



**RocSlope**

# **Kinematics Computations**

Verification Manual

# Table of Contents

<b>1. RocSlope Verification Problem #1</b> .....	<b>5</b>
1.1. Problem Description .....	5
1.2. Geometry and Material Properties .....	5
1.2.1. Example 1 .....	5
1.2.2. Example 2.....	7
1.2.3. Example 3.....	8
1.2.4. Example 4.....	10
1.2.5. Example 5.....	11
1.2.6. Example 6.....	13
1.2.7. Example 7.....	14
1.2.8. Example 8.....	16
1.2.9. Example 9.....	17
1.2.10. Example 10.....	19
1.2.11. Example 11.....	20
1.2.12. Example 12.....	22
1.2.13. Example 13.....	23
1.2.14. Example 14.....	25
1.2.15. Example 15.....	26
1.3. Results.....	28
<b>2. RocSlope Verification Problem #2</b> .....	<b>29</b>
2.1. Problem Description .....	29
2.2. Geometry and Material Properties .....	29
2.3. Results.....	30
<b>3. RocSlope Verification Problem #3</b> .....	<b>31</b>
3.1. Problem Description .....	31
3.2. Geometry and Material Properties .....	31
3.3. Building a Compatible RS3 Model .....	31
3.4. Results.....	33
<b>4. RocSlope Verification Problem #4</b> .....	<b>34</b>
4.1. Problem Description .....	34
4.2. Geometry and Material Properties .....	34
4.3. Building a Compatible RS3 Model .....	36

4.4. Results.....	37
<b>5. RocSlope Verification Problem #5 .....</b>	<b>38</b>
5.1. Problem Description .....	38
5.2. Geometry and Material Properties .....	38
5.3. Building a Compatible RS3 Model .....	39
5.4. Building a Compatible SWedge Model.....	40
5.5. Results.....	41
<b>6. RocSlope Verification Problem #6 .....</b>	<b>43</b>
6.1. Problem Description .....	43
6.2. Geometry and Material Properties .....	43
6.3. Building a Compatible RS3 Model .....	44
6.4. Results.....	46
<b>7. RocSlope Verification Problem #7 .....</b>	<b>47</b>
7.1. Problem Description .....	47
7.2. Geometry and Material Properties .....	47
7.3. Results.....	48
<b>8. RocSlope Verification Problem #8 .....</b>	<b>49</b>
8.1. Problem Description .....	49
8.2. Geometry and Material Properties .....	49
8.3. Groundwater.....	49
8.3.1. Uniform Water Pressure on Joints.....	49
8.3.2. Pondered Water.....	50
8.4. Results.....	51
<b>9. RocSlope Verification Problem #9 .....</b>	<b>52</b>
9.1. Problem Description .....	52
9.2. Geometry and Material Properties .....	52
9.3. Analytical Solution .....	53
9.4. Results.....	53
<b>10. RocSlope Verification Problem #10 .....</b>	<b>54</b>
10.1. Problem Description .....	54
10.2. Geometry and Material Properties .....	54
10.3. Analytical Solution .....	57
10.3.1. Sample Calculation.....	59
10.4. Results.....	59

<b>11.RocSlope Verification Problem #11 .....</b>	<b>62</b>
11.1. Problem Description .....	62
11.2. Geometry and Material Properties .....	62
11.3. Building a Compatible SWedge Model.....	62
11.4. Results.....	64
<b>12.RocSlope Verification Problem #12 .....</b>	<b>65</b>
12.1. Problem Description .....	65
12.2. Geometry and Material Properties .....	65
12.3. Results.....	66
<b>13.RocSlope Verification Problem #13 .....</b>	<b>67</b>
13.1. Problem Description .....	67
13.2. Geometry.....	67
13.3. Results.....	68
<b>14.RocSlope Verification Problem #14 .....</b>	<b>70</b>
14.1. Problem Description .....	70
14.2. Geometry.....	70
14.3. Results.....	71
<b>15.References.....</b>	<b>72</b>

# 1. RocSlope Verification Problem #1

---

Geometry Verification Problem [RocSlope version 1.001 & SWedge version 7.020]

## 1.1. Problem Description

The following examples can be modelled in SWedge using the basal joint block shape with or without a tension crack and cover all potential wedge geometries. For each one, the equivalent SWedge model is imported into RocSlope.

## 1.2. Geometry and Material Properties

Rock unit weight for all models is 0.026 MN/m<sup>3</sup>.

The joints representing a tension crack have no shear strength.

The tables below outline the block geometry definitions as inputted in SWedge, as well as the shear strength properties and waviness of the joints.

### 1.2.1. Example 1

Table 1.1: Wedge geometry definition

Angle	Value
Slope Dip (°)	80
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	52
Joint 1 Dip Direction (°)	125
Joint 2 Dip (°)	57
Joint 2 Dip Direction (°)	250
Basal Plane Dip (°)	13
Basal Plane Dip Direction (°)	20

Table 1.2: Joint properties

Property	Value
Waviness (°)	0
Shear Strength Model	Mohr-Coulomb
c (MPa)	0
Phi (°):	35

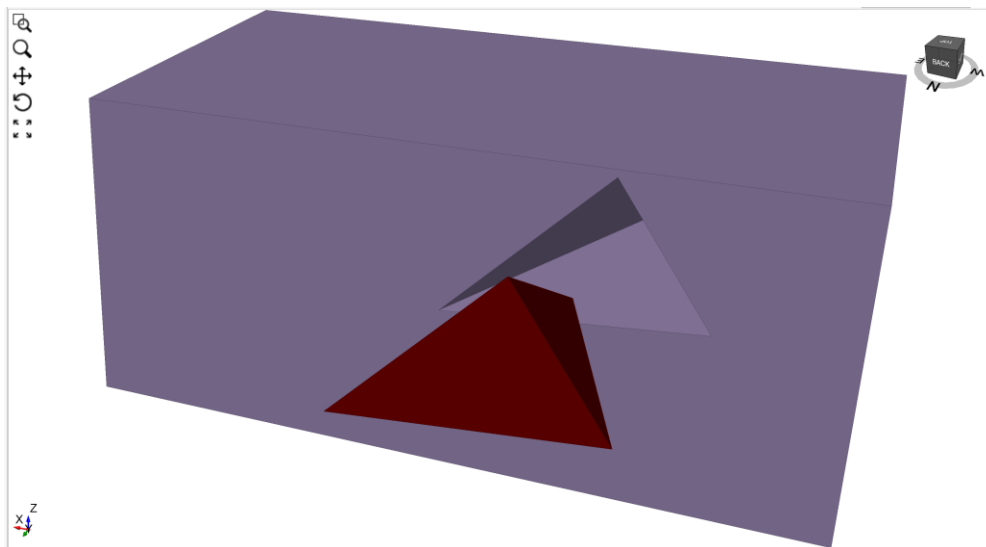


Figure 1.1: Block in RocSlope

## 1.2.2. Example 2

Table 1.3: Wedge geometry definition

<b>Angle</b>	<b>Value</b>
Slope Dip (°)	90
Slope Dip Direction (°)	0
Upper Face Dip (°)	12
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	70
Joint 1 Dip Direction (°)	45
Joint 2 Dip (°)	70
Joint 2 Dip Direction (°)	315
Basal Plane Dip (°)	30
Basal Plane Dip Direction (°)	15

Table 1.4: Joint properties

<b>Property</b>	<b>Value</b>
Waviness (°)	0
Shear Strength Model	Barton-Bandis
JRC	10
JCS (MPa)	30
Phir (°)	30

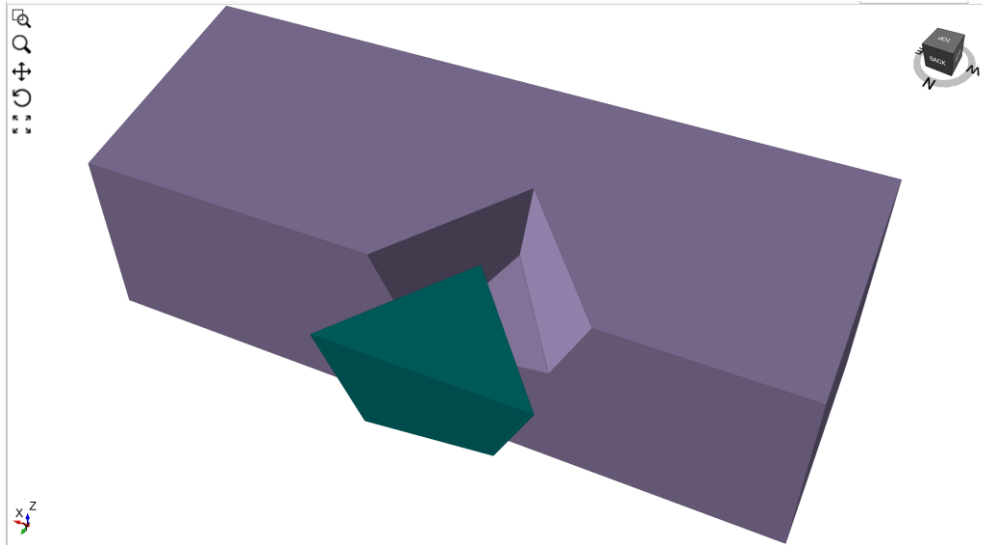


Figure 1.2: Block in RocSlope

### 1.2.3. Example 3

Table 1.5: Wedge geometry definition

Angle	Value
Slope Dip (°)	80
Slope Dip Direction (°)	0
Upper Face Dip (°)	12
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	90
Joint 1 Dip Direction (°)	80
Joint 2 Dip (°)	70
Joint 2 Dip Direction (°)	90
Basal Plane Dip (°)	40
Basal Plane Dip Direction (°)	5



Table 1.6: Joint properties

Property	Value
Waviness (°)	0
Shear Strength Model	Mohr-Coulomb
c (MPa)	1
Phi (°)	32

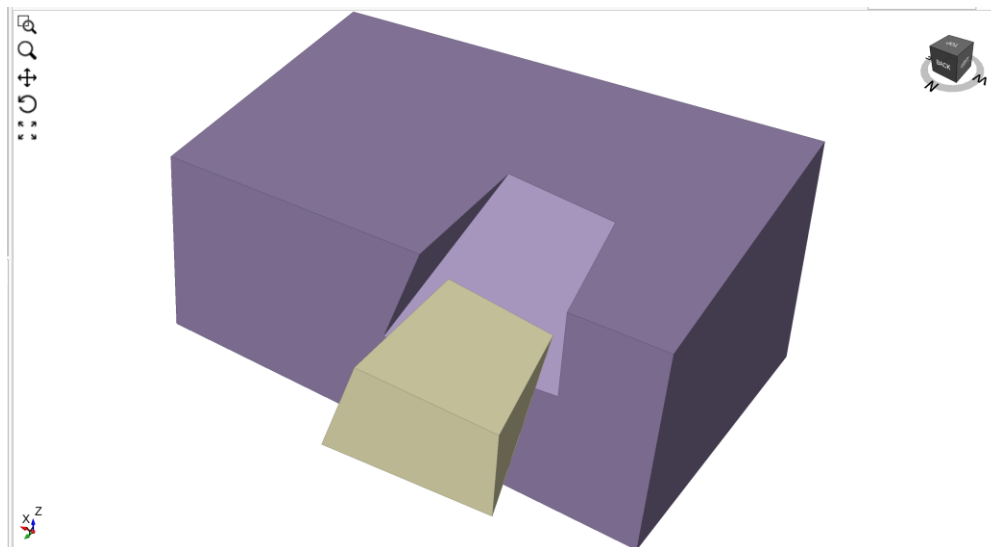


Figure 1.3: Block in RocSlope

#### 1.2.4. Example 4

Table 1.7: Wedge geometry definition

Angle	Value
Slope Dip (°)	80
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	40
Joint 1 Dip Direction (°)	38
Joint 2 Dip (°)	78
Joint 2 Dip Direction (°)	272
Basal Plane Dip (°)	45
Basal Plane Dip Direction (°)	9

Table 1.8: Joint properties

Property	Value
Waviness (°)	0
Shear Strength Model	Power Curve
a	0.7
b	1
c	3
d	0

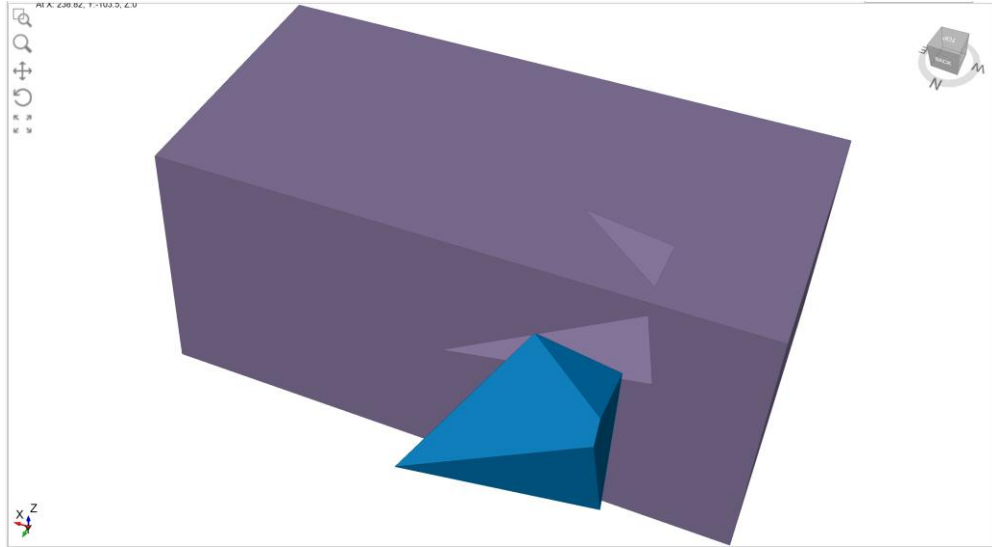


Figure 1.4: Block in RocSlope

### 1.2.5. Example 5

Table 1.9: Wedge geometry definition

Angle	Value
Slope Dip (°)	90
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	90
Joint 1 Dip (°)	70
Joint 1 Dip Direction (°)	90
Joint 2 Dip (°)	70
Joint 2 Dip Direction (°)	225
Basal Plane Dip (°)	30
Basal Plane Dip Direction (°)	0

Table 1.10: Joint properties

Property	Value
Waviness (°)	0
Shear Strength Model	Power Curve
a	0.7
b	0.5
c	0
d	0

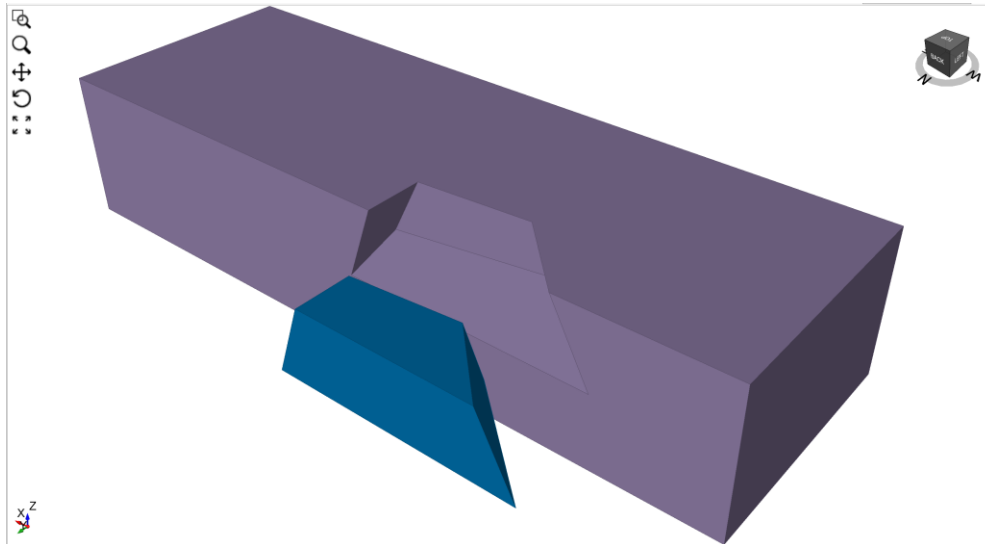


Figure 1.5: Block in RocSlope

### 1.2.6. Example 6

Table 1.11: Wedge geometry definition

Angle	Value
Slope Dip (°)	90
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	73
Joint 1 Dip Direction (°)	90
Joint 2 Dip (°)	78
Joint 2 Dip Direction (°)	270
Basal Plane Dip (°)	40
Basal Plane Dip Direction (°)	14
Tension Crack Dip (°)	70
Tension Crack Dip Direction (°)	2

Table 1.12: Joint properties

Property	Value
Waviness (°)	0
Shear Strength Model	Power Curve
a	1
b	1
c	0
d	2

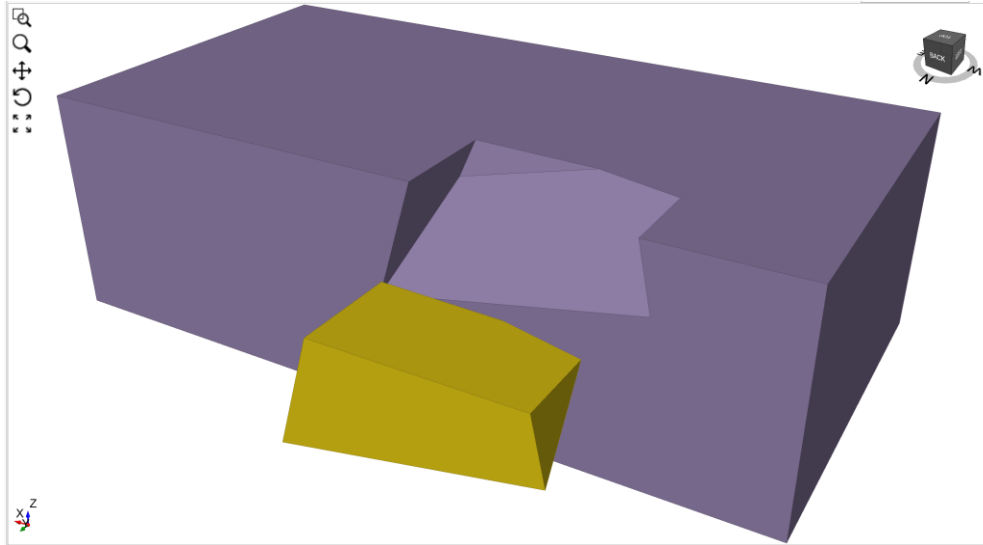


Figure 1.6: Block in RocSlope

### 1.2.7. Example 7

Table 1.13: Wedge geometry definition

Angle	Value
Slope Dip (°)	90
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	90
Joint 1 Dip Direction (°)	90
Joint 2 Dip (°)	78
Joint 2 Dip Direction (°)	270
Basal Plane Dip (°)	40
Basal Plane Dip Direction (°)	0
Tension Crack Dip (°)	70
Tension Crack Dip Direction (°)	345

