RS2

2D finite element program for stress analysis and support design
around excavations in soil and rock

Slope Stability Verification Manual

Part III

Table of Contents

Introduction

This problem is taken from the slope stability problem in "Slope stability assessment of weathered clay by using field data and computer modelling: a case study from Budapest", a paper by Gorog, P. and Torok, Á. (2007).

Description

A three layered soil slope with given geometry is shown in Figure 1. Two cases with constant and varying Young's Modulus were studied. Mohr-Coulomb failure criteria was used in the analysis. The material properties of both cases are given in Table 1. The results of all cases are compared to those of Slide2 5.0 and Plaxis.

Geometry and Properties

Table 1 - Material Properties

	Material	Young modulus, E (kPa)	Poisson Ratio, ν	Weight, γ (kN/m^3)	Cohesion, c (kPa)	Friction angle, ϕ (^{0})	Dilatancy angle, ψ (^{0})
Case 1	Grey Clay	50,000	0.4	22	250	30	0
	Yellow Clay / Debris			19	50	15	
	Waste			14	1	5	
Case 2	Grey Clay	20, 000	0.4	22	250	30	0
	Yellow Clay / Debris	18, 000		19	50	15	
	Waste	2, 000		14	1	5	

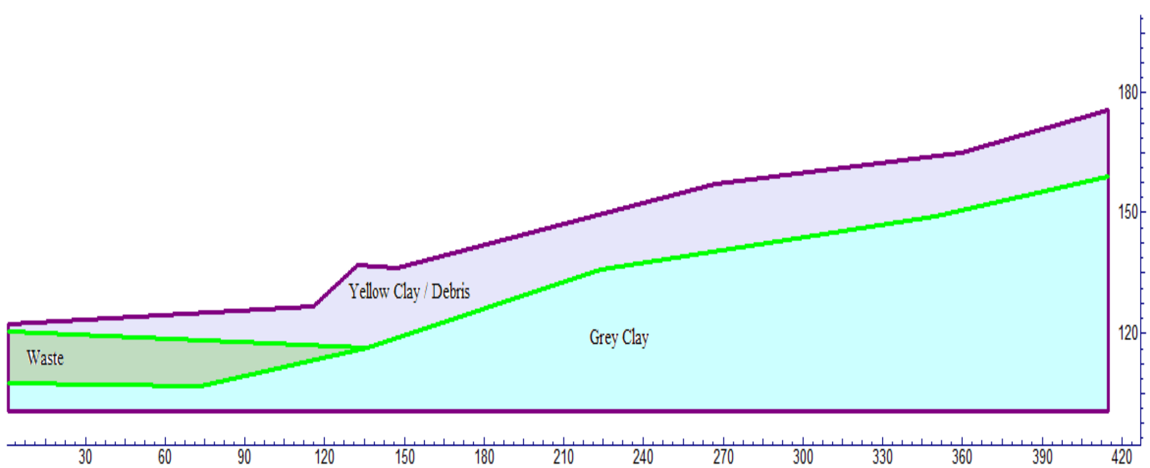


Figure 1 - Geometry

Results: Case 1

	Slide2	RS2	Plaxis
Case 1	1.567	1.57	1.6

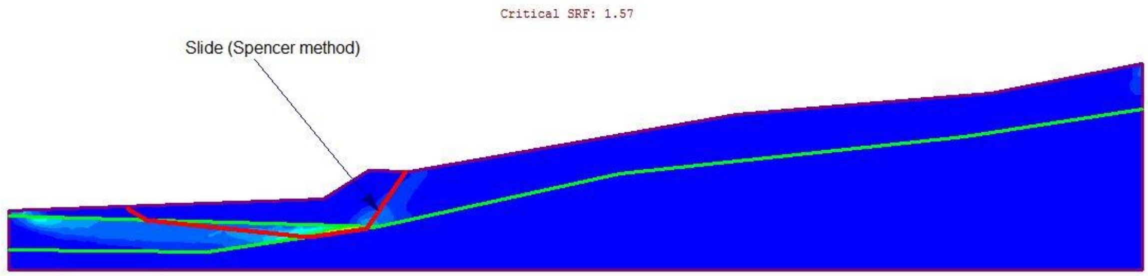


Figure 2 - Maximum Shear Strain Plot of Case 1

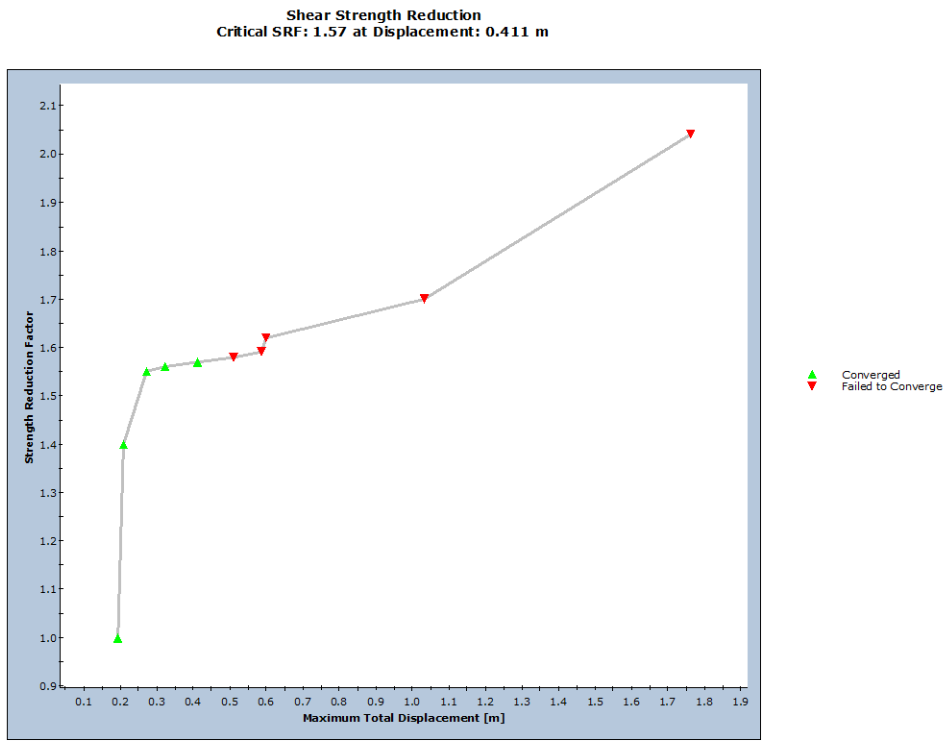


Figure 3 – SSR Convergence Graph of Case 1

Results: Case 2

	Slide2	RS2	Plaxis
Case 2	1.567	1.56	1.6

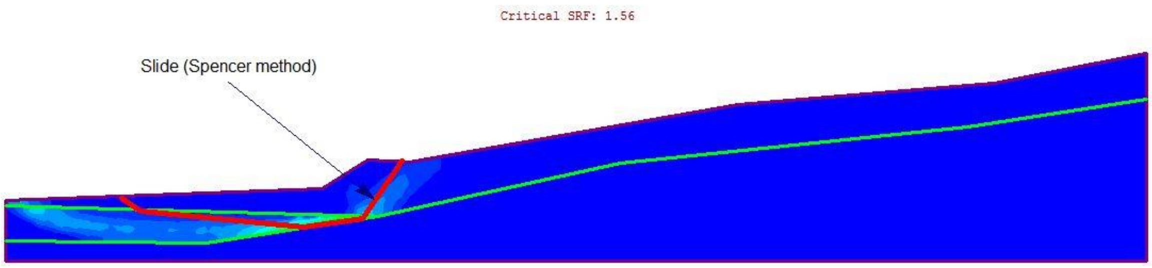


Figure 4 - Maximum Shear Strain Plot of Case 2

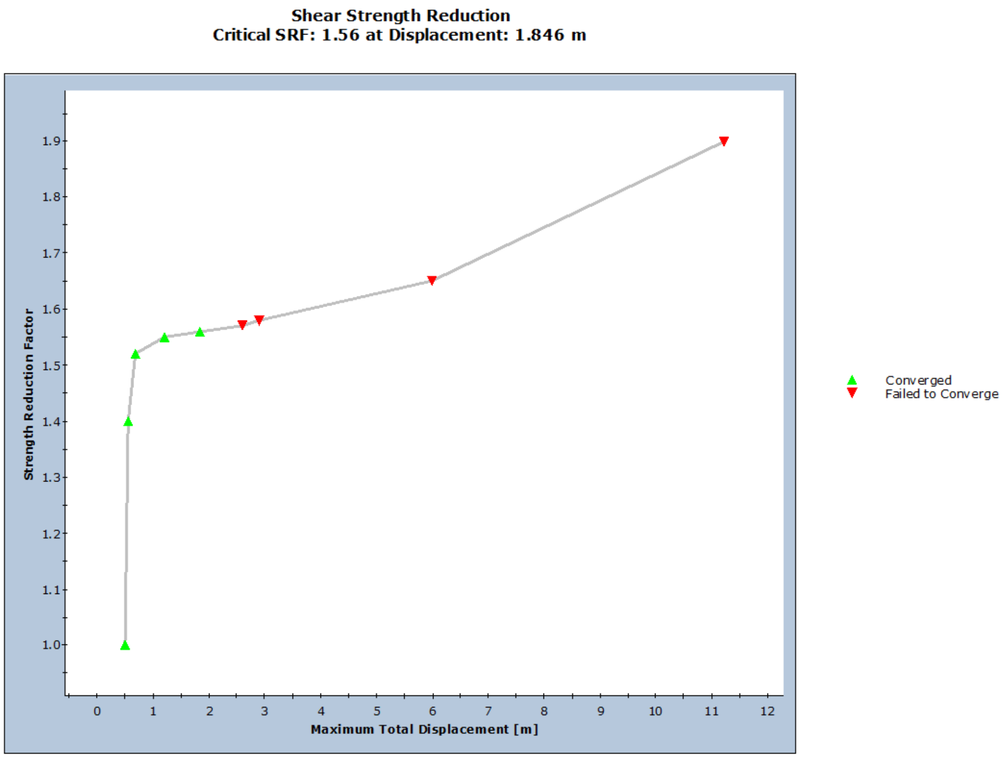


Figure 5 – SSR Convergence Graph of Case 2

Introduction

This problem is taken from the slope stability problem in “Stability charts for rock slopes based on the Hoek-Brown failure criterion”, a paper by Li, A.J., Merifield, R. S., and Lyamin, A.V. (2008).

Description

A homogeneous slope is shown in Figure 1. The overall length and height of the figure were shown to be insignificant. Three cases with varying slope angle were studied and the Generalized Hoek-Brown failure criterion was used in the analysis. The material properties of the soil are given in Table 1. The results of this study are compared to those of A.J. Li (et al.).

Geometry and Properties

Table 1 - Material Properties

Soil Name	Height, H (m)	Unit weight, γ (kN/m^3)	Poisson ratio, ν	Geological Strength Index, GSI	Intact Rock Yield Parameter, m_i
Soil 1	1	23	0.3	70	15

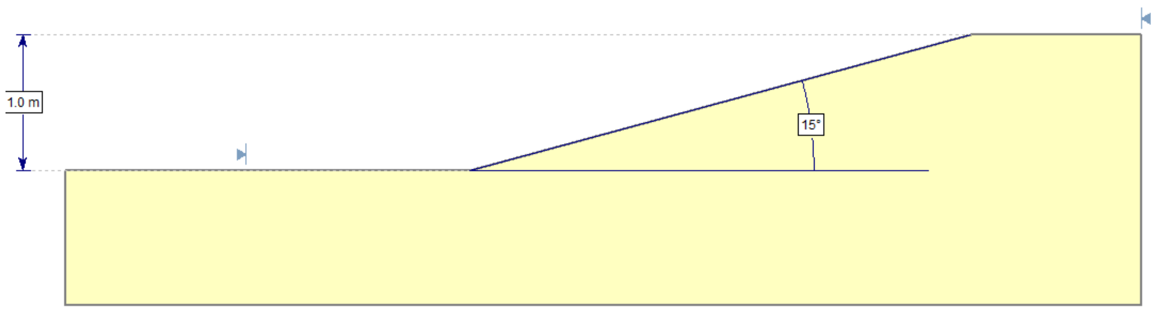


Figure 1 - Case 1, Geometry β = 15°

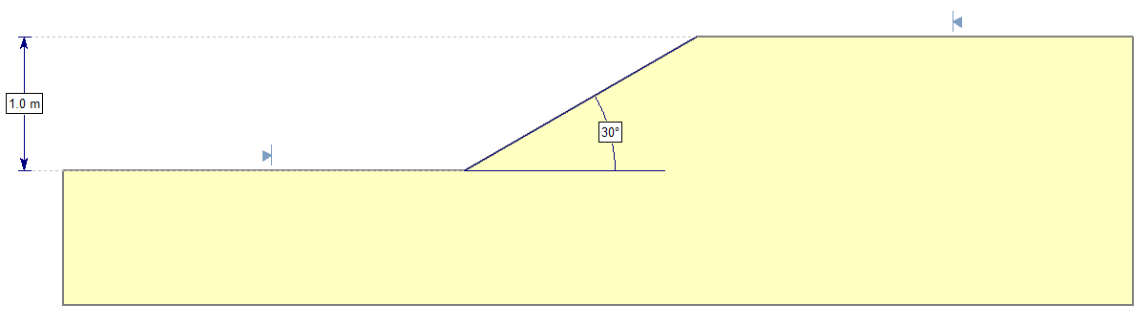


Figure 2 - Case 2, Geometry β = 30°

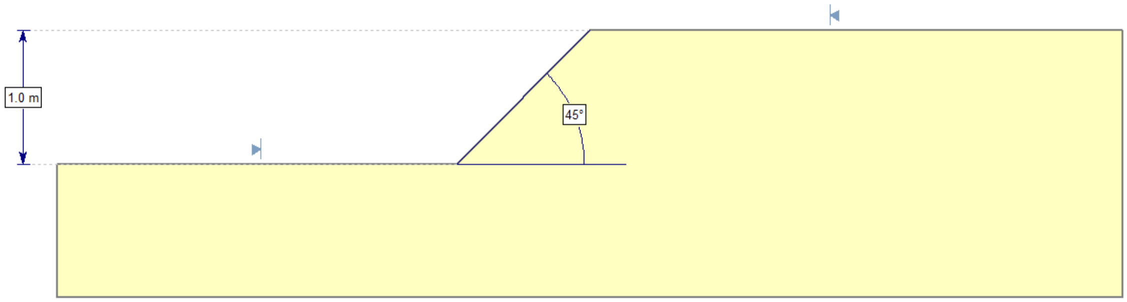


Figure 3 - Case 3, Geometry β = 45˚

Results

	RS2	SLIDE2	Ref*
Case1	1.02	1.011	1
Case 2	1.02	0.992	1
Case 3	1.1	1.035	1

* A.J. Li et al.

