rocscience

RocTopple

Topping Analysis and Support Design of Rock Slops

Verification Manual

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1. *RocTopple* Block Toppling Verification

This document presents several examples, which have been used as verification problems for *RocTopple*. *RocTopple* is an engineering analysis program for performing toppling analysis and support design of rock slopes, produced by Rocscience Inc. of Toronto, Canada.

RocTopple is verified against published examples and against results produced by *RS2* and UDEC. The results produced by *RocTopple* agree very well with the documented examples and confirm the reliability of *RocTopple* results.

1.1. *RocTopple* Verification Problem #1

[*RocTopple* Build 2.001]

1.1.1. Problem Description

This verification looks at Example 1 in the paper:

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

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

Geometry and Material Properties

Table 1.1.1: Material Properties

Analysis	ϕ' (deg.)	Force on Toe Block (kN)	γ (kN/m^3)
Example 1a	38.15	0.5	25.0
Example 1b	33.02	2013	25.0
Example 1c	38.66	0.5	25.0
Example 1d	38.66	2013	25.0

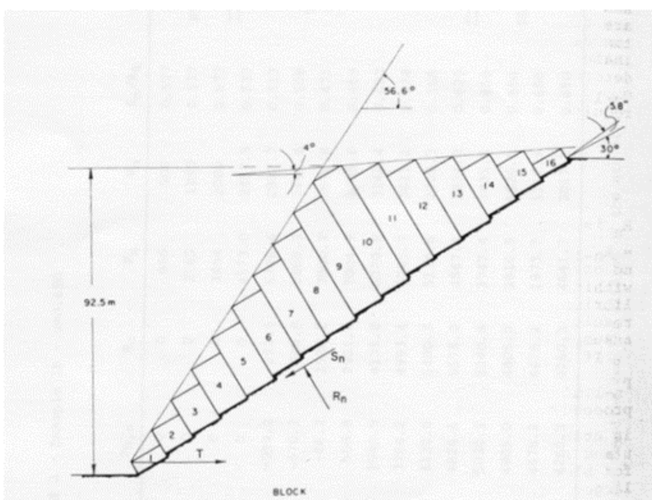


Figure 1.1.1: Geometry with 16 Blocks (Goodman and Bray, 1976)

1.1.2. *RocTopple* Analysis

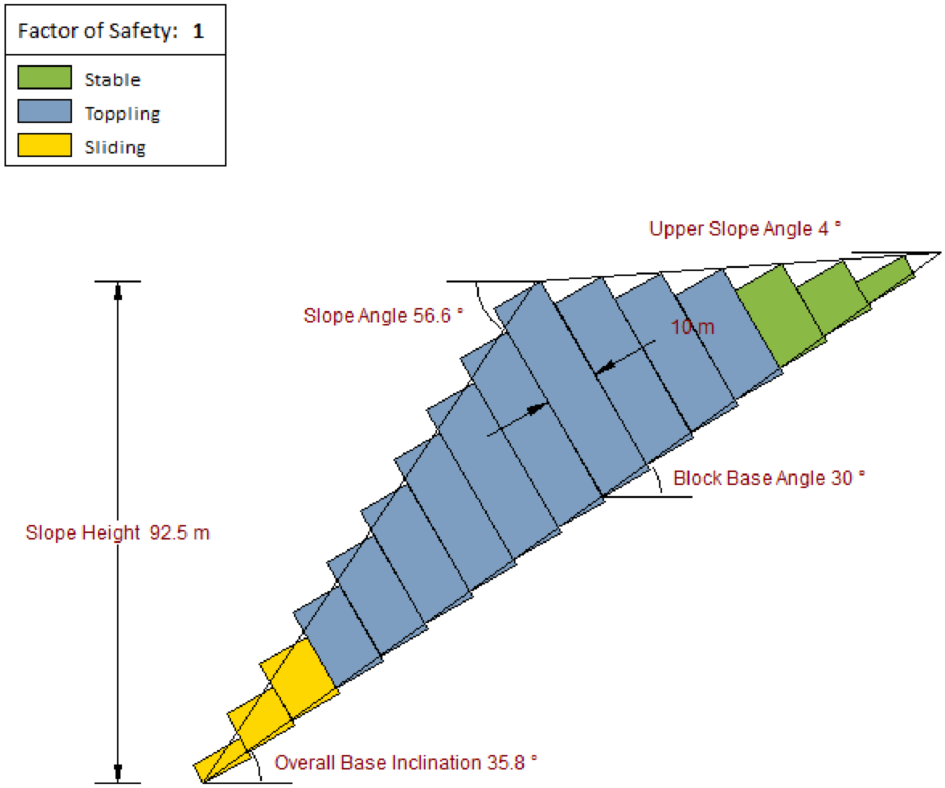
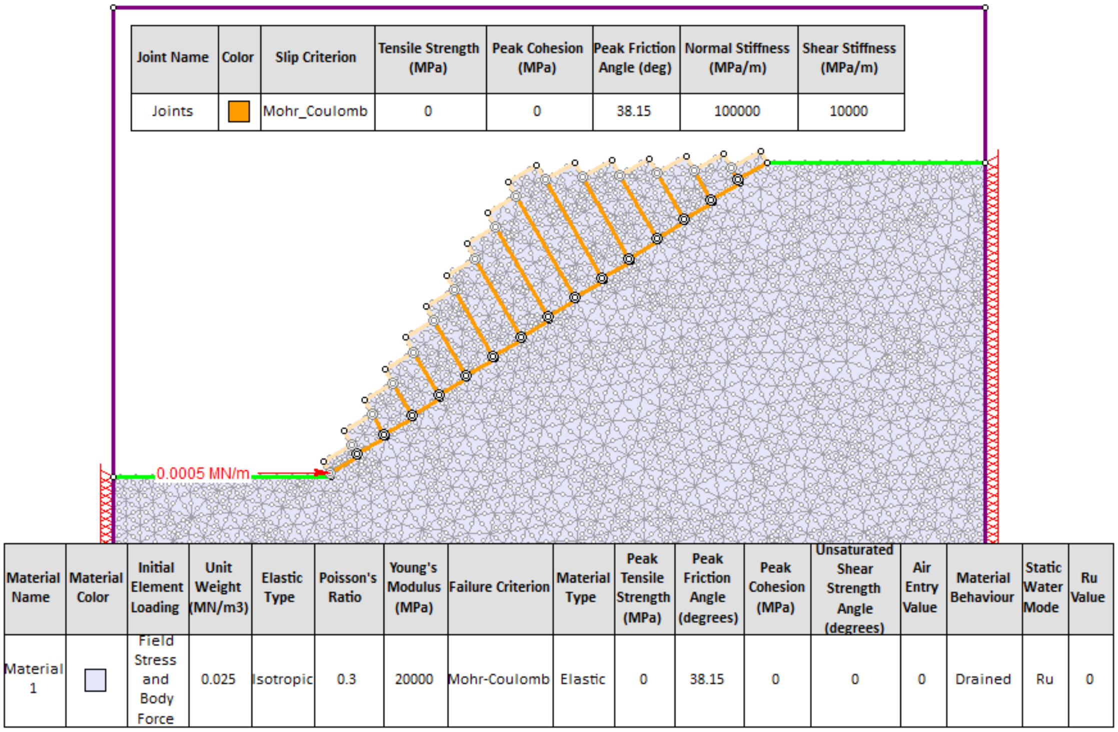


Figure 1.1.2: *RocTopple* Model using Goodman and Bray Input Geometry (16 Blocks)

1.1.3. Building a Compatible *RS2* Model



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

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

Figure 1.1.3: *RS2* Model of Example 1a (Geometry Exported from *RocTopple*)

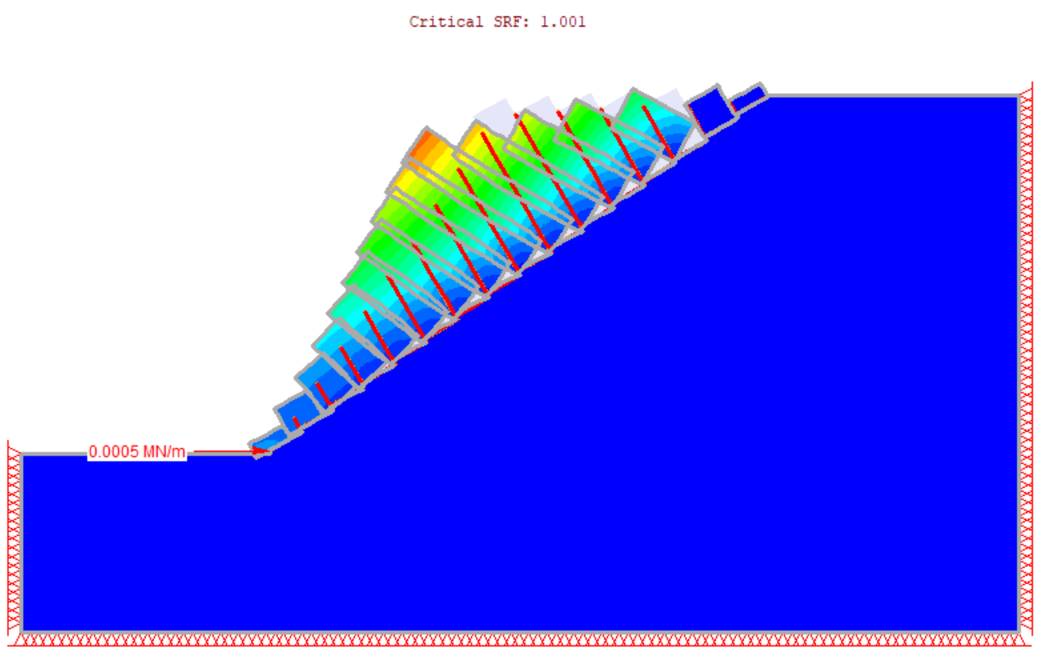


Figure 1.1.4: *RS2* Results of Example 1a at Critical SRF (Total Displacement Contours)

1.1.4. UDEC Analysis

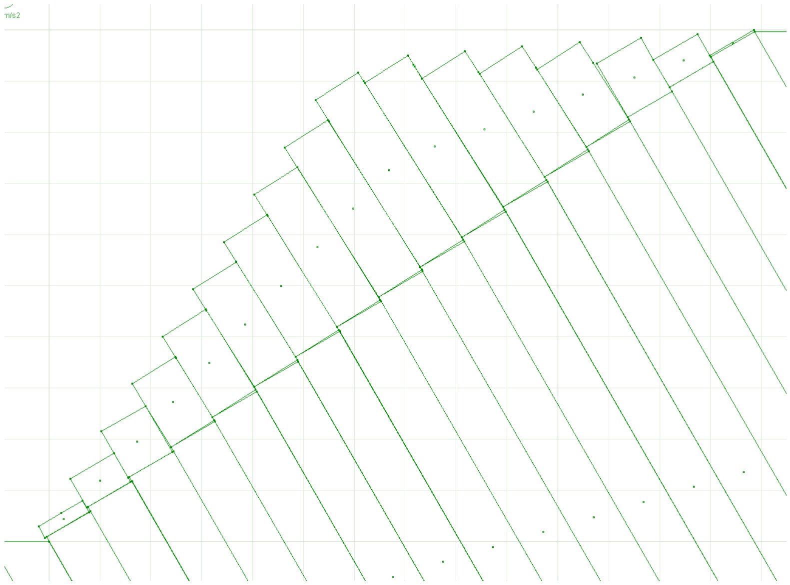


Figure 1.1.5: Deformation in UDEC

1.1.5. Results

Table 1.1.2: Factors of Safety

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

1.2. *RocTopple* Verification Problem #2

[*RocTopple Build 2.001*]

1.2.1. Problem Description

This verification looks at Example 2 in the paper:

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

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

Geometry and Material Properties

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

Table 1.2.1: Material Properties

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

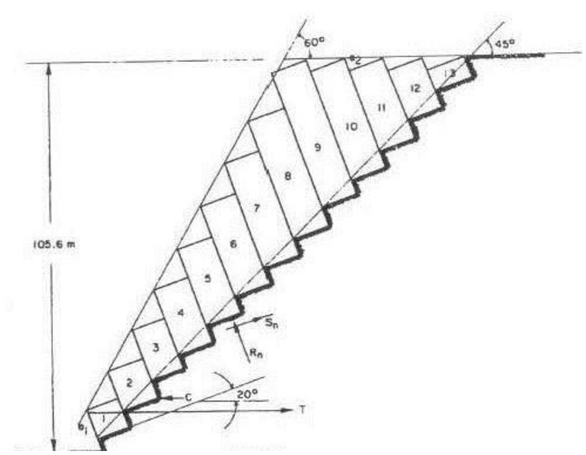


Figure 1.2.1: Goodman and Bray Example 2 Geometry (13 Blocks)

1.2.2. *RocTopple* Analysis

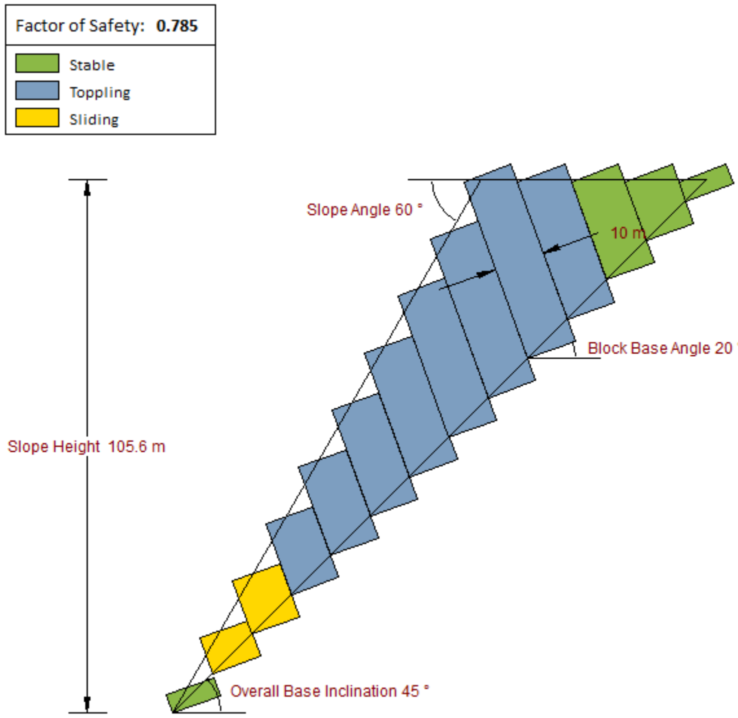
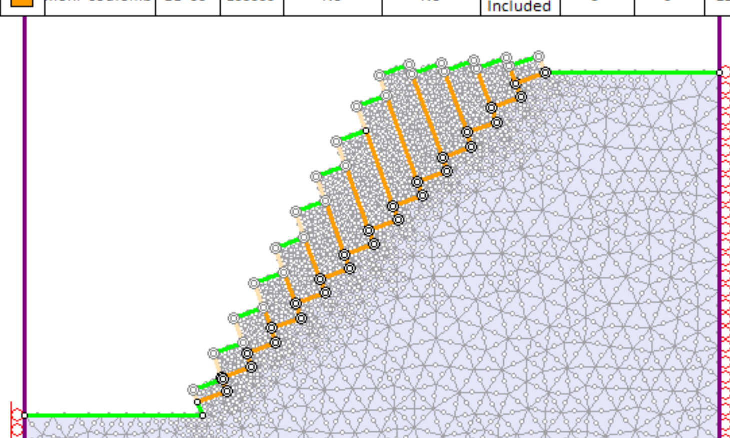


Figure 1.2.2: *RocTopple* Geometry (14 Blocks, Separate First Block)

1.2.3. Building a Compatible *RS2* Model

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



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

Figure 1.2.3: *RS2* Geometry and Properties (14 Blocks)

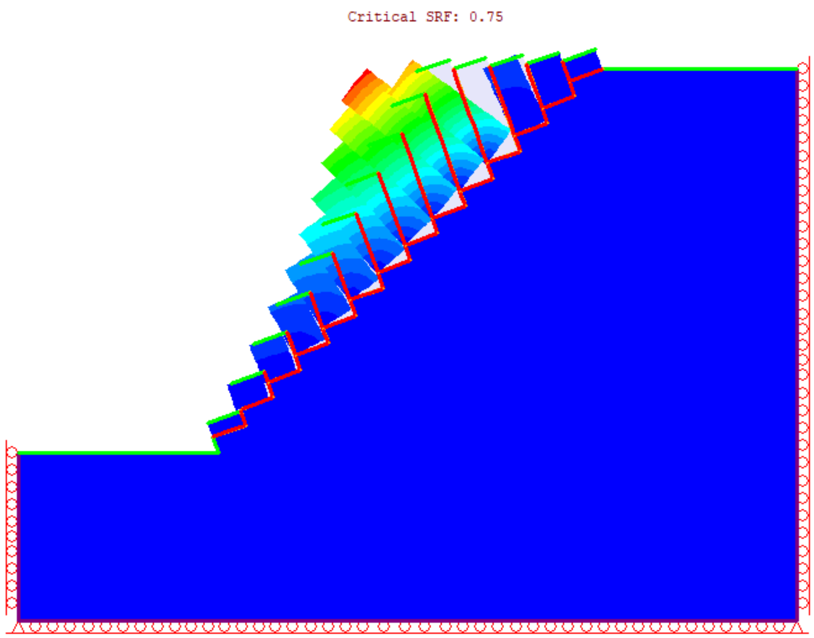


Figure 1.2.4: *RS2* Total Displacement Contours and Deformed Shape

1.2.4. UDEC Analysis

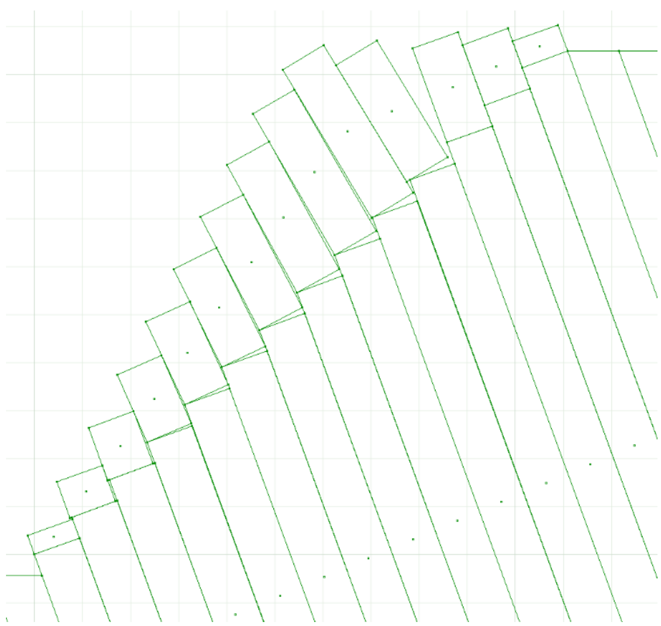


Figure 1.2.5: Deformation in UDEC

1.2.5. Results

Table 1.2.2: Factors of Safety

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

1.3. *RocTopple* Verification Problem #3

[*RocTopple Build 2.001*]