Table 1.14: Joint properties

Property	Value
Waviness (°)	0
Shear Strength Model	Barton-Bandis
JRC	10
JCS (MPa)	1
Phir (°)	0

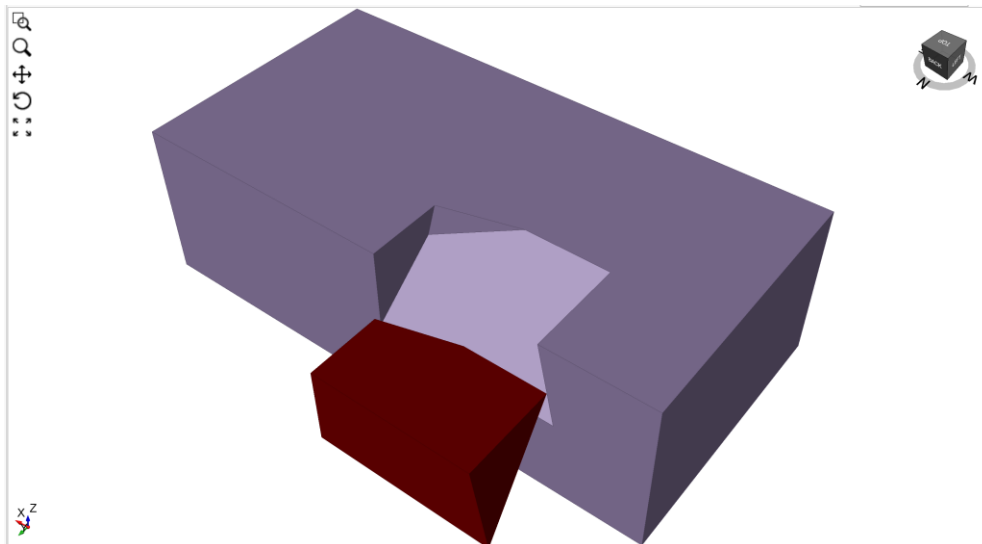


Figure 1.7: Block in RocSlope

### 1.2.8. Example 8

Table 1.15: Wedge geometry definition

Angle	Value
Slope Dip (°)	90
Slope Dip Direction (°)	0
Upper Face Dip (°)	12
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	70
Joint 1 Dip Direction (°)	45
Joint 2 Dip (°)	70
Joint 2 Dip Direction (°)	315
Basal Plane Dip (°)	10
Basal Plane Dip Direction (°)	15
Tension Crack Dip (°)	83
Tension Crack Dip Direction (°)	0

Table 1.16: Joint properties

Property	Value
Waviness (°)	3
Shear Strength Model	Mohr-Coulomb
c (MPa)	0
Phi (°):	38



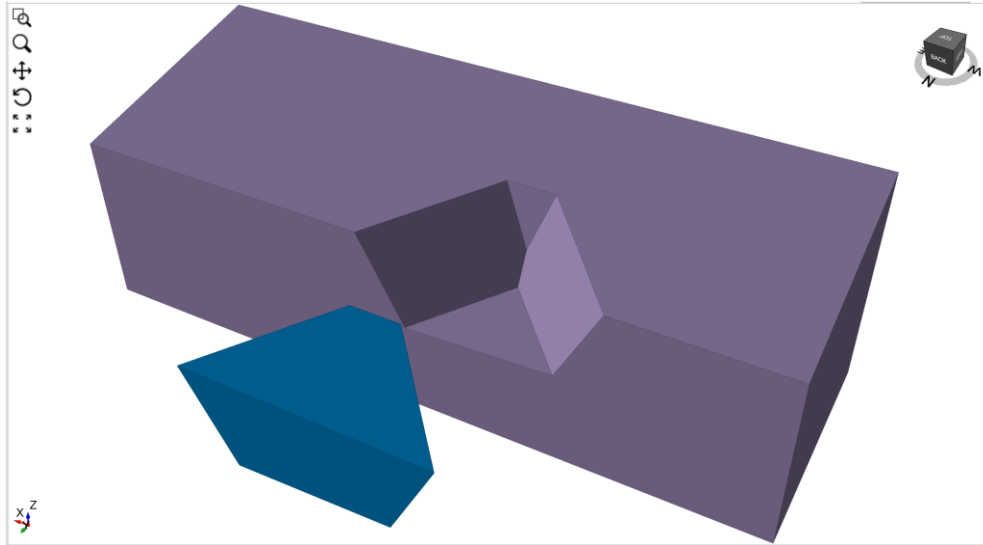


Figure 1.8: Block in RocSlope

### 1.2.9. Example 9

Table 1.17: Wedge geometry definition

Angle	Value
Slope Dip (°)	90
Slope Dip Direction (°)	0
Upper Face Dip (°)	12
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	90
Joint 1 Dip Direction (°)	103
Joint 2 Dip (°)	72
Joint 2 Dip Direction (°)	221
Basal Plane Dip (°)	26
Basal Plane Dip Direction (°)	0
Tension Crack Dip (°)	75
Tension Crack Dip Direction (°)	0

Table 1.18: Joint properties

Property	Value
Waviness (°)	5
Shear Strength Model	Barton-Bandis
JRC	1
JCS (MPa)	100
Phir (°)	0

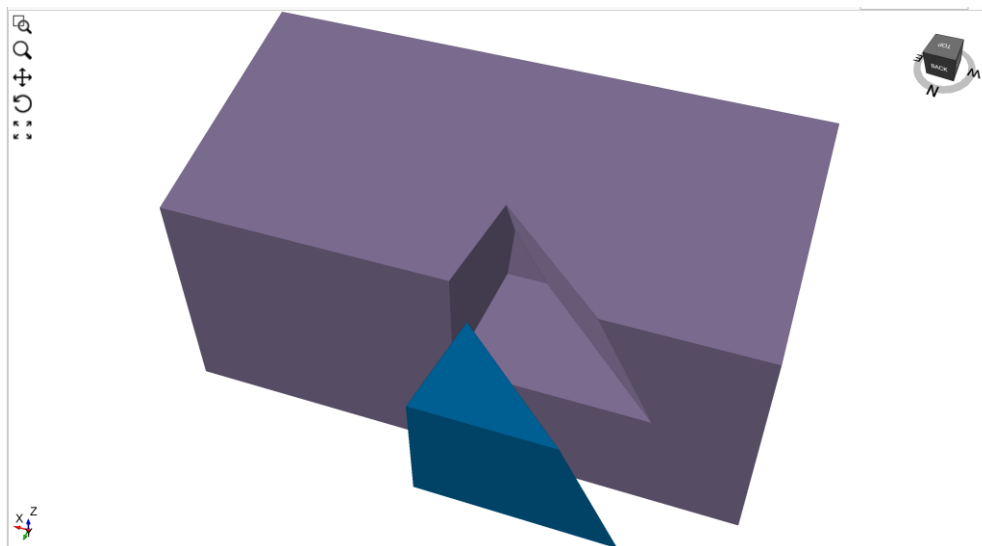


Figure 1.9: Block in RocSlope

## 1.2.10. Example 10

Table 1.19: Wedge geometry definition

<b>Angle</b>	<b>Value</b>
Slope Dip (°)	80
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	40
Joint 1 Dip Direction (°)	38
Joint 2 Dip (°)	78
Joint 2 Dip Direction (°)	272
Basal Plane Dip (°)	45
Basal Plane Dip Direction (°)	9
Tension Crack Dip (°)	90
Tension Crack Dip Direction (°)	0

Table 1.20: Joint properties

<b>Property</b>	<b>Value</b>
Waviness (°)	2
Shear Strength Model	Mohr-Coulomb
c (MPa)	6
Phi (°)	30

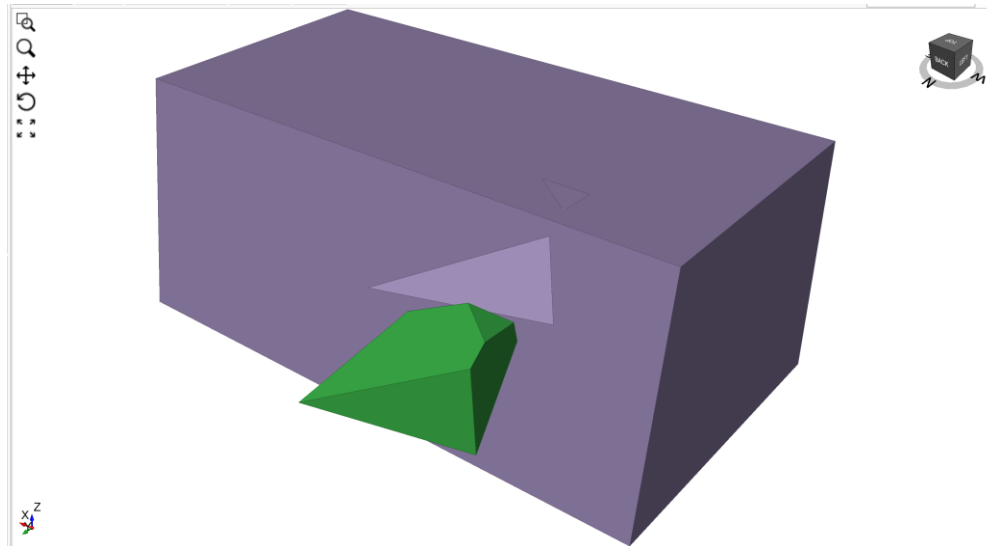


Figure 1.10: Block in RocSlope

### 1.2.11.Example 11

Table 1.21: Wedge geometry definition

Angle	Value
Slope Dip (°)	80
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	40
Joint 1 Dip Direction (°)	38
Joint 2 Dip (°)	78
Joint 2 Dip Direction (°)	272
Basal Plane Dip (°)	45
Basal Plane Dip Direction (°)	9
Tension Crack Dip (°)	74
Tension Crack Dip Direction (°)	26

Table 1.22: Joint properties

Property	Value
Waviness (°)	4
Shear Strength Model	Power Curve
a	0.3
b	0.75
c	2
d	1

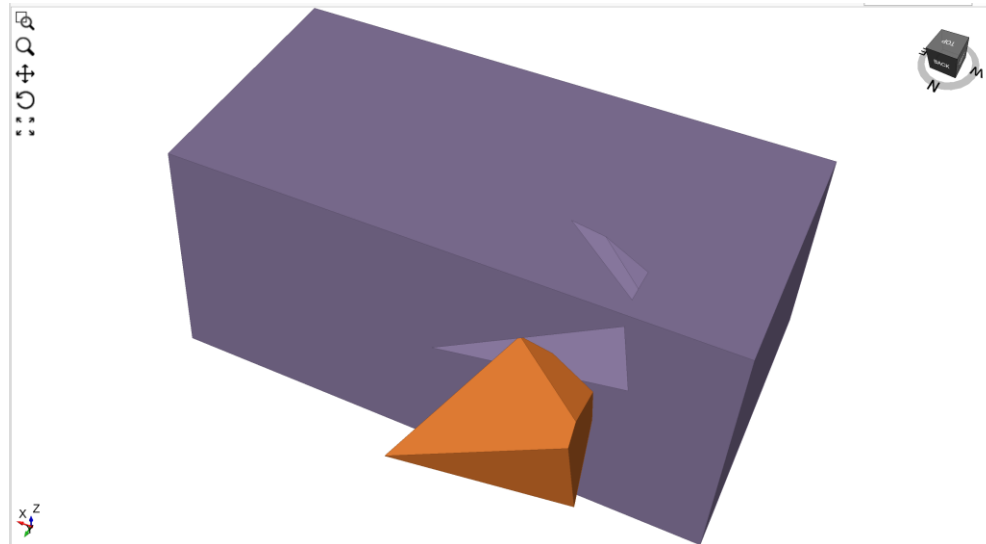


Figure 1.11: Block in RocSlope

## 1.2.12. Example 12

Table 1.23: Wedge geometry definition

Angle	Value
Slope Dip (°)	80
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	40
Joint 1 Dip Direction (°)	38
Joint 2 Dip (°)	78
Joint 2 Dip Direction (°)	272
Basal Plane Dip (°)	45
Basal Plane Dip Direction (°)	9
Tension Crack Dip (°)	90
Tension Crack Dip Direction (°)	353

Table 1.24: Joint properties

Property	Value
Waviness (°)	1
Shear Strength Model	Power Curve
a	1
b	1
c	0
d	0

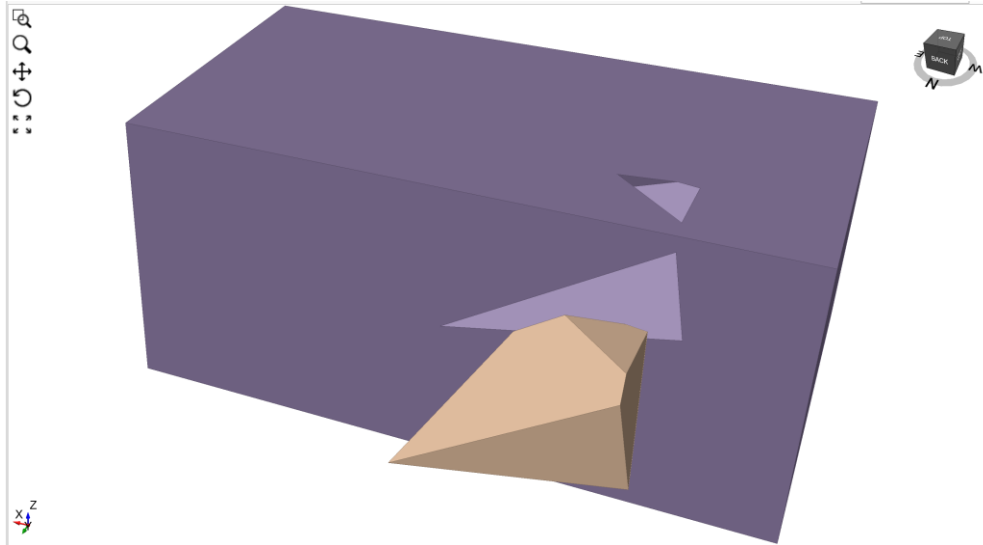


Figure 1.12: Block in RocSlope

### 1.2.13.Example 13

Table 1.25: Wedge geometry definition

Angle	Value
Slope Dip (°)	80
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	52
Joint 1 Dip Direction (°)	125
Joint 2 Dip (°)	57
Joint 2 Dip Direction (°)	250
Basal Plane Dip (°)	13
Basal Plane Dip Direction (°)	20
Tension Crack Dip (°)	90
Tension Crack Dip Direction (°)	0

Table 1.26: Joint properties

Property	Value
Waviness (°)	3
Shear Strength Model	Power Curve
a	1
b	1
c	0
d	3

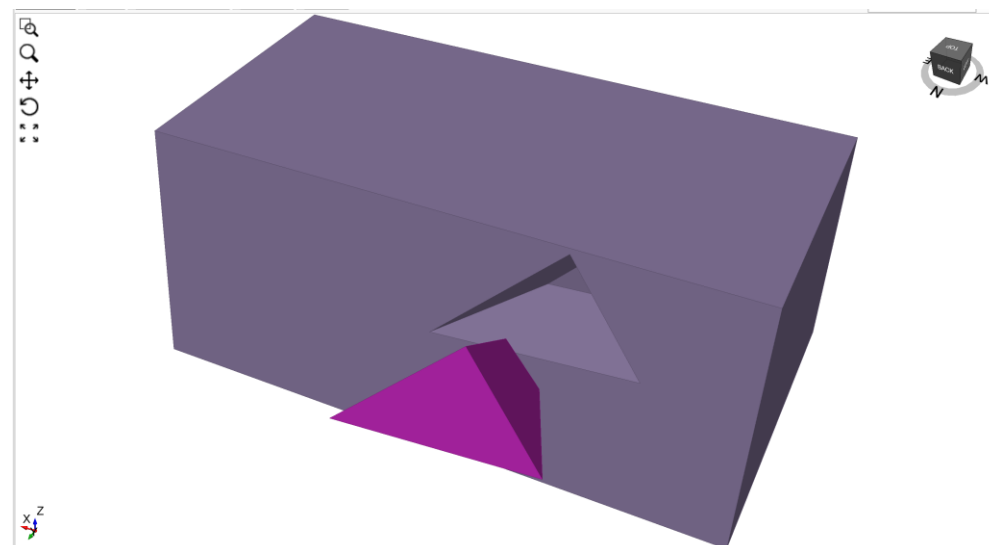


Figure 1.13: Block in RocSlope



## 1.2.14. Example 14

Table 1.27: Block geometry definition

<b>Angle</b>	<b>Value</b>
Slope Dip (°)	90
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	90
Joint 1 Dip (°)	90
Joint 1 Dip Direction (°)	315
Joint 2 Dip (°)	28
Joint 2 Dip Direction (°)	45
Basal Plane Dip (°)	38
Basal Plane Dip Direction (°)	0
Tension Crack Dip (°)	84
Tension Crack Dip Direction (°)	259