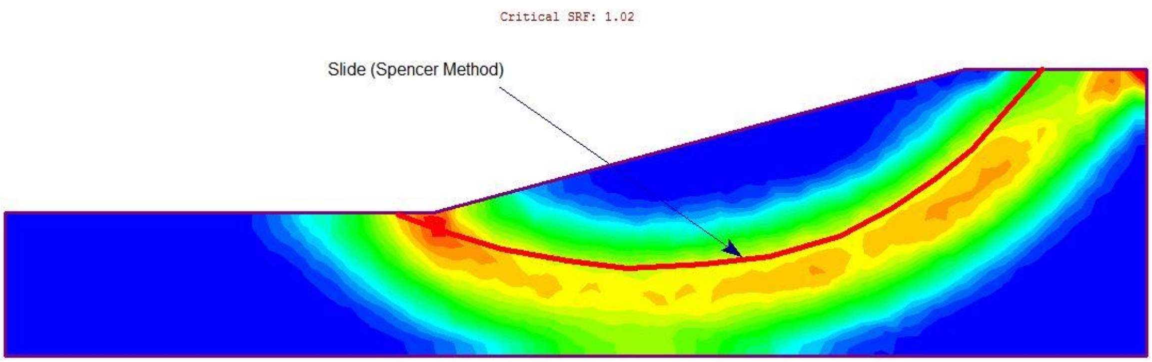


Figure 4 – Maximum Shear Strain Plot of Case 1

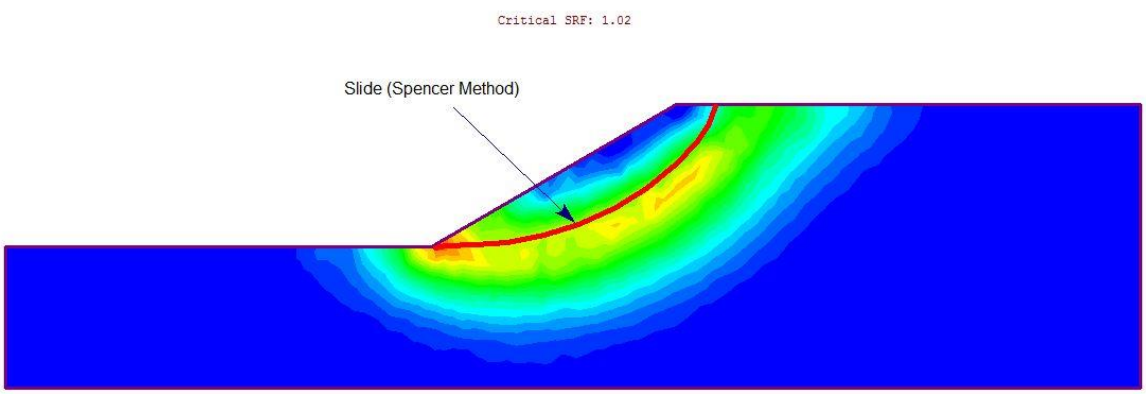


Figure 5 – Maximum Shear Strain Plot of Case 2

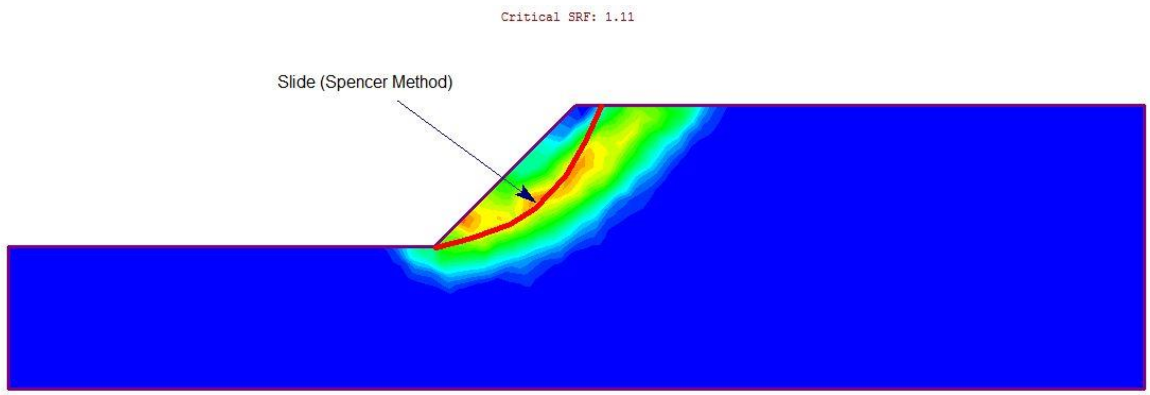


Figure 6 – Maximum Shear Strain Plot of Case 3

Introduction

This problem is taken from the slope stability problem in "Two-dimensional slope stability analysis by limit equilibrium and strength reduction methods", a paper by Cheng, Y.M., Lansivaara, T. and Wei, W.B. (2007).

Description

A homogeneous slope is shown in Figure 1. The RS2 SSR Polygon Search Area option was used to determine varying local minima for all cases (except the first, a global minimum without a Search Area). Mohr-Coulomb (M-C) failure criterion was used in the analysis. The material properties of the soil are given in Table 1. The results of this study are compared to those of Slide2 5.0 and LEM (Cheng, Y.M. et al.).

Geometry and Properties

Table 1 - Material Properties

Soil Name	Cohesion, c (kPa)	Friction angle, ϕ (^{0})	Unit weight, γ (kN/m^3)	Elastic modulus, E (MPa)	Poisson ratio, ν
Soil 1	5	30	20	14	0.3

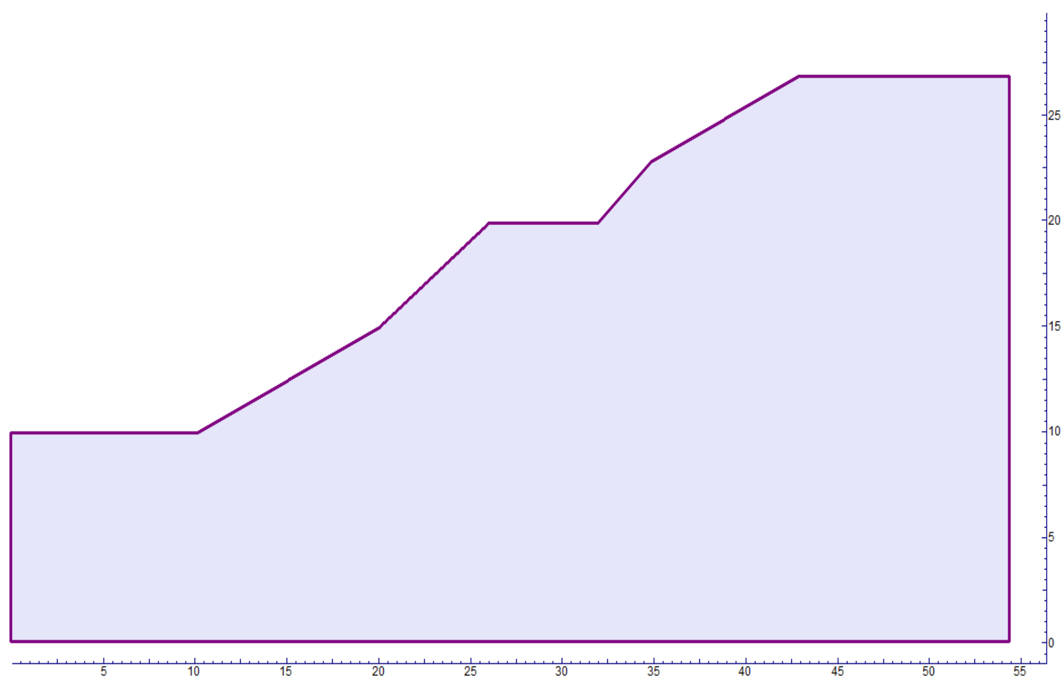


Figure 1 Geometry

Results:

	RS2	Ref*	Slide2
Case 1	1.35	1.327	1.336
Case 2	1.36	1.375	1.385
Case 3	1.42	1.415	1.443
Case 4	1.42	1.40	1.397

*Cheng et al.