1.3.1. Problem Description

This verification looks at the block toppling example from:

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

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

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

Geometry and Material Properties

Table 1.3.1: Material Properties

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

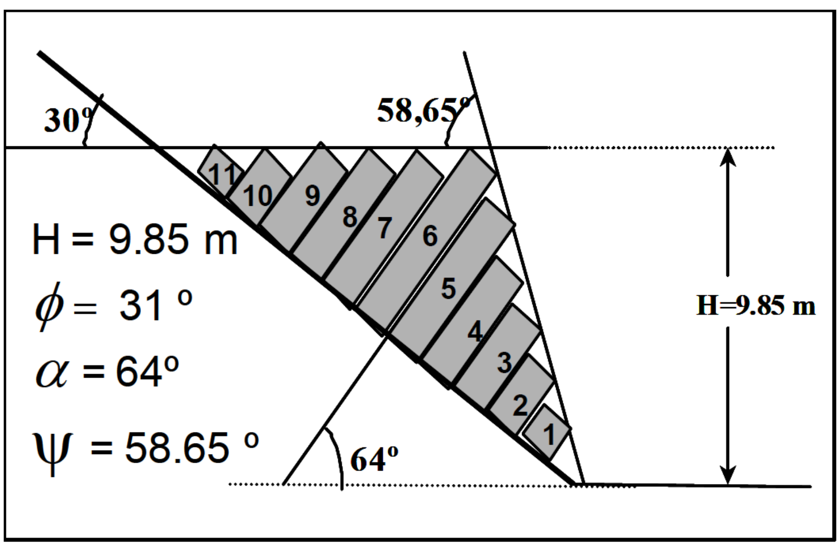


Figure 1.3.1: Goodman & Bray Geometry (Alejano & Alonso, 2005)

1.3.2. *RocTopple* Analysis

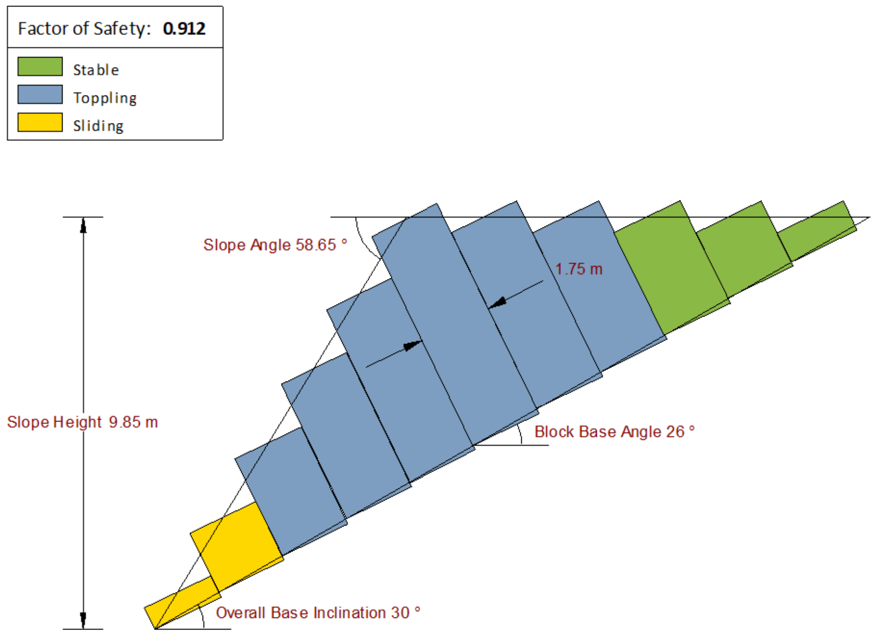
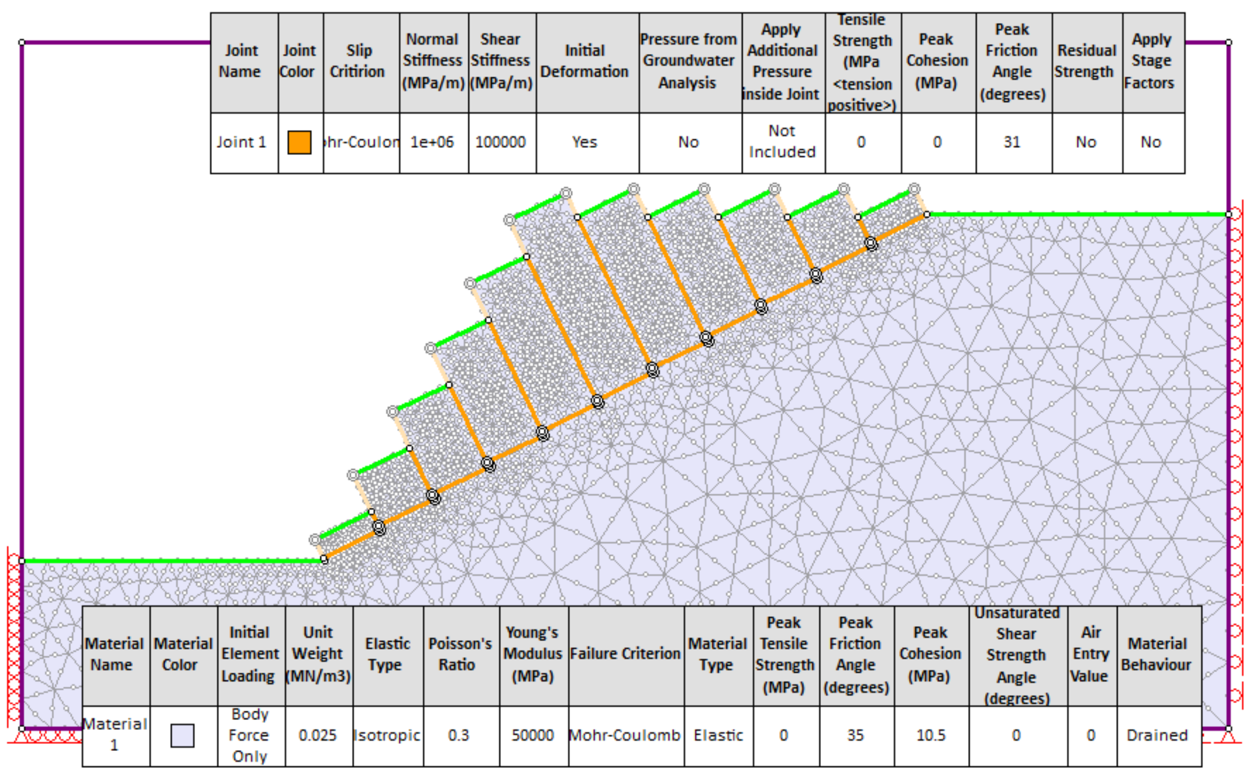


Figure 1.3.2: *RocTopple* Geometry

1.3.3. Building a Compatible *RS2* Model



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

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

Figure 1.3.3: *RS2* Geometry and Properties

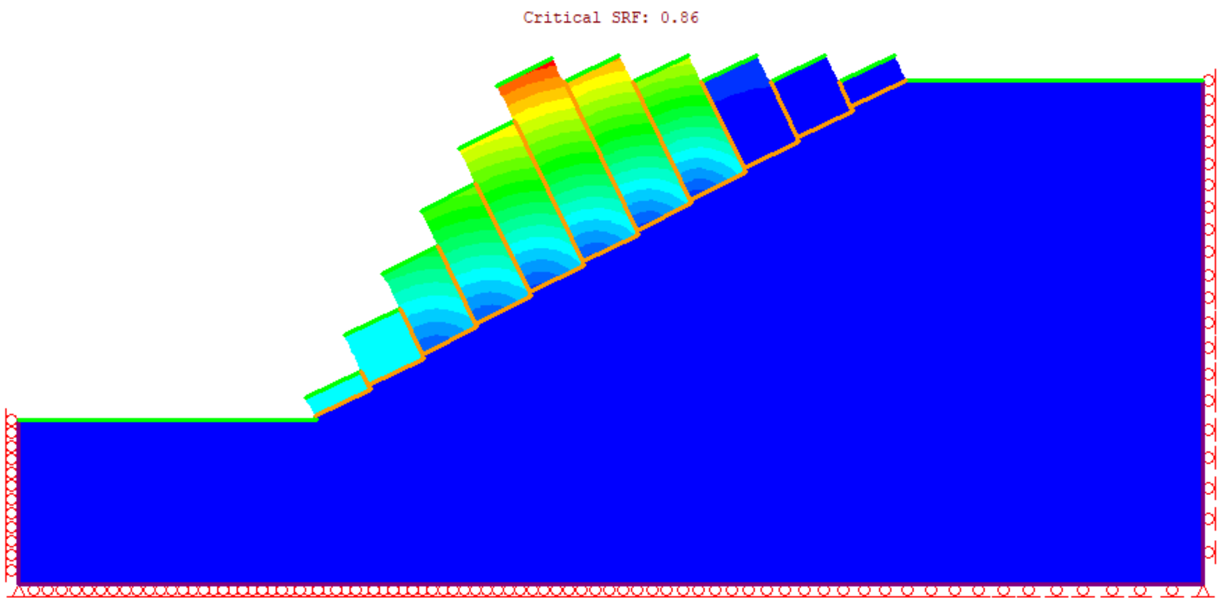


Figure 1.3.4: *RS2* Displacement Contours

1.3.4. UDEC Analysis

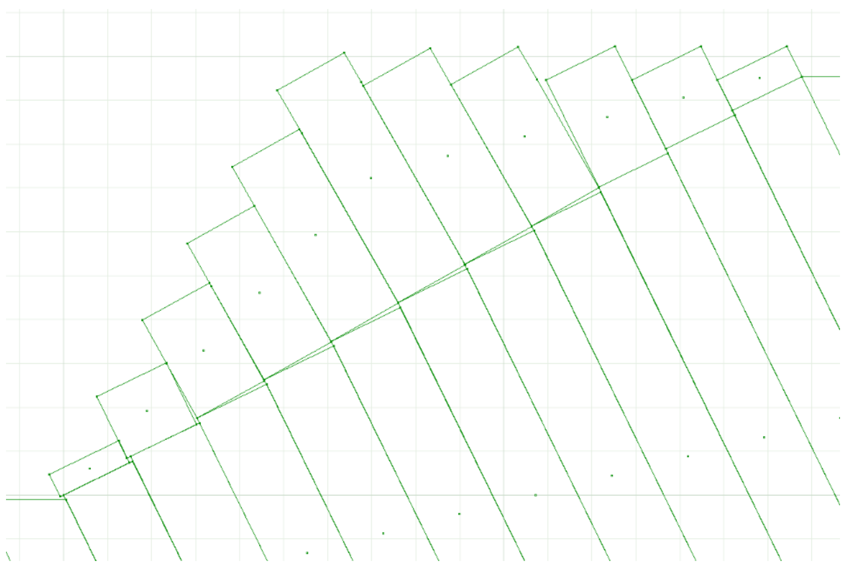


Figure 1.3.5: Deformation in UDEC

1.3.5. Results

Table 1.3.2: Factors of Safety

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

1.4. *RocTopple* Verification Problem #4

[*RocTopple Build 2.001*]

1.4.1. Problem Description

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

Geometry and Material Properties

Table 1.4.1: Properties

Material	Joints
Unit Weight = 2.5 t/m^3	ϕ = 38.15°

1.4.2. *RocTopple* Analysis

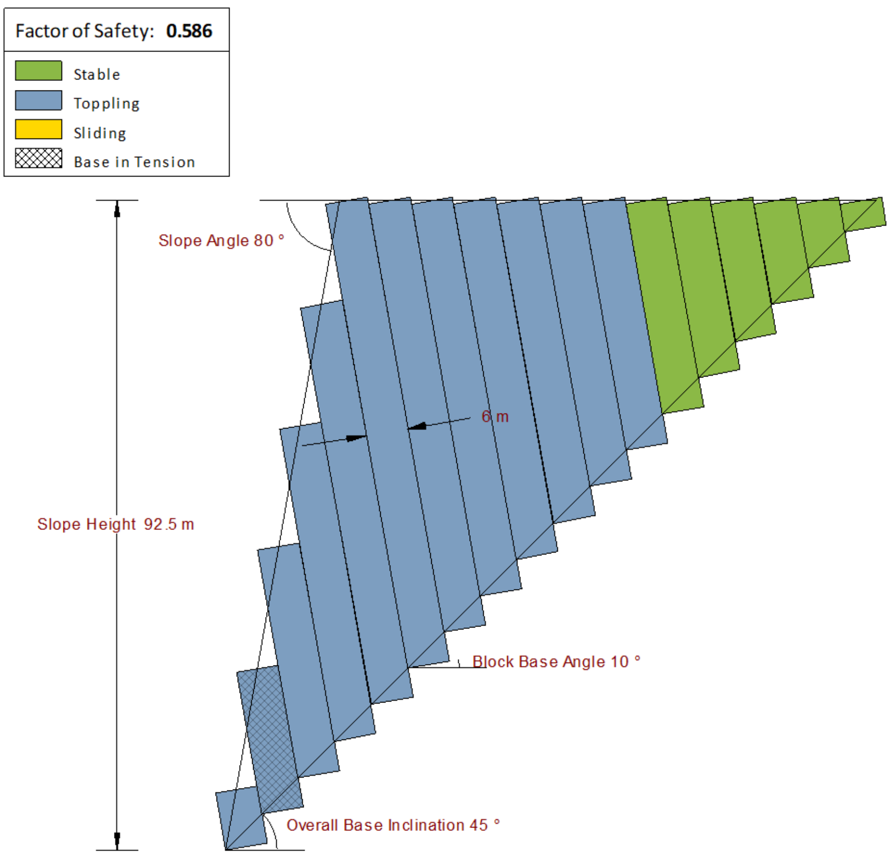
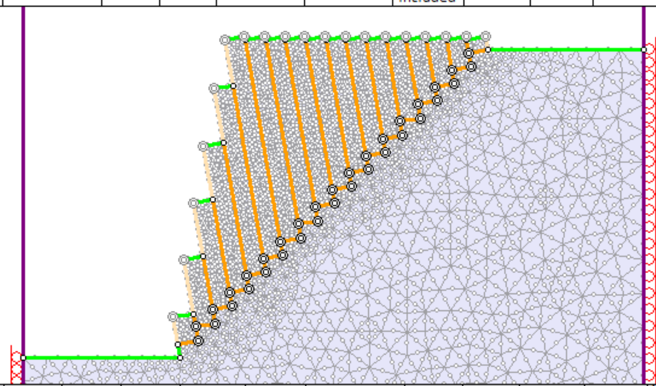


Figure 1.4.1: *RocTopple* Geometry and Block Failure Modes at Limit Equilibrium

1.4.3. Building a Compatible *RS2* Model

Results are verified in UDEC and *RS2*. Both programmes also predict that blocks are toppling from the 7th block from the top all the way to the toe block. These programs also generated comparable factors of safety.

