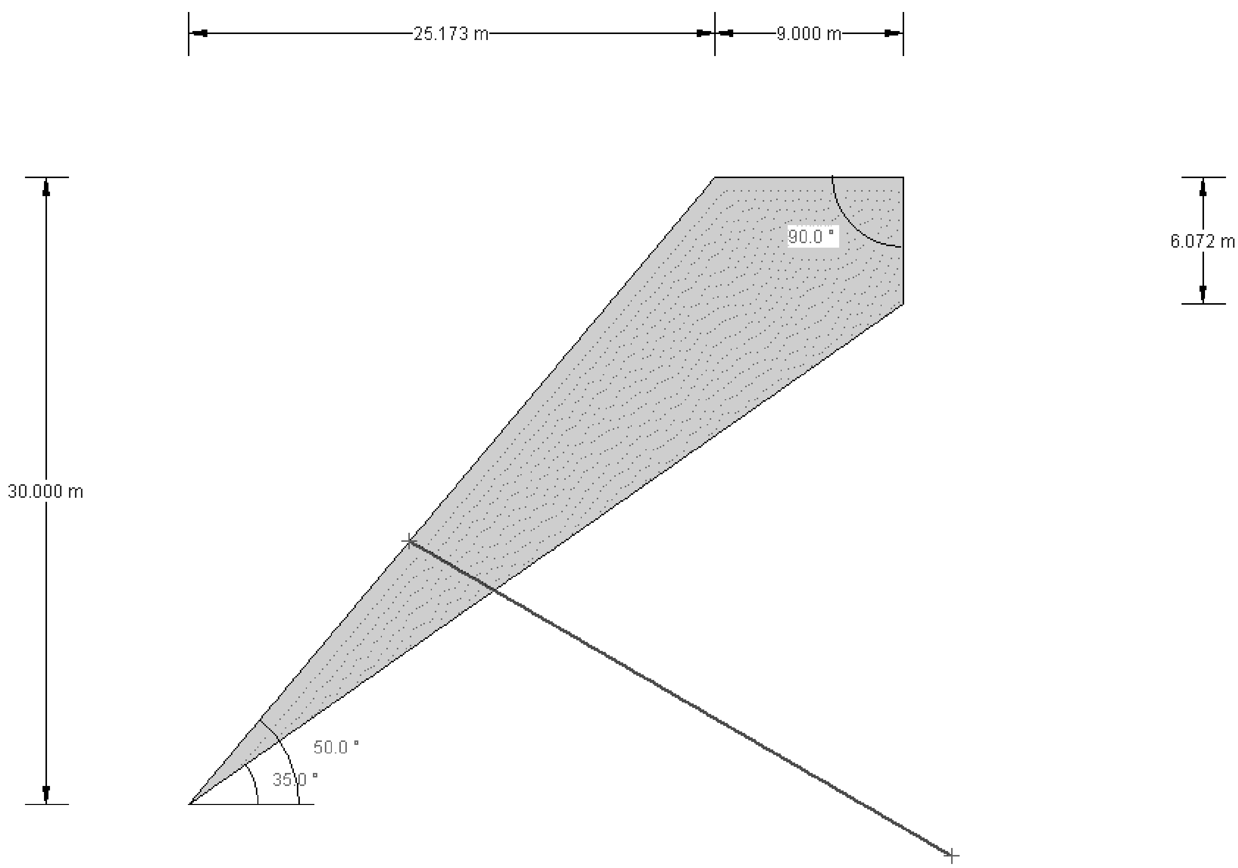



**Figure 7.1 - Geometry**

### 7.4 Results

No reinforcement ➔ FS = 1.222

With rock bolt ➔ Capacity of 111 t/m gives an FS = 1.5006

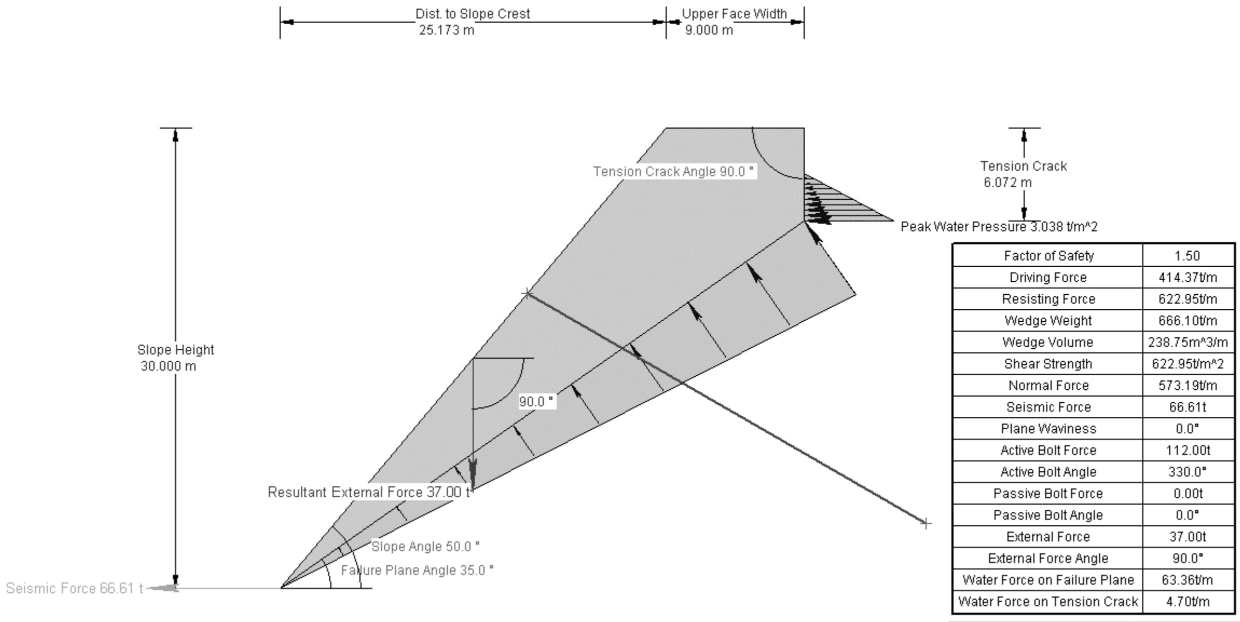



**Figure 7.2 – Results of reinforced wedge**

These results agree with Kliche's required rock bolt capacity of 111 t/m.

**8.1 Introduction**

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

**8.2 Description**

Verification problem #8 analyzes a simple slope with three different definitions of material properties (Table 8.1). There is no tension crack present, and the failure surface is dry. The upper slope is horizontal. The geometry is given in Figure 8.1.
Note: Parameters are given in kg/ft$^3$. In order to change them into t/ft$^3$, divide by 907 (short tons).

**8.3 Geometry and Properties**

**Table 8.1: Material Properties**

| Case | c′ (t/ft$^2$) | ϕ′ (deg.) | γ (t/ft$^3$) |
|---|---|---|---|
| 1 | 0 | 20 | 0.18192 |
| 2 | 1.1025 | 20 | 0.18192 |
| 3 | 2.2051 | 35 | 0.18192 |