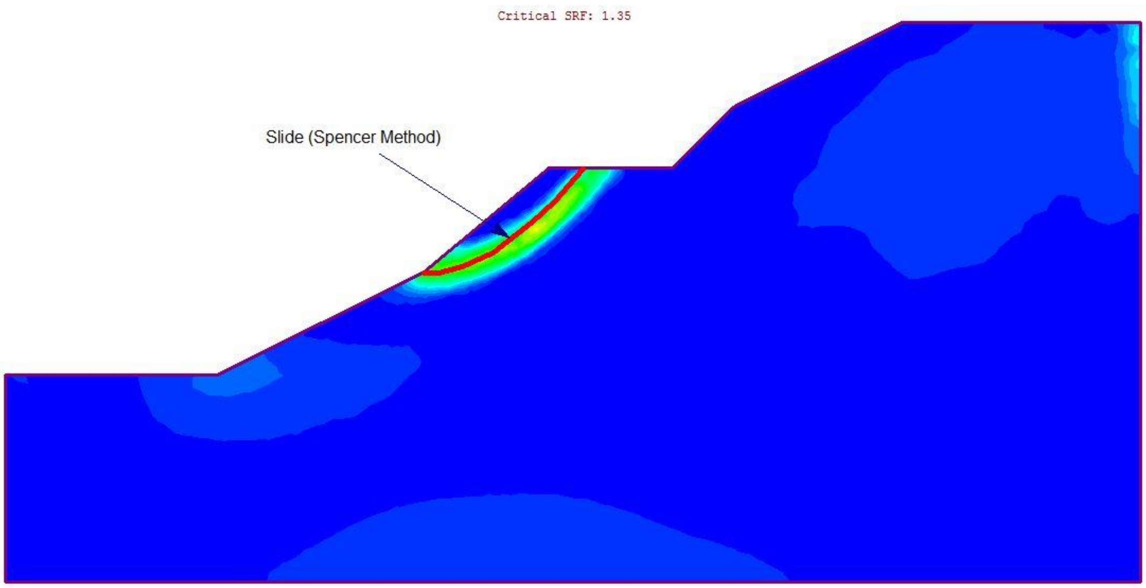


Figure 2 – Maximum Shear Strain Plot of Case 1

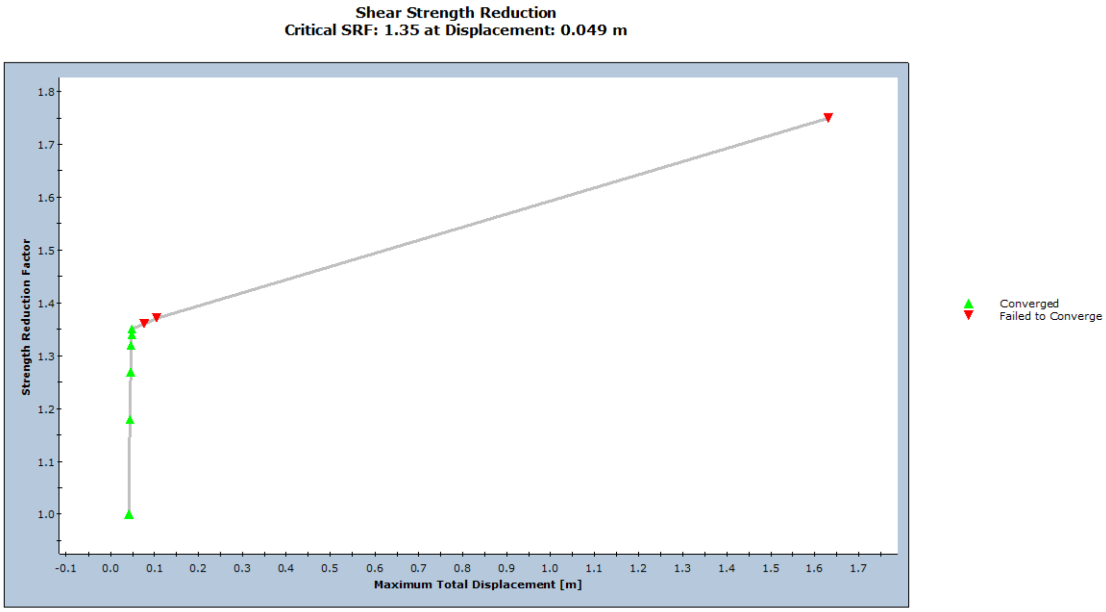


Figure 3 – Graph of Shear Strength Reduction for Case 1

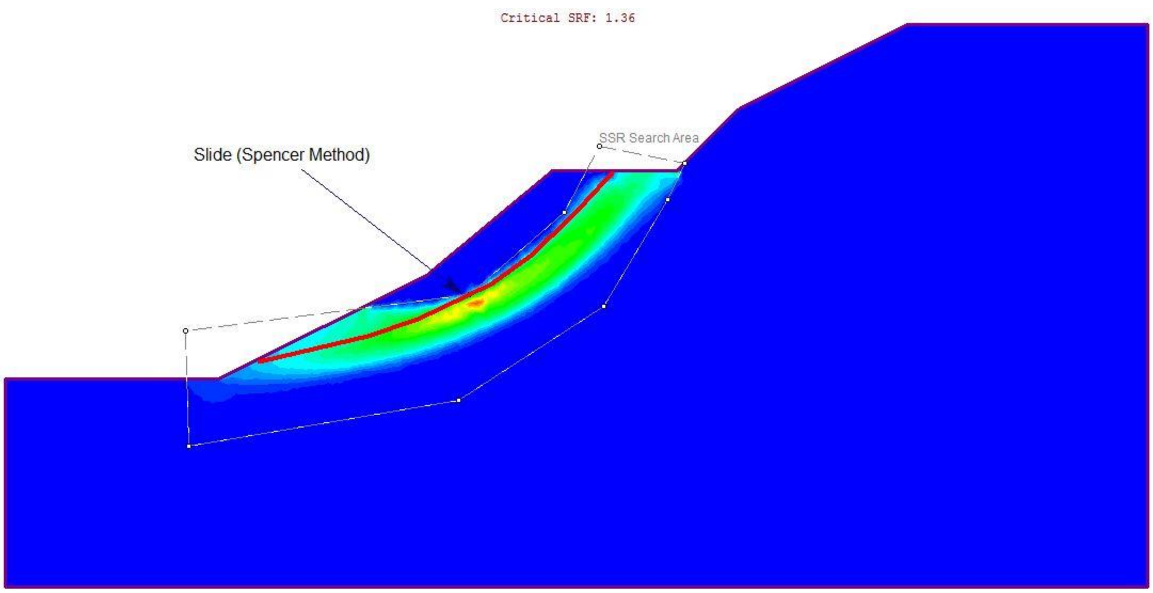


Figure 4 – Maximum Shear Strain Plot of Case 2

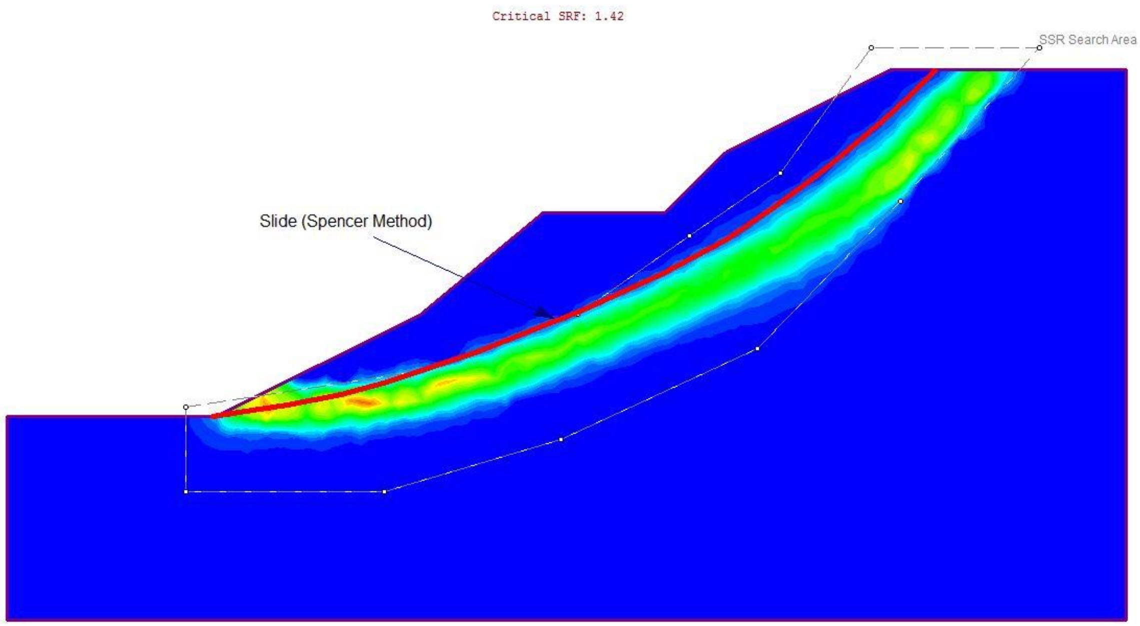


Figure 5 – Maximum Shear Strain Plot of Case 3

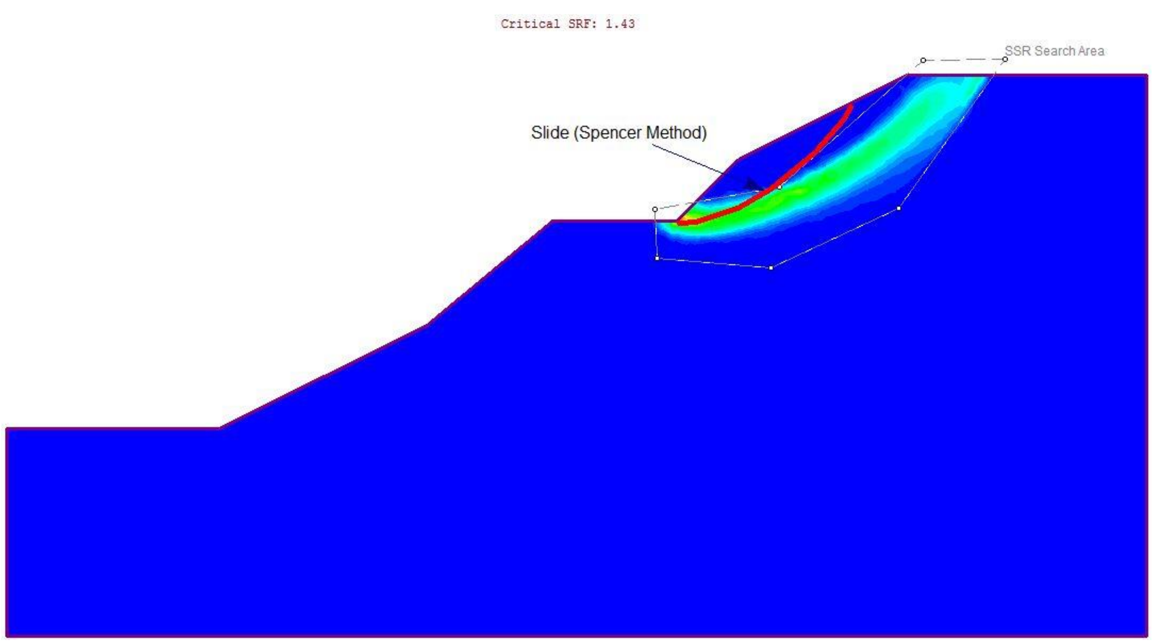


Figure 6 – Maximum Shear Strain Plot of Case 4

Introduction

This problem is taken from the slope stability problem in "Two-dimensional slope stability analysis by limit equilibrium and strength reduction methods", a paper by Cheng, Y.M., Lansivaara, T. and Wei, W.B. (2007).

Description

A three layer slope with a soft band is shown in Figure 1. Three analyses with different widths and dilation angles were studied. Mohr-Coulomb (M-C) failure criterion was used in each analysis. The material properties of all three analyses are given in Table 1. The results of all cases are compared to those of Flac3D and Plaxis.

Geometry and Properties

Table 1 - Material Properties

Soil Name	Cohesion, c (kPa)	Friction angle, ϕ (^{0})	Unit weight, γ (kN/m^3)	Elastic modulus, E (MPa)	Poisson ratio, ν
Soil 1	20	35	19	14	0.3
Soil 2	0	25	19	14	0.3
Soil 3	10	35	19	14	0.3

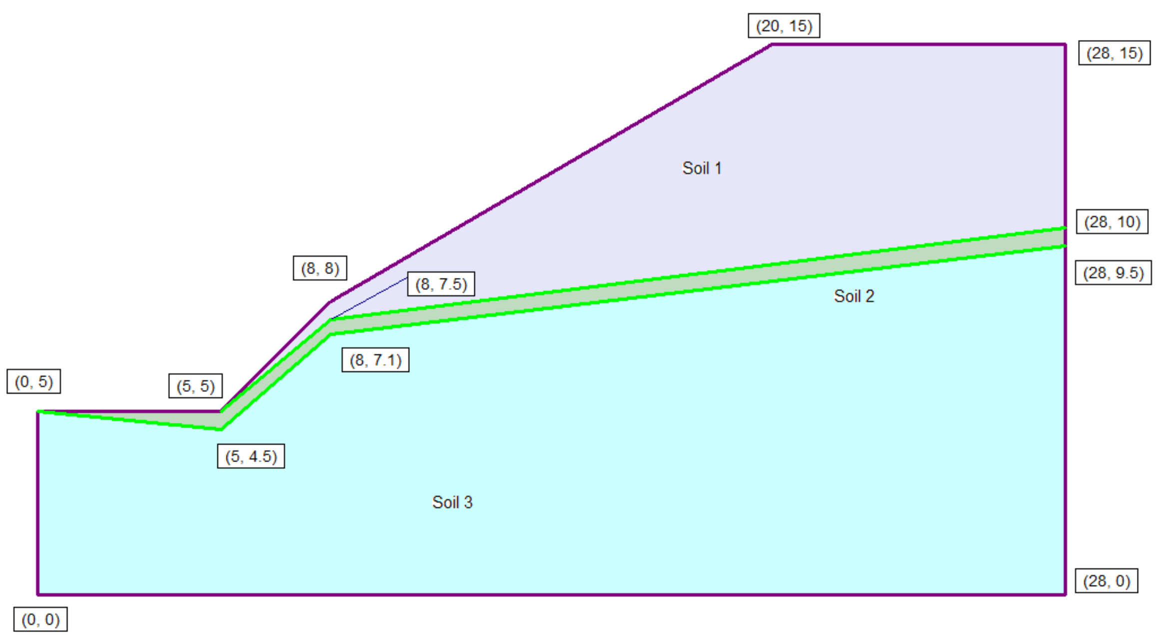


Figure 1 - Geometry I (28 m Domain)

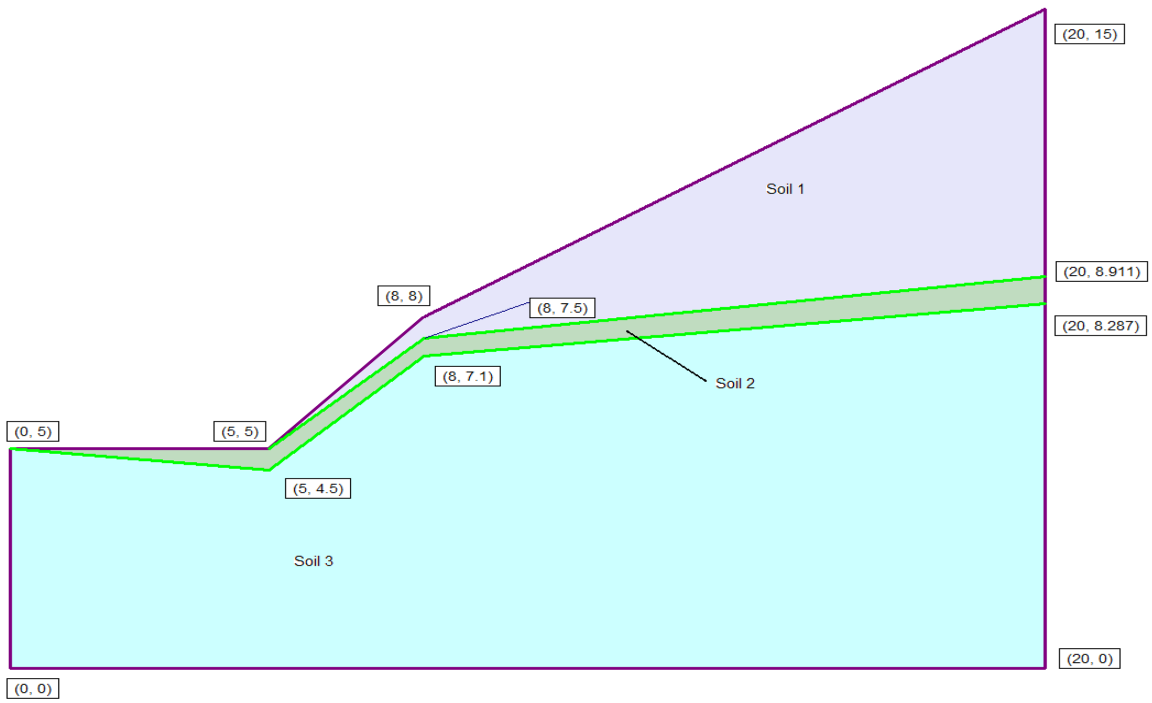


Figure 2 - Geometry II (20 m Domain)

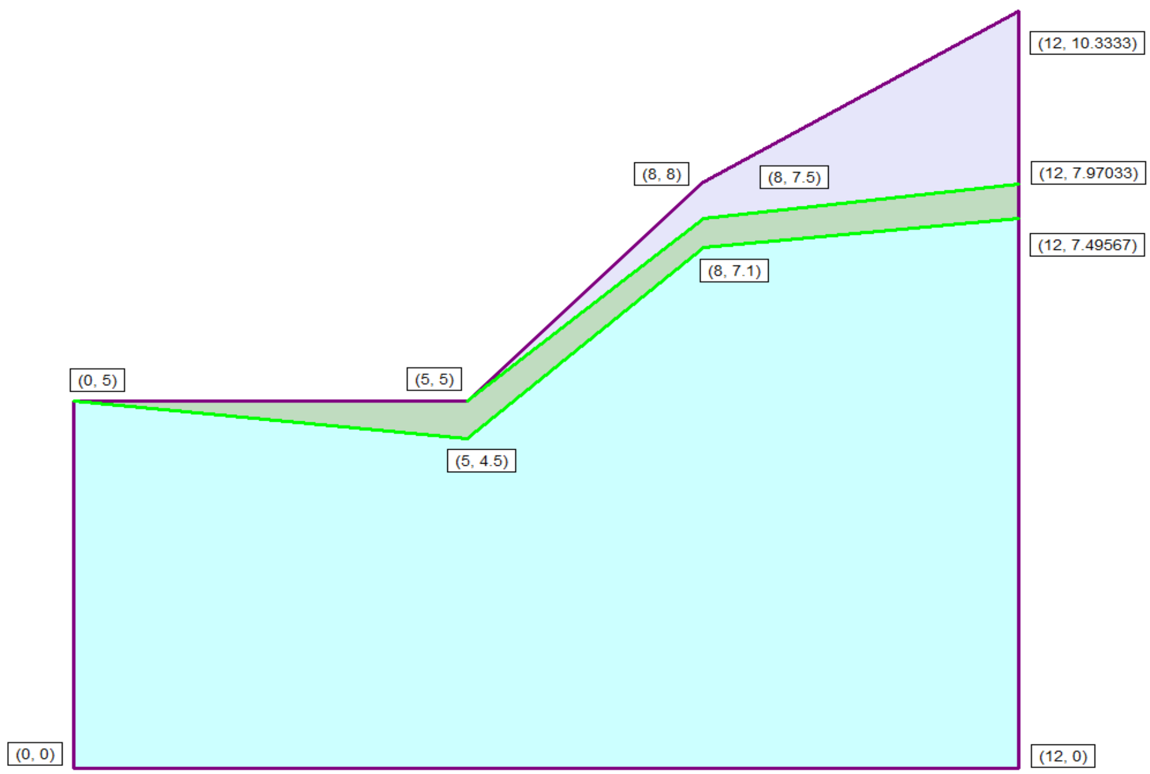


Figure 3 - Geometry III (12 m Domain)

Results: Analysis I

Program	Case 1 $\psi = 0$	Case 2 $\psi = \phi$
Flac3D	1.64	1.61
Plaxis	0.86	0.97
RS2	0.88	0.98