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



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

Figure 1.4.2: *RS2* Geometry and Properties

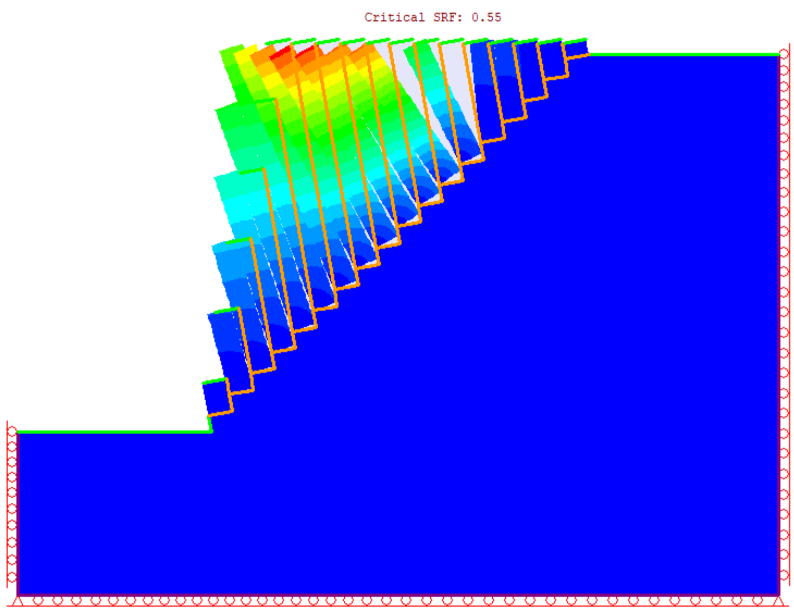


Figure 1.4.3: *RS2* Displacement Contours

1.4.4. Results

Table 1.4.2: Factors of Safety

RocTopple	*RS2*	UDEC
0.59	0.55	0.59

1.5. *RocTopple* Verification Problem #5

[*RocTopple Build 2.001*]

1.5.1. Problem Description

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

Geometry and Material Properties

Table 1.5.1: Properties

Material	Joints
Unit Weight = 2.5 t/m^3	ϕ = 30°

1.5.2. *RocTopple* Analysis

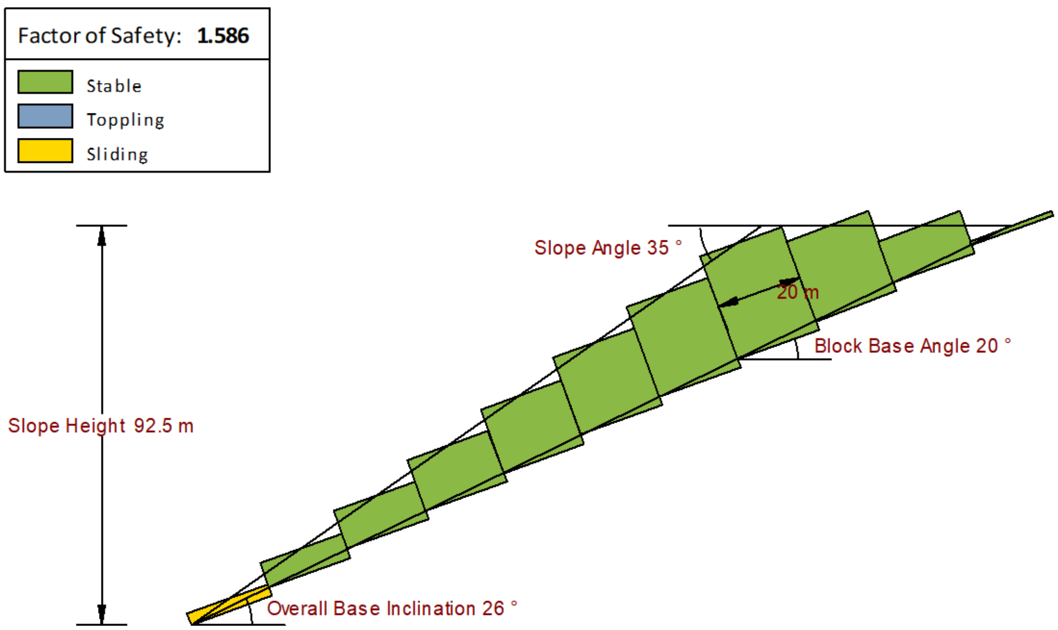
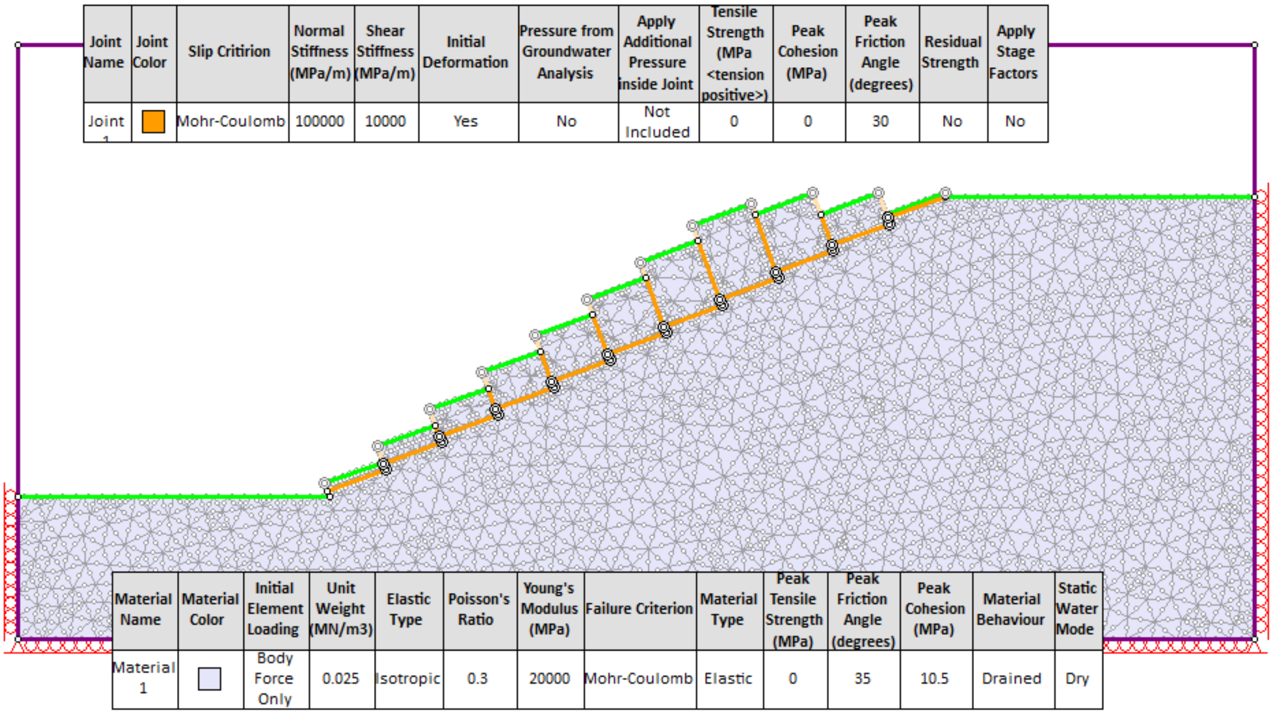


Figure 1.5.1: *RocTopple* Geometry

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

Results were verified in *RS2* and RocPlane, which uses the limit equilibrium method to predict the factor of safety for 2-D planar failure. The analysis in RocPlane used a failure plane angle of 20°.

1.5.3. Building a Compatible *RS2* Model



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

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

Figure 1.5.2: *RS2* Geometry and Properties

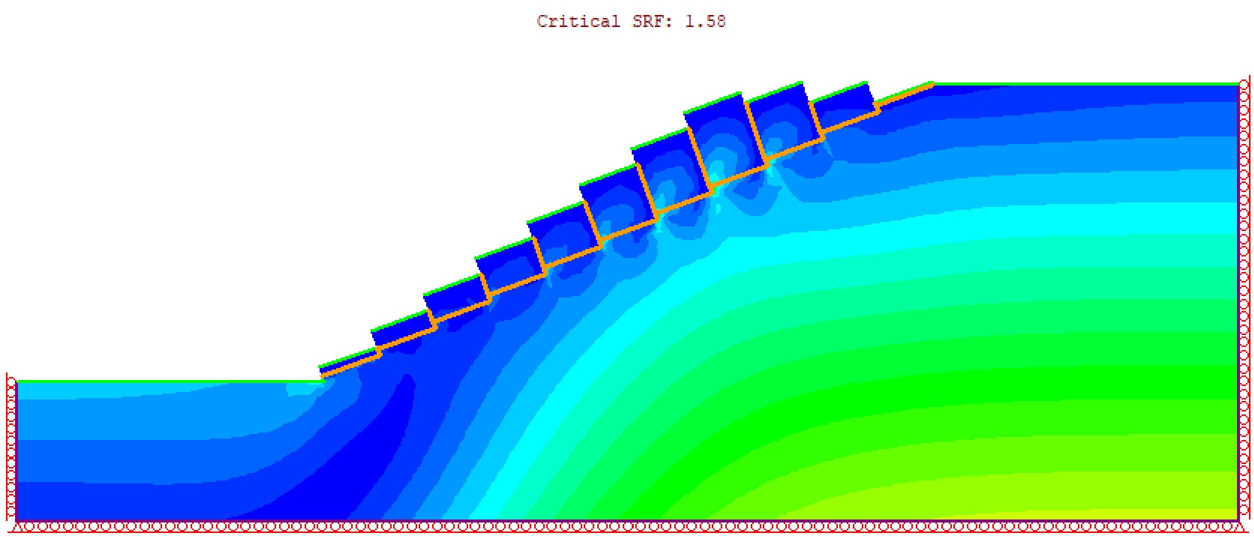


Figure 1.5.3: *RS2* Displacement Contours

1.5.4. Results

Table 1.5.2: Factors of Safety

RocTopple	*RS2*	RocPlane
1.59	1.58	1.59

1.6. *RocTopple* Verification Problem #6

[*RocTopple Build 2.001*]

1.6.1. Problem Description

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

Geometry and Material Properties

Table 1.6.1: Properties

	Material	Joints		
		JRC	JCS (t/m^2)	PhiR
A	Unit Weight = 2.5 t/m^3	10	10000	30°
B		8	7000	20°
C		5	5000	15°

1.6.2. *RocTopple* Analysis

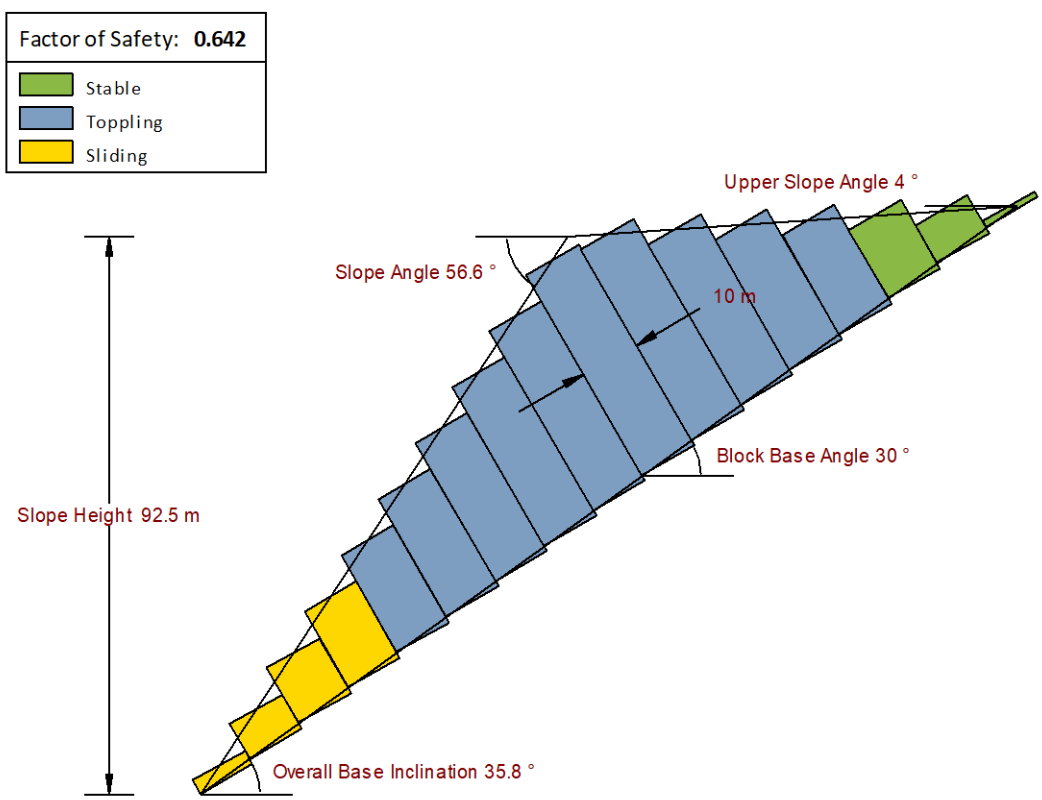
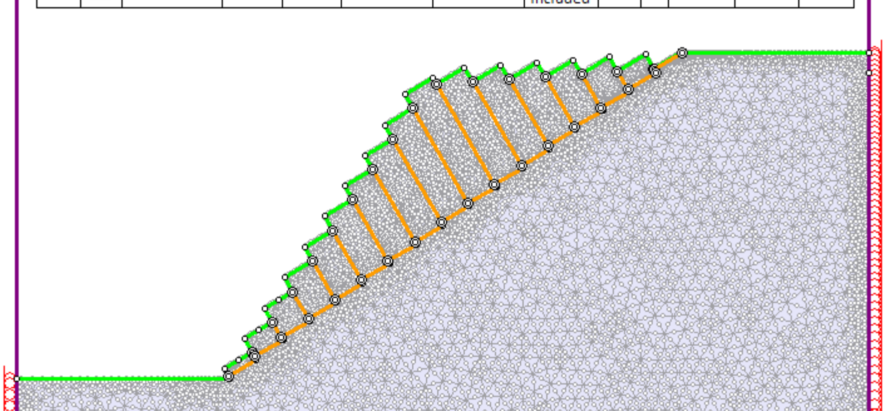


Figure 1.6.1: *RocTopple* Geometry of Example 6c and Block Failure Modes at Limit Equilibrium

Results were verified using manual shear strength reduction in *RS2*. The joint strength parameters could not be divided by the factor of safety values in finding a shear strength reduction factor because the Barton Bandis model is non-linear. Instead, normal and shear stress data at the given shear strength model had to be exported to Excel from RocData, where the shear stresses were manually adjusted for different factors of safety (shear stress/FS). The normal stress and new shear stress values were imported back into RocData, which uses the Levenberg-Marquardt algorithm to fit the stress values to a set of Barton Bandis parameters. Finally, the slope stability was evaluated using stress analysis in *RS2* given the adjusted parameters. A discrepancy is seen in one of the factors of safety because the parameters did not give a perfect fit to the stress data. As seen in Table 6-2, factors of safety between *RocTopple* and *RS2* do not agree when there are large residuals in the parameter fitting process.

1.6.3. Building a Compatible *RS2* Model

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



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

Figure 1.6.2: *RS2* Geometry and Properties for Example 6a

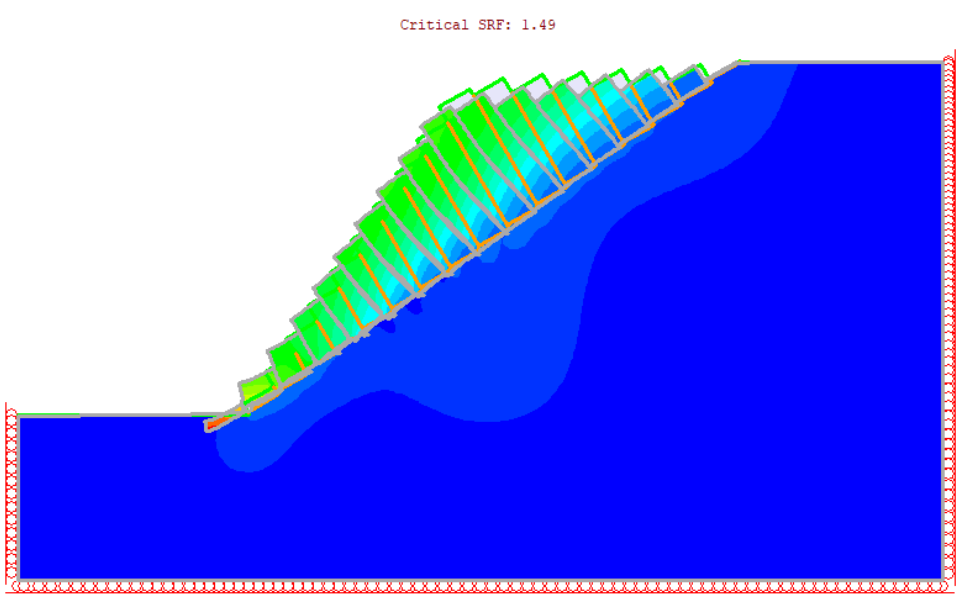


Figure 1.6.3: *RS2* Displacement Contours for Example 6a

1.6.4. Results

Table 1.6.2: Factors of Safety

	Factors of Safety		RocData Residuals
	RocTopple	***RS2***	**(Fit at *RS2* FS)**
A	1.93	1.49	17.964
B	1.07	0.96	0.020
C	0.64	0.57	4.414

1.7. *RocTopple* Verification Problem #7

[*RocTopple Build 2.001*]

1.7.1. Problem Description

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

Since the formulation for end-anchored bolts consists of having two forces applied at the two ends, having a bolt that is anchored in the slope bedrock is equivalent to having a line load applied at where the bolt is installed (Table 1.7.1).