Table 1.28: Joint properties

<b>Property</b>	<b>Value</b>
Waviness (°)	5
Shear Strength Model	Barton-Bandis
JRC	15
JCS (MPa)	1
Phir (°)	0

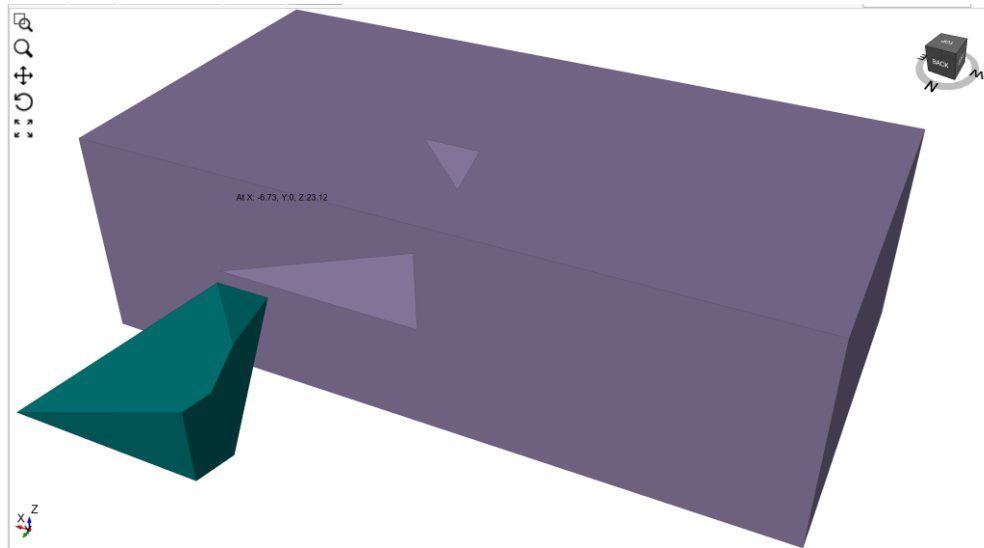


Figure 1.14: Block in RocSlope

### 1.2.15.Example 15

Table 1.29: Wedge geometry definition

Angle	Value
Slope Dip (°)	90
Slope Dip Direction (°)	0
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	90
Joint 1 Dip (°)	24
Joint 1 Dip Direction (°)	33
Joint 2 Dip (°)	90
Joint 2 Dip Direction (°)	315
Basal Plane Dip (°)	38
Basal Plane Dip Direction (°)	0
Tension Crack Dip (°)	90
Tension Crack Dip Direction (°)	55

Table 1.30: Joint properties

Property	Value
Waviness (°)	0
Shear Strength Model	Mohr-Coulomb
c (MPa)	3
Phi (°)	27

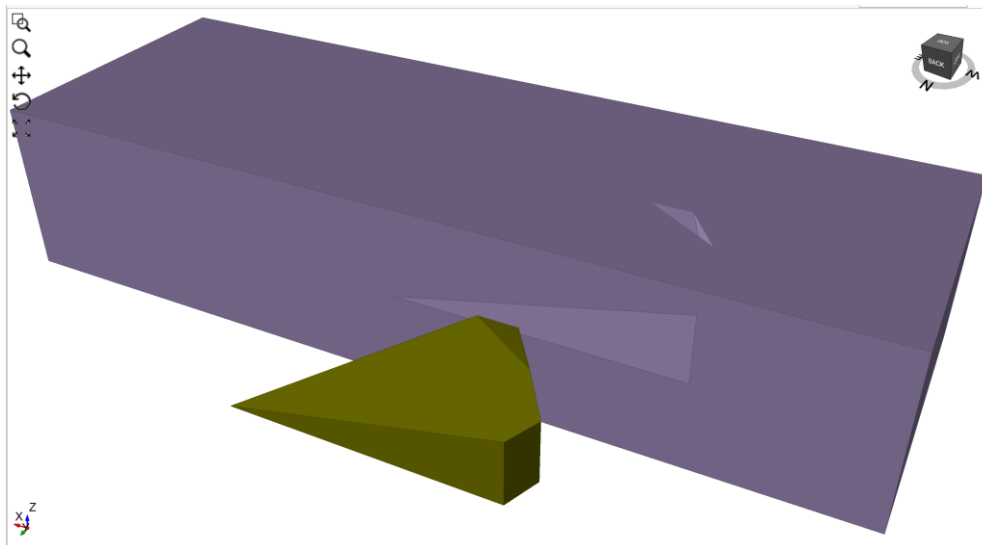


Figure 1.15: Block in RocSlope

## 1.3. Results

The factors of safety are verified against SWedge:

Table 1.31: Geometry verification results compared to SWedge

<b>Example</b>	<b>FS RocSlope</b>	<b>FS SWedge</b>
1	3.0329	3.0329
2	1.8657	1.8657
3	6.9327	6.9327
4	34.1695	34.1695
5	2.2716	2.2716
6	13.8989	13.8989
7	0.1294	0.1294
8	4.7281	4.7281
9	0.2588	0.2588
10	50.0409	50.0409
11	25.0129	25.0129
12	1.000	1.000
13	47.2000	47.2000
14	0.7031	0.7031
15	40.9312	40.9312

## 2. RocSlope Verification Problem #2

Geometry Verification Problem [RocSlope version 1.001]

### 2.1. Problem Description

When a block is formed having multiple pairs of joints whose joint plane vectors of intersection are equal, it may slide while remaining in contact with more than two joints.

This verification problem is taken from Mauldon (1996), namely their Example from East Tennessee. It analyzes the stability of a prismatic block, having four joints whose normal vectors are all in the same plane. The example models a sliding stability investigation of a road cut.

### 2.2. Geometry and Material Properties

The block is modelled in RocSlope using joint surfaces. To do so, the discretization of the curved failure surface defined in the reference paper is drawn as a polyline.

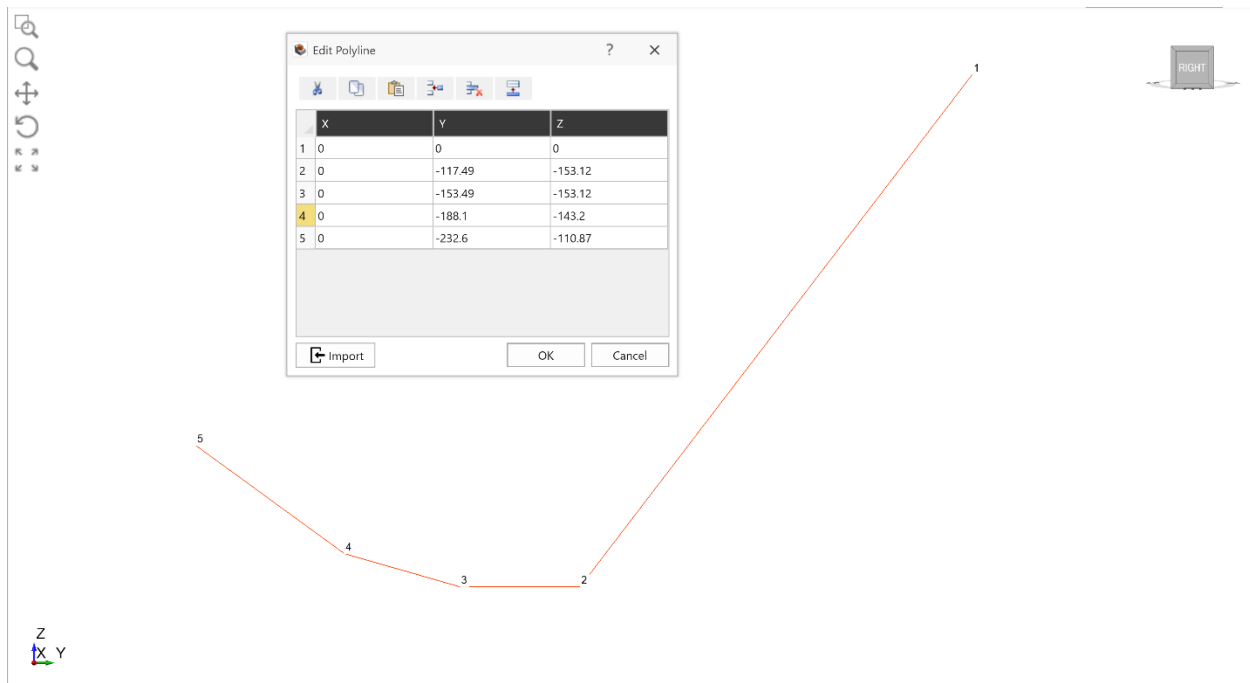


Figure 2.1: Joints viewed in the plane orthogonal to the sliding direction

This polyline is extruded in the direction of the X axis, then the resultant surface is rotated about the Y axis by the plunge angle of  $32^\circ$ .

The slope is modelled as a box around the bottom of the block and the rock is assigned a unit weight of  $0.026 \text{ MN/m}^3$ .

The geometry of the modelled block is shown in Figure 2.2.

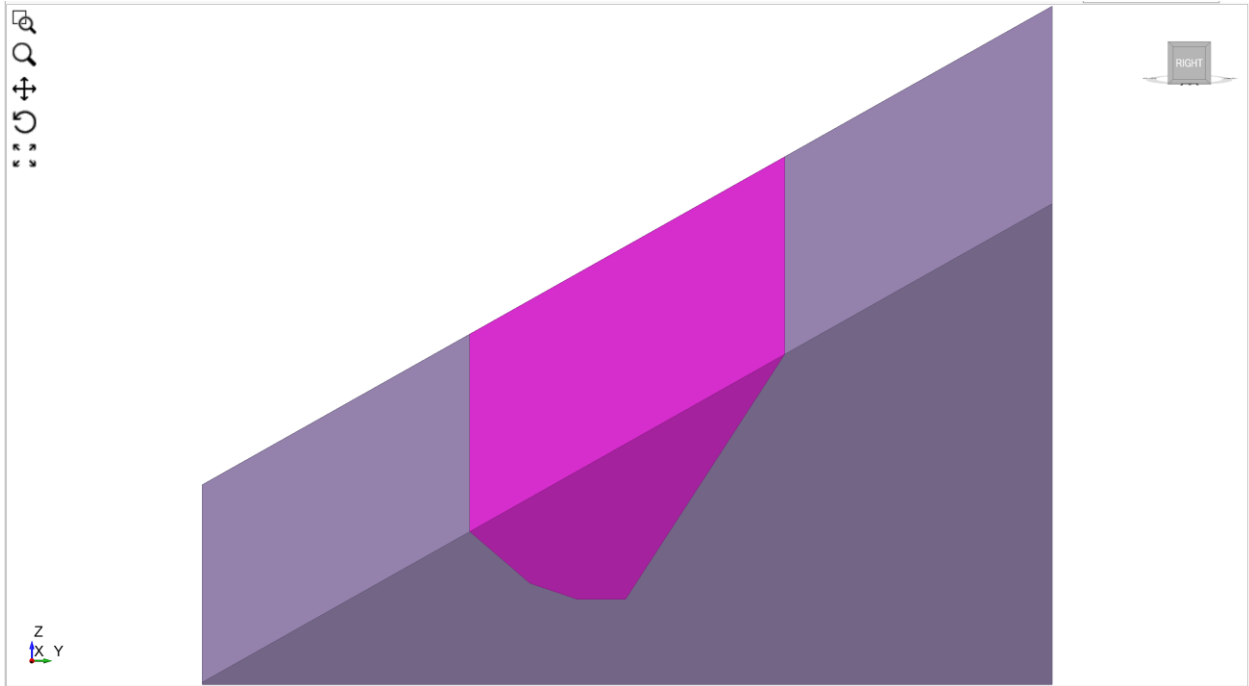


Figure 2.2: Prismatic block

As in the referenced example, all joints are using the Mohr-Coulomb shear strength model without cohesion and with a friction angle of 27°.

### 2.3. Results

The factor of safety outputted by RocSlope matches the result from the referenced paper when performing prismatic block analysis.

Table 2.1: Geometry verification result compared to Mauldon and Ureta reference paper

	<b>RocSlope</b>	<b>Mauldon and Ureta</b>
<b>FS</b>	1.00	1.00

The paper also documents the factor of safety when modelling the road cut in question as a wedge, instead of a prismatic block. When doing so, the results are overly conservative, giving a factor of safety of 1.14.

## 3. RocSlope Verification Problem #3

Geometry Verification Problem [RocSlope version 1.001 & RS3 version 4.028]

### 3.1. Problem Description

In this verification example, RocSlope models are produced that consists of sliding blocks that do not have shapes of typical tetrahedral or pentahedral wedge, or plane. The corresponding SSR analysis models are constructed using RS3 with geometry and applied conditions closely matching with those from RocSlope. The FS computed with RocSlope is compared to the critical SRF of RS3.

### 3.2. Geometry and Material Properties

RocSlope models are produced to examine two different block sliding geometries. They include a case that involves a sliding block making concaved contact surface with the slope; and another case of block sliding along four joint surfaces (See Figure 3.1). The external volume has the unit weight of  $0.026 \text{ MN/m}^3$  and the joints have a cohesion and friction angle of  $0 \text{ MPa}$  and  $30^\circ$ , respectively.

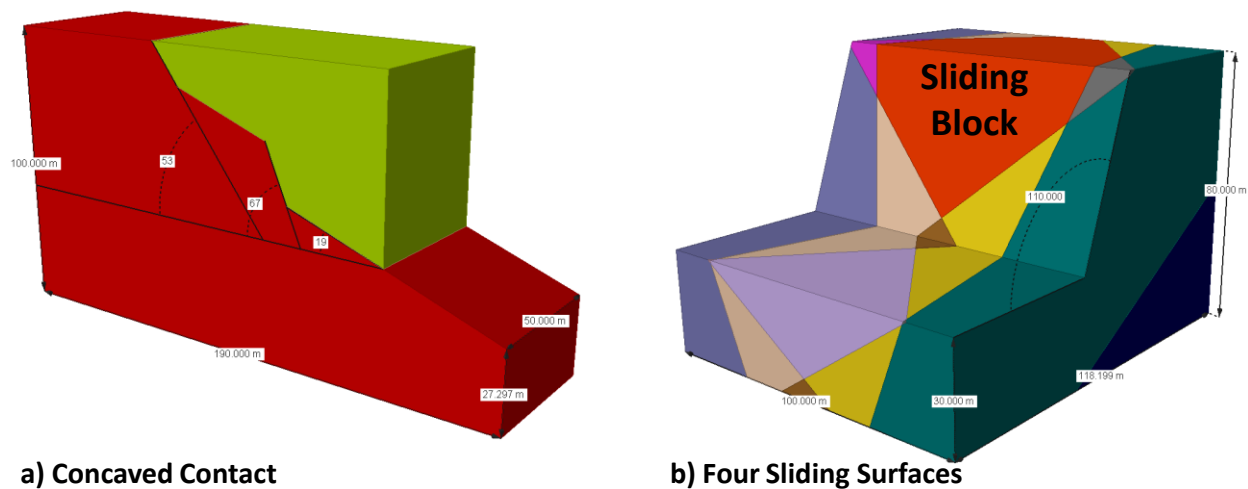


Figure 3.1 Model Geometries

### 3.3. Building a Compatible RS3 Model

A valid RS3 model is constructed by directly importing the external geometry and blocks generated with RocSlope. The SSR analysis is conducted to compute the critical SRF of the wedge, which is a comparable metrics to the FS computed with RocSlope.

The concaved contact model follows identical geometry as that of the RocSlope model (See Figure 3.2). However, the Four Sliding Surfaces model has the vertical surface striking the same direction as the slope extended further back to minimize the impact of restraints applied at the that surface to the behaviour of the wedge. Due to the extension, a new interface is formed indicated by the red surface on

Figure 3.2. This interface is assigned with peak cohesion and a 0 ° friction angle to make sure it casts negligible impact on the behaviour of the wedge.

No restraint is applied for both models at the ground surface, including bench face and bench floor. For Concaved Contact Model, Y restraint is applied at the two XZ surfaces and XYZ restraint is applied to the rest of the surface. The Four Sliding Surfaces model has XYZ restraint applied to all surfaces except for the free surfaces.

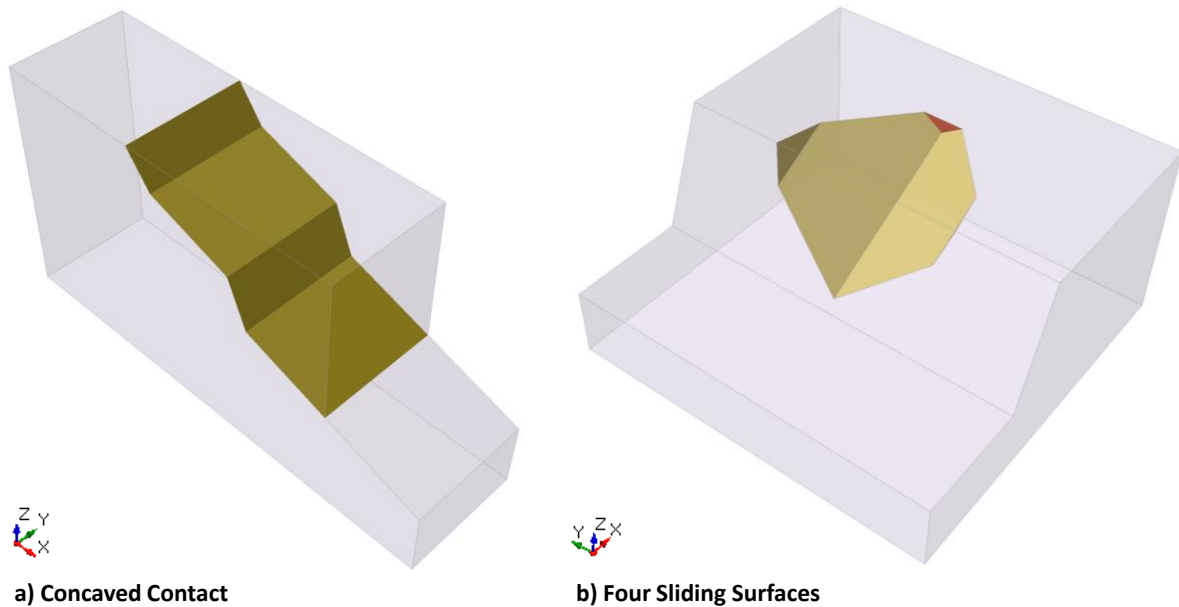


Figure 3.2 RS3 Model Geometry with Curved Water Surface and Pondered Water Load on Slope Surface

In order to reproduce the rigid body sliding failure mechanism as simulated with RocSlope models, it is important to establish an appropriate condition in the Finite Element model. It is primarily done through manipulating the material properties. External volume is set as a stiff elastic material and Mohr-Coulomb slip criterion is assigned to the joint surface with “Apply SSR” enabled, which forces the instability to be solely controlled by the failure of joint elements. Moreover, the initial element loading is set to Body Force Only to restrict influence of field stress and force the displacement due to the model settling under its own weight. The assigned material properties are presented in Table 3.1.