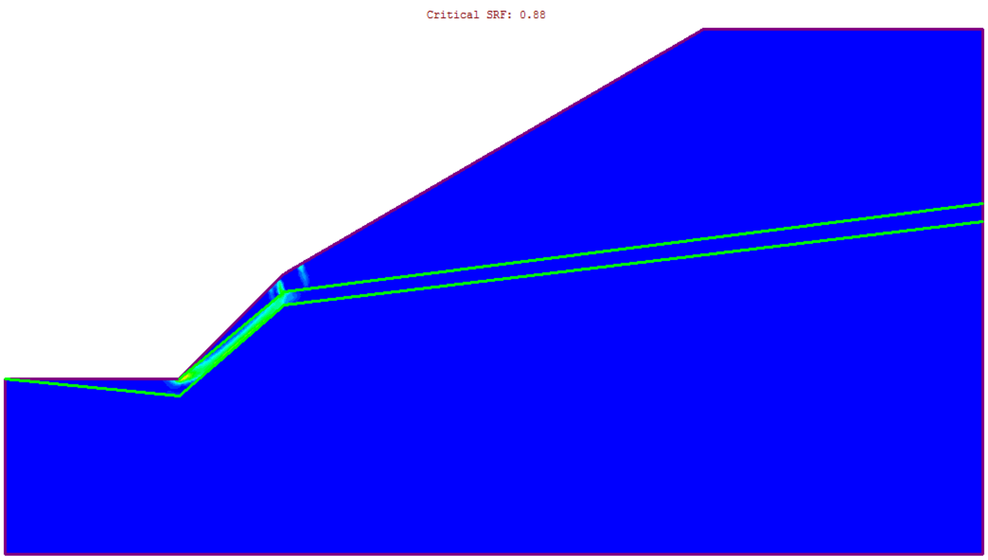


Figure 4 - Maximum Shear Strain Plot of Analysis I Case 1

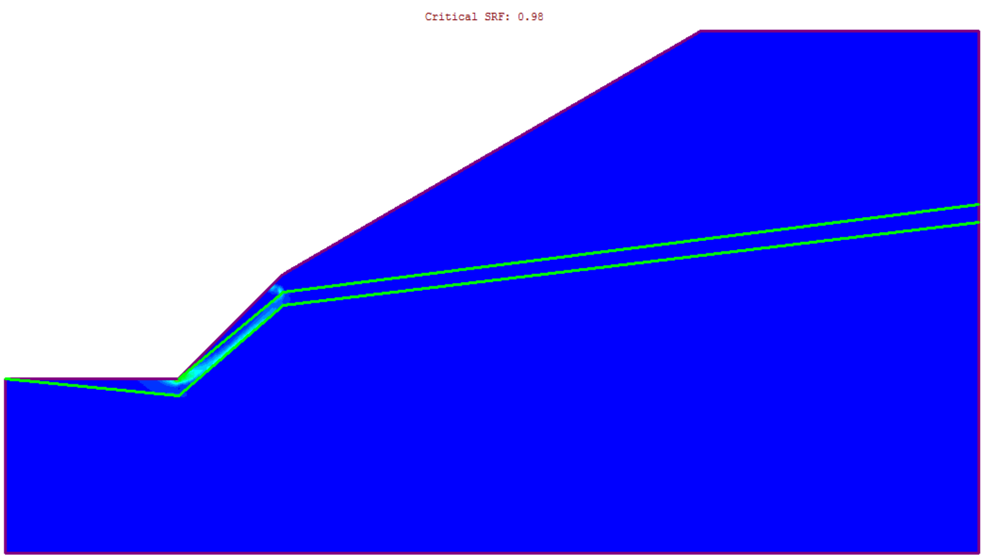


Figure 5 - Maximum Shear Strain Plot of Analysis I Case 2

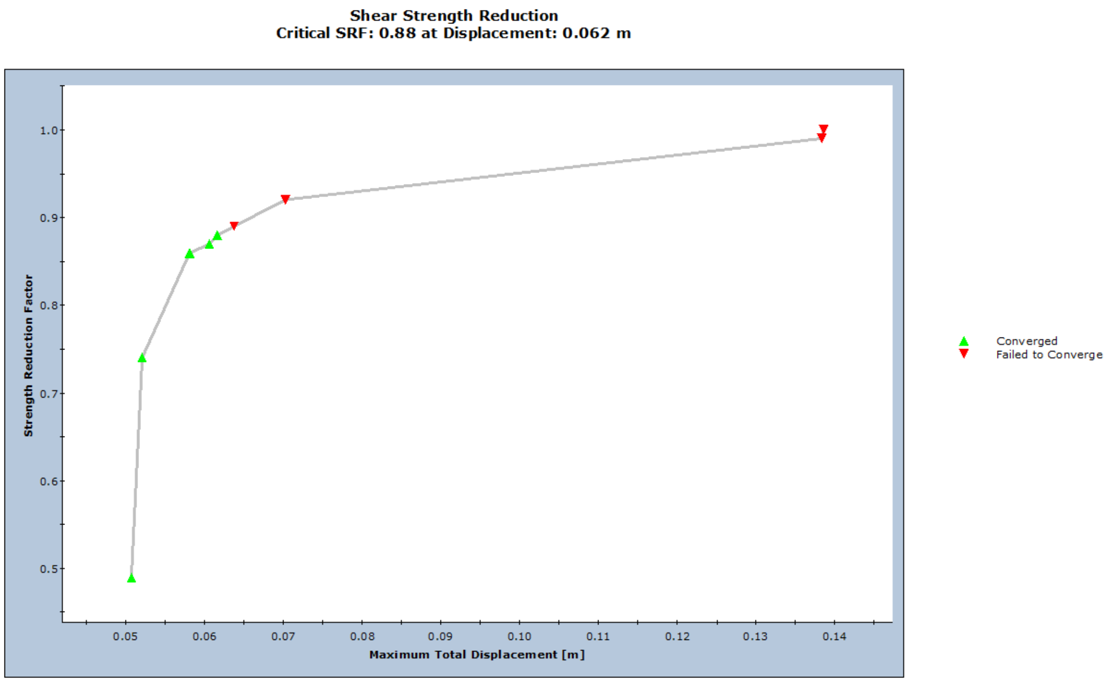


Figure 6 - SSR Convergence Graph of Analysis I Case 1

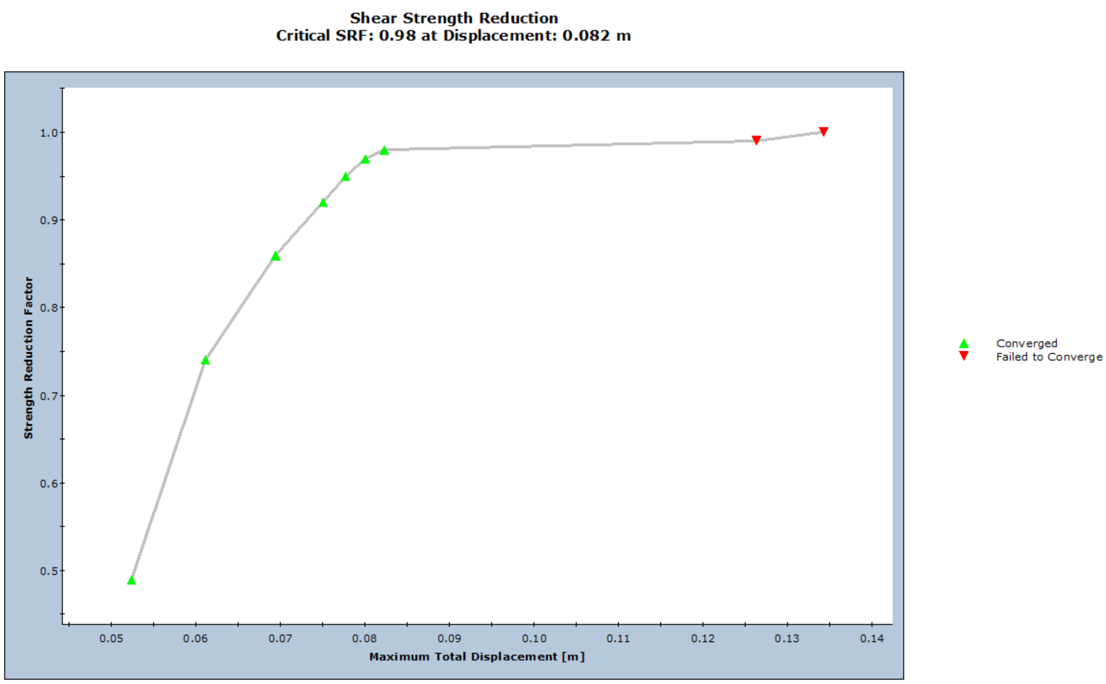


Figure 7 - SSR Convergence Graph of Analysis I Case 2

Results: Analysis II

Program	Case 1 $\psi = 0$	Case 2 $\psi = \phi$
Flac3D	1.30	1.28
Plaxis	0.85	0.97
RS2	0.89	0.98

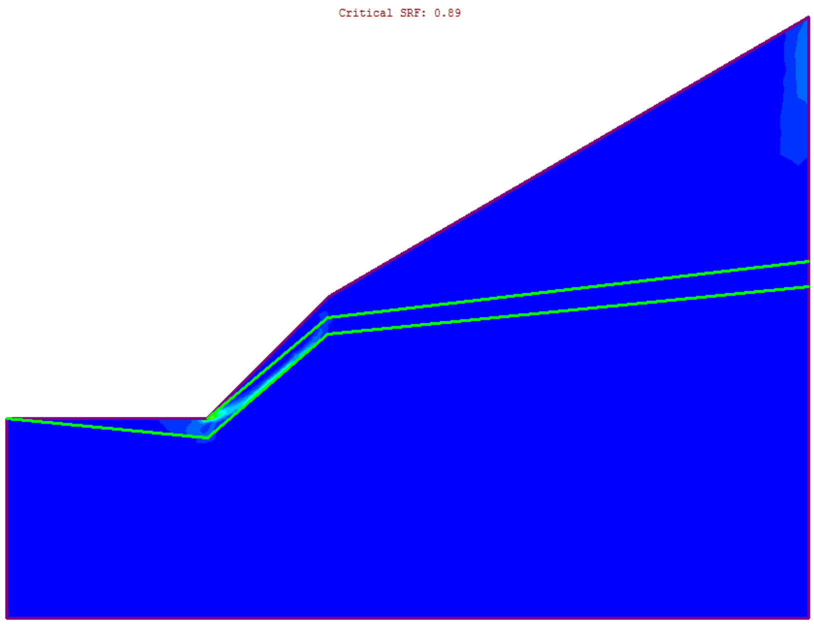


Figure 8 - Maximum Shear Strain Plot of Analysis II Case 1

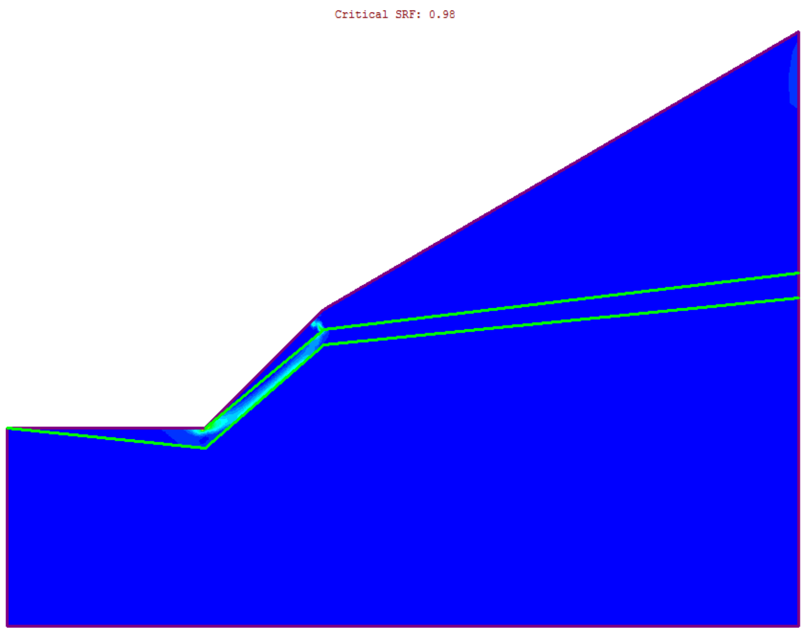


Figure 9 **- Maximum Shear Strain Plot of Analysis II Case 2**

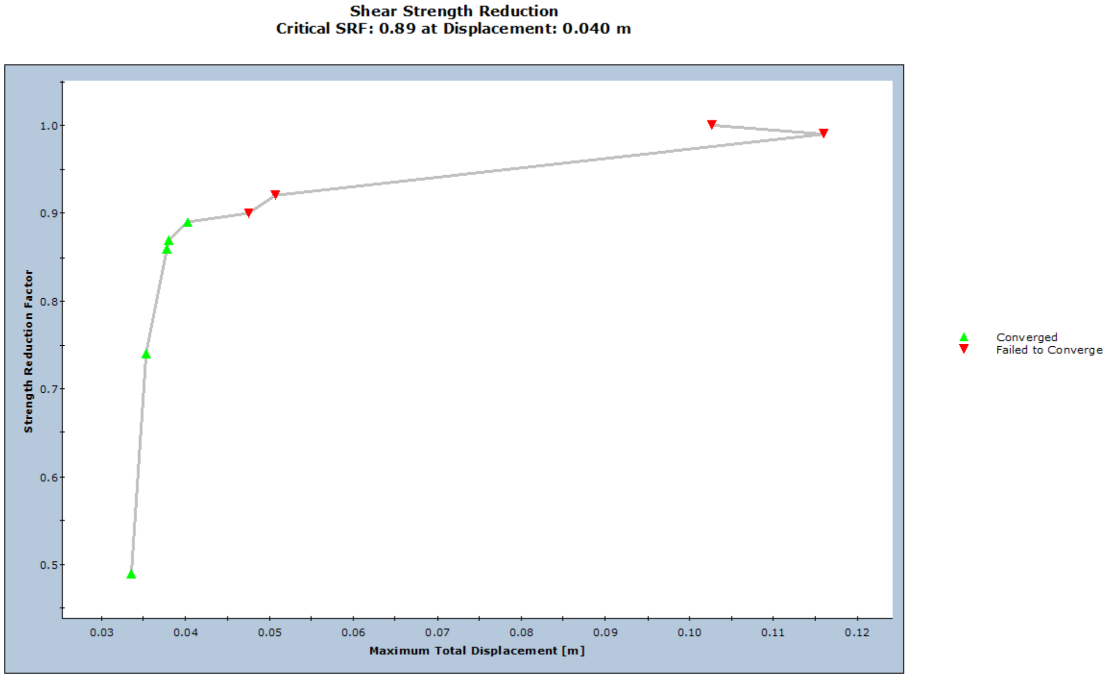


Figure 10 - SSR Convergence Graph of Analysis II Case 1

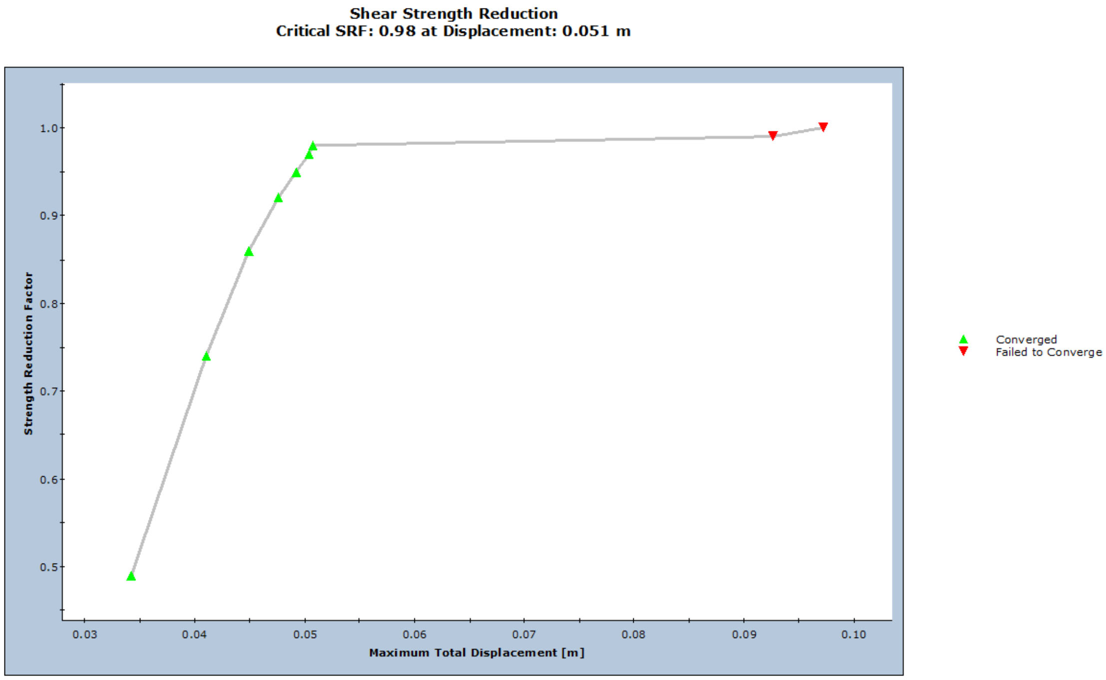


Figure 11 - SSR Convergence Graph of Analysis II Case 2

Results: Analysis III

Program	Case 1 $\psi = 0$	Case 2 $\psi = \phi$
Flac3D	1.03	1.03
Plaxis	0.82	0.94
RS2	0.81	0.93