Geometry and Properties

Table 1.7.1: Properties

Material	Joints
Unit Weight = 2.5 t/m^3	ϕ = 38.15°

1.7.2. *RocTopple* Analysis

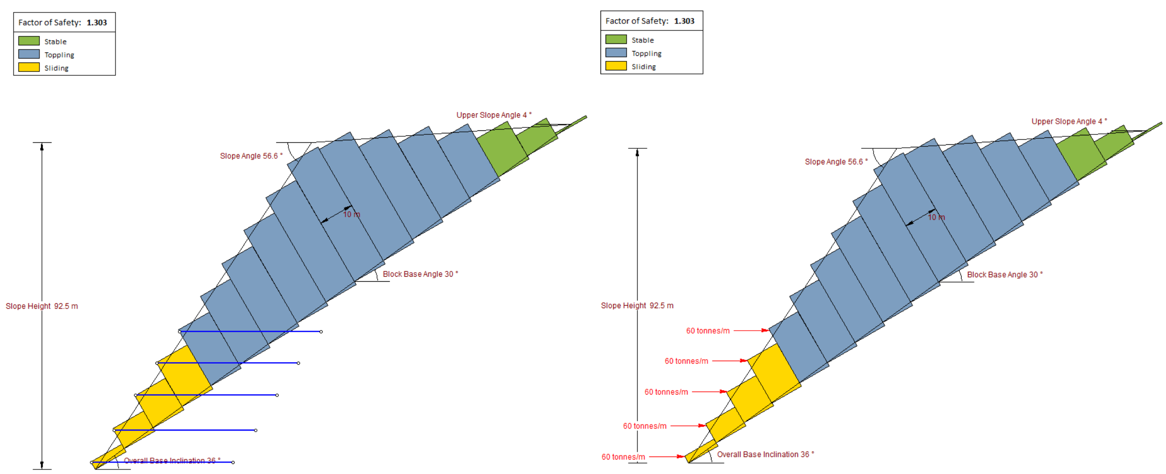
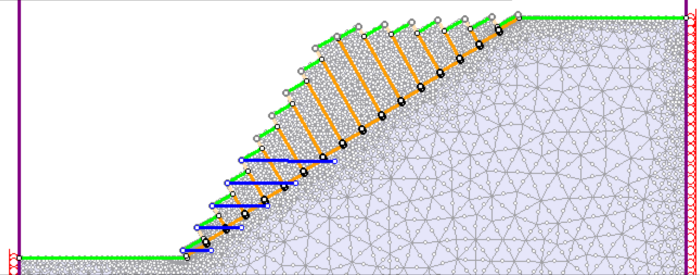


Figure 1.7.1: *RocTopple* Geometry with Bolts Each at 60 tonnes/m (left); Equivalent Line Loads at 60 tonnes/m (right)

1.7.3. Building a Compatible *RS2* Model

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

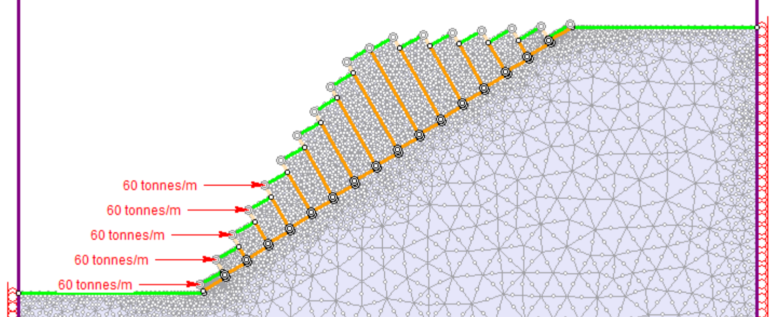
Bolt Name	Bolt Color	Bolt Type	Bolt Diameter (mm)	Bolt Modulus,E (tonnes/m2)	Tensile Capacity (tonnes)	Residual Tensile Capacity (tonnes)	Out-of-Plane Spacing (m)	Pre-Tensioning Force (tonnes)	Constant Pre-tensioning Force in Install Stage
Bolt 1		End Anchored	19	2.03943e+07	80	0	1	60	Yes



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

Figure 1.7.2: *RS2* Geometry and Properties for Bolts

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



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

Figure 1.7.3: *RS2* Geometry and Properties for Equivalent Line Loads

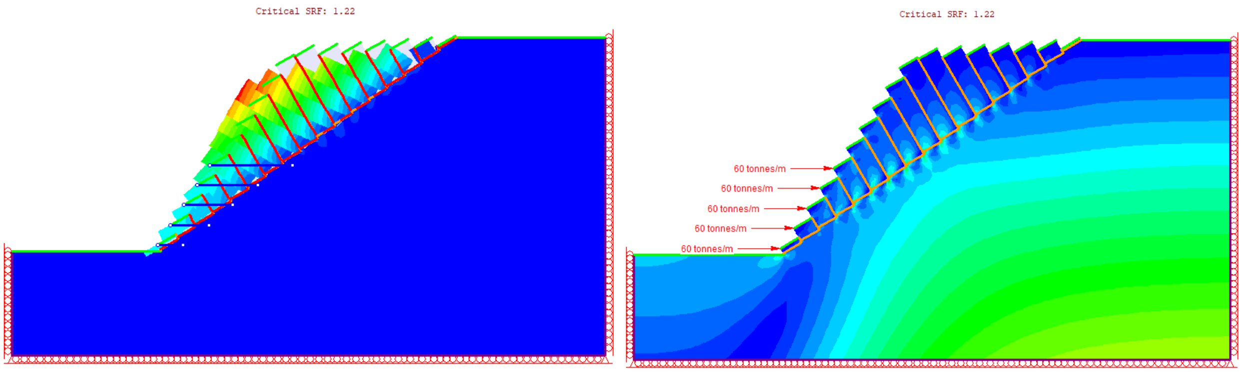


Figure 1.7.4: *RS2* Displacement Contours for Bolts (left) and Equivalent Line Loads (right)

1.7.4. Results

Table 1.7.2: Factors of Safety

Example	*RocTopple*	*RS2*
7A with Bolts	1.30	1.22
7B with Line Loads	1.30	1.22

1.8. *RocTopple* Verification Problem #8

[*RocTopple Build 2.001*]

1.8.1. Problem Description

This verification problem examines the application of distributed loads.

Geometry and Properties

Table 1.8.1: Properties

Material	Joints
Unit Weight = 2.5 t/m^3	ϕ = 38.15°

1.8.2. *RocTopple* Analysis

Case 1:

Distributed loads are assumed to apply on top of blocks and are taken into account in the calculation as equivalent line loads.

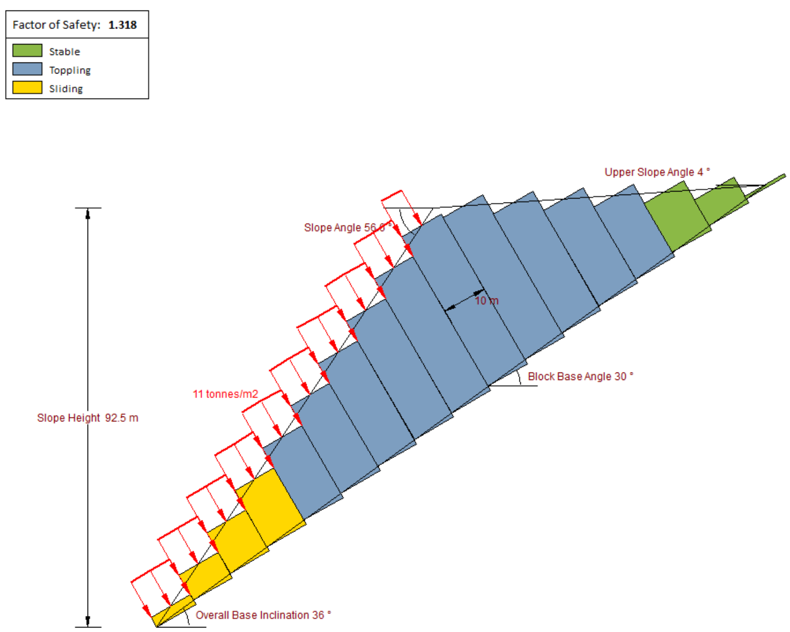


Figure 1.8.1: *RocTopple* Slope Face Pressure of 11 tonnes/m^2

Case 2:

A similar analysis for pressure on the upper slope face is illustrated below.

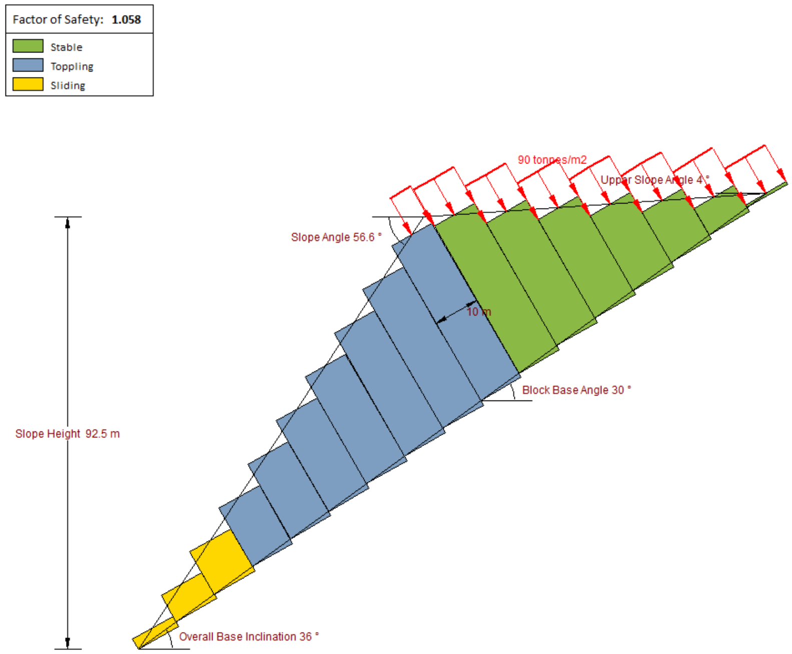
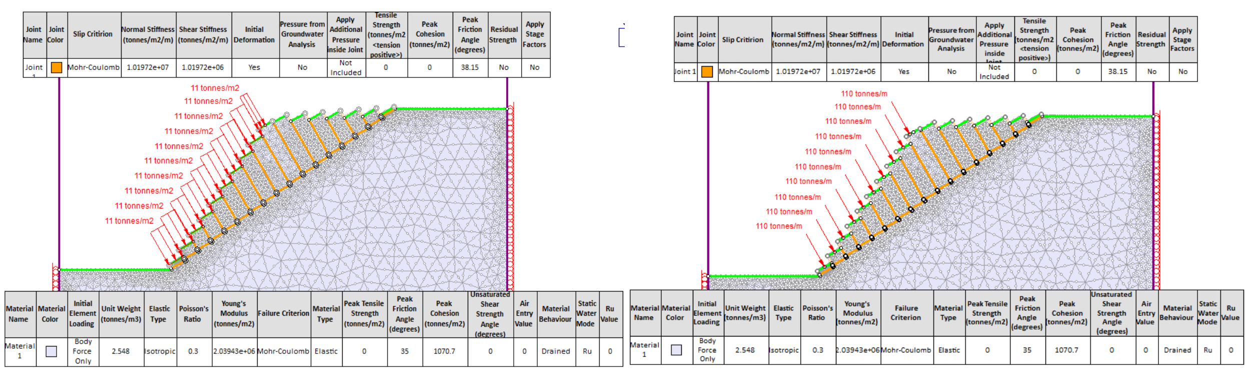


Figure 1.8.2: *RocTopple* Upper Slope Face Pressure of 90 tonnes/m²

The example was verified in two ways. The first was by applying equivalent line loads in *RocTopple*, and the second was to model the slope in *RS2* using distributed loads and by equivalent line loads.

1.8.3. Building a Compatible *RS2* Model

Case 1:



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

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

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

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

Figure 1.8.3: *RS2* Geometry and Properties for Examples 8a and 8b

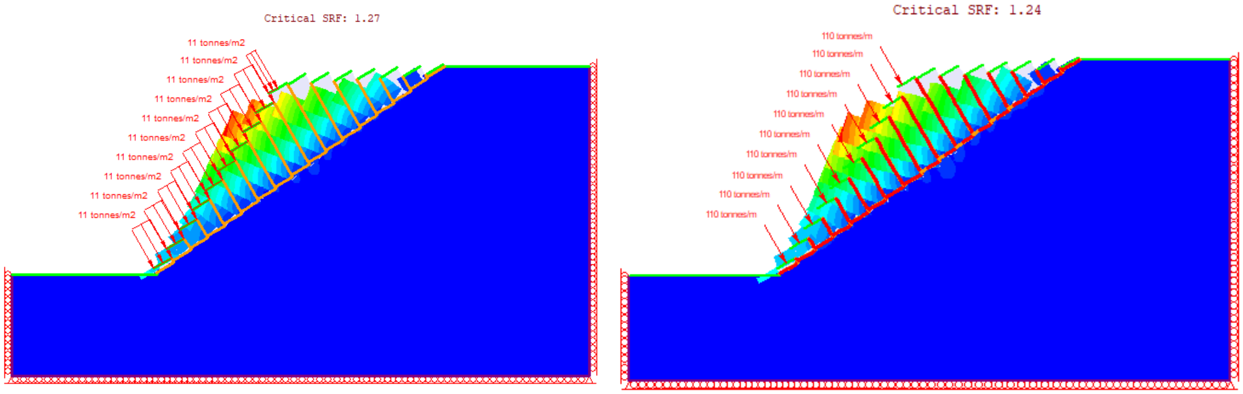


Figure 1.8.4: *RS2* Displacement Contours for Examples 8a and 8b

Case 2:

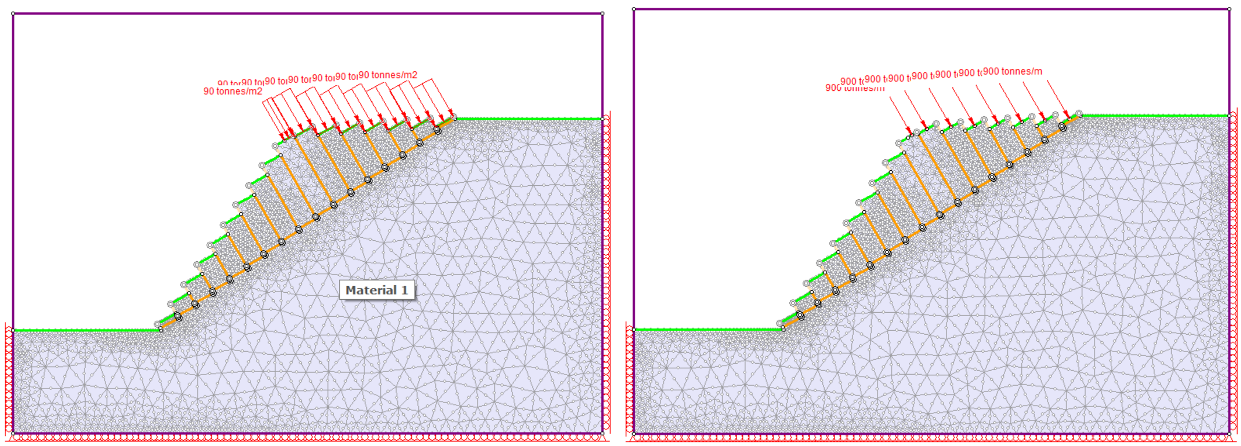


Figure 1.8.5: *RS2* Geometry for Examples 8c and 8d

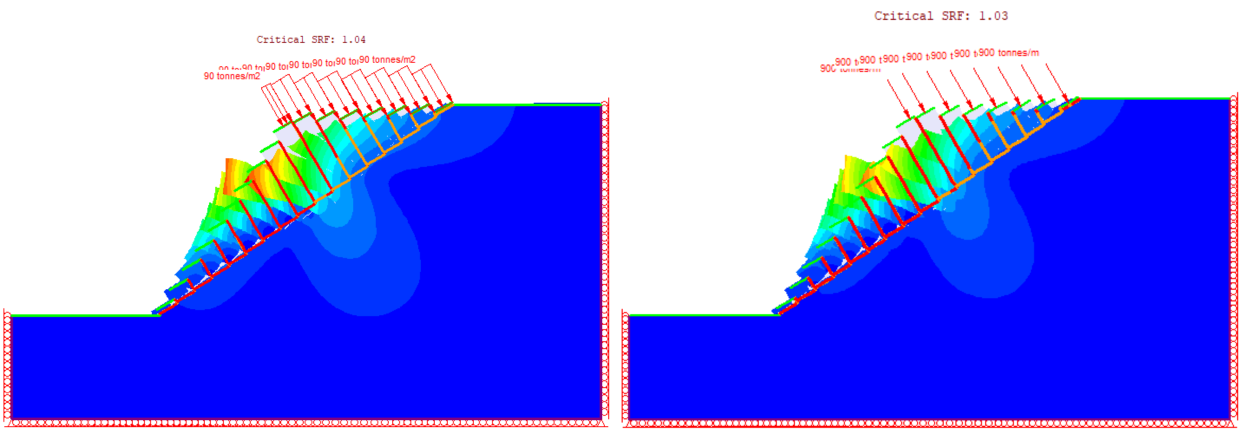


Figure 1.8.6: *RS2* Displacement Contours for Examples 8c and 8d

1.8.4. Results

Table 1.8.2: Factors of Safety for Model with Slope Face Pressure

Example	Note	*RocTopple*	*RS2*
8A	Distributed Load (11 tonnes/m^2)	1.32	1.27
8B	Equivalent Line Loads	1.32	1.24

Table 1.8.3: Factors of Safety for Model with Upper Slope Face Pressure

Example	Notes	*RocTopple*	*RS2*
8C	Distributed Load (90 tonnes/m^2)	1.06	1.04
8D	Equivalent Line Loads	1.07	1.03

1.9. *RocTopple* Verification Problem #9

[*RocTopple Build 2.001*]

1.9.1. Problem Description

This verification problem examines the Mohr-Coulomb Joint Shear Strength model.

Geometry and Properties

Table 1.9.1: Properties

Example	Material	Joints	
		ϕ (°)	Cohesion (tonnes/m^2)
A	Unit Weight = 2.5 t/m^3	38.15	0
B		30	10
C		25	25
D		10	40
E		0	50

1.9.2. *RocTopple* Analysis

Results for a series of analyses using Mohr-Coulomb shear strength are shown below. The analyses represent a variety of combinations of friction angle and cohesion.