Table 3.1 Material Properties

Material Parameter		Value
Initial Conditions	Initial Element Loading	Body Force Only
	Unit Weight (MN/m <sup>3</sup> )	0.026
Stiffness	Type	Linear Isotropic
	Poisson's Ratio	0.4
	Young's Modulus (MPa)	10000
Joint Parameter		Value
Slip Criterion	Failure Criterion	Mohr-Coulomb
	Tensile Strength (MPa)	0.001
	Peak Cohesion (MPa)	0
	Peak Friction Angle (°)	30
	Dilation Angle (°)	0
Stiffness	Normal Stiffness (MPa/m)	100000
	Shear Stiffness (MPa/m)	10000



### 3.4. Results

The FS of the wedge computed with RocSlope shows a good agreement with critical SRF computed with RS3. The results are shown in Table 3.2.

Table 3.2 RocSlope and RS3 Modelling Results

<b>Model</b>	<b>FS RocSlope</b>	<b>Critical SRF RS3</b>
<b>Concaved Contact</b>	1.592	1.51
<b>Four Sliding Surfaces</b>	1.174	1.15

# 4. RocSlope Verification Problem #4

Loading Verification Problem [RocSlope version 1.001 & RS3 version 4.028]

## 4.1. Problem Description

In this verification example, a simple sliding wedge model is constructed with RocSlope in different loading application cases. Each case incorporates an application of a single loading type, which includes loading applied on vertex (point load), edge (line load), or face (surface load) of the wedge. The corresponding SSR analysis models are constructed using RS3 with geometry and applied conditions closely matching with those from RocSlope. The FS computed with RocSlope is compared to the critical SRF of RS3.

## 4.2. Geometry and Material Properties

A sloped model inclined at  $42.357^\circ$  as shown in Figure 4.1 is shared between all cases. The external volume has the unit weight of  $26 \text{ kN/m}^3$  and the Wedge is located at the center along the thickness of the slope (along y-axis) confined by two joints as defined in Table 4.1. The strength of the joints is defined by Mohr-Coulomb strength criteria with a cohesion and friction angle of  $0 \text{ kPa}$  and  $30^\circ$ , respectively.

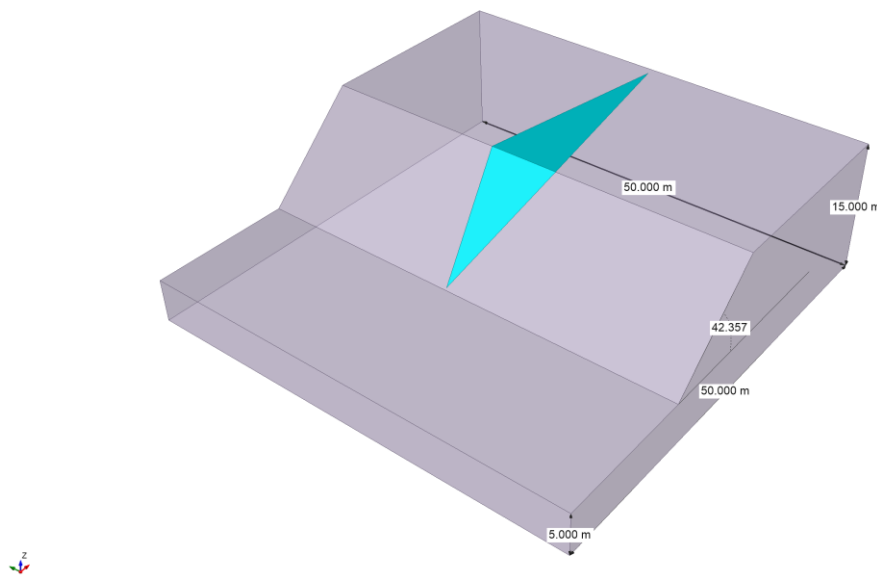


Figure 4.1 Model Geometry

Table 4.1 Joint Orientation

Dip (°)	Dip Direction (°)	X (m)	Y (m)	Z (m)	Radius (m)
55	350	51	25	32.5	100
65	190	51	25	29	100

Investigated loading application cases, except for no external loading case, are presented in Figure 4.2. The point load case has the vertical load applied on the vertex of the wedge and the line load and surface load cases have loading applied parallel to the sliding direction (trend/plunge: 272/16.6).

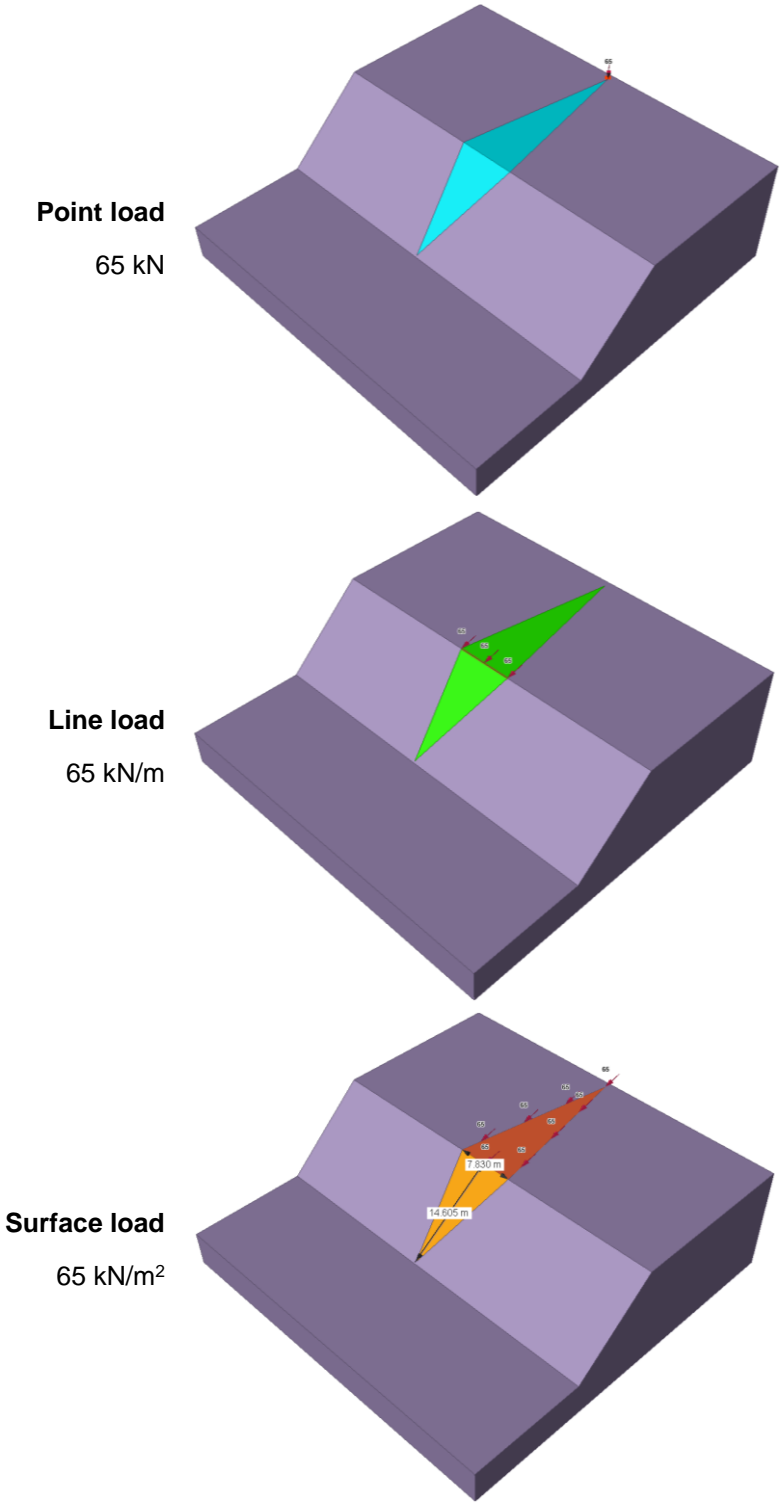


Figure 4.2 Loading Cases

### 4.3. Building a Compatible RS3 Model

A valid RS3 model is constructed by directly importing the external geometry and blocks generated with RocSlope. The SSR analysis is conducted to compute the critical SRF of the wedge, which is a comparable metric to the FS computed with RocSlope.

The surface load model geometry is presented in Figure 4.3 as an example. Adjustments are made to the boundary of the external volume, such as extending the portion behind the tip of the wedge (vertical surface striking same direction as the sliding direction) and reducing the thickness. The extension is necessary to minimize the impact of restraints applied at that surface to the behaviour of the wedge. The thickness reduction, however, eliminates the unnecessary portion of the model to improve the computation efficiency. XYZ restraints are applied to all surfaces except for the slope surface, including bench face and bench floor.

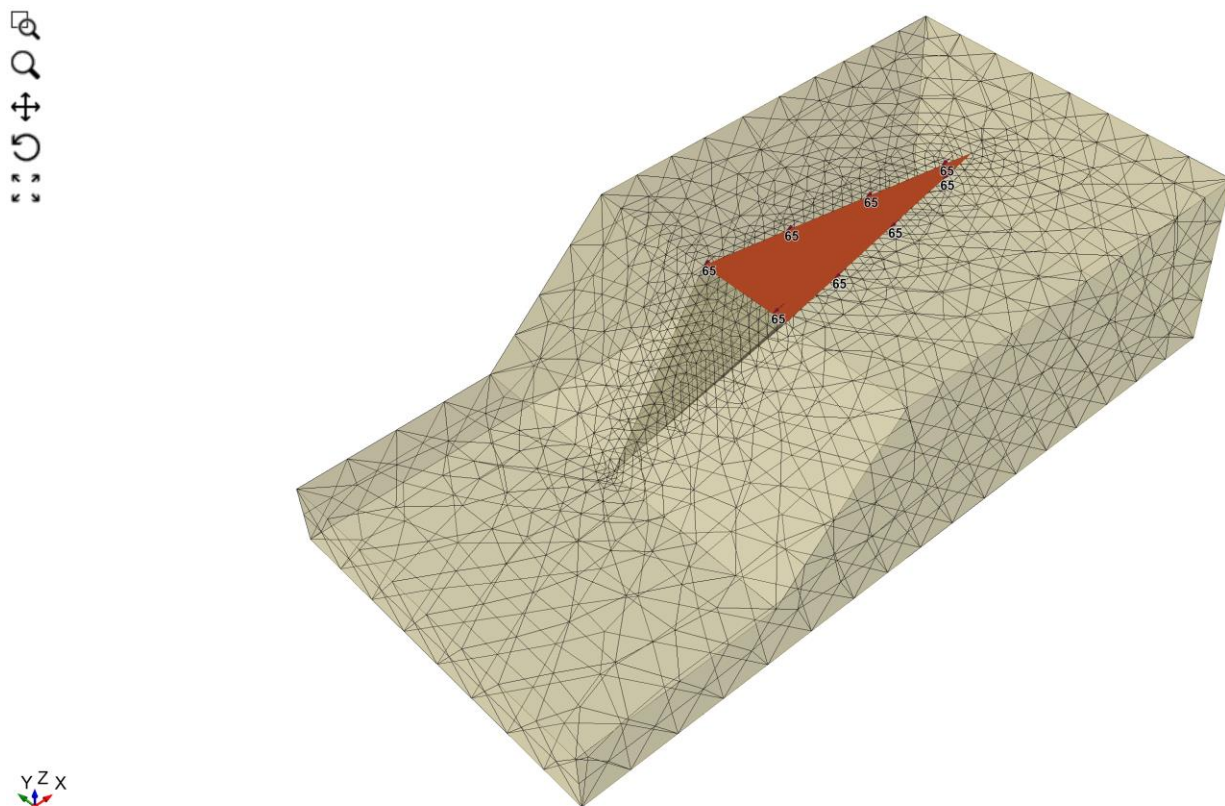


Figure 4.3 RS3 Surface Loading Case Model Geometry

In order to reproduce the rigid body sliding failure mechanism as simulated with RocSlope models, it is important to establish an appropriate condition in the Finite Element model. It is primarily done through manipulating the material properties. External volume is set as a stiff elastic material and Mohr-Coulomb slip criterion is assigned to the joint surface with “Apply SSR” enabled, which forces the instability to be solely controlled by the failure of joint elements. Moreover, the initial element loading is set to Body Force Only to restrict influence of field stress and force the displacement due to the model settling under its own weight. The assigned material properties are presented in Table 4.2.

Table 4.2 Material Properties

Material Parameter		Value
Initial Conditions	Initial Element Loading	Body Force Only
	Unit Weight (kN/m <sup>3</sup> )	26
Stiffness	Type	Linear Isotropic
	Poisson's Ratio	0.4
	Young's Modulus (kPa)	5000000
Joint Parameter		Value
Slip Criterion	Failure Criterion	Mohr-Coulomb
	Tensile Strength (kPa)	0.001
	Peak Cohesion (kPa)	0
	Peak Friction Angle (°)	30
	Dilation Angle (°)	0
Stiffness	Normal Stiffness (kPa/m)	10000000
	Shear Stiffness (kPa/m)	1000000

## 4.4. Results

The FS of the wedge computed with RocSlope shows a good agreement with the critical SRF computed with RS3. The results are shown in Table 4.3.

Table 4.3 RocSlope and RS3 Modelling Results

Loading Case	FS	Critical SRF
	RocSlope	RS3
No Loading Point	3.702	3.79
	3.702	3.79
Line	2.982	3.04
Surface	1.005	1.01

# 5. RocSlope Verification Problem #5

Seismic Loading Verification Problem [RocSlope version 1.001 & RS3 version 4.028]

## 5.1. Problem Description

In this verification example, a simple sliding wedge model is constructed with RocSlope in different seismic loading application cases. Each case incorporates an application of seismic loading in a different orientation. The corresponding SSR analysis models are constructed using RS3 with geometry and applied conditions closely matching with those from RocSlope. Additionally, the corresponding wedge analysis is constructed in SWedge. The FS computed with RocSlope is compared to the critical SRF of RS3 and the FS of SWedge.

## 5.2. Geometry and Material Properties

A sloped model inclined at  $42.357^\circ$  as shown in Figure 5.1 is shared between all cases. The external volume has the unit weight of  $26 \text{ kN/m}^3$  and wedge is located at the center along the thickness of the slope (along y-axis) confined by two joints as defined in Table 5.1. The strength of the joints is defined by the Mohr-Coulomb strength criteria with a cohesion and friction angle of  $0 \text{ kPa}$  and  $30^\circ$ , respectively.

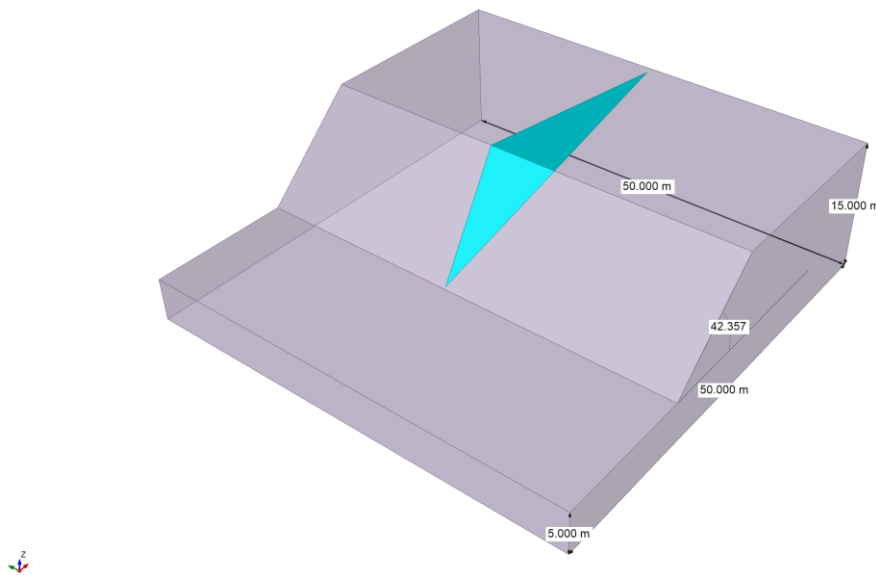


Figure 5.1 Model Geometry

Table 5.1 Joint Orientation

Dip (°)	Dip Direction (°)	X (m)	Y (m)	Z (m)	Radius (m)
55	350	51	25	32.5	100
65	190	51	25	29	100

For this exercise, four seismic loading cases are computed with each case simulating a different seismic loading orientation. The considered cases for this example are presented in Table 5.2.