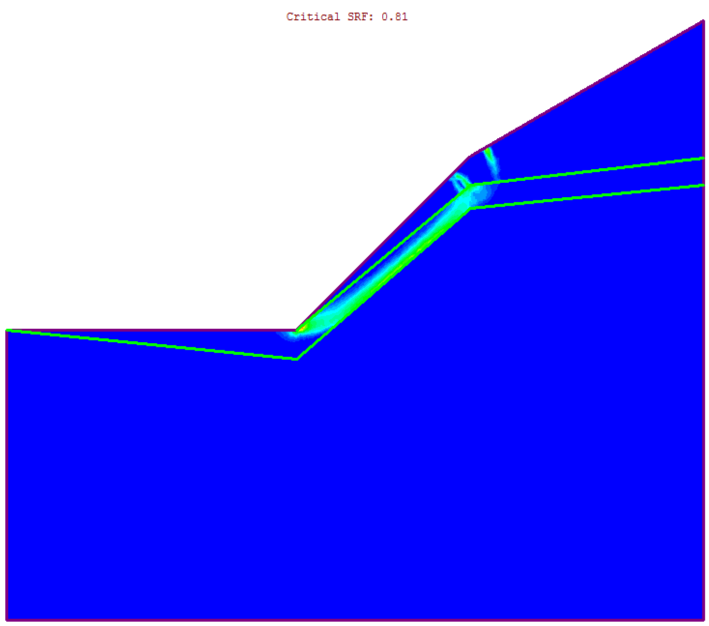


Figure 12 - Maximum Shear Strain Plot of Analysis III Case 1

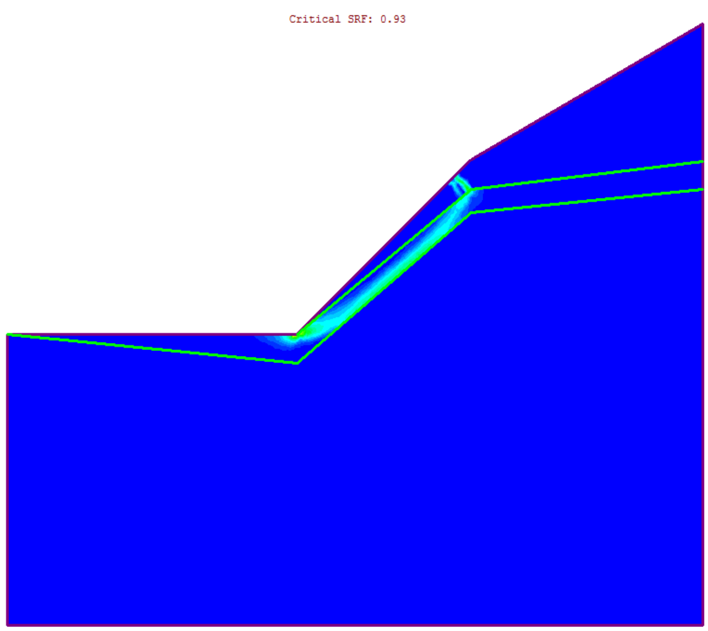


Figure 13 - Maximum Shear Strain Plot of Analysis III Case 2

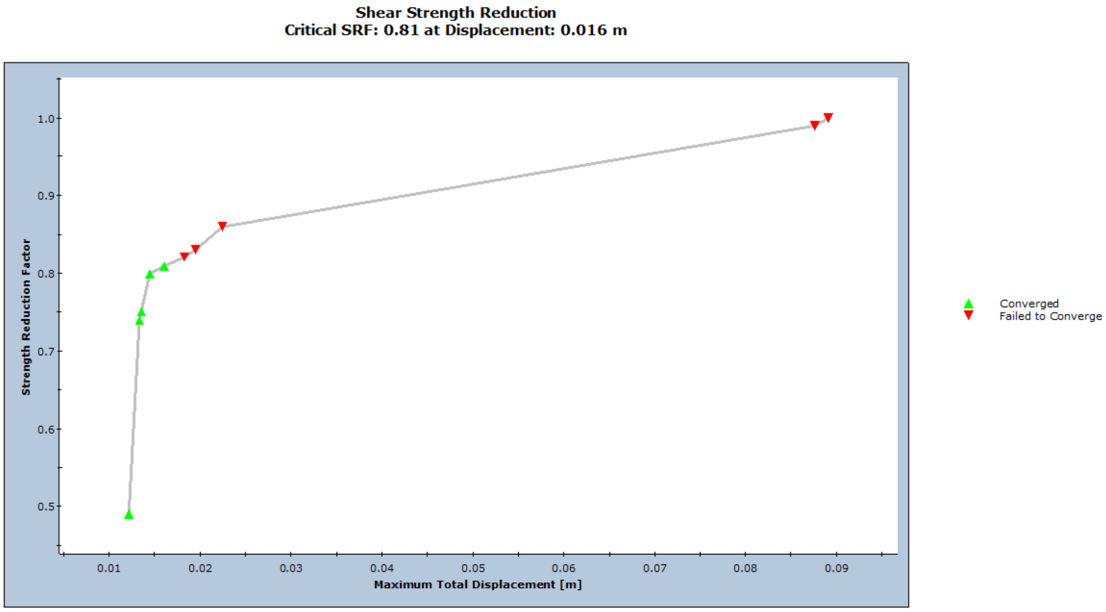


Figure 14 - SSR Convergence Graph of Analysis III Case 1

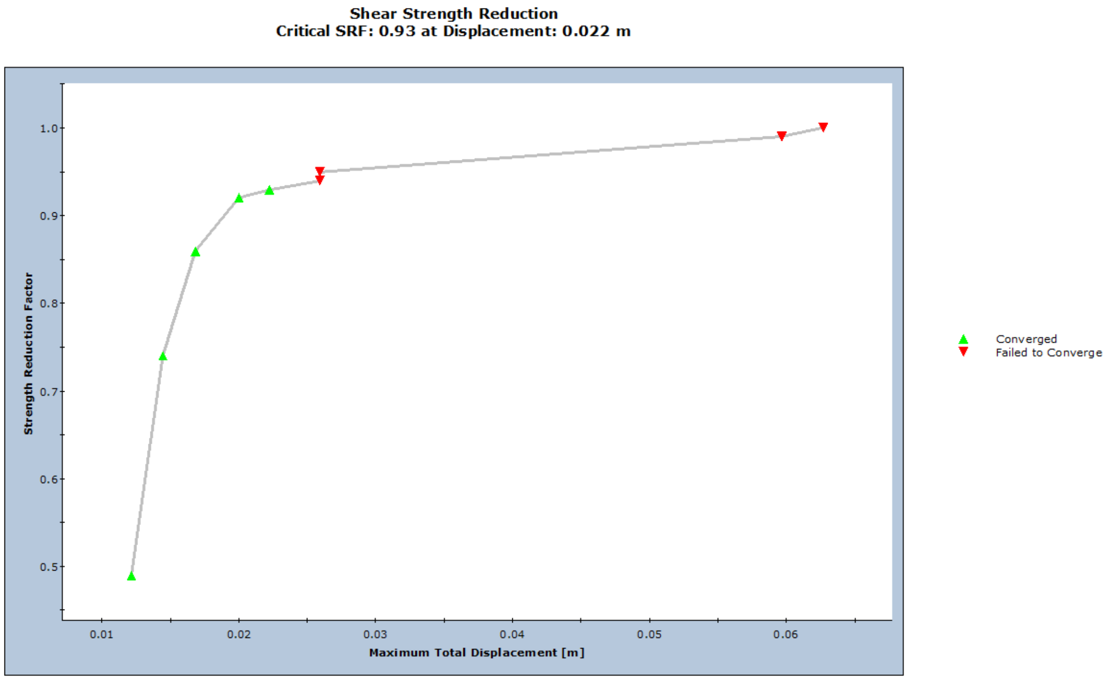


Figure 15 - SSR Convergence Graph of Analysis III Case 2

Introduction

This problem is taken from the slope stability problem in "Two-dimensional slope stability analysis by limit equilibrium and strength reduction methods", a paper by Cheng, Y.M., Lansivaara, T. and Wei, W.B. (2007).

Description

A homogeneous slope with a slope height of 11m is shown in Figure 1. A single case was studied and Mohr-Coulomb (M-C) failure criterion was used in the analysis. The material properties of the soil are given in Table 1. The results of this study are compared to those of Slide2 5.0 and LEM (Cheng, Y.M. et al.).

Geometry and Properties

Table 1 - Material Properties

Soil Name	Cohesion, c (kPa)	Friction angle, ϕ (^{0})	Unit weight, γ (kN/m^3)	Elastic modulus, E (MPa)	Poisson ratio, ν
Soil 1	10	30	20	14	0.3

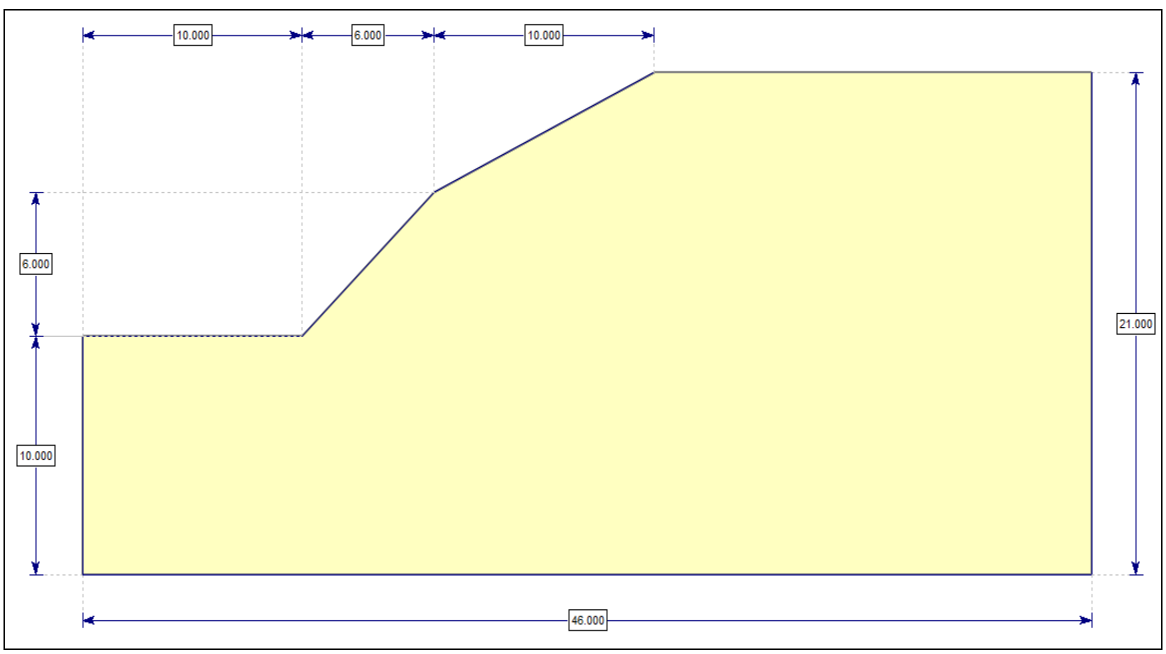


Figure 1 Geometry

Results: Case 1

	Slide2	RS2	LEM
Case 1	1.380	1.38	1.3830

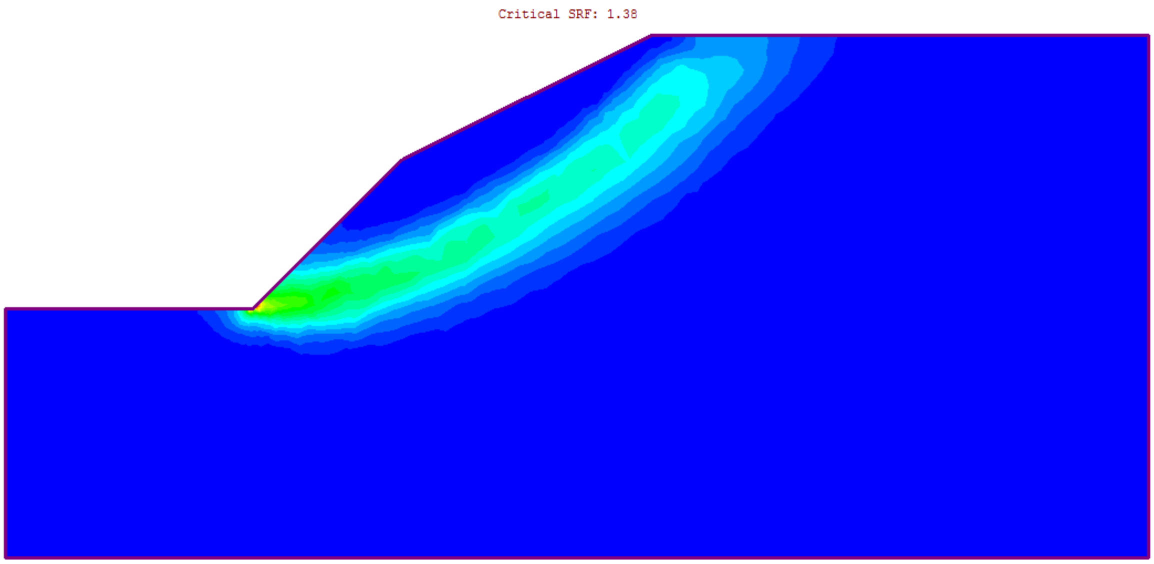


Figure 2 – Maximum Shear Strain Plot of Case 1

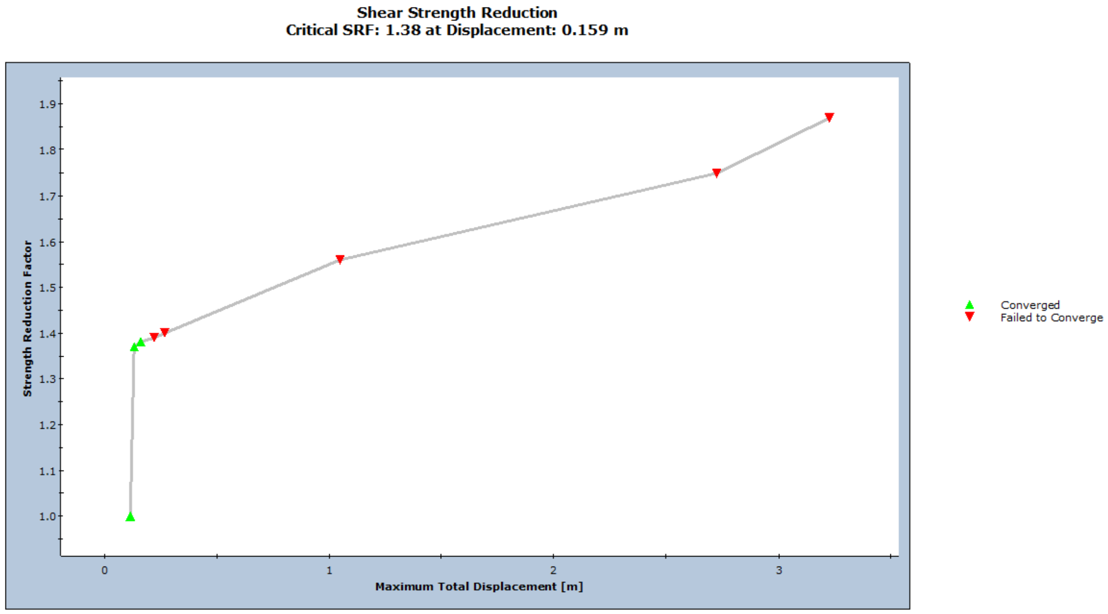


Figure 3 – SSR Convergence Graph of Case 1

Introduction

This problem is taken from the slope stability problem in “Assessment of slope stability in Ankara clay: a case study along E90 highway”, a paper by M. B. Teoman, T. Topal, N. S. Isik (2004).