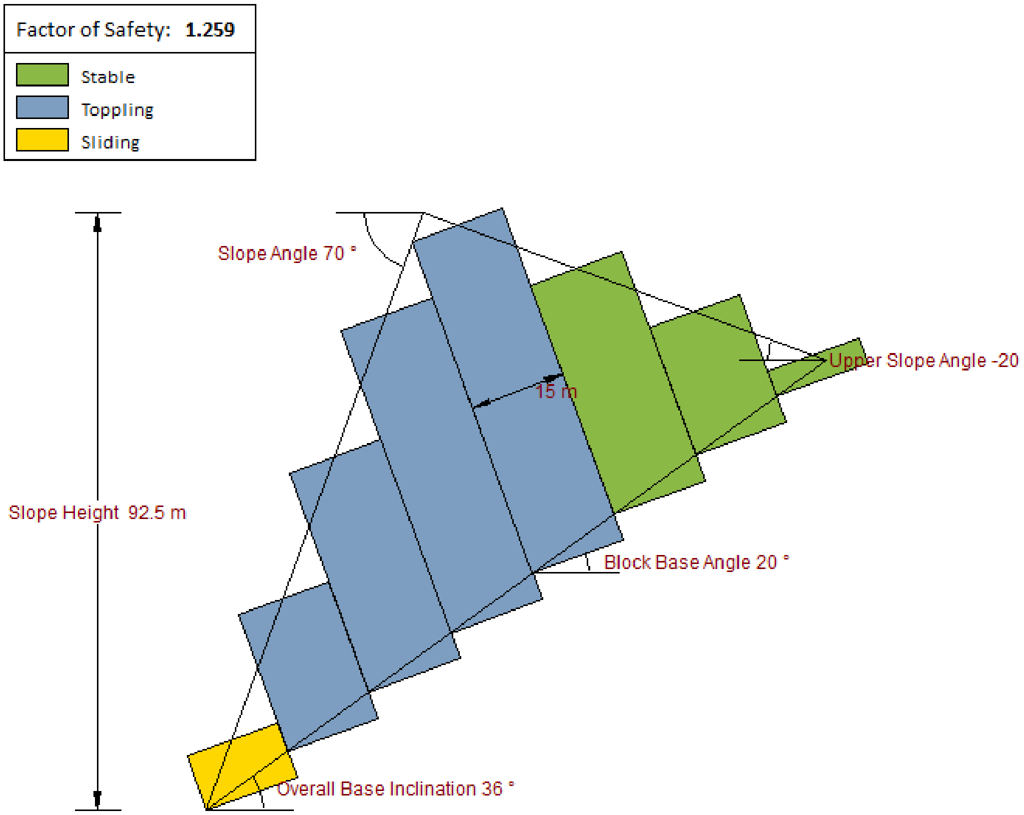


Figure 1.9.1: *RocTopple* Failure Mode of Blocks for Model A

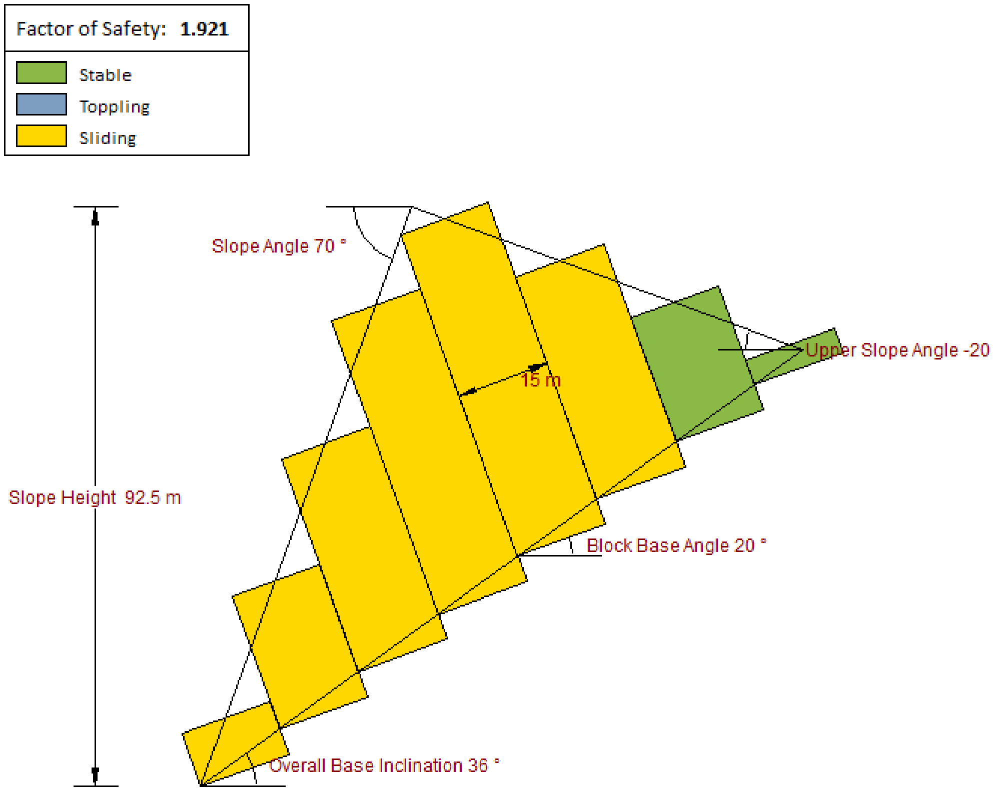
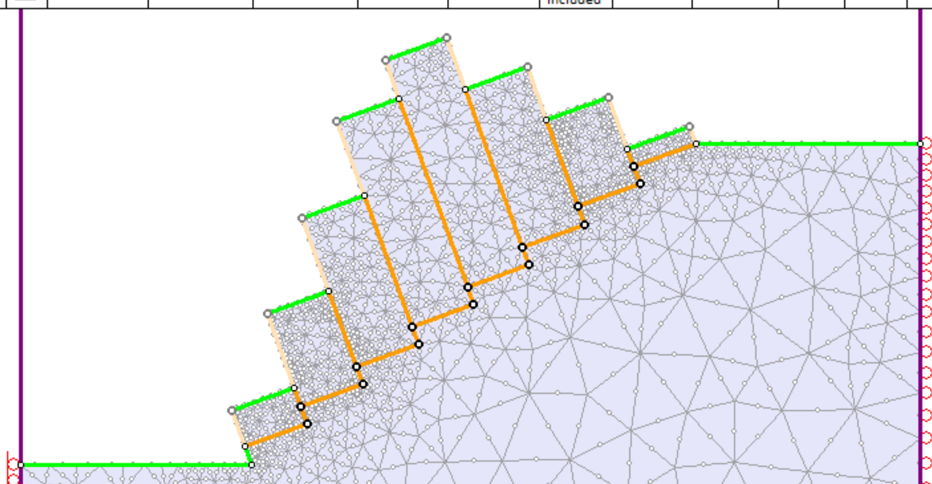


Figure 1.9.2: *RocTopple* Failure Mode of Blocks of Slopes B, C, D and E (Screen Capture for Model B)

1.9.3. Building a Compatible *RS2* Model

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



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

Figure 1.9.3: *RS2* Geometry and Properties for Example 9a

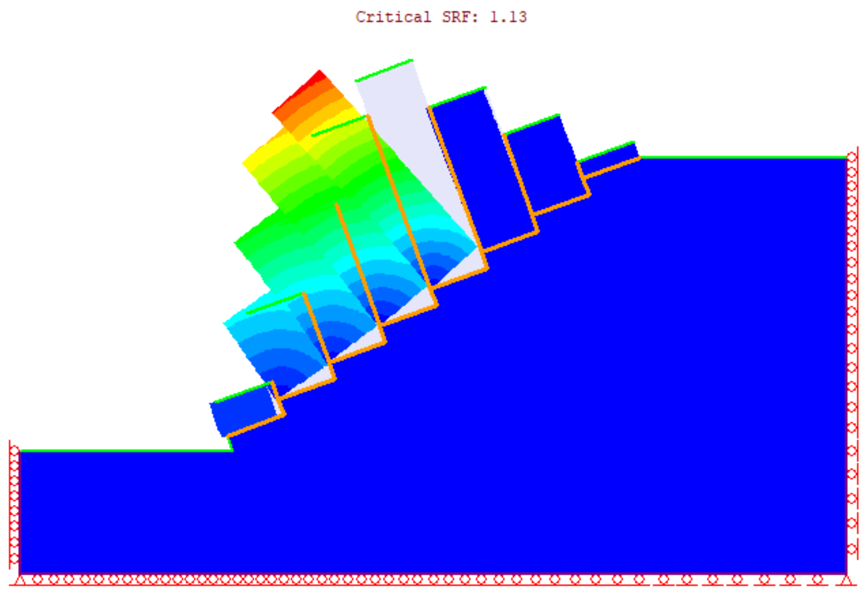


Figure 1.9.4: *RS2* Deformation and Yielded Joints for Example 9a (Same Failure Mode as Examples 9b and 9c)

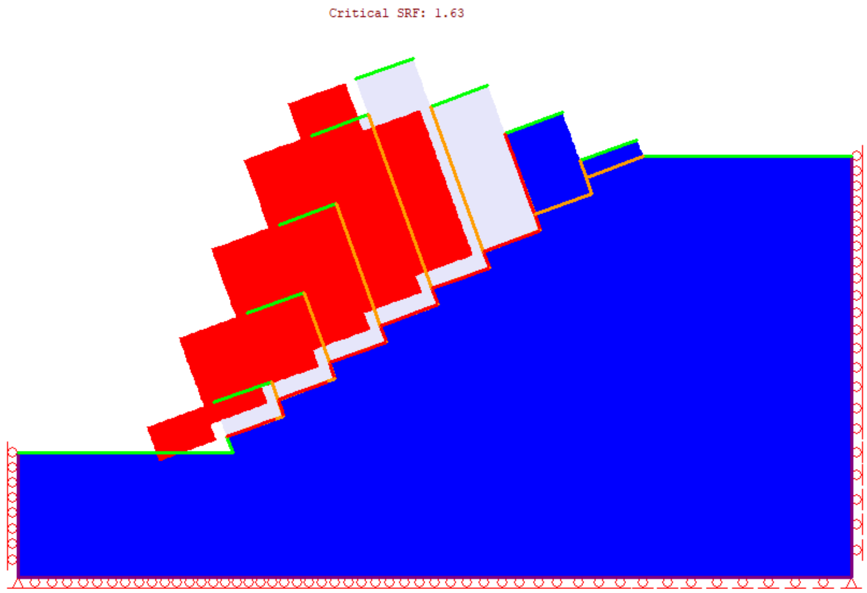


Figure 1.9.5: *RS2* Deformation and Yielded Joints for Example 9e (Same Failure Mode as Example 9d)

1.9.4. Results

Table 1.9.2: Factor of Safety

	ϕ (°)	Cohesion (tonnes/m^2)	*RocTopple*	*RS2*
A	38.15	0	1.26	1.13
B	30	10	1.92	1.97
C	25	25	2.12	2.15
D	10	40	1.82	1.81
E	0	50	1.67	1.63

1.10. *RocTopple* Verification Problem #10

[*RocTopple Build 2.001*]

1.10.1. Problem Description

This verification problem examines the application of seismic loads.

A shallow slope with all sliding critical blocks at the point of failure, is now exhibiting toppling failure under a large seismic load.

Geometry and Properties

Table 1.10.1: Properties

Material	Joints
Unit Weight = 2.5 t/m^3	ϕ = 30°

1.10.2. *RocTopple* Analysis

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

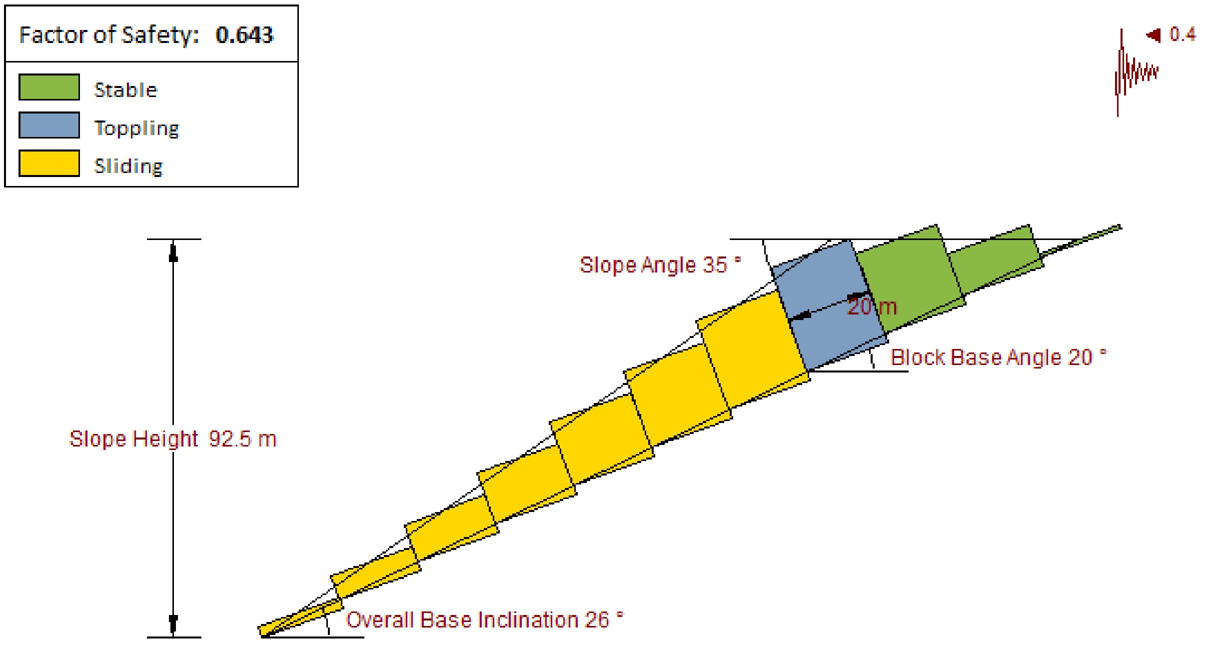


Figure 1.10.1: *RocTopple* Geometry with Seismic Loading

1.10.3. Building a Compatible *RS2* Model

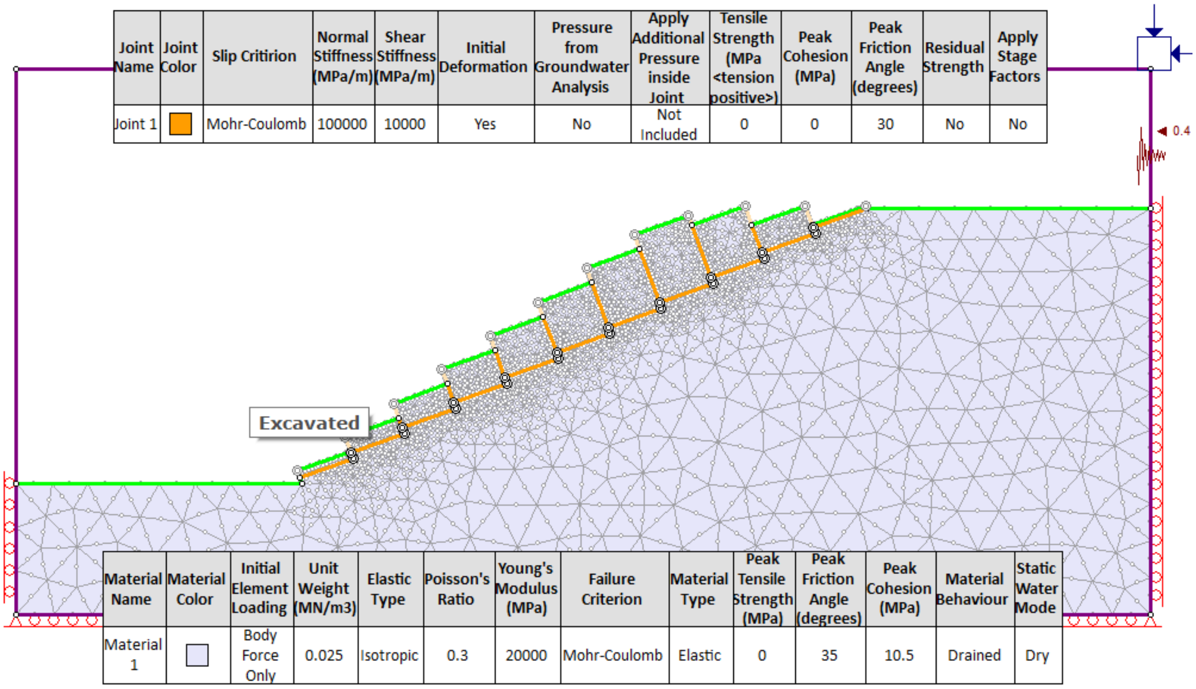


Figure 1.10.2: *RS2* Geometry and Properties

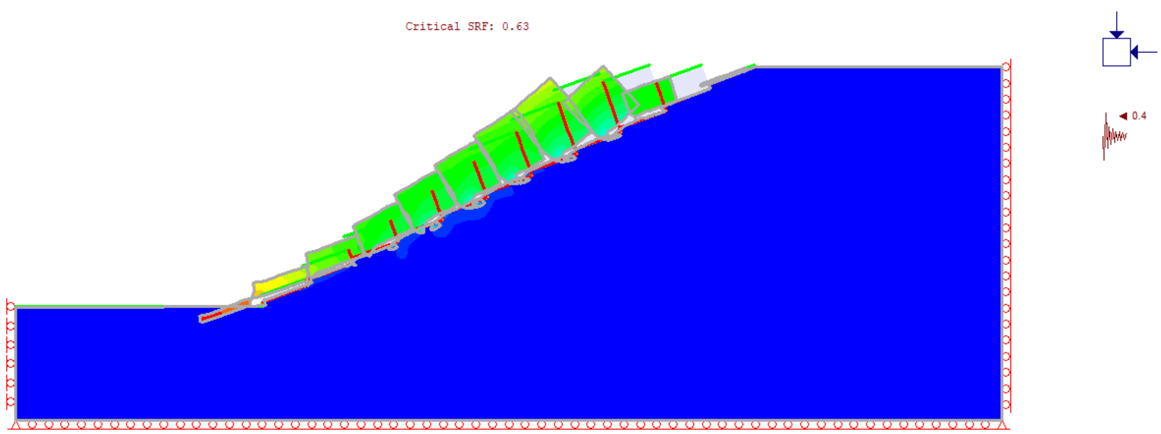


Figure 1.10.3: *RS2* Deformation and Yielded Joints

1.10.4. Results

Table 1.10.2: Factors of Safety

RocTopple	*RS2*
0.64	0.63

1.11. *RocTopple* Verification Problem #11

[*RocTopple Build 2.001*]

1.11.1. Problem Description

This verification problem examines the application of water pressure.