Table 5.2 Seismic Loading cases

Cases	Seismic Coefficient	Orientation (Trend/Plunge)
No Seismic Load	-	-
Sliding Direction	0.3	272/16.6
Horizontal	0.3	270/0
Vertical	0.3	270/90

### 5.3. Building a Compatible RS3 Model

A valid RS3 model is constructed by directly importing the external geometry and blocks generated with RocSlope. The SSR analysis is conducted to compute the critical SRF of the wedge, which is a comparable metric to the FS computed with RocSlope.

The RS3 model geometry is presented in Figure 5.2. Adjustments are made to the boundary of the external volume, such as extending the portion behind the tip of the wedge (vertical surface striking same direction as the sliding direction) and reducing the thickness. The extension is necessary to minimize the impact of restraints applied at that surface to the behaviour of the wedge. The thickness reduction, however, eliminates the unnecessary portion of the model to improve the computation efficiency. XYZ restraints are applied to all surfaces except for the slope surface, including bench face and bench floor.

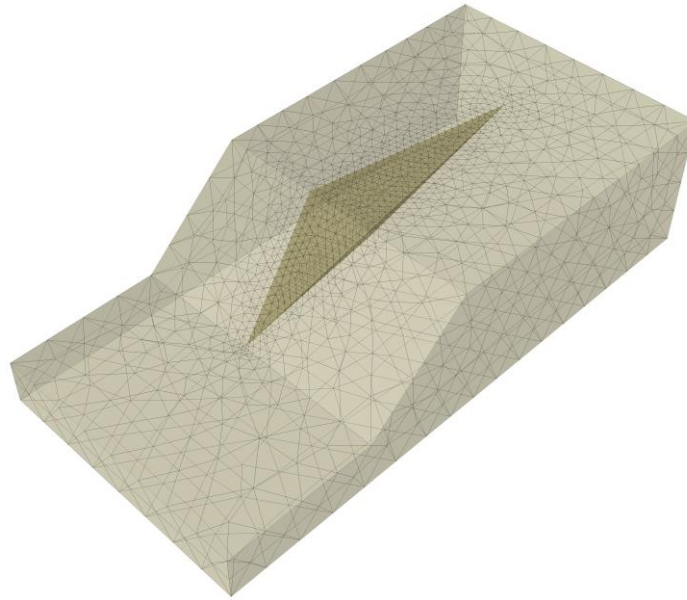


Figure 5.2 RS3 Model Geometry

In order to reproduce the rigid body sliding failure mechanism as simulated with RocSlope models, it is important to establish an appropriate condition in the Finite Element model. It is primarily done through manipulating the material properties. External volume is set as a stiff elastic material and Mohr-Coulomb slip criterion is assigned to the joint surface with “Apply SSR” enabled, which forces the instability to be solely controlled by the failure of joint elements. Moreover, the initial element loading is set to Body Force Only to restrict influence of field stress and force the displacement due to the model settling under its own weight. The assigned material properties are presented in Table 5.3.

Table 5.3: Material Properties

Material Parameter		Value
Initial Conditions	Initial Element Loading	Body Force Only
	Unit Weight (kN/m <sup>3</sup> )	26
Stiffness	Type	Linear Isotropic
	Poisson's Ratio	0.4
	Young's Modulus (kPa)	5000000
Joint Parameter		Value
Slip Criterion	Failure Criterion	Mohr-Coulomb
	Tensile Strength (kPa)	0.001
	Peak Cohesion (kPa)	0
	Peak Friction Angle (°)	30
	Dilation Angle (°)	0
Stiffness	Normal Stiffness (kPa/m)	10000000
	Shear Stiffness (kPa/m)	1000000

## 5.4. Building a Compatible SWedge Model

To define the geometry of the block in SWedge, the following inputs are used:



Table 5.4: Wedge geometry definition

Angle	Value
Slope Dip (°)	42.357
Slope Dip Direction (°)	270
Upper Face Dip (°)	0
Upper Face Dip Direction (°)	270
Joint 1 Dip (°)	55
Joint 1 Dip Direction (°)	350
Joint 2 Dip (°)	65
Joint 2 Dip Direction (°)	190

The joint strength properties are defined to match those in RocSlope.

The User Defined direction definition method is used to set the seismic load, which requires Trend/Plunge angles as input. For the sliding direction case, the Line of Intersection definition method is also used as this orientation is equivalent because the block is sliding on joints 1 and 2.

## 5.5. Results

The FS of the wedge computed with RocSlope shows a good agreement with the critical SRF computed with RS3 and FS computed with SWedge. The results are shown in Table 5.5.

Table 5.5: RocSlope and RS3 Modelling Results

Loading Case	FS RocSlope	FS RocSlope	FS RocSlope	FS SWedge	FS SWedge	Critical SRF RS3
Definition Method	Trend/plunge	Vector	Sliding Direction	Trend/Plunge	Line of Intersection	Vector
<b>No Seismic Loading</b>	3.702					3.79
<b>Sliding Direction</b>	1.804	1.804	1.804	1.804	1.804	1.82
<b>Horizontal</b>	1.678	1.678	-	1.679	-	1.695
<b>Vertical</b>	3.702	3.702	-	3.702	-	3.83

All models used in this verification exercise are named *RocSlope\_Verification\_#5-X\_Seismic* for varying X. Table 6-6 maps the specific models to the number X in their names.

Table 5.6: Model lookup

Loading Case	RocSlope Model #	RocSlope Model #	RocSlope Model #	SWedge Model #	SWedge Model #	RS3 Model #
Definition Method	Trend/plunge	Vector	Sliding Direction	Trend/Plunge	Line of Intersection	Vector
No Seismic Loading	1			1		1
Sliding Direction	2	3	4	2	3	2
Horizontal	5	6	-	5	-	5
Vertical	7	8	-	7	-	7

# 6. RocSlope Verification Problem #6

Groundwater Verification Problem [RocSlope version 1.001 & RS3 version 4.028]

## 6.1. Problem Description

In this verification example, a simple sliding wedge model is constructed with RocSlope in different ground water conditions defined by water surface. The corresponding SSR analysis models are constructed using RS3 with geometry and applied conditions closely matching with those from RocSlope. The FS computed with RocSlope is compared to the critical SRF of RS3.

## 6.2. Geometry and Material Properties

A sloped model inclined at  $42.357^\circ$  as shown in Figure 6.1 is shared between all cases. The external volume has the unit weight of  $26 \text{ kN/m}^3$  and the wedge is located at the center along the thickness of the slope (along y-axis) confined by two joints as defined in Table 6.1. The strength of the joints is defined by Mohr-Coulomb strength criteria with a cohesion and friction angle of  $0 \text{ kPa}$  and  $30^\circ$ , respectively.

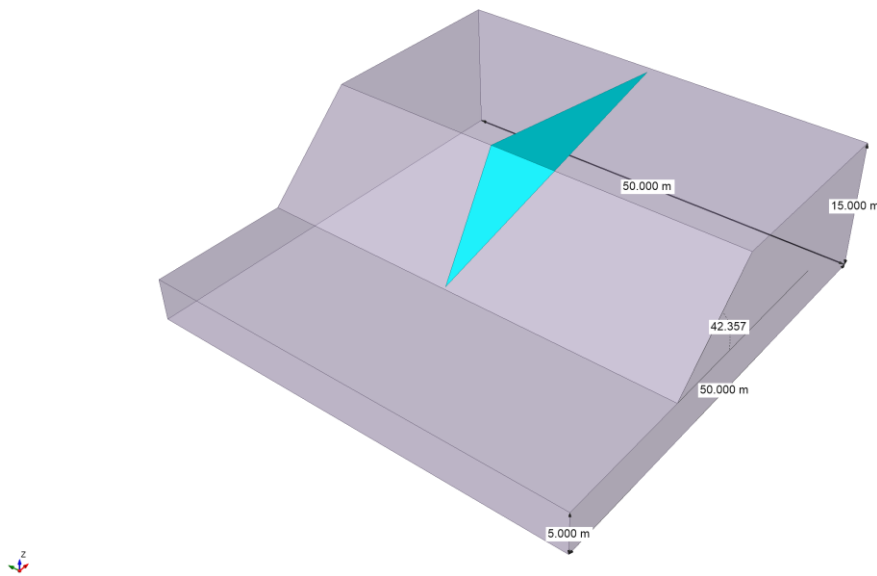


Figure 6.1 Model Geometry

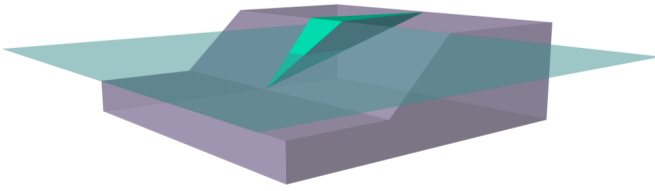
Table 6.1 Joint Orientation

Dip (°)	Dip Direction (°)	X (m)	Y (m)	Z (m)	Radius (m)
55	350	51	25	32.5	100
65	190	51	25	29	100

For this verification exercise, water surfaces with planar and curved shapes are used with each shape being assigned as water table and piezometric surface to represent different water conditions. Therefore, five cases are examined, as presented in Table 6.2. When the water surface is assigned as a water table,

the corresponding ponded water load is applied at the surface of external volume below the water table, whereas no load is automatically applied when the water surface is assigned as a piezometric surface.

Table 6.2 Ground Water Cases

Case	Water Surface Shape	Surface Type
Dry	N/A	N/A
Planar - Piezometric		Piezometric
Planar - Water Table		Water Table
Curved - Piezometric		Piezometric
Curved - Water Table		Water Table

The model is set to select the water surface for both external volume and joints. Water parameters assigned for both joint and the external volume are presented in Table 6.3.

Table 6.3 Water Parameters Assigned for External Volume and Joints

Groundwater Method / Water Pressure Method	Water Surfaces
Water Surface	Water Table / Piezometric Surface
Hu type	Custom
Hu	1

### 6.3. Building a Compatible RS3 Model

A valid RS3 model is constructed by directly importing the water surface, external geometry and blocks generated with RocSlope. The SSR analysis is conducted to compute the critical SRF of the wedge, which is a comparable metric to the FS computed with RocSlope.

The RS3 model geometry of curved water surface is presented in Figure 6.2 as an example. Adjustments are made to the boundary of the external volume, such as extending the portion behind the tip of the wedge (vertical surface striking same direction as the sliding direction) and reducing the thickness. The extension is necessary to minimize the impact of restraints applied at that surface to the behaviour of the wedge. The thickness reduction, however, eliminates the unnecessary portion of the model to improve

the computation efficiency. XYZ restraints are applied to all surfaces except for the slope surface, including bench face and bench floor.

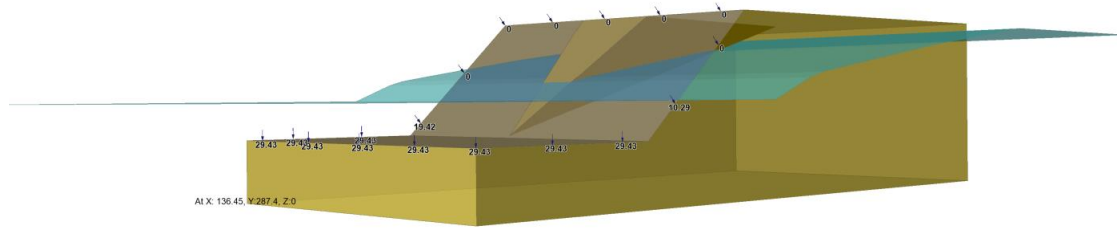


Figure 6.2 RS3 Model Geometry with Curved Water Surface and Ponded Water Load on Slope Surface

To reproduce the wedge sliding failure mode from RocSlope, external volume is set as an elastic material and Mohr-Coulomb slip criterion is assigned to the joint surface with “Apply SSR” enabled which forces the instability to be solely controlled by the failure of joint elements. Moreover, the initial element loading is set to Body Force Only to restrict influence of field stress and force the displacement due to the model settling under its own weight.

In order to compute the interaction between water surface and the external volume and joints, Phreatic Surfaces was selected from the Groundwater method in Project Setting. The imported surface that is used as the water table and piezometric surface in RocSlope is converted into the water surface in RS3, as well. It is made sure from the material properties that the default water condition is set to that water surface and the ground water pore pressure is enabled in joint properties. The assigned material properties are presented in Table 6.4. For those RS3 models that represent the cases, which have water table, ponded water load is applied to the slope surface with total head following the water surface (See Figure 6.2).

Table 6.4 Material Properties

Material Parameter		Value
Initial Conditions	Initial Element Loading	Body Force Only
	Unit Weight (kN/m <sup>3</sup> )	26
Stiffness	Type	Linear Isotropic
	Poisson's Ratio	0.4
	Young's Modulus (kPa)	5000000
Hydraulics	Material Behaviour Type	Drained
	Porosity Type	Porosity
	Porosity	0.3
Joint Parameter		Value
Slip Criterion	Failure Criterion	Mohr-Coulomb
	Tensile Strength (kPa)	0.001
	Peak Cohesion (kPa)	0
	Peak Friction Angle (°)	30
	Dilation Angle (°)	0
Stiffness	Normal Stiffness (kPa/m)	10000000
	Shear Stiffness (kPa/m)	1000000

## 6.4. Results

The FS of the wedge computed with RocSlope shows a good agreement with the critical SRF computed with RS3. The results are shown in Table 6.5. The modelling results show that the FS and the critical SRF is always higher in cases, which have water surface modelled as water table than the corresponding cases with piezometric surface. This is due to the ponded water load being applied to the submerged portion of the wedge acts against the sliding direction.

Table 6.5 RocSlope and RS3 Modelling Results

<b>Groundwater Case</b>	<b>FS RocSlope</b>	<b>Critical SRF RS3</b>
<b>Dry</b>	3.702	3.79
<b>Planar - Piezometric</b>	3.435	3.51
<b>Planar - Water Table</b>	3.702	3.79
<b>Curved - Piezometric</b>	3.411	3.49
<b>Curved - Water Table</b>	3.52	3.6

# 7. RocSlope Verification Problem #7

Groundwater Verification Problem [RocSlope version 1.001 & RS3 version 4.028]

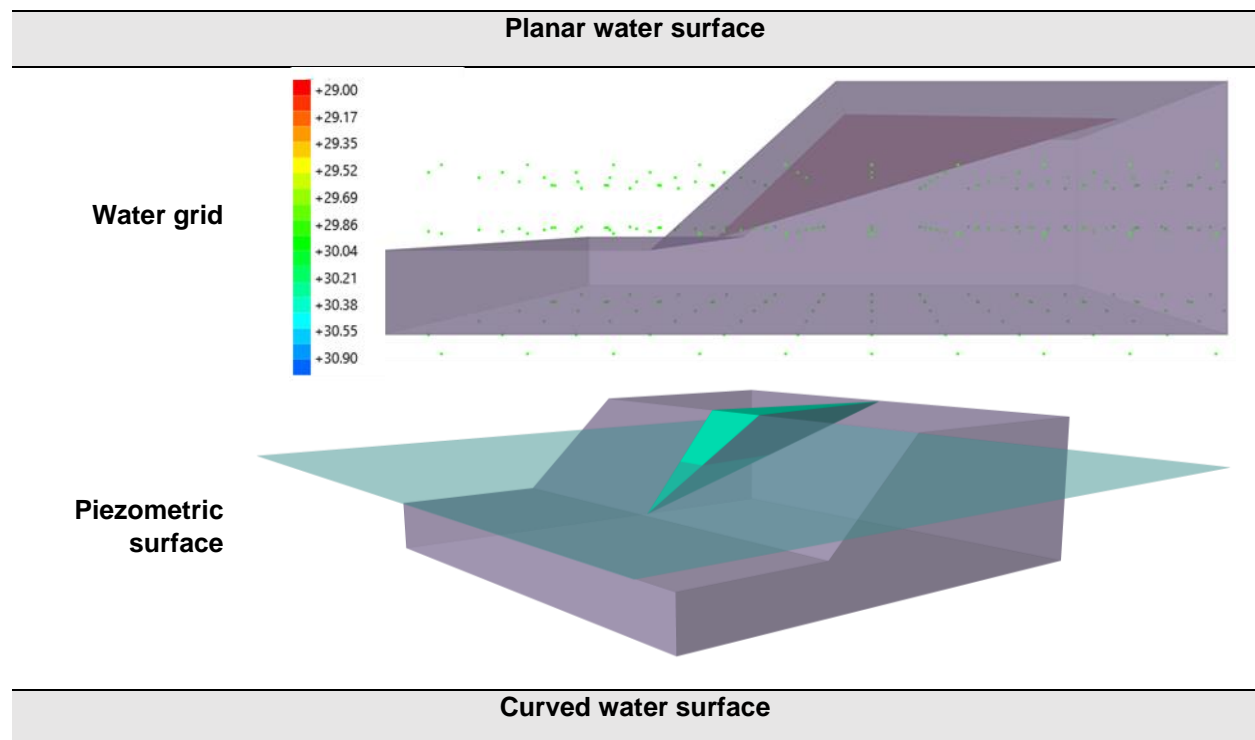
## 7.1. Problem Description

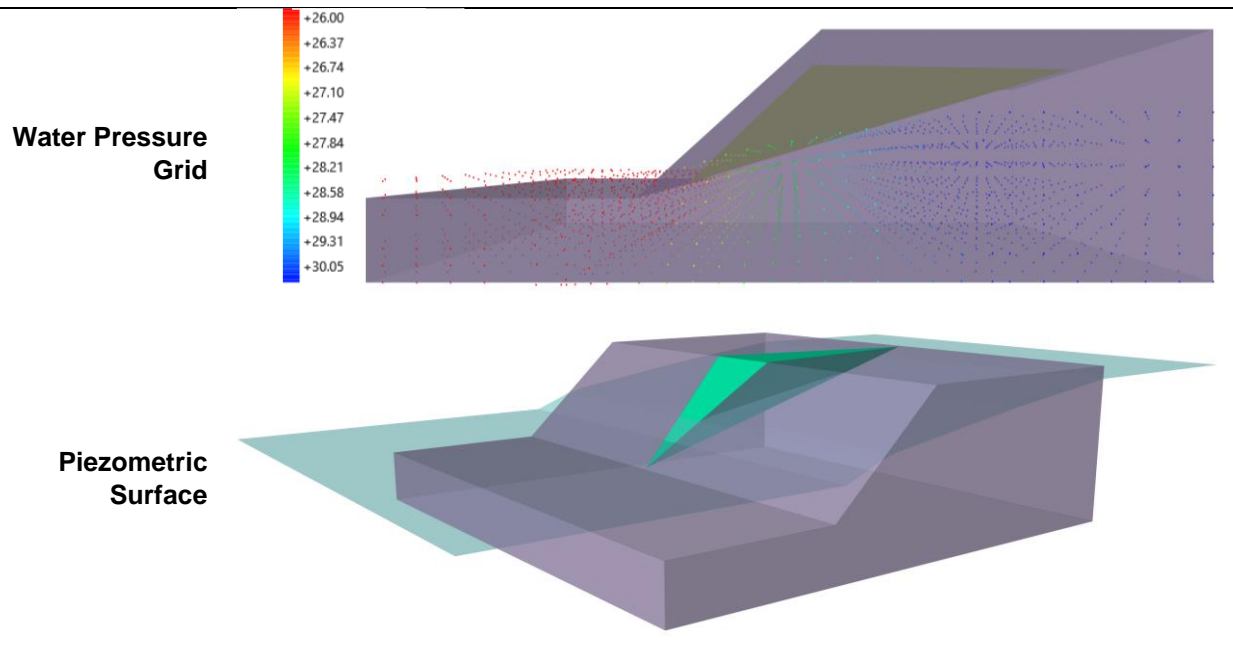
In this verification example, a simple sliding wedge model is constructed with RocSlope in different ground water conditions defined by a water pressure grid. The water grid is produced to replicate the cases from Section 6 with groundwater condition represented by piezometric surface.