Description

Figures 1 through 3 show the slope geometry for each landslide in Ankara clay before failure (Original) and after failure (Failed) for both short-term and long-term scenarios. The long-term models have fully saturated slopes and are subjected to a pseudo-static seismic load coefficient of 0.03g in the direction of the slope.

The RS2 SSR Search Area option was used to obtain the factor of safety for each of the proposed slip surfaces. Mohr-Coulomb (M-C) failure criterion was used in the analysis. The material properties of the soil are given in Tables 1 and 2 for short-term and long-term cases respectively. The results of this study are compared to the Bishop Methods of Slide2 5.0 and SLOPE/W v.4 (Teoman, M. B. et al.).

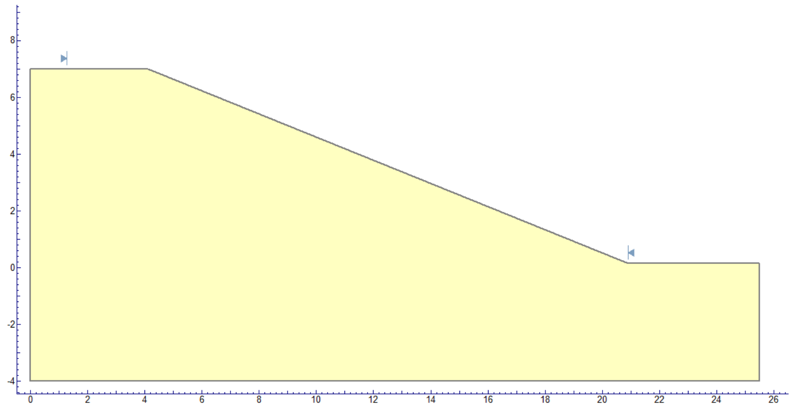
Geometry and Properties

Table 1 - Short-Term Material Properties

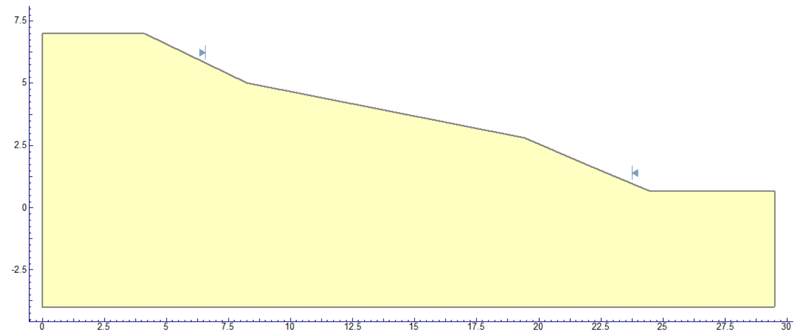
Soil Name	Case	Type	Cohesion, c (kPa)	Friction angle, ϕ (^{0})	Unit weight, γ (kN/m^3)
Slope 1	1	Original	40.9	40.2	20.5
	2	Failed	27.8	34	
Slope 2	3	Original	33.6	41.4	20
	4	Failed	28.4	33	
Slope 3	5	Original	33.6	41.4	20
	6	Failed	28.4	33	

Table 2 - Long-Term Material Properties

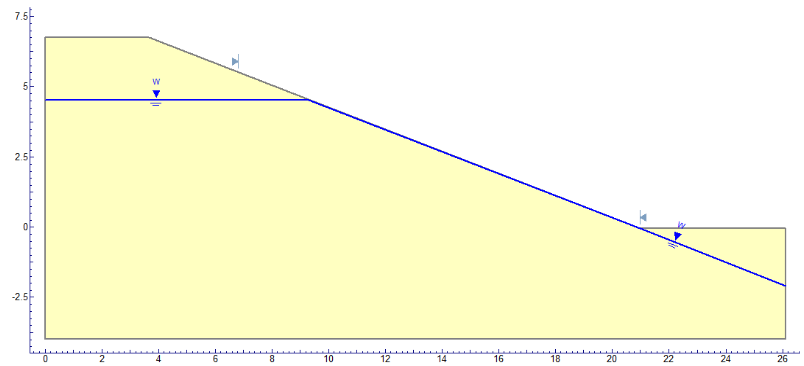
Soil Name	Case	Type	Cohesion, c (kPa)	Friction angle, ϕ (^{0})	Unit weight, γ (kN/m^3)
Slope 1	7	Original	12	26	20.5
	8	Failed	3	19	
Slope 2	9	Original	7	32	20
	10	Failed	4	25	
Slope 3	11	Original	7	32	20
	12	Failed	2	25	



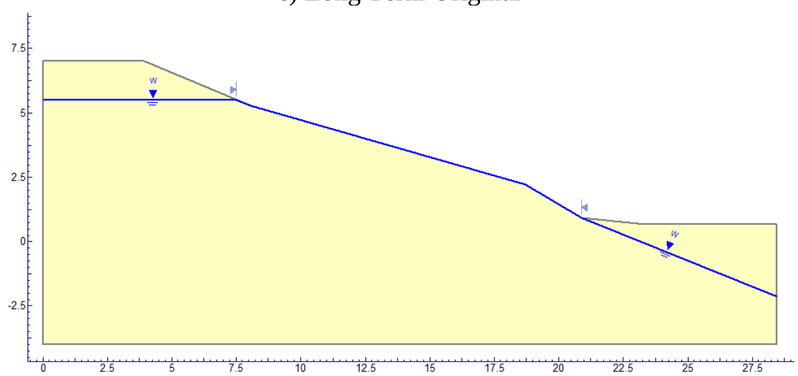
a) Slope 1 Short Term Original



b) Short Term Failed

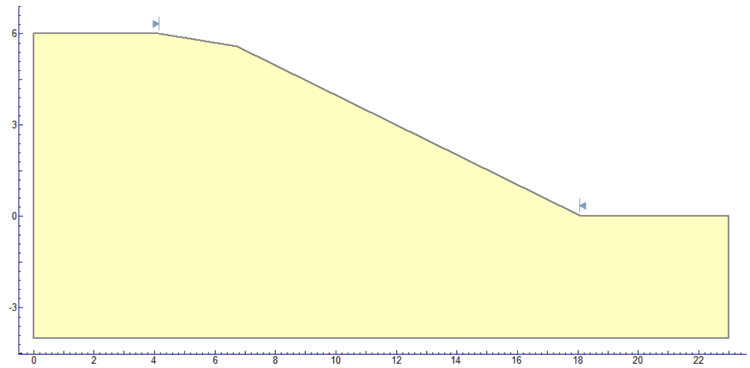


c) Long Term Original

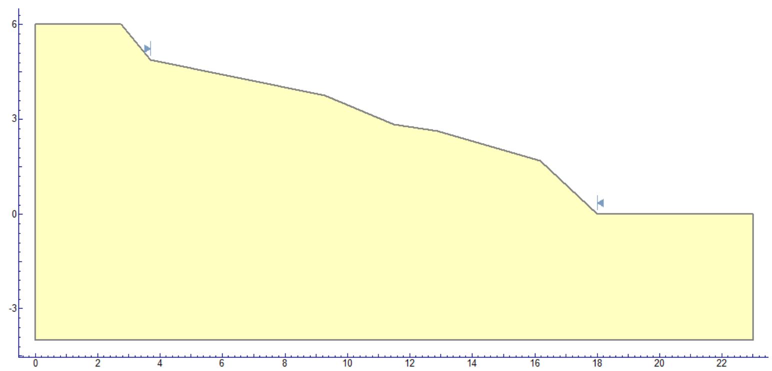


d) Long Term Failed

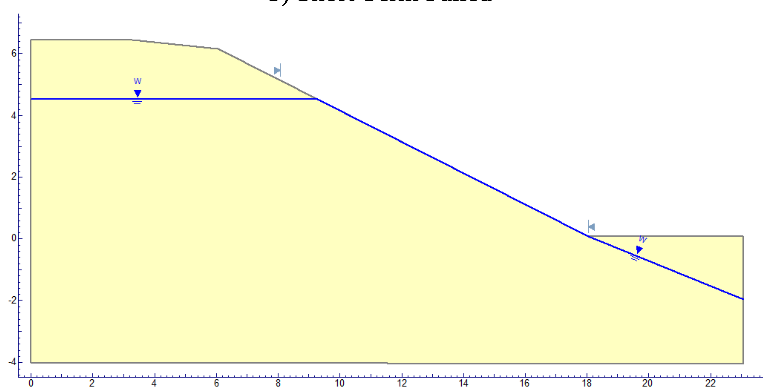
Figure 1 - Slope 1 Geometry



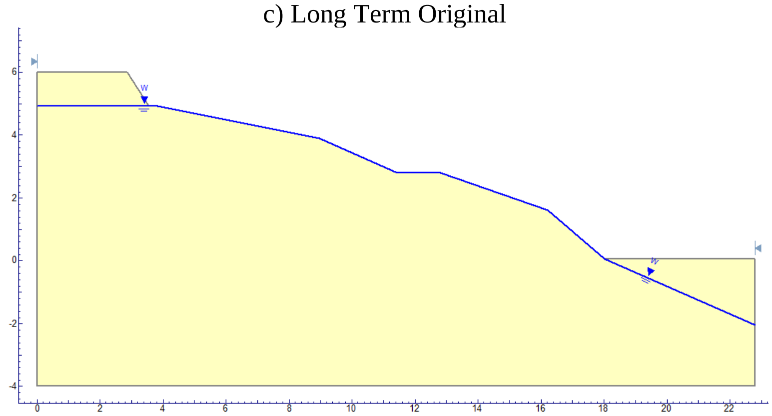
a) Slope 2 Short Term Original



b) Short Term Failed

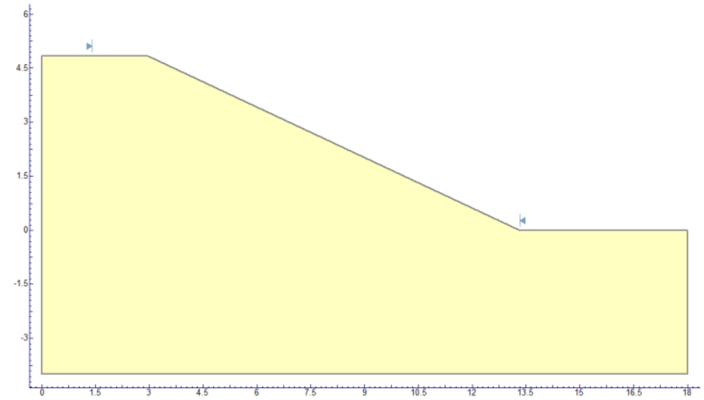


c) Long Term Original

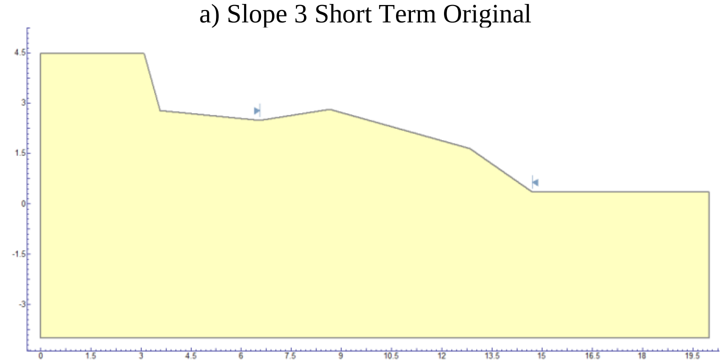


d) Long Term Failed

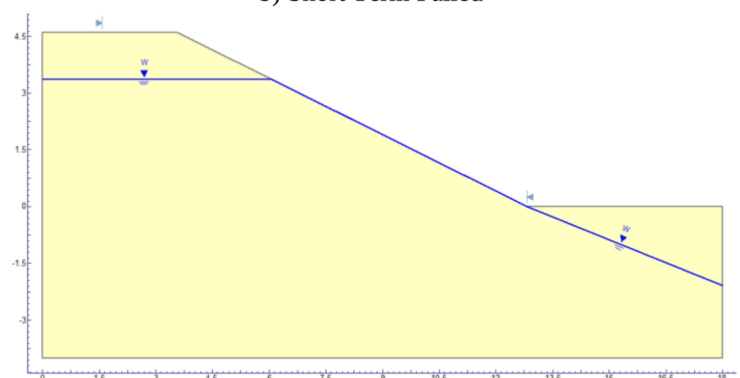
Figure 2 – Slope 2 Geometry



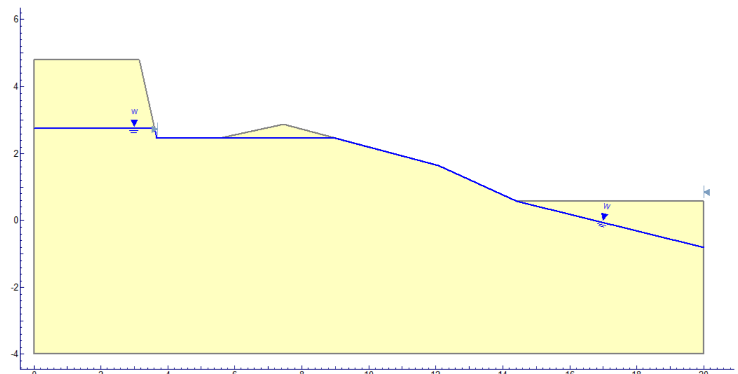
a) Slope 3 Short Term Original



b) Short Term Failed



c) Long Term Original



d) Long Term Failed

Figure 3 – Slope 3 Geometry

Short Term Results:

	RS2	Ref*	Slide2
Case 1	5.14	5.25	5.24
Case 2	6.10	6.67	6.64
Case 3	4.69	4.87	4.89
Case 4	4.95	5.32	5.32
Case 5	5.47	5.44	5.45
Case 6	6.97	7.02	6.96

*Teoman et al.