A slope with 100% fill joints in *RocTopple* is modelled in *RS2* using a phreatic surface that fully spans across the joints. The pressure is calculated using the Hu Auto option, which extrapolates the phreatic surface at a 45° angle. This example is modified from the slope in Verification Example #1.

Geometry and Properties

Table 1.11.1: Properties

Material	Joints
Unit Weight = 2.5 t/m^3	ϕ = 38.15°

1.11.2.*RocTopple* Analysis

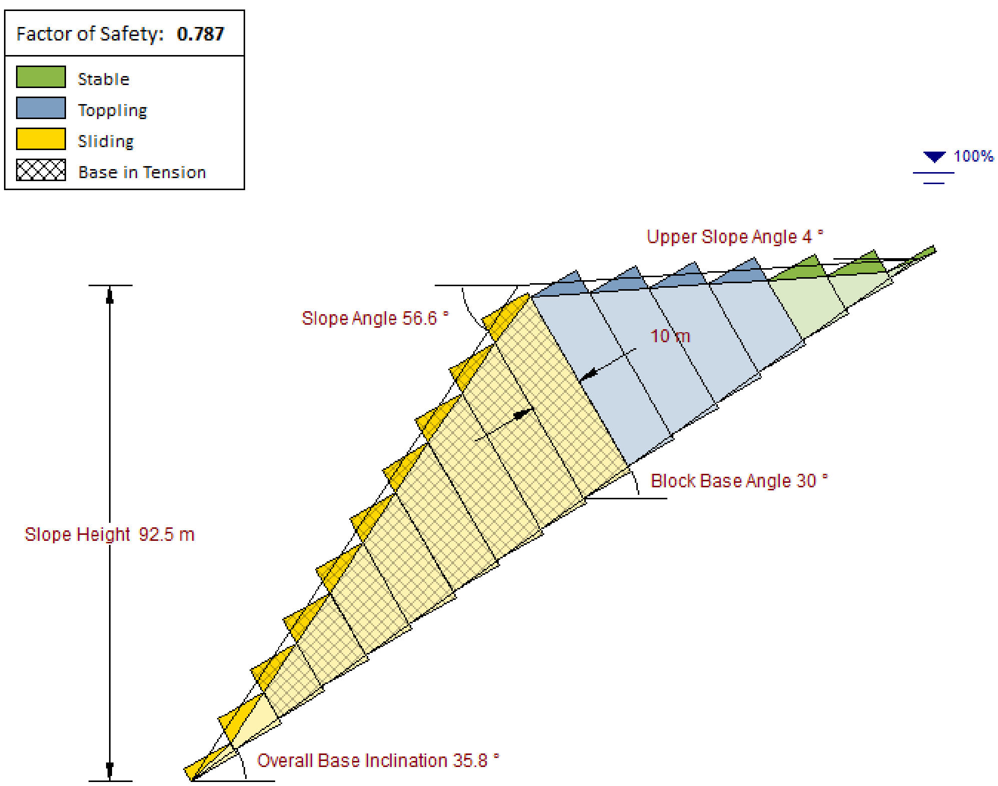
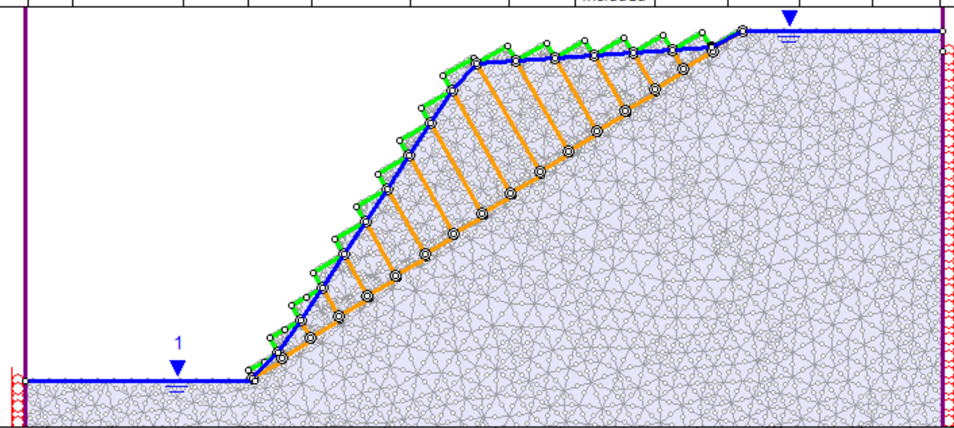


Figure 1.11.1: *RocTopple* with Water Pressure

The model shows sliding blocks starting from the crest block to the toe.

1.11.3. Building a Compatible *RS2* Model

Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Pressure to Linear Side Only	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joints		Mohr-Coulomb	100000	10000	Yes	Yes	No	Not Included	0	0	38.15	No	No



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

Figure 1.11.2: *RS2* Geometry and Properties

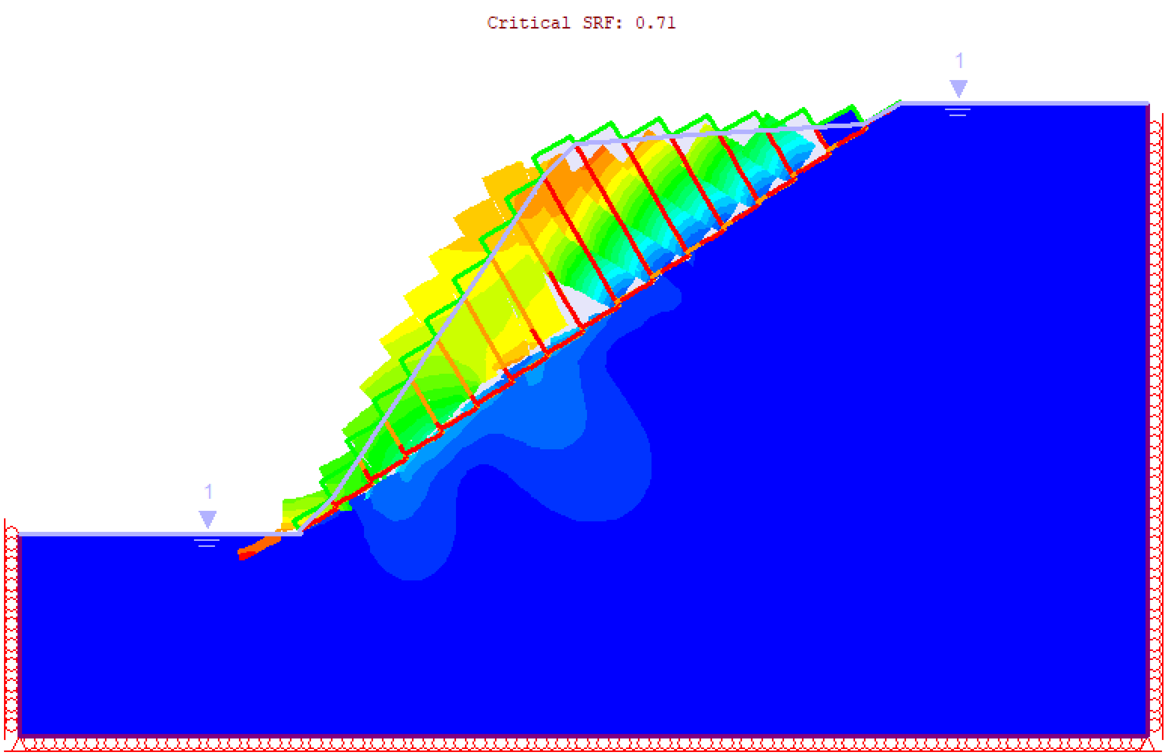


Figure 1.11.3: *RS2* Deformation and Yielded Joints

1.11.4. Results

Table 1.11.2: Factors of Safety

RocTopple	*RS2*
0.79	0.71

Note that while *RocTopple* reports tension at base of sliding blocks, *RS2* does not. Also note that while *RocTopple* assumes all joints are fully mobilized in shear, *RS2* results reflect that not all joints (i.e. toppling joints) are fully yielded for the sliding blocks (Figure 1.11.3). When shear is fully mobilized in the toppling joints, as is the case in *RocTopple*, it creates an uplifting force on the blocks and in the calculation results in base tension.

1.12. *RocTopple* Verification Problem #12

[*RocTopple Build 2.001*]

1.12.1. Problem Description

This verification problem examines the case of upslope toppling blocks.

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

Geometry and Properties

Table 1.12.1: Properties

Material	Joints
Unit Weight = 2.5 t/m^3	ϕ = 40°

1.12.2. *RocTopple* Analysis

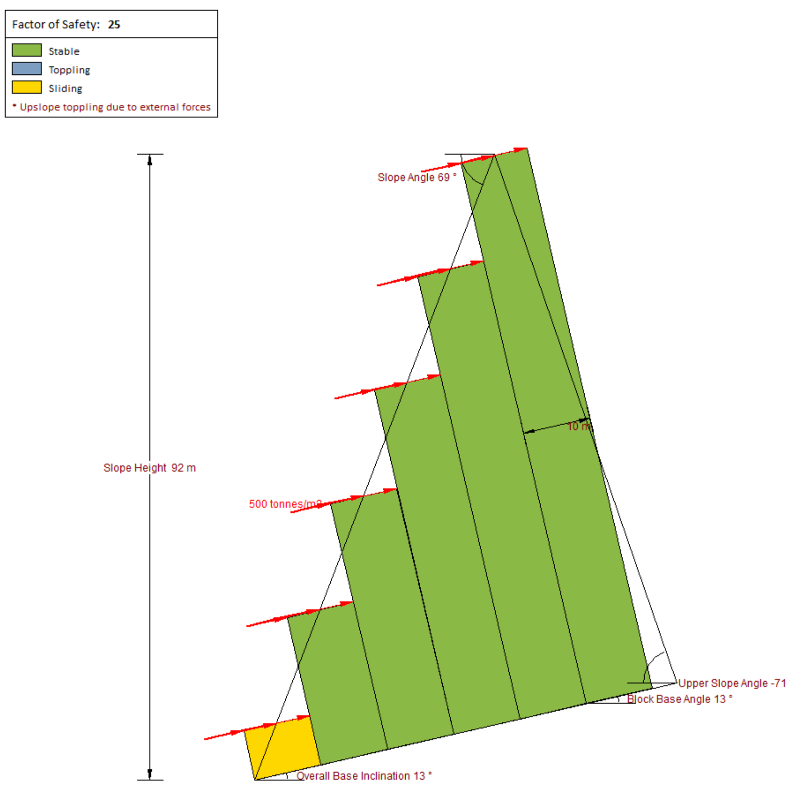


Figure 1.12.1: *RocTopple* Geometry with a Pressure of 500t/m^2 Supporting the Slope

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

1.12.3. Building a Compatible *RS2* Model

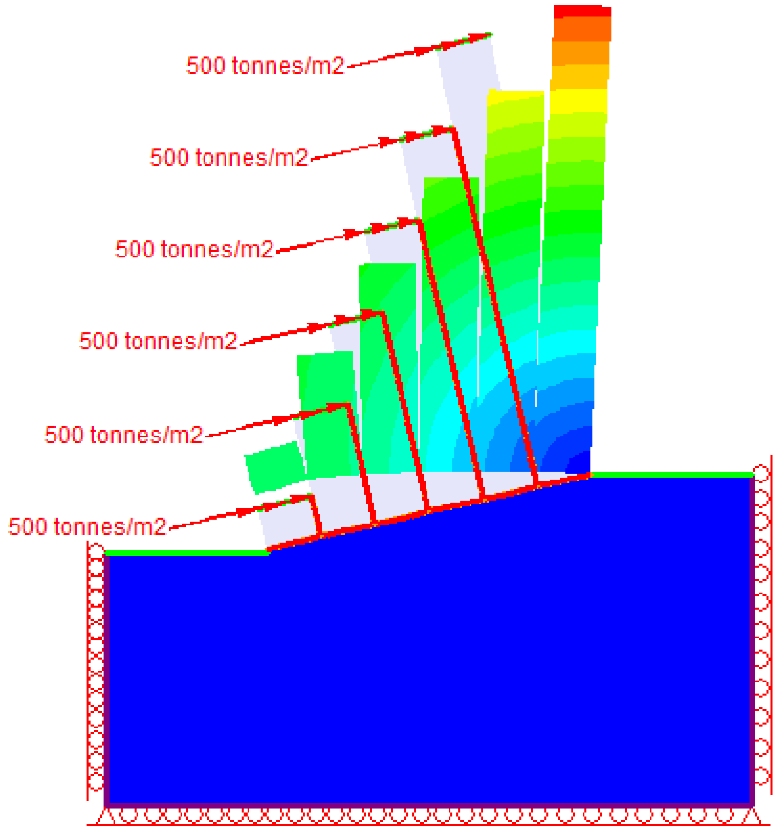


Figure 1.12.2: *RS2* Stress Analysis

RS2 stress analysis confirms that the blocks are rotating upslope.

2. *RocTopple* Block-Flexural Toppling Verification

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

2.1. *RocTopple* Verification Problem #1

[*RocTopple Build 2.001*]

2.1.1. Problem Description

This verification problem examines a linear plane geometry.

Geometry and Material Properties

With the given geometry below:

Table 2.1.1: Geometry

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

Examples 1a, 1b, 1c and 1d were investigated and are listed below.

Table 2.1.2: Material Properties

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

2.1.2. *RocTopple* Analysis

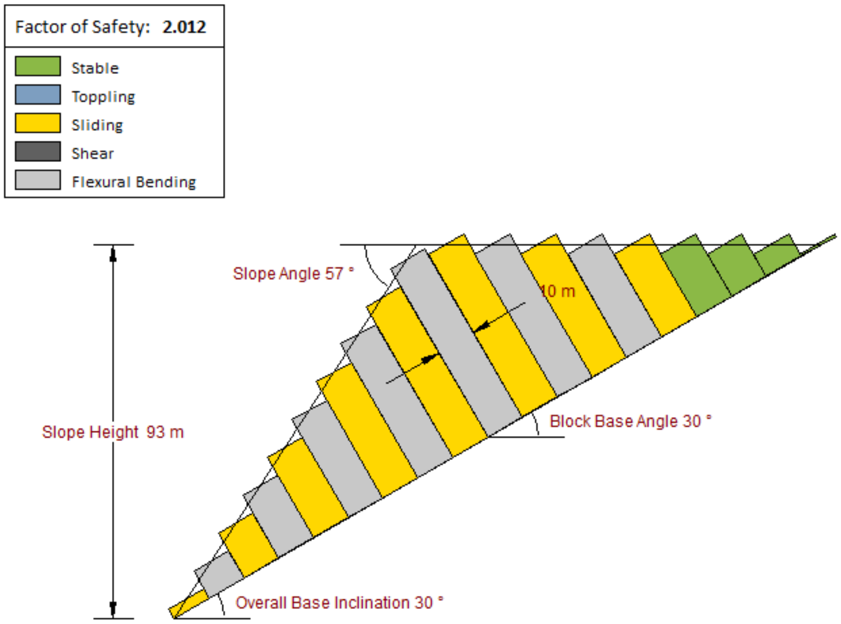


Figure 2.1.1: *RocTopple* Model of Example 1a

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

2.1.3. Building a Compatible *RS2* Model

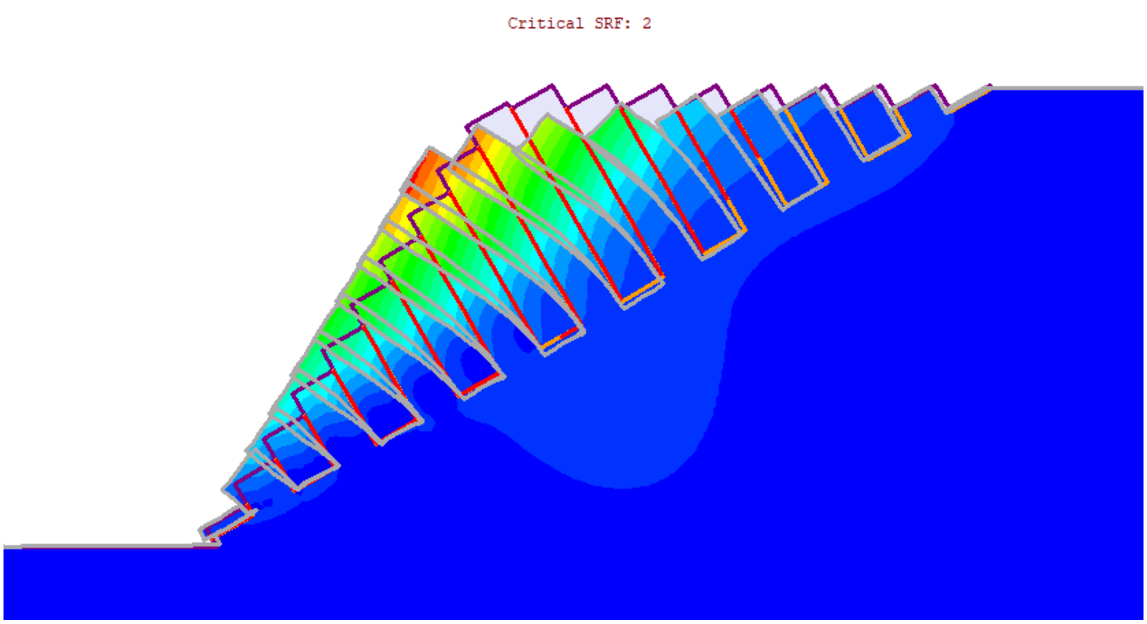


Figure 2.1.2: *RS2* Total Displacement Contours of Example 1a at Critical SRF

2.1.4. Results

Table 2.1.3: Factors of Safety

	SRF (*RS2*)	FS (*RocTopple*) Final
Example 1a	2.0	2.01
Example 1b	1.25	1.27
Example 1c	2.85	2.78
Example 1d	3.05	3.04

2.2. *RocTopple* Verification Problem #2

[*RocTopple Build 2.001*]

2.2.1. Problem Description

This verification problem examines another linear plane geometry.