## 7.2. Geometry and Material Properties

The model geometry and set up is identical to the Section 6 example. However, for this example, the water grid is used to match the planar and curved piezometric surface cases verified in Section 6. The water pressure grid option enables modelling the groundwater pore pressure distribution by defining the total head, pressure head or pore pressure at any point in the ground, which is determined using the specified interpolation method (See Table 7.1). In this case, hybrid method is used to interpolate the total head grid data to assign distribution of pore pressure in the joint.

Table 7.1 Water Pressure Grid Models and Corresponding Piezometric Surface Models





### 7.3. Results

The FS of the wedge computed with RocSlope shows a good agreement with the critical SRF computed with RS3. The results are shown in Table 7.2. The modelling results show that the FS and the critical SRF is always higher in cases, which have water surface modelled as a water table than the corresponding cases with piezometric surface. This is due to the ponded water load being applied to the submerged portion of the wedge which acts against the sliding direction.

Table 7.2 RocSlope and RS3 Modelling Results

Groundwater Case	Piezometric Surface	Water Grid
Planar	3.435	3.435
Curved	3.411	3.408



# 8. RocSlope Verification Problem #8

---

Groundwater Verification Problem [RocSlope version 1.001 & SWedge version 7.020]

## 8.1. Problem Description

Some groundwater definition methods can be compared with SWedge. This example verifies the validity of results for uniform water pressure on joints and water tables.

## 8.2. Geometry and Material Properties

Analysis is performed on a wedge, whose geometry is defined by the following properties:

Table 8.1: Wedge geometry definition

Angle	Value
Slope Dip (°)	60
Slope Dip Direction (°)	0
Upper Face Dip (°)	20
Upper Face Dip Direction (°)	0
Joint 1 Dip (°)	55
Joint 1 Dip Direction (°)	320
Joint 2 Dip (°)	50
Joint 2 Dip Direction (°)	50

Joints use Mohr-Coulomb shear strength model without cohesion and with a friction angle of 35°.

Rock unit weight is 0.026 MN/m<sup>3</sup>.

The slope and joint geometries and properties are imported from SWedge.

## 8.3. Groundwater

### 8.3.1. Uniform Water Pressure on Joints

In RocSlope, uniform water pressure on joints can be defined in the water parameters section of the joint properties or directly as a property of a measured joint when using the same shear models for all joints. In this verification problem, both methods are used and confirmed to give the same results.

Uniform water pressure on joints can also be modelled in SWedge by using the Custom Pressure distribution model with 100 % filled water depth.

Joints 1 and 2 are assigned water pressure of 0.025 MPa and 0.015 MPa, respectively.

### 8.3.2. Ponded Water

In RocSlope, water tables are used to model ponded water forces. A water table can be added in RocSlope by assigning it to an already defined surface or by adding it by location, namely inputting elevation values at specific X, Y points and defining an interpolation method for the surface reconstruction. For this verification problem, both methods are used during model creation to ensure matching results.

When a water table is defined, it may also be applied to a joint property to account for the effect of the water forces acting on the joints.

This example uses horizontal surfaces defined at specific elevations to be compatible with SWedge.

In SWedge, ponded water pressure is turned on to replicate RocSlope's water table. The ponded water depth is defined as the elevation of the water table. For this geometry elevation and depth are equivalent measures because the bottom-most vertex of the analyzed block is at elevation 0 m. Setting the slope face type to impervious accounts for only ponded water forces. Conversely, setting it to pervious along with turning on joint water pressure with 100% filled water depth accounts for both ponded water and water forces acting on the joints.

To verify solely ponded water, the elevation of the water table is set to 10 m, such that the block is partially submerged.

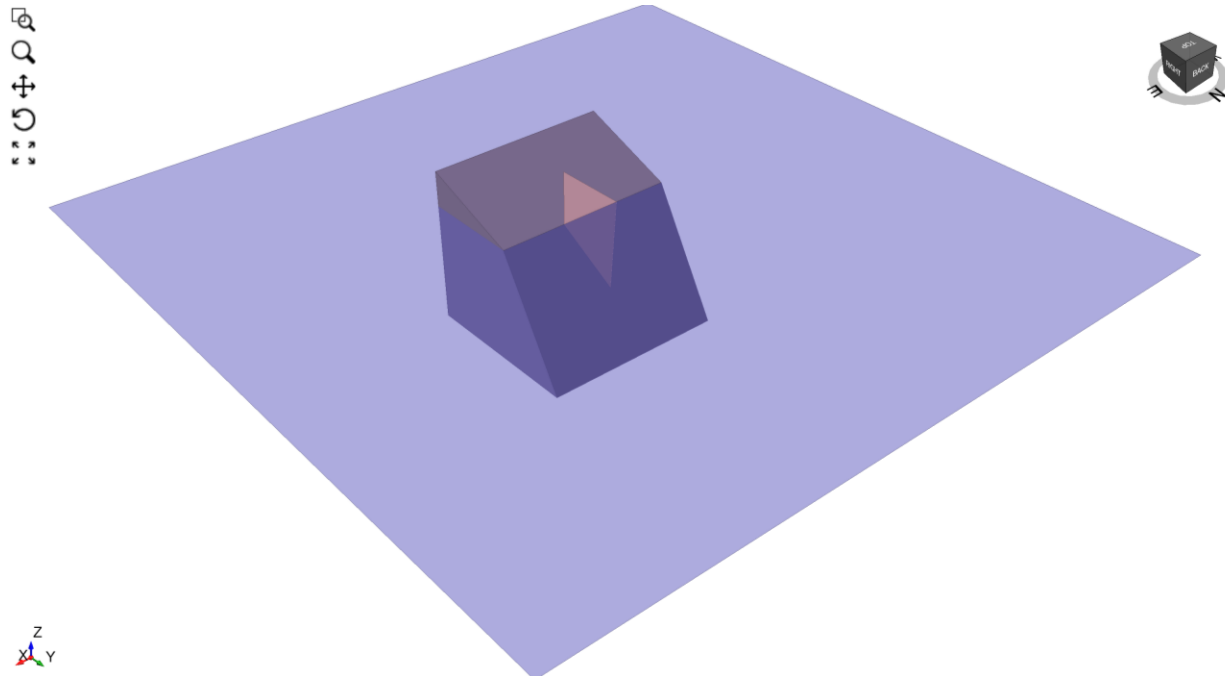


Figure 8.1: Block partially submerged by water table

To additionally account for water pressure on the joints, the water table is defined at a 30 m elevation to fully submerge the wedge.

## 8.4. Results

The resultant factors of safety match with SWedge:

Table 8.2: Groundwater verification results compared to SWedge

Groundwater Method	FS RocSlope	FS SWedge	Model Name
Uniform Pressure on Joints	1.023	1.023	<i>RocSlope_Verification_#9-1_GW, RocSlope_Verification_#9-2_GW</i>
Water Table (only Poned)	2.1651	2.1651	<i>RocSlope_Verification_#9-3_GW, RocSlope_Verification_#9-4_GW</i>
Water Table (Poned and Joints)	0.9218	0.9218	<i>RocSlope_Verification_#9-5_GW</i>

# 9. RocSlope Verification Problem #9

Groundwater Verification Problem [RocSlope version 1.001]

## 9.1. Problem Description

The Ru coefficient groundwater method computes the water pressure at any given point in the model as a factor of the vertical stress.

Since water pressure on each joint is reported in RocSlope's detailed block information view, the verification of the water pressure values themselves is sufficient to ensure the validity of the computations when using the Ru coefficient groundwater modeling method.

## 9.2. Geometry and Material Properties

The slope geometry is an axis-aligned box split by a horizontal plane at  $z = 5$  such that Material 1 is on top of Material 2.

The analyzed block takes on the shape of a triangular prism as seen below:

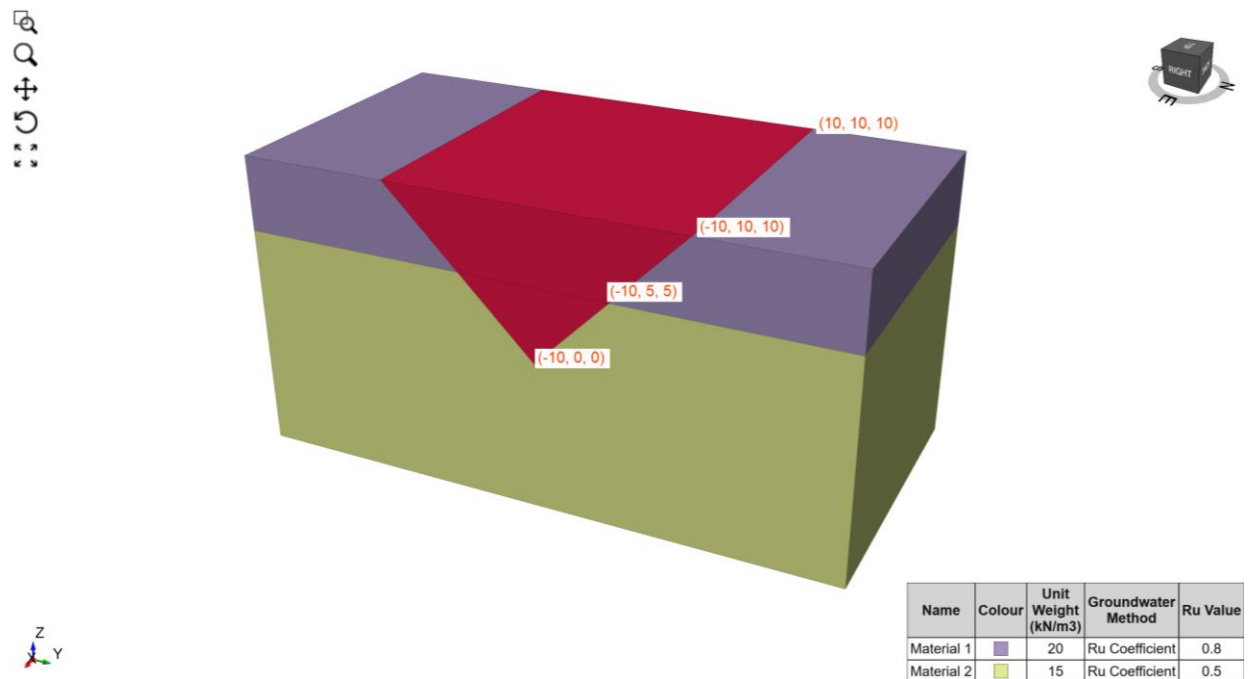


Figure 9.1: Block geometry with vertex labels

### 9.3. Analytical Solution

Let  $\gamma_1, \gamma_2$  be the rock unit weights of materials 1 and 2 respectively and  $RU_1, RU_2$  be the Ru values of materials 1 and 2 respectively. Given the slope geometry in this model, the water pressure at a point  $(x, y, z)$  is given by:

$$9.1 \quad \begin{cases} 5\gamma_1 RU_1 + (5 - z)\gamma_2 RU_2, & 0 \leq z \leq 5 \\ (10 - z)\gamma_1 RU_1, & 5 \leq z \leq 10 \end{cases}$$

Consider the line defined by the projection of the joint into the YZ-plane. To calculate the water force along this line, integrate over the distance from bottom-right point of the line. Since the equation of this line is  $y = z$ , at a distance  $\ell$ , the z-coordinate of the point is  $\frac{\ell}{\sqrt{2}}$ . Then, the water force on the entire joint can be found by multiplying the water force on the line by the X-dimension. Subsequently dividing by the area  $A$  of the joint gives the water pressure on the joint:

$$9.2 \quad \frac{20}{A} \left( \int_0^{\sqrt{50}} \left( 5\gamma_1 RU_1 + \left( 5 - \frac{\ell}{\sqrt{2}} \right) \gamma_2 RU_2 \right) d\ell + \int_{\sqrt{50}}^{\sqrt{200}} \left( 10 - \frac{\ell}{\sqrt{2}} \right) \gamma_1 RU_1 d\ell \right)$$

This simplifies to:

$$9.3 \quad \frac{750\sqrt{2}\gamma_1 RU_1 + 250\sqrt{2}\gamma_2 RU_2}{A}$$

Substituting in the values for rock unit weight, Ru coefficients, and area yields the result of the analytical solution.

### 9.4. Results

The water pressure on the joint reported by RocSlope matches the computed value from the analytical solution above.

Table 9.1: Groundwater verification result compared to analytical solution

	RocSlope (kPa)	Analytical Solution (kPa)
<b>Water Pressure</b>	69.36	69.38

# 10. RocSlope Verification Problem #10

Ground Support Verification Problem [RocSlope version 1.001 & RS3 version 4.028]

## 10.1. Problem Description

This section presents several verification examples of different failure modes of bolts in RocSlope. Users can select from a list of pre-defined different types of bolts, choose to use either shear strength or tensile strength of bolts, and select to apply bolt orientation efficiency factor. Depending on the length, orientation, location, and material properties assigned to the bolt, different failure modes can be propagated in bolts. These failure modes include tensile, stripping, pullout, and shear failures. In this example, all four types of failure modes are verified with respect to the analytical solution.

## 10.2. Geometry and Material Properties

In this example, grouted dowel is employed for all verification models as all four failure modes can be simulated with this bolt type. The external volume has the unit weight of 26 kN/m<sup>3</sup>; and its geometry is presented in Figure 10.1. The model is designed to induce planar sliding of a wedge controlled by a joint with a cohesion and friction angle of 0 kPa and 35 °. The geometry of the joint is presented in Table 10.1.

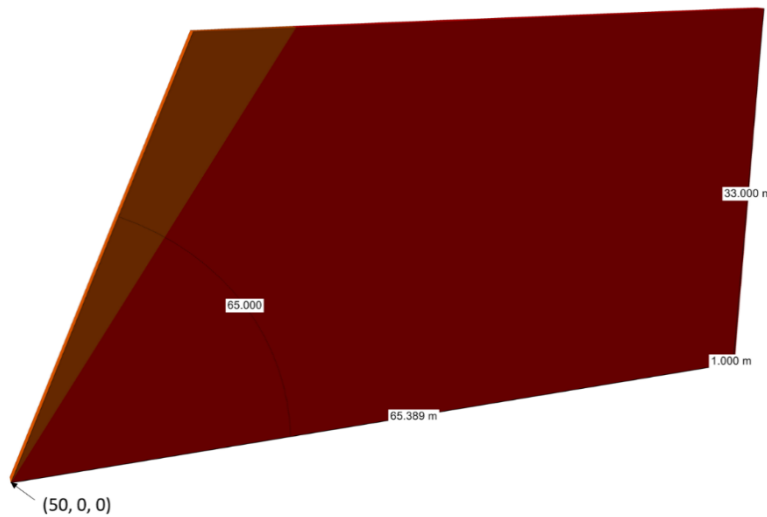


Figure 10.1 Model Geometry

Table 10.1 Joint Geometry

Dip (°)	Dip Direction (°)	X (m)	Y (m)	Z (m)	Radius (m)
55	270	50	0	0	100

The Bolt force model can be applied in two different force application methods, known as active and passive. If the bolt model is active, a bolt is exactly equivalent to an external force with the same magnitude and orientation. If the bolt model is passive, a bolt and an external force with the same magnitude and orientation are equivalent. Active support is assumed to act in such a manner as to

decrease the driving force in the FS calculation. Tensioned cables or rock bolts, which exert a force on the wedge before any movement has taken place, are considered Active support. Passive support, however, is assumed to increase the resisting force provided by shear restraint. Both active and passive bolt models are tested for each failure mode carried by separate cases (Table 10.2 Table 11.2).

Table 10.2 Cases of Different Failure Modes

Case	Failure Mode	Bolt Force Model
<b>Tensile- Active</b>	Tensile	Active
<b>Tensile- Passive</b>		Passive
<b>Stripping- Active</b>	Stripping	Active
<b>Stripping- Passive</b>		Passive
<b>Pullout- Active</b>	Pullout	Active
<b>Pullout- Passive</b>		Passive
<b>Shear- Active</b>	Shear	Active
<b>Shear- Passive</b>		Passive

A single grouted dowel is installed at the center of the sloped surface of the wedge, penetrating the joint. In order to induce different failure modes in the grouted dowel, it is necessary to manipulate both the geometry and its properties (Table 10.3). A sketch of different failure modes and corresponding bolt force diagrams are presented in Figure 10.2 - Figure 10.5.