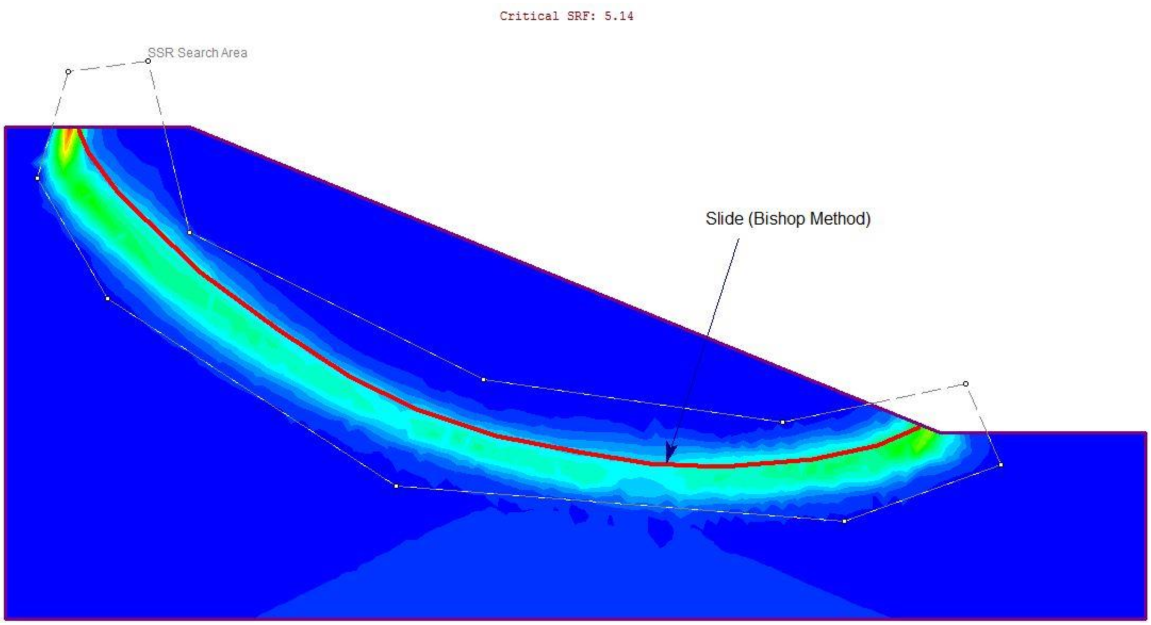


Figure 4 – Maximum Shear Strain Plot of Case 1

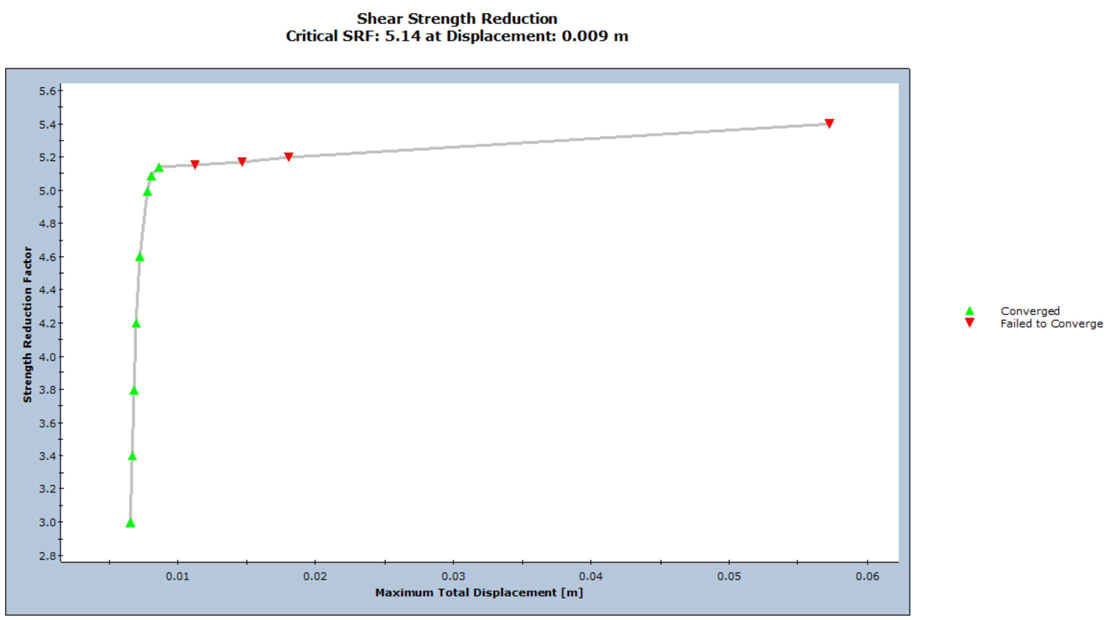


Figure 5 – Graph of Shear Strength Reduction for Case 1

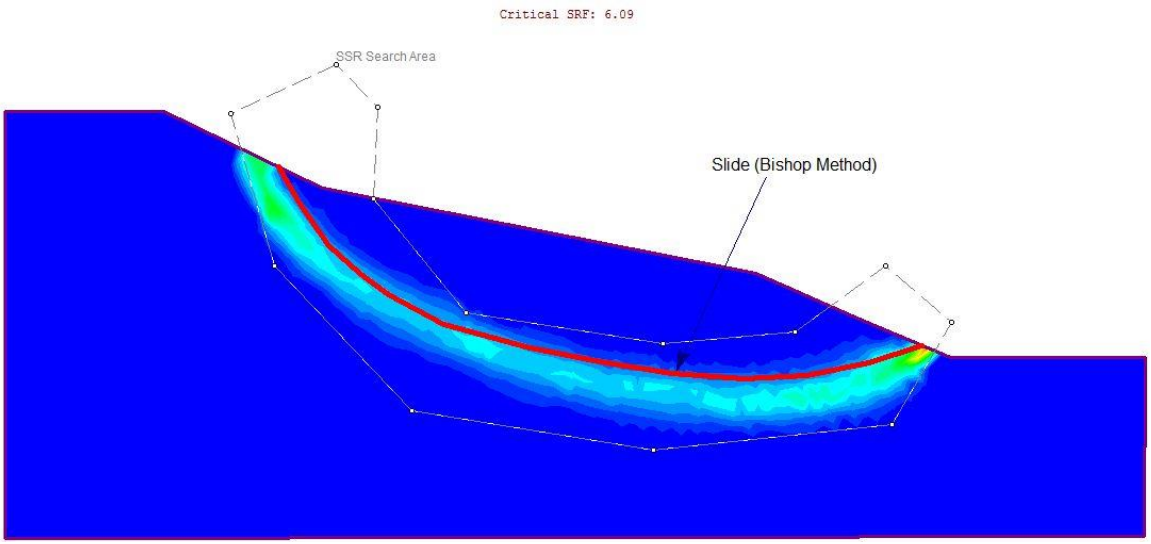


Figure 6 – Maximum Shear Strain Plot of Case 2

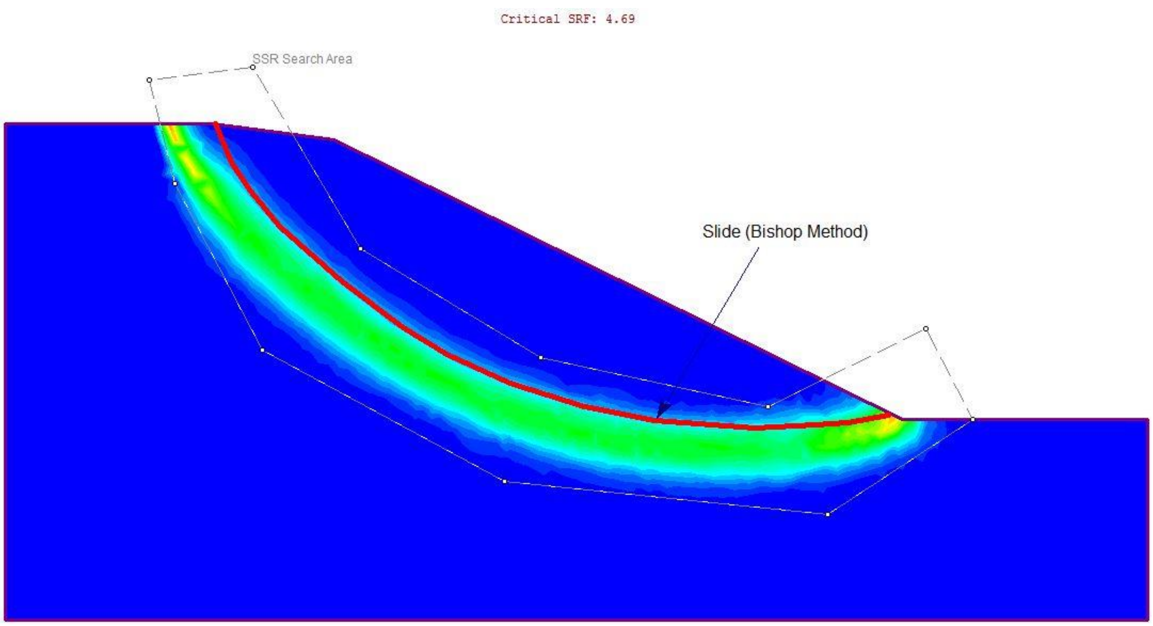


Figure 7 – Maximum Shear Strain Plot of Case 3

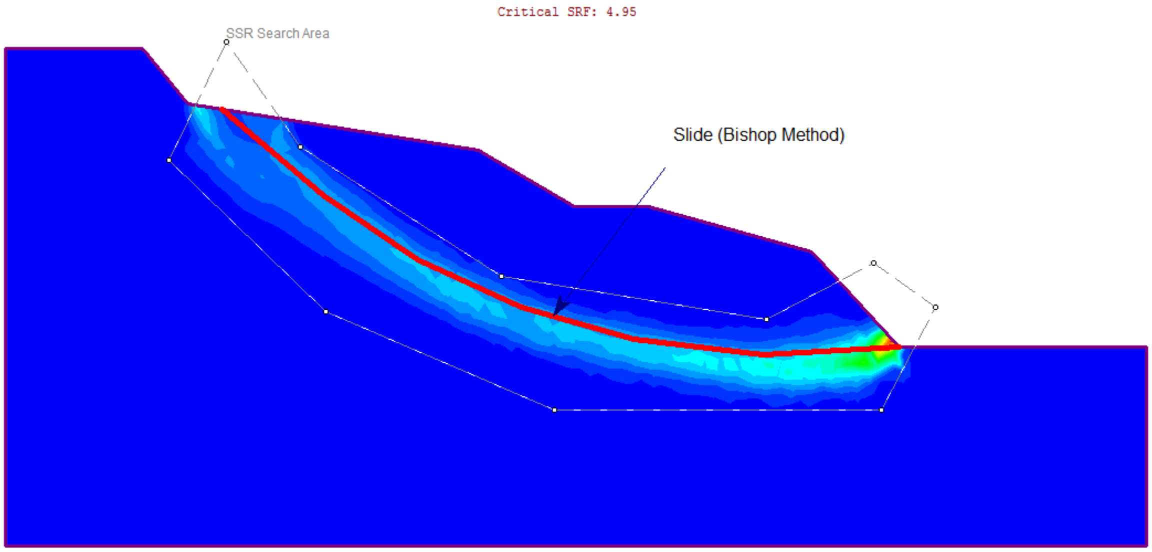


Figure 8 – Maximum Shear Strain Plot of Case 4

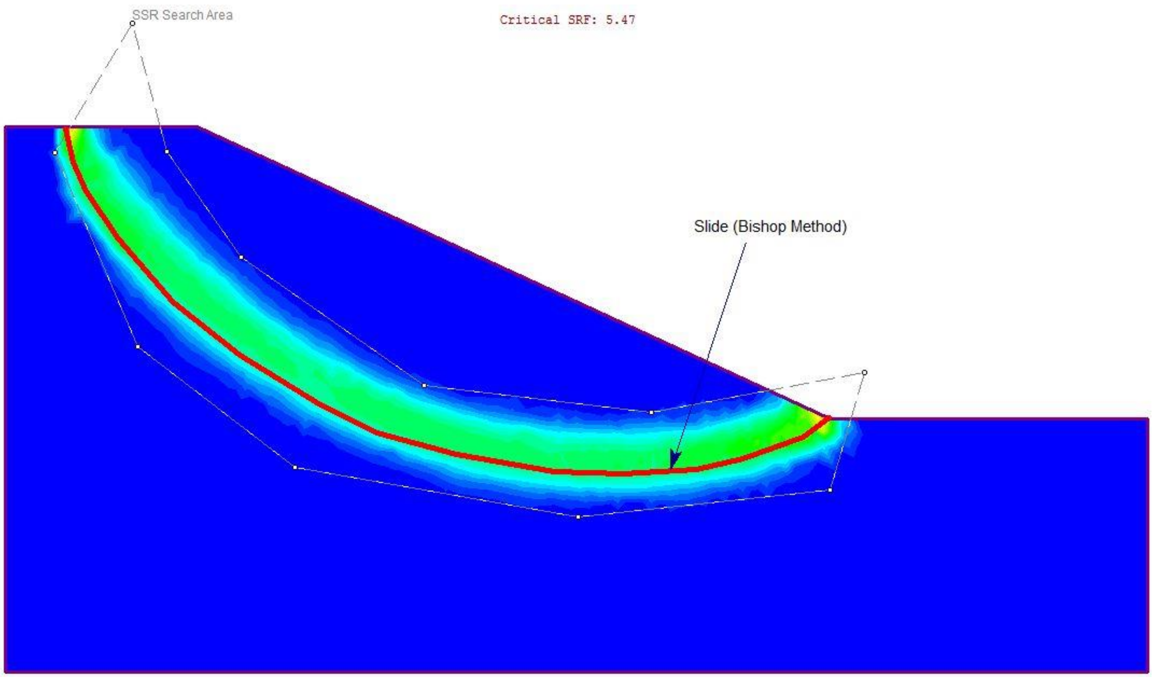


Figure 9 – Maximum Shear Strain Plot of Case 5

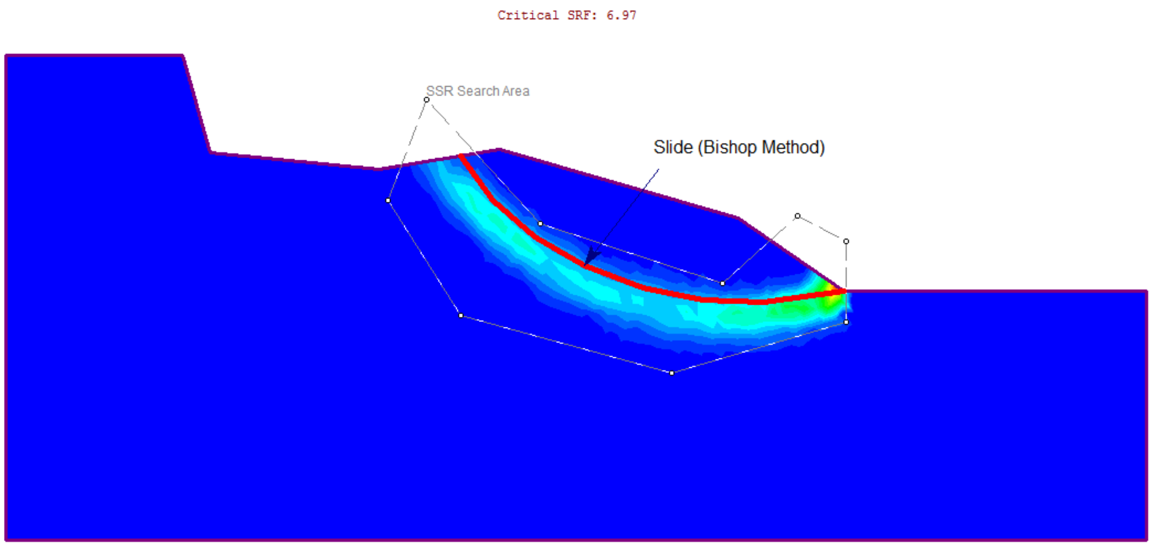


Figure 10 – Maximum Shear Strain Plot of Case 6

Long-Term Results:

	RS2	Ref*	Slide2
Case 7	1.7	1.79	1.68
Case 8	0.99	1.13	1.09
Case 9	1.30	1.30	1.30
Case 10	1.09	1.08	1.07
Case 11	1.46	1.51	1.51
Case 12	1.22	1.13	1.15

*Teoman et al.