Geometry and Material Properties

With the given geometry below:

Table 2.2.1: Geometry

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

4 examples (with varying material properties) were investigated and the results are listed below.

Table 2.2.2: Material Properties

	Angle of Friction of Joints (°)	Cohesion of Joint (kPa)	Tensile Strength of Joints (kPa)	Angle of Friction of Rock (°)	Cohesion of Rock (kPa)	Tensile Strength of Rock (kPa)	Density (kN)
Example 2a	38	100	100	40	1000	100	27
Example 2b	25	50	50	54	1200	85	27
Example 2c	45	250	150	60	4000	100	33
Example 2d	30	60	40	43	800	52	23
Example 2d2	Base: 30 Bed: 50	Base: 60 Bed: 100	Base: 40 Bed: 100	43	800	52	23

2.2.2. *RocTopple* Analysis

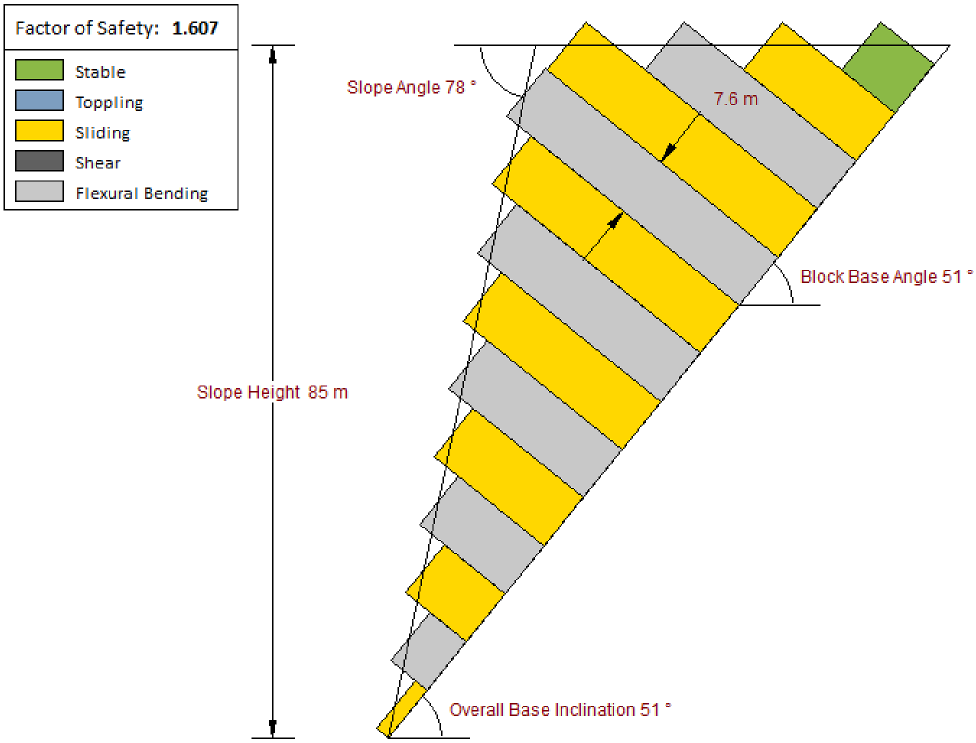


Figure 2.2.1: *RocTopple* Model of Example 2a

2.2.3. Building a Compatible *RS2* Model

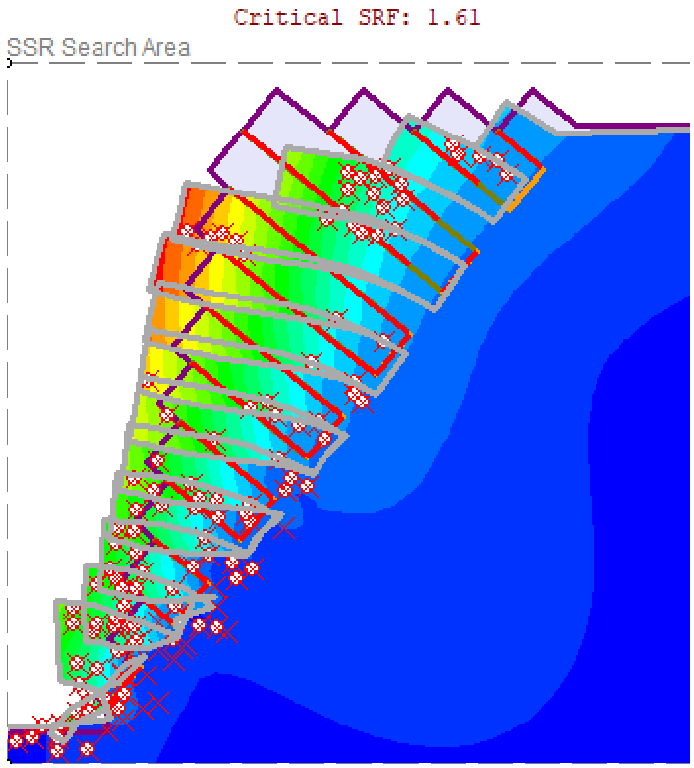


Figure 2.2.2: *RS2* Results of Example 2a at Critical SRF

2.2.4. Results

Table 2.2.3: Factors of Safety

	SRF (*RS2*)	FS (*RocTopple*) Final
Example 2a	1.61	1.61
Example 2b	1.01	0.96
Example 2c	2.34	2.27
Example 2d	1.22	1.16
Example 2d2	1.89	1.76

2.3. *RocTopple* Verification Problem #3

[*RocTopple Build 2.001*]

2.3.1. Problem Description

This verification problem examines the case where shear failure occurs.

Geometry and Material Properties

With the given geometry below:

Table 2.3.1: Geometry

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

3 examples with varying material properties were investigated and the results are shown below.

Table 2.3.2: Material Properties

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

2.3.2. *RocTopple* Analysis

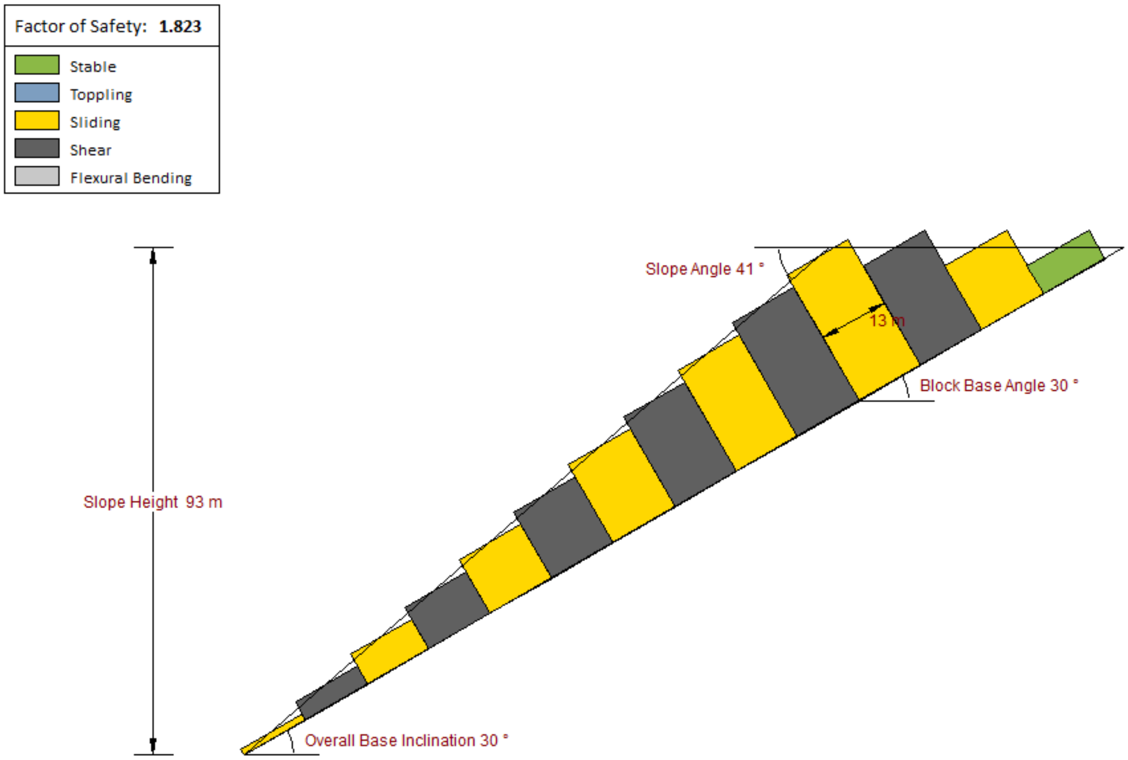


Figure 2.3.1: *RocTopple* Model of Example 3a

2.3.3. Building a Compatible *RS2* Model

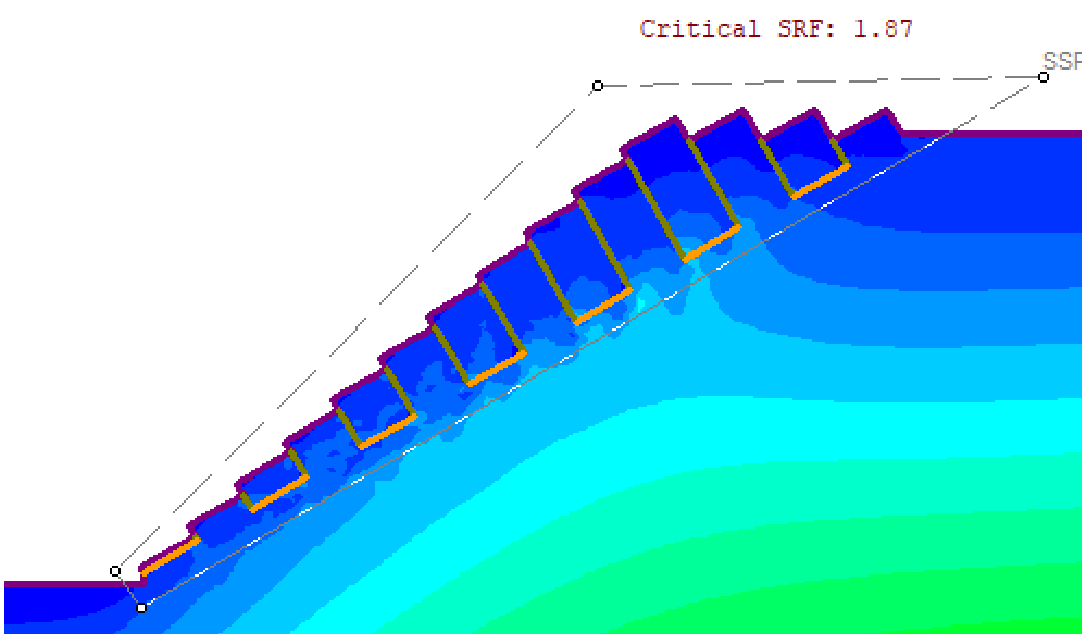


Figure 2.3.2: *RS2* Results of Example 3a at Critical SRF

2.3.4. Results

Table 2.3.3: Factors of Safety

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

2.4. *RocTopple* Verification Problem #4

[*RocTopple Build 2.001*]

2.4.1. Problem Description

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

Geometry and Material Properties

The geometry identical to Verification Example #1.

3 examples with varying Barton-Bandis (BB) Shear Strength models were investigated.

Table 2.4.1: Material Properties

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

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

Table 2.4.2: Mohr-Coulomb Shear Strength Properties

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

2.4.2. *RocTopple* Analysis

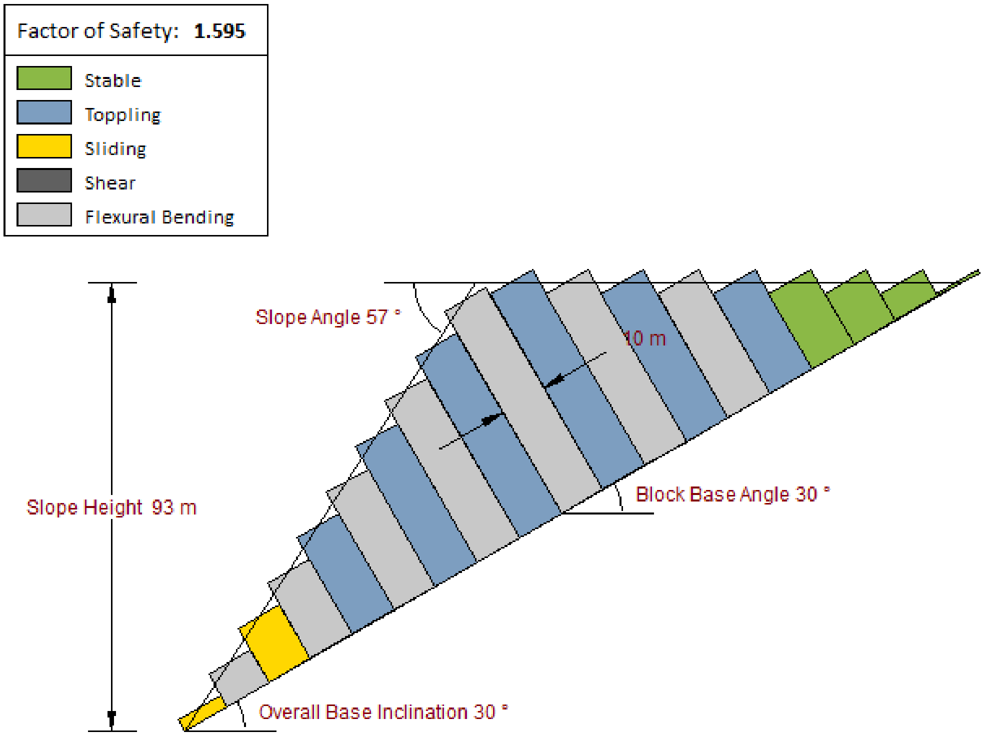


Figure 2.4.1: *RocTopple* Model of Example 4a Barton-Bandis

2.4.3. Building a Compatible *RS2* Model

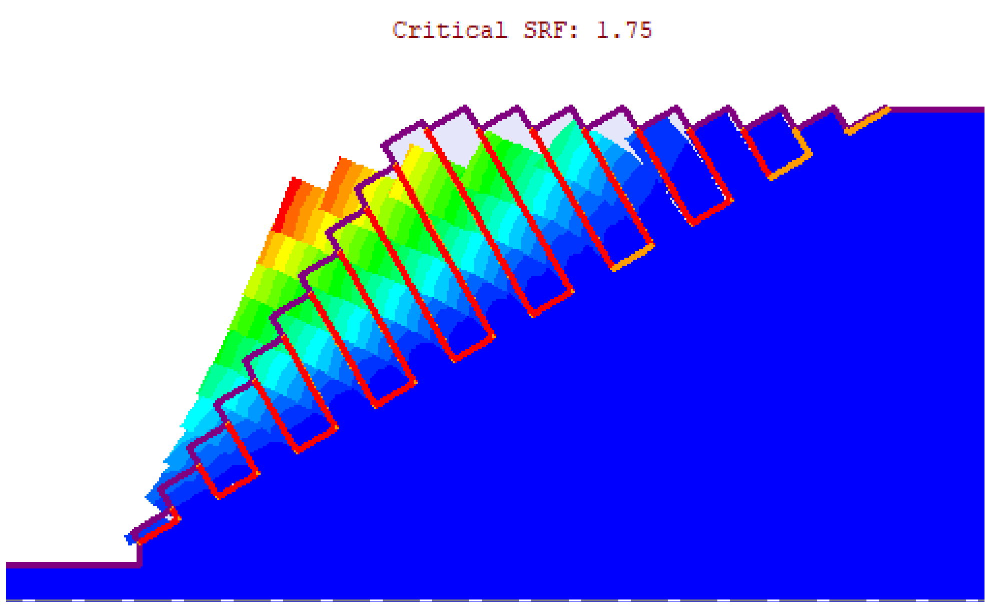


Figure 2.4.2: *RS2* Results of Example 4a

2.4.4. Results

Table 2.4.3: Factors of Safety

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

2.5. *RocTopple* Verification Problem #5

[*RocTopple Build 2.001*]