Table 10.3 Bolt Geometry and Properties

Failure Modes		Tensile	Stripping	Pullout	Shear
<b>Bolt Geometry</b>	Bolt Length (m)	36	36	3.5	20
	Trend/Plunge	090/25			090/35
	Projection	Left Surface			
<b>Support Type</b>		Grouted Dowel			
<b>General Bolt Properties</b>	Force Application	Active & Passive			
	Bolt Orientation Efficiency	Cosine Tension/Shear			
	Tensile capacity (kN)	240			240
	Use Shear Capacity	False			True
	Shear Capacity (kN)	N/A			100
	Use Compression Capacity	False			
<b>Pullout and Stripping Bolt Properties</b>	Plate Capacity (kN)	100			
	Bond Strength (kN/m)	100			
	Material Dependent	False			

	Use Percent of Length	True			
	Percent of Length (%)	100	90	100	100

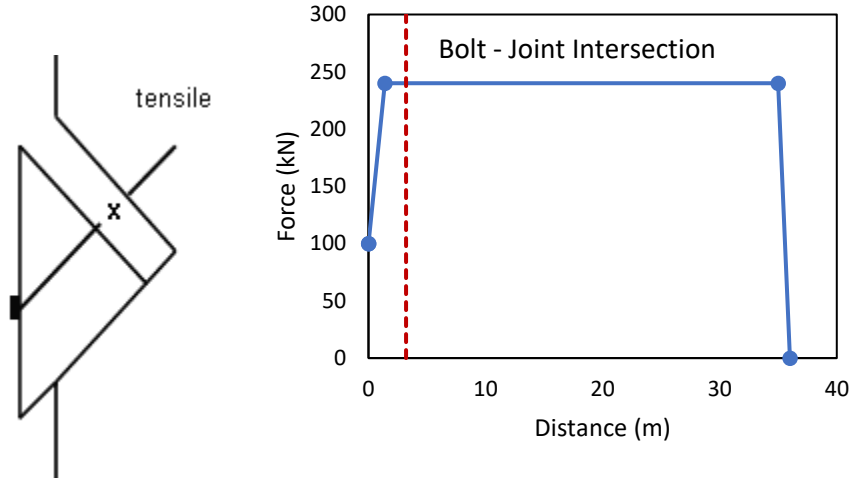


Figure 10.2 Sketch of Tensile Failure and Bolt Force Diagram

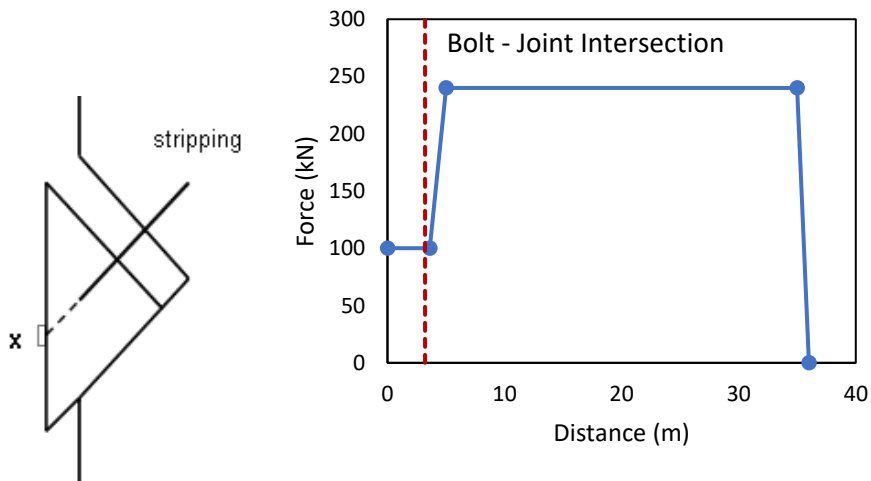


Figure 10.3 Sketch of Stripping Failure and Bolt Force Diagram



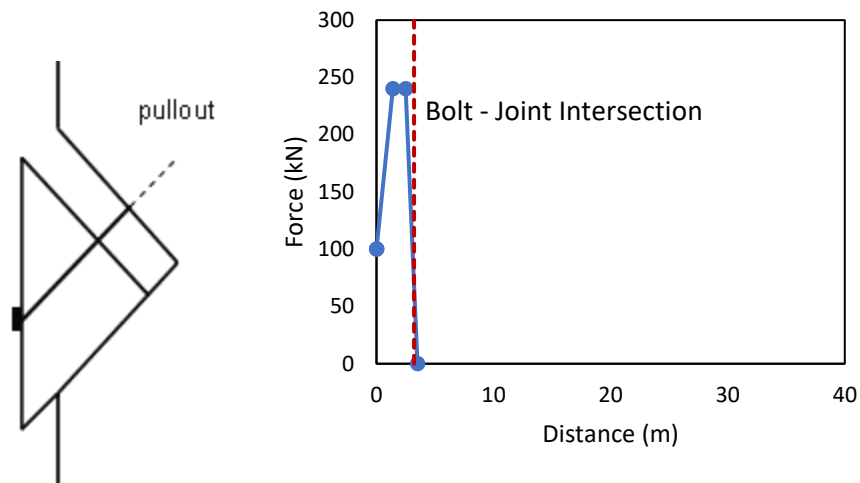


Figure 10.4 Sketch of Pullout Failure and Bolt Force Diagram

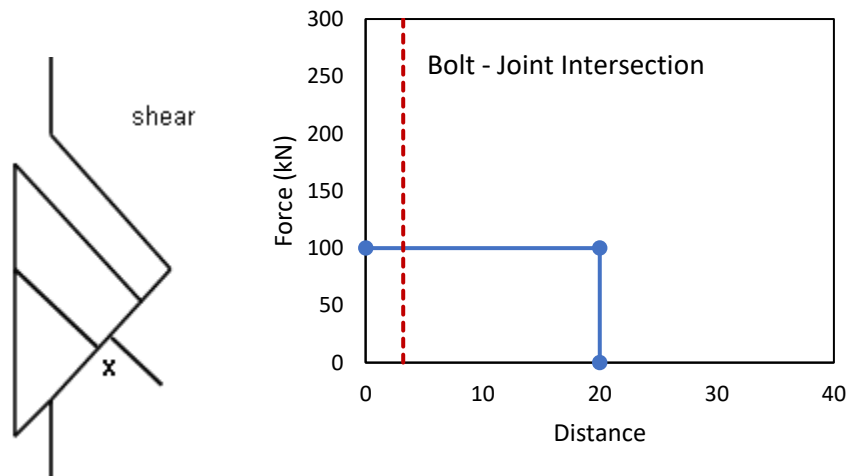


Figure 10.5 Sketch of Shear Failure and Bolt Force Diagram

### 10.3. Analytical Solution

This Section presents the calculation of resultant resisting and driving forces induced at the sliding surface with the presence of the bolt. Based on the bolt properties and geometry setup for the four cases, the bolt loading capacity ( $C_L$ ) is calculated as follows,

$$10.1 \quad C_L = E \min(F1, F2, F3)$$

Where:

$$\text{Pullout: } F1 = B_s L_a$$

$$\text{Tensile: } F2 = T$$

$$\text{Stripping: } F3 = P + B_s L_w$$

$B_s$  is bond strength

- $L_a$  is anchorage length (Bonded length of dowel embedded in rock beyond wedge)
- T is tensile capacity
- P is plate capacity
- $L_w$  is wedge length (Bonded length of dowel within wedge)
- E is efficiency factor

The bolt force vector (B) is calculated as follows,

$$10.2 \quad B = C_L \hat{e}$$

Where:

- $\hat{e}$  is the unit direction vector of bolt

Taking into account the weight of wedge (W) and the bolt force vector, total normal force on joint (N) is calculated as follows,

$$10.3 \quad N = (B + W \hat{g}) \cdot \hat{n}$$

Where:

- $\hat{n}$  is the inward (into the wedge) normal of joint
- $\hat{g}$  is the gravity direction (0, 0, -1)

Using N, joint shear strength ( $\tau$ ) is calculated based on Mohr-Coulomb strength criterion as follows,

$$10.4 \quad \tau = c + \frac{N}{a} \tan \phi$$

Where:

- c is the cohesion of joint
- a is the area of joint
- $\phi$  is the friction angle of joint

Depending on the force application setting between active and passive, the shear component of the force applied by the bolt is added to resisting force and subtracted to driving force, respectively. Thus, the active and passive resisting forces are calculated as follows,

$$10.5 \quad \text{Active Resisting force} = \tau a \cos \theta$$

$$10.6 \quad \text{Passive Resisting force} = \tau a \cos \theta - (B \cdot \hat{s})$$

Where:

- $\theta$  is the angle between sliding direction and joint
- $\hat{s}$  is sliding direction

Moreover, active and passive driving forces are calculated as follows,

$$10.7 \quad \text{Active Driving force} = (W \hat{g} + B) \cdot \hat{s}$$

$$10.8 \quad \text{Passive Driving force} = W \hat{g} \cdot \hat{s}$$

### 10.3.1. Sample Calculation

Sample calculation is performed for the tensile failure mode case that incorporates active bolt force model and cosine tension/shear bolt orientation efficiency. Of three forces, tensile resistance, F2 provides the lowest value of 240 kN (while F1 being 11148.6 kN and F3, 1191.4 kN). Based on the relative orientation between the grouted dowel and sliding direction, the cosine tension/shear orientation efficiency factor is calculated to be 0.174. Thus,  $C_L$  can be calculated using equation 5.1 as follows,

$$C_L = 0.174 \cdot 240 = 41.7 \text{ kN}$$

As  $\hat{e}$  and  $\hat{n}$  can be derived from the orientations of bolt and joint, respectively, N is calculated using equation 5.3.

$$N = ((37.8, 0, -17.6) + (0, 0, 1899.3)) \cdot (0.819, 0, -0.574) = 1940.3 \text{ kN}$$

Using equation 5.4, the shear strength is calculated as follows,

$$\tau = 0 + \frac{1940.3}{40.3} \tan 35 = 33.7 \text{ kPa}$$

In this case, the sliding occurs along a single joint, resulting in  $\theta$  of 0. Hence, active and passive resisting force is calculated as follows,

$$\text{Active Resisting force} = 33.7 \cdot 40.3 \cos 0 = 1358.6 \text{ kN}$$

$$\text{Passive Resisting force} = 33.7 \cdot 40.3 \cos 0 - [(37.8, 0, -17.6) \cdot (-0.574, 0, -0.819)] = 1365.9 \text{ kN}$$

Active and passive driving force is calculated as follows,

$$\text{Active Driving force} = [(0, 0, 1899.3) + (37.8, 0, -17.6)] \cdot (-0.574, 0, -0.819) = 2705.2 \text{ kN}$$

$$\text{Passive Driving force} = (37.8, 0, -17.6) \cdot (-0.574, 0, -0.819) = 2712.5 \text{ kN}$$

## 10.4. Results

The RocSlope model results shows a matching result as the analytical solution. The sample block details on the tensile failure mode case with active bolt force model is presented in Figure 10.6. Modelling results show equal driving force, resisting force and FS to the sample calculation results from Section 10.3.1. The comparison between the analytical solution and modelling results is shown in Table 10.4.

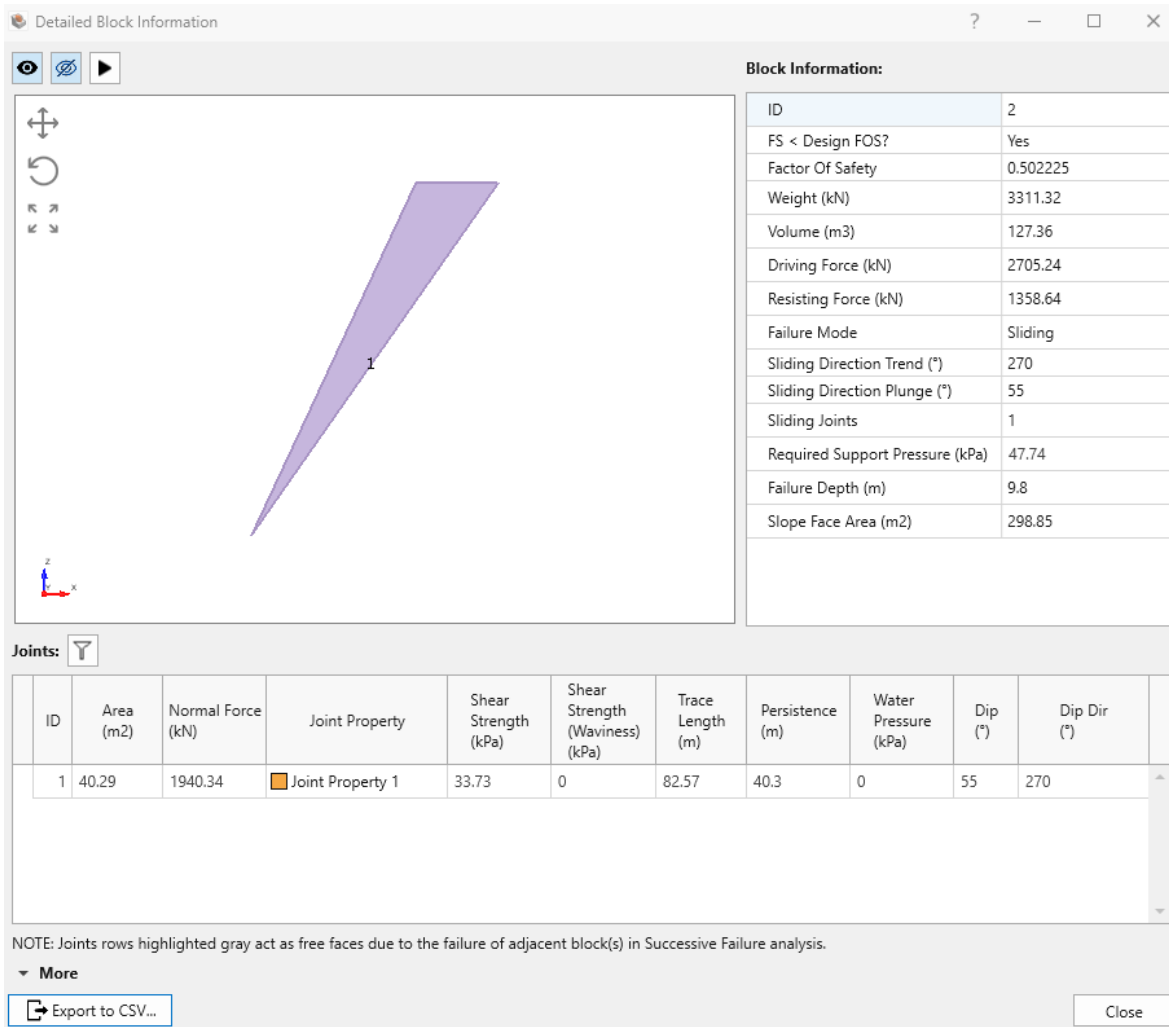


Figure 10.6 Detailed Information of Sliding Wedge of Tensile-Active Case Model

Table 10.4 Calculation Results for Different Failure Modes

Case	RocSlope vs Analytical	min(F1, F2, F3)	Resisting Force	Driving Force	FS $\left(\frac{\text{Resisting Force}}{\text{Driving Force}}\right)$
Tensile- Active	RocSlope	240 (F2)	1358.6	2705.2	0.502
	Analytical	240 (F2)	1358.6	2705.2	0.502
Tensile- Passive	RocSlope	240 (F2)	1365.9	2712.5	0.504
	Analytical	240 (F2)	1365.9	2712.5	0.504
Stripping- Active	RocSlope	100 (F3)	1341.9	2709.5	0.495
	Analytical	100 (F3)	1341.9	2709.5	0.495
Stripping- Passive	RocSlope	100 (F3)	1344.9	2712.5	0.496
	Analytical	100 (F3)	1344.9	2712.5	0.496

Case	RocSlope vs Analytical	min(F1, F2, F3)	Resisting Force	Driving Force	FS ( $\frac{\text{Resisting Force}}{\text{Driving Force}}$ )
<b>Pullout- Active</b>	RocSlope	100 (F1)	1333.4	2711.6	0.492
	Analytical	100 (F1)	1333.4	2711.6	0.492
<b>Pullout- Passive</b>	RocSlope	100 (F1)	1334.3	2712.5	0.492
	Analytical	100 (F1)	1334.3	2712.5	0.492
<b>Shear- Active</b>	RocSlope	100 (Shear)	1329.9	2612.5	0.509
	Analytical	100 (Shear)	1329.9	2612.5	0.509
<b>Shear- Passive</b>	RocSlope	100 (Shear)	1429.9	2712.5	0.527
	Analytical	100 (Shear)	1429.9	2712.5	0.527

# 11. RocSlope Verification Problem #11

Ground Support Verification Problem [RocSlope version 1.001 & SWedge version 7.020]

## 11.1. Problem Description

This section presents the RocSlope verification example on shotcrete support applied to the slope face. The maximum force which the shotcrete can exert on the wedge is obtained by adding the trace lengths of joints on the slope face and multiplying by the shotcrete thickness and shear strength. The weight of shotcrete is also added to the driving force calculation in RocSlope. The corresponding SWedge model is constructed for the verification.

## 11.2. Geometry and Material Properties

The model consists of a sloped external volume with the unit weight of  $26 \text{ kN/m}^3$ . The geometry of the model used for this verification example is presented in Figure 11.1. A wedge is confined by two joints and cut by the upper face. The strength of the joints is defined by Mohr-Coulomb strength criteria with a cohesion and friction angle of  $0 \text{ kPa}$  and  $35^\circ$ , respectively. Shotcrete, represented as the grey surface in Figure 11.1, is applied at the sloped face, covering the entire wedge surface exposed at the sloped face. It has  $10 \text{ cm}$  thickness with the shear strength of  $1 \text{ MPa}$  and unit weight of  $0 \text{ kN/m}^3$  to disregard the weight of shotcrete in the driving force calculation.