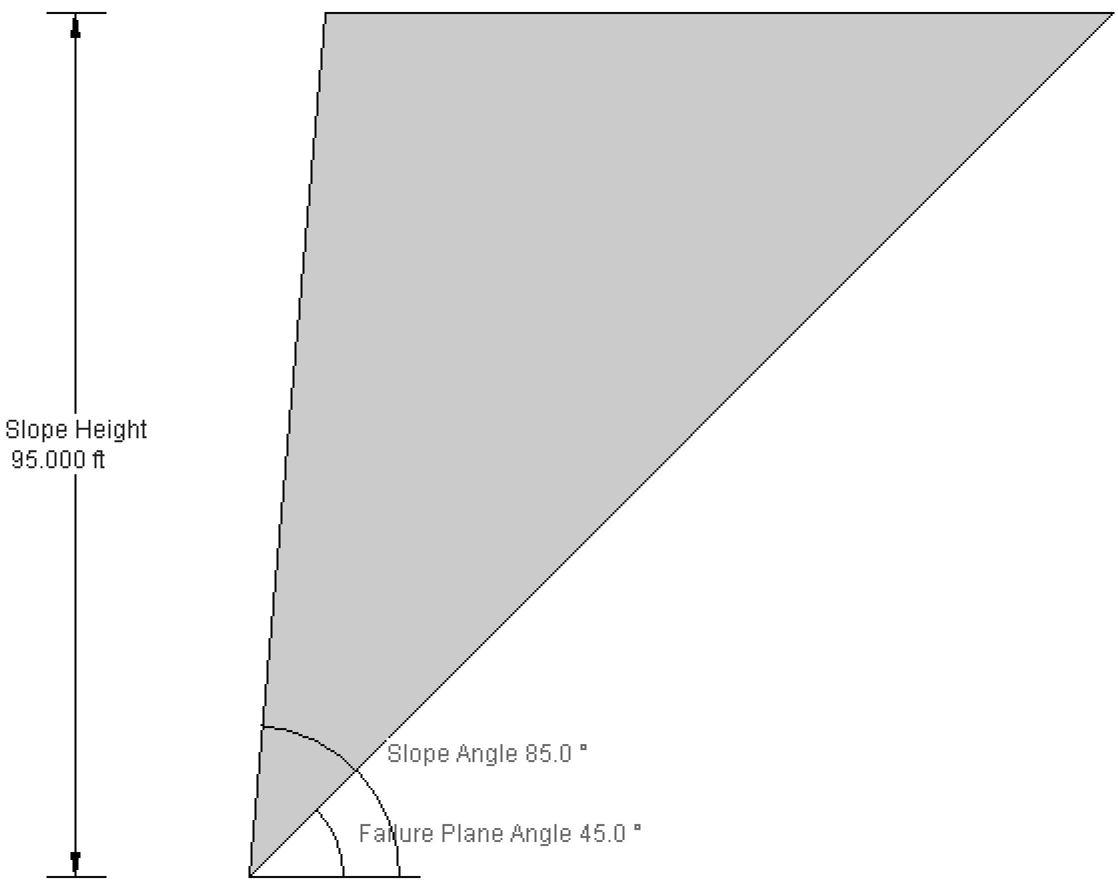



**Figure 8.1 – Geometry of slope**

## 8.4 Results

| Case | ROCPLANE Factor of Safety | Watts and West Factor of Safety |
|---|---|---|
| 1 | 0.364 | 0.364 |
| 2 | 0.644 | 0.644 |
| 3 | 1.260 | 1.260 |

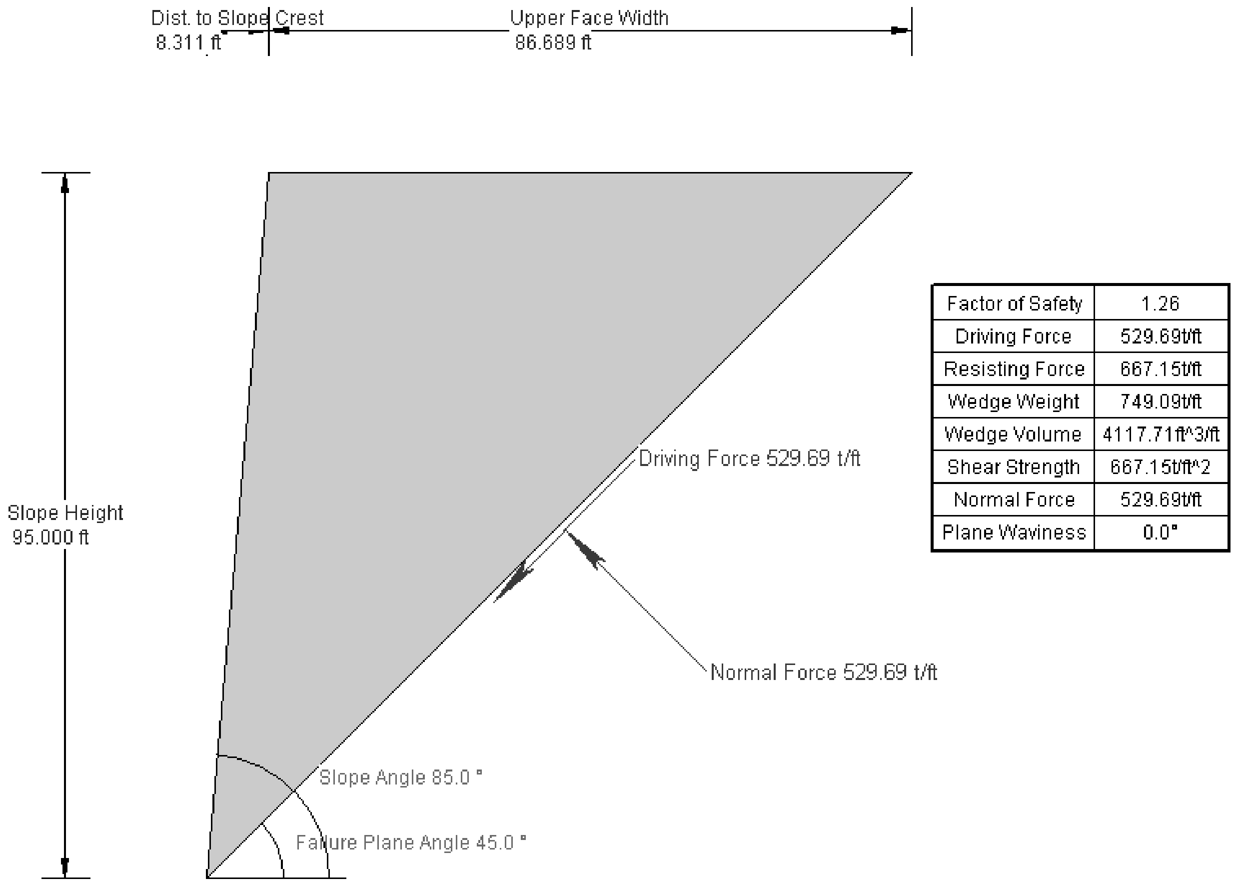



**Figure 8.2 – Case 3 in ROCPLANE, also showing wedge properties**

```
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 8.3 – Case 3 using the author's electronic filed notebook system**

# REFERENCES


1. Dr. E Hoek, 2000, "A slope stability problem in Hong Kong", *Practical Rock Engineering***,** pp. 92-104.

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