2.5.1. Problem Description

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

Geometry and Material Properties

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

2.5.2. *RocTopple* Analysis

Bolts Model

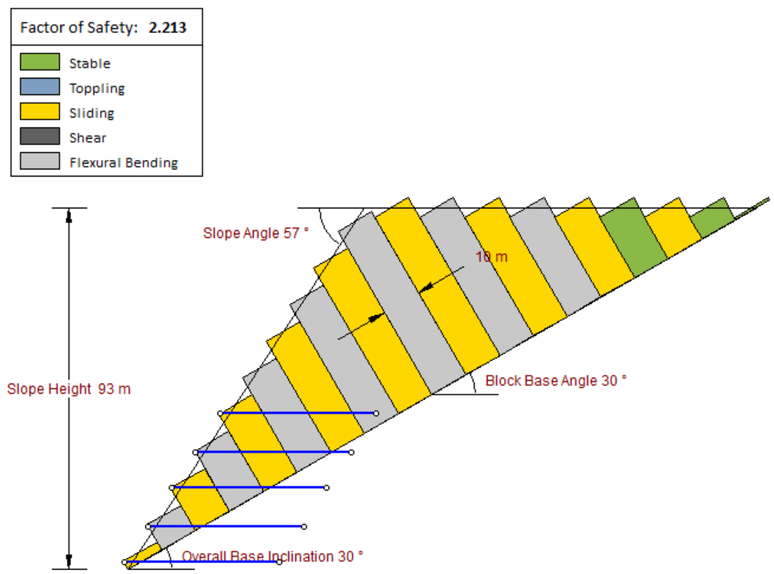


Figure 2.5.1: *RocTopple* Model of Example 5a, Bolt Capacity = 600 kN

Line Loads Model

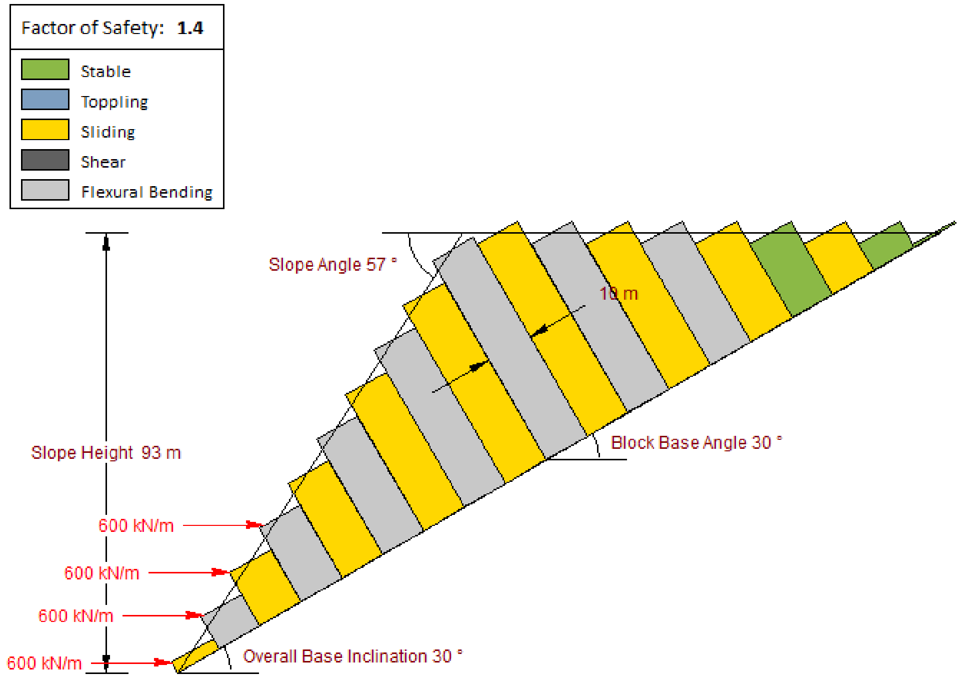


Figure 2.5.2: *RocTopple* Model of Example 5b, Line Loads = 600 kN

2.5.3. Building a Compatible *RS2* Model

Bolts Model

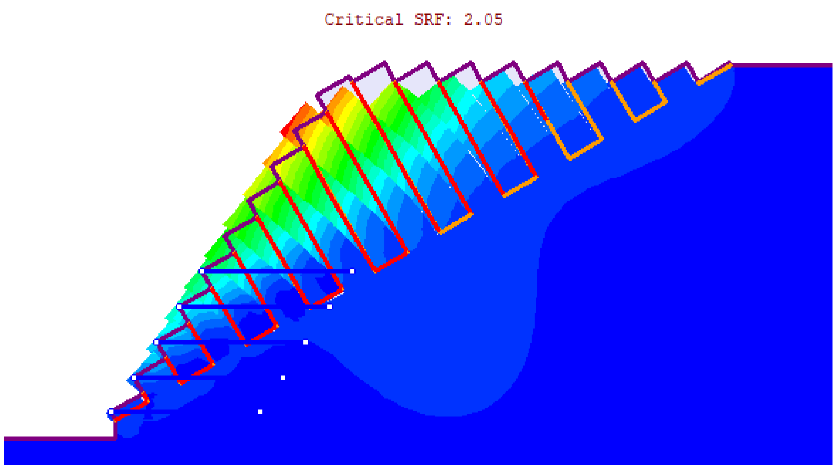


Figure 2.5.3: *RS2* Results of Example 5a, Bolt Capacity = 600 kN

Line Loads Model

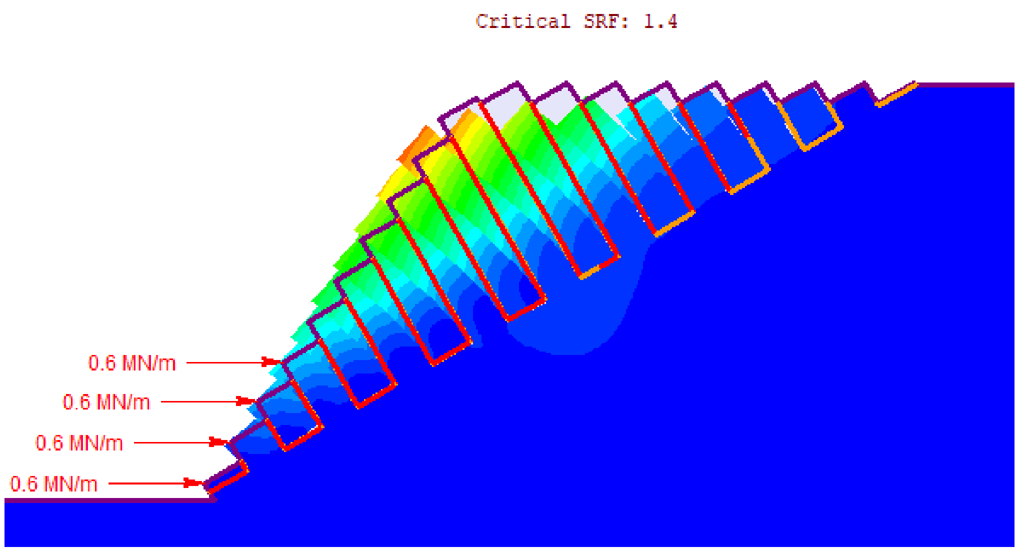


Figure 2.5.4: *RS2* Results of Example 5b, Line Loads = 600 kN

2.5.4. Results

Results are shown below.

Table 2.5.1: Factors of Safety

	FS (*RocTopple*) Final	SRF (*RS2*)
Example 5a	2.21	2.05
Example 5b	1.40	1.40

2.6. *RocTopple* Verification Problem #6

[*RocTopple Build 2.001*]

2.6.1. Problem Description

This verification problem examines the application of distributed loads.

Geometry and Material Properties

The geometry and strength properties identical to Example 3b.

Forces

Example 6 is analyzed with distributed load applied.

Table 2.6.1: Distributed Load

	Distributed Load
Example 6	300 kN

2.6.2. *RocTopple* Analysis

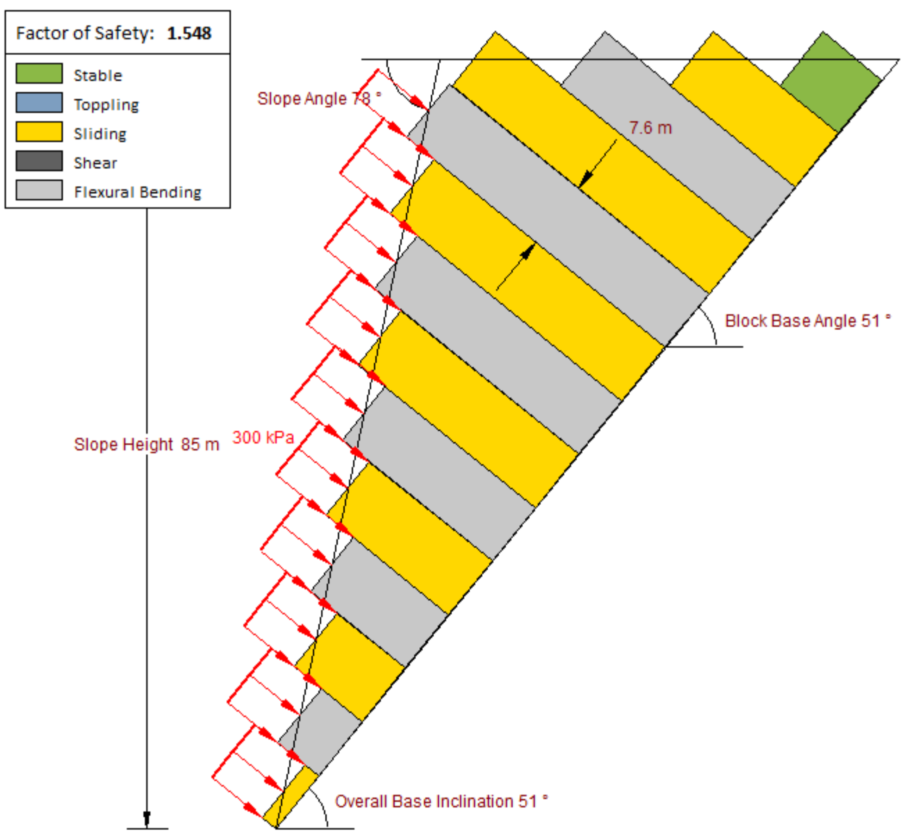


Figure 2.6.1: *RocTopple* Model of Example 6

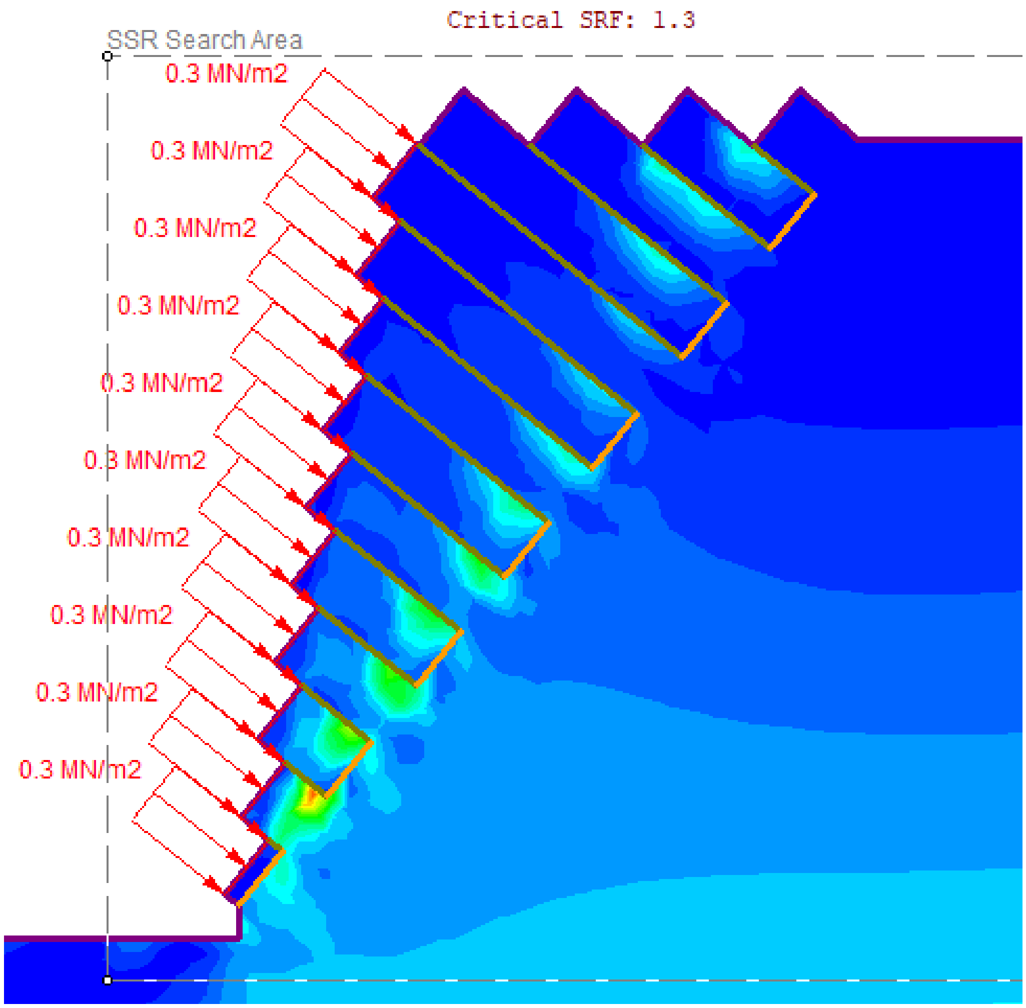


Figure 2.6.2: *RS2* Results of Example 6

2.6.3. Results

Table 2.6.2: Factors of Safety

	FS (*RocTopple*) Final	SRF (*RS2*)
Example 6	1.55	1.30

2.7. *RocTopple* Verification Problem #7

[*RocTopple Build 2.001*]

2.7.1. Problem Description

This verification problem examines the application of seismic loads.

Geometry and Material Properties

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

Forces

Table 2.7.1: Seismic Coefficient

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

2.7.2. *RocTopple* Analysis

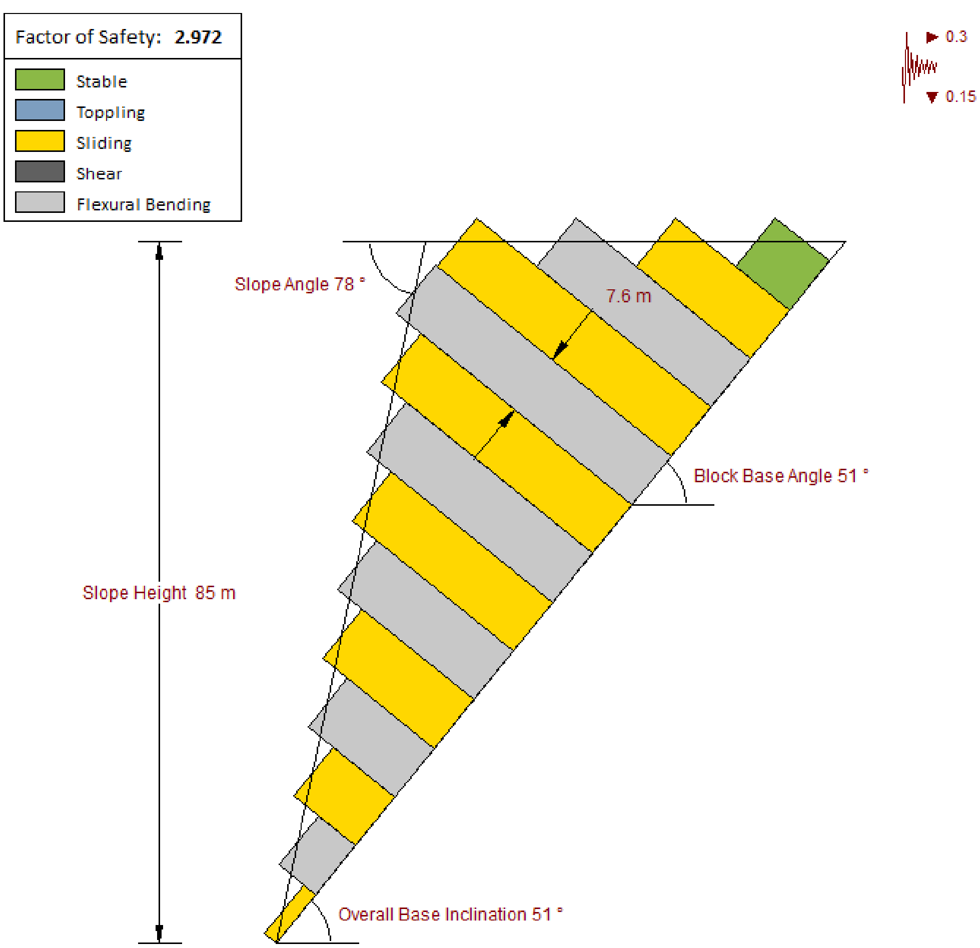


Figure 2.7.1: *RocTopple* Model of Example 7

2.7.3. Building a Compatible *RS2* Model

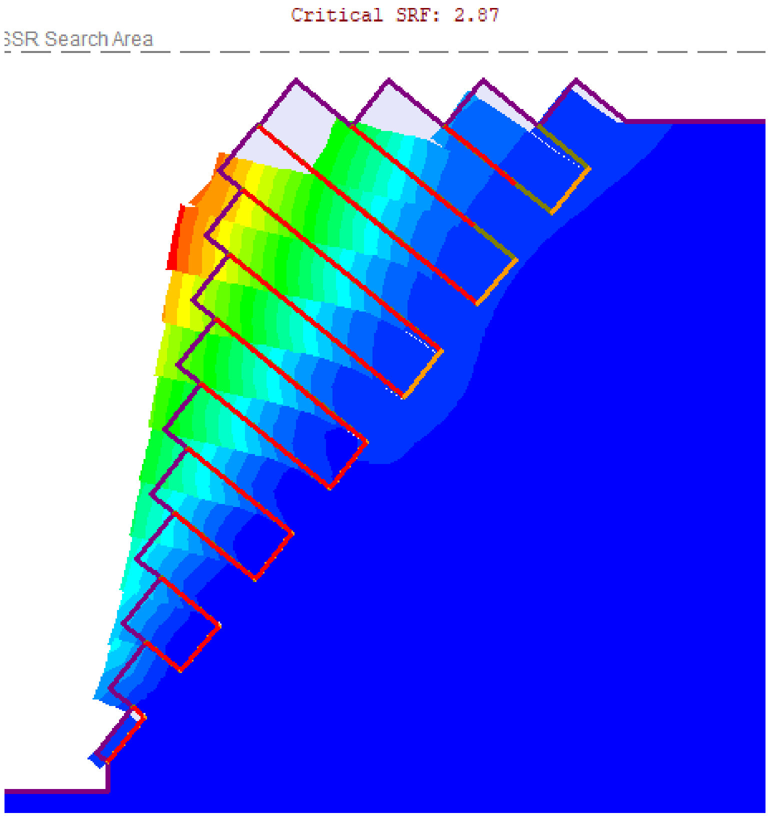


Figure 2.7.2: *RS2* Result of Example 7

2.7.4. Results

Table 2.7.2: Factors of Safety

	FS (*RocTopple*) Final	SRF (*RS2*)
Example 7	2.97	2.87