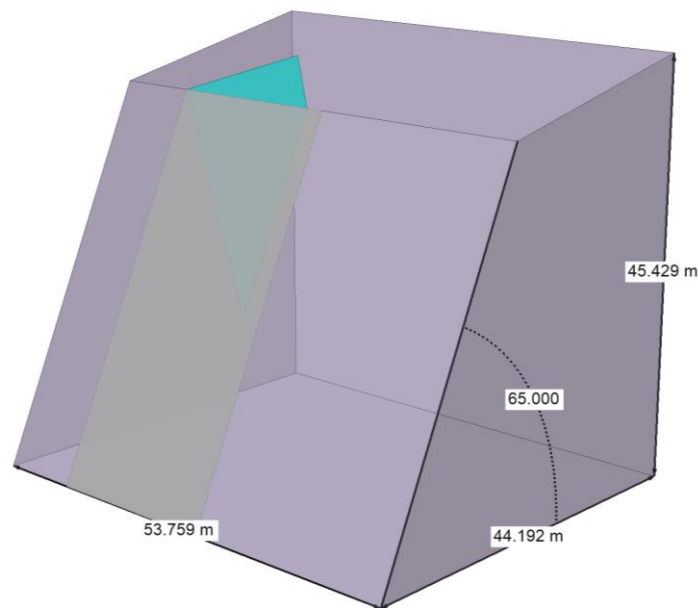


Figure 11.1 Model Geometry

## 11.3. Building a Compatible SWedge Model

The equivalent SWedge Model is constructed with the input parameters as summarized in Table 11.1 and Table 11.2. Shotcrete with  $10 \text{ cm}$  thickness and  $1 \text{ MPa}$  shear strength is applied on the slope face. The model geometry is presented in Figure 11.2.

Table 11.1 Slope Input Data

<b>Slope</b>	
Dip	65
Dip Direction	185
Height	20
<b>Upper Face</b>	
Dip	12
Dip Direction	185

Table 11.2 Joint Input Data

<b>Joint 1</b>	
Dip	45
Dip Direction	125
Waviness	0
Cohesion (MPa)	0
Phi (°)	35
<b>Joint 2</b>	
Dip	45
Dip Direction	125
Waviness	0
Cohesion (MPa)	0
Phi (°)	35

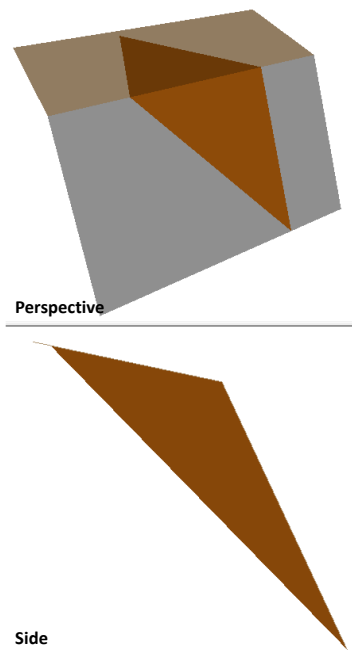


Figure 11.2 SWedge Model Geometry

## 11.4. Results

The FS of the wedge computed with RocSlope and SWedge shows a good agreement. The results are shown in Table 11.3.

Table 11.3 RocSlope and SWedge Modelling Results

	<b>RocSlope</b>	<b>SWedge</b>
<b>FS</b>	1.494	1.494



# 12. RocSlope Verification Problem #12

---

Ground Support Verification Problem [RocSlope version 1.001 & SWedge version 7.020]

## 12.1. Problem Description

Adding support pressure is one of the numerous ways to model supports in RocSlope. To verify the results of the effect of uniform support pressure on the stability of a block, SWedge can be used. The slope and joint definitions can be imported from SWedge into RocSlope.

## 12.2. Geometry and Material Properties

The wedge of the geometry analyzed is defined by the following properties:

Table 12.1: Wedge geometry definition

Angle	Value
Slope Dip (°)	65
Slope Dip Direction (°)	185
Upper Face Dip (°)	12
Upper Face Dip Direction (°)	185
Joint 1 Dip (°)	45
Joint 1 Dip Direction (°)	125
Joint 2 Dip (°)	70
Joint 2 Dip Direction (°)	225

The Mohr-Coulomb model is used to represent the shear strength of the joints, with no cohesion and a friction angle of 35°.

The rock unit weight used is 0.026 MN/m<sup>3</sup>.

The support pressure is defined separately on the slope and upper faces uniformly as follows:

Table 12.2: Support pressure application properties

Property	Applied on Slope Face	Applied on Upper Face
Trend (°)	5	5
Plunge (°)	25	78
Pressure (MPa)	1	1.1
Model	Passive	Active

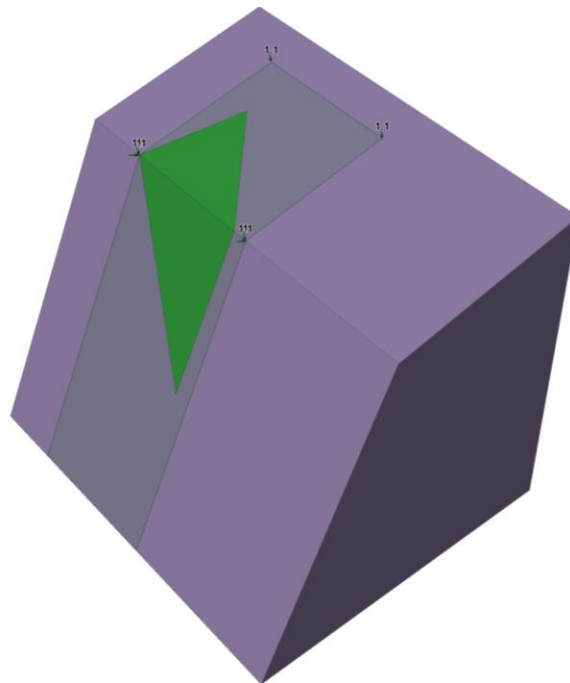


Figure 12.1: Support pressure applied on wedge

## 12.3. Results

The two equivalent models in RocSlope and SWedge reach the same computed safety factor:

Table 12.3: Ground support verification result compared to SWedge

	RocSlope	SWedge
<b>FS</b>	4.434	4.4500

# 13. RocSlope Verification Problem #13

Successive Failure Verification Problem [Rocslope version 1.001]

## 13.1. Problem Description

Assuming the correctness of safety factor computations for an individual block, this section will detail the verification of the successive analysis of block failure in iterations.

This example does not model a realistic problem. It serves as a simple verification that the failure iteration of the blocks is correct.

## 13.2. Geometry

The external volume is defined as 3 x 3 x 3 m cube split into 1 x 1 x 1 m sub-cubes. This is done using 3 synthetic joint sets of 1 m spacing oriented in the XY-plane, YZ-plane, and XZ-plane.



Figure 13.1: Blocks defined by subdivision of a cube

There is also a search limit defined containing the entire external volume, with the option to ignore blocks attached to non-terrain surfaces disabled to ensure that all cubes are treated as blocks.

The rock unit weight and shear strength parameters assigned to the joints are irrelevant to this problem.

### 13.3. Results

Since the only force acting on each of the blocks is its own weight, the driving force for each one is pointing in the negative Z direction. The only direction in which the blocks may be removed from the slope is downward. Therefore, the expected result is to see the bottom layer of blocks fail in the first iteration by means of falling, followed by the middle and subsequently top layers.

Filtering the results by failure iteration visualizes the progression of failure of the blocks. Removing those failing in the first iteration yields the following:

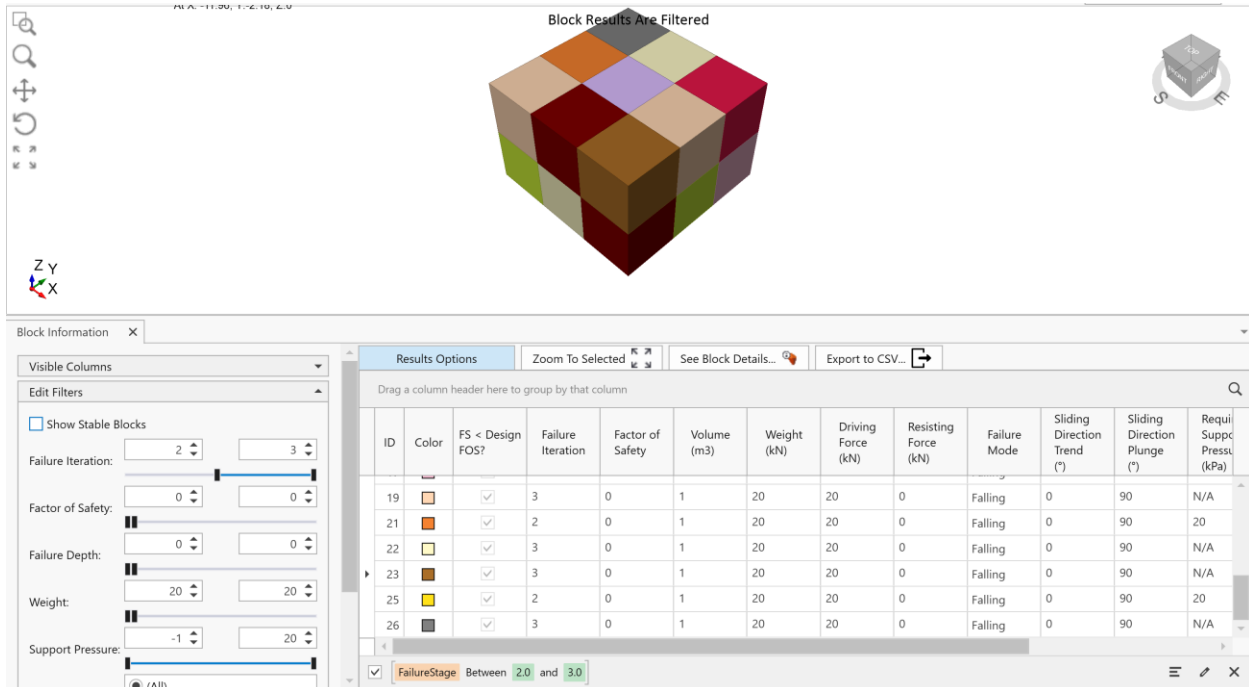


Figure 13.2: Hide blocks that fail in the first iteration

Removing the blocks whose failure iteration is 2 leaves only those failing in the third iteration:

Block Results Are Filtered

Block Information

Visible Columns

Edit Filters

Show Stable Blocks

Failure Iteration: 3

Factor of Safety: 0

Failure Depth: 0

Weight: 20

Support Pressure: -1 to 20

Results Options

Zoom To Selected

See Block Details...

Export to CSV...

Drag a column header here to group by that column

ID	Color	FS < Design FOS?	Failure Iteration	Factor of Safety	Volume (m3)	Weight (kN)	Driving Force (kN)	Resisting Force (kN)	Failure Mode	Sliding Direction Trend (°)	Sliding Direction Plunge (°)	Required Support Pressure (kPa)
16	Green	<input checked="" type="checkbox"/>	3	0	1	20	20	0	Falling	0	90	N/A
17	Pink	<input checked="" type="checkbox"/>	3	0	1	20	20	0	Falling	0	90	N/A
19	Orange	<input checked="" type="checkbox"/>	3	0	1	20	20	0	Falling	0	90	N/A
22	Yellow	<input checked="" type="checkbox"/>	3	0	1	20	20	0	Falling	0	90	N/A
23	Brown	<input checked="" type="checkbox"/>	3	0	1	20	20	0	Falling	0	90	N/A
26	Grey	<input checked="" type="checkbox"/>	3	0	1	20	20	0	Falling	0	90	N/A

FailureStage = 3.0

Figure 13.3: Hide blocks that fail in the first and second iterations

RocSlope's results for failure iteration are as expected.

The expected failure mode of all blocks is also correctly "Falling", which results in factors of safety of 0, as expected.

# 14. RocSlope Verification Problem #14

---

Successive Failure Verification Problem [RocSlope version 1.001]

## 14.1. Problem Description

This example demonstrates that a block that is geometrically non-removable, when analyzed with all other blocks in place, can fail in a subsequent iteration by the failure of adjacent blocks that make some of its joints act as free faces.

In this section, the correctness of the factor of safety calculations for an individual block is assumed.

## 14.2. Geometry

Measured joints with the following properties are defined:

Table 14.1: Measured joint properties

Dip (°)	Dip Dir. (°)	X (m)	Y (m)	Z (m)	Radius (m)
45	335	0	0	0	115.9038
70	25	0	0	0	103.3587
10	180	0	0	10	100
10	0	0	0	25	100

The parameter used to determine failure of a block is the design factor of safety, which is 1 for this example.

The remaining program inputs are not relevant to this exercise.

## 14.3. Results

Running the model without Successive Failure analysis turned on demonstrates the results when a single analysis is performed for each block independently.

(Please refer to *Rocslope\_Verification\_#14-1\_Successive.rocslope\_model*.)

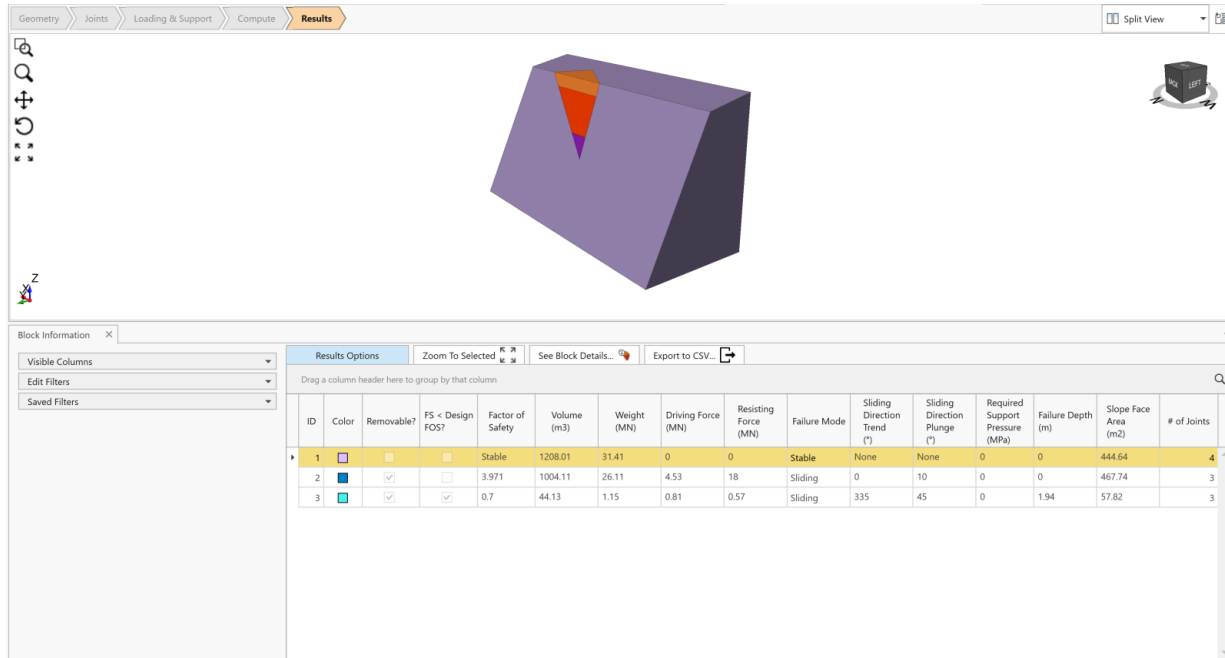


Figure 14.1: Results when model run with successive failure analysis turned off

Relying on the validity of the factor of safety computations, as seen above, the bottom block fails. The middle block is bounded by all four joints and is not geometrically removable when all four planes are included in its joint pyramid. The top block is geometrically removable, but its safety factor is higher than the design such that it does not fail.

When Successive Failure analysis is turned on, all three blocks eventually fail:

(Please refer to *Rocslope\_Verification\_#14\_Successive.rocslope\_model*.)

ID	Color	FS < Design FOS?	Failure Iteration	Factor of Safety	Volume (m3)	Weight (MN)	Driving Force (MN)	Resisting Force (MN)	Failure Mode	Sliding Direction Trend (°)	Sliding Direction Plunge (°)	Required Support Pressure (MPa)	Failure Depth (m)	Slope Face Area (m2)	# of Joints
1	Blue	<input checked="" type="checkbox"/>	2	0.7	1208.01	31.41	22.21	15.55	Sliding	335	45	0.02	6.28	444.64	4
2	Green	<input checked="" type="checkbox"/>	3	0.7	1004.11	26.11	18.46	12.93	Sliding	335	45	0.03	9.63	467.74	3
3	Red	<input checked="" type="checkbox"/>	1	0.7	44.13	1.15	0.81	0.57	Sliding	335	45	0	1.94	57.82	3

Figure 14.2: Results when model run with successive failure analysis turned on

For the analysis of the second iteration, the joint bounding the middle block from the bottom acts as a free face due to the failure of the bottom block in the first iteration. Removing this plane from its joint pyramid makes it geometrically removable and the results show a failing factor of safety. The analysis of the top block remains the same as it was when computing the model without Successive Failure analysis because no block adjacent to it fails in the first iteration.

In the third iteration, the top block will also fail due to the joint bounding it from the bottom acting as a free face, similarly to the analysis of the middle block in the second iteration.

## 15. References

---

Mauldon, M., and Ureta, J. (1996). *Stability analysis of rock wedges with multiple sliding surfaces*. Geotechnical and Geological Engineering 14, pp. 41-66.