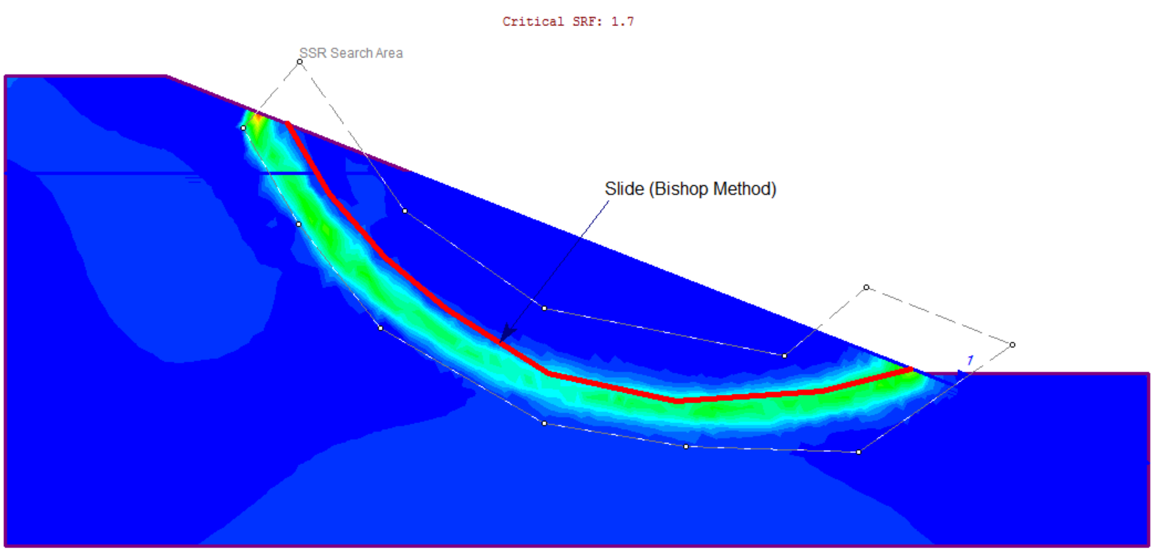


Figure 11 – Maximum Shear Strain Plot of Case 7

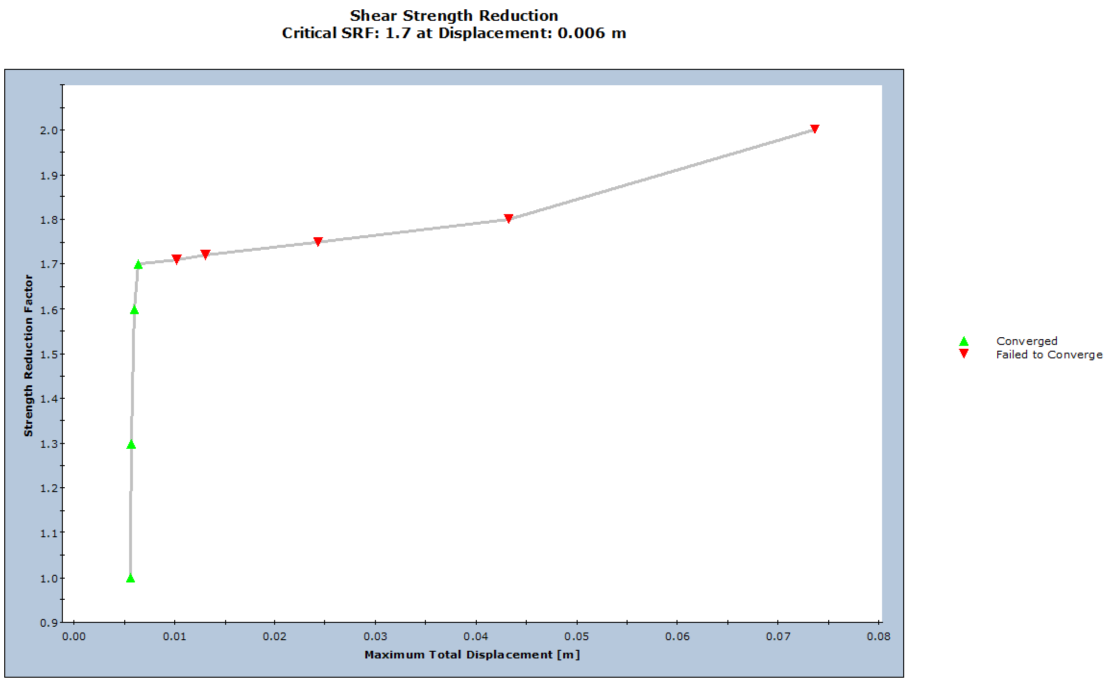


Figure 12 – Graph of Shear Strength Reduction for Case 7

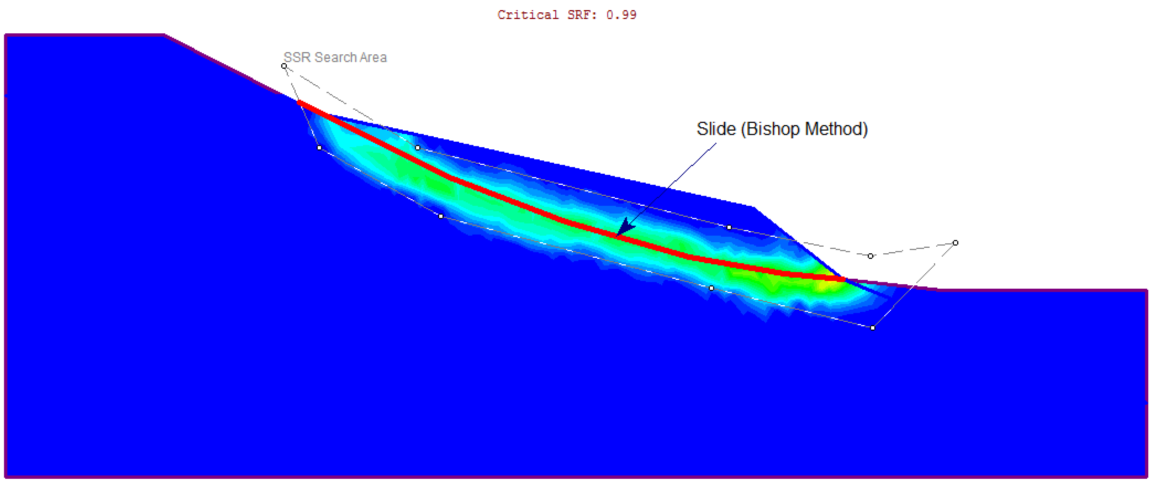


Figure 13 – Maximum Shear Strain Plot of Case 8

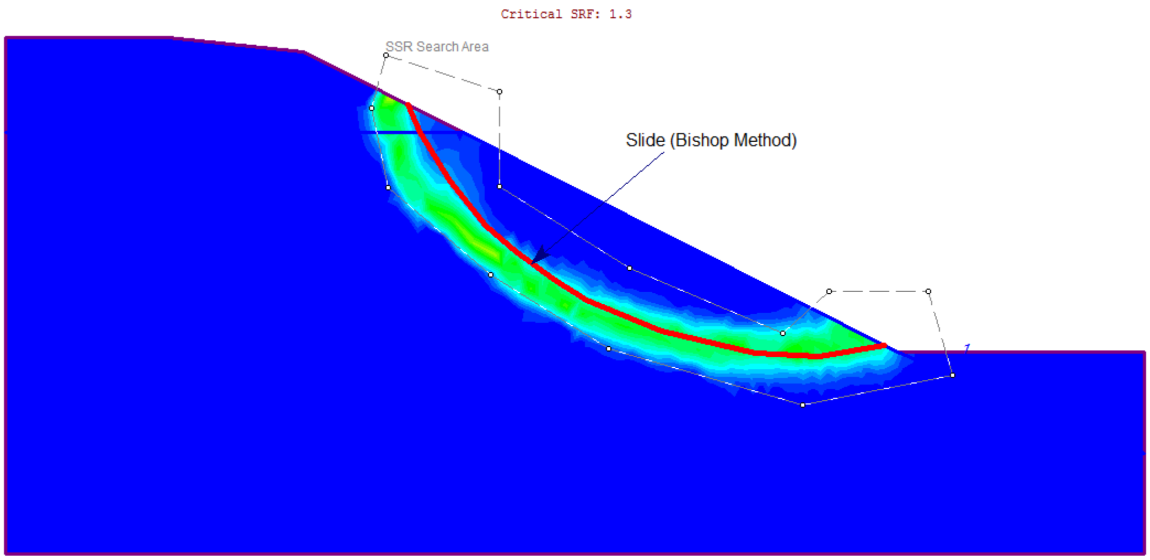


Figure 14 – Maximum Shear Strain Plot of Case 9

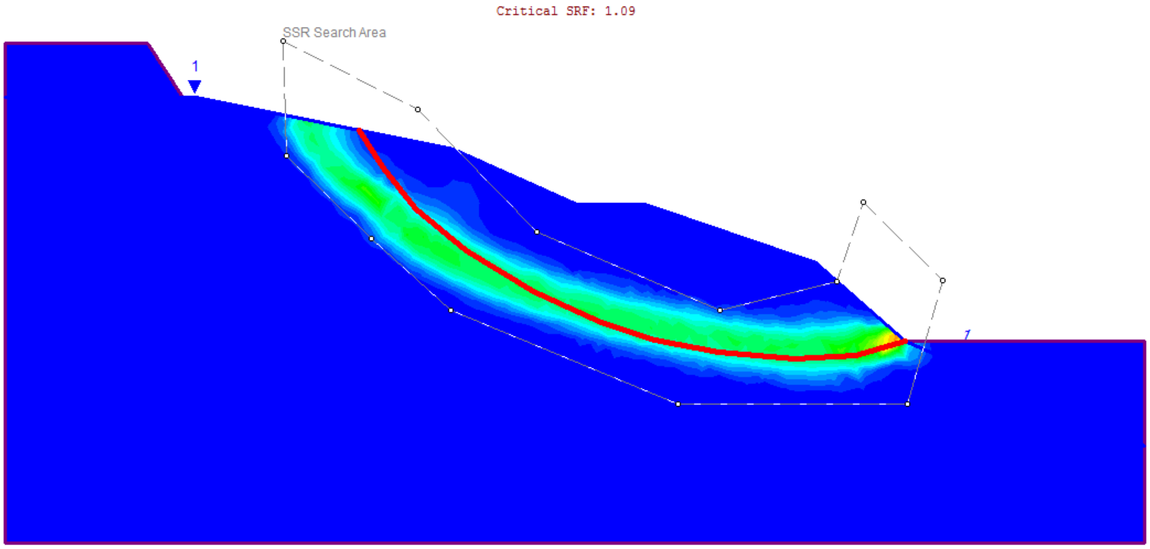


Figure 15 – Maximum Shear Strain Plot of Case 10

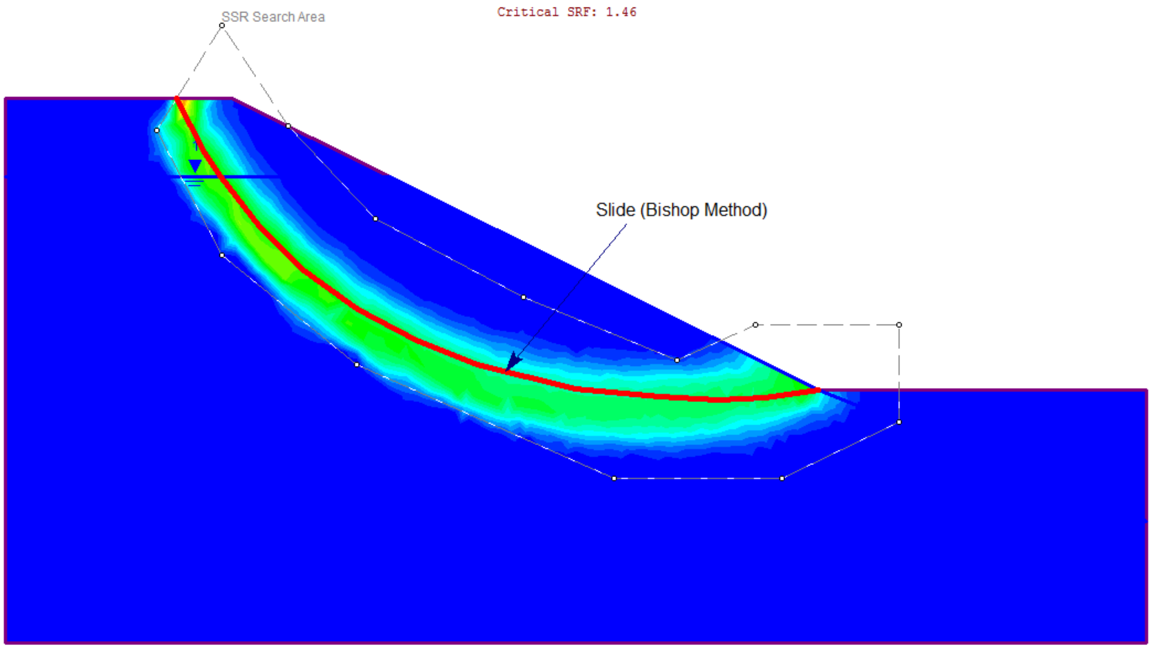


Figure 16 – Maximum Shear Strain Plot of Case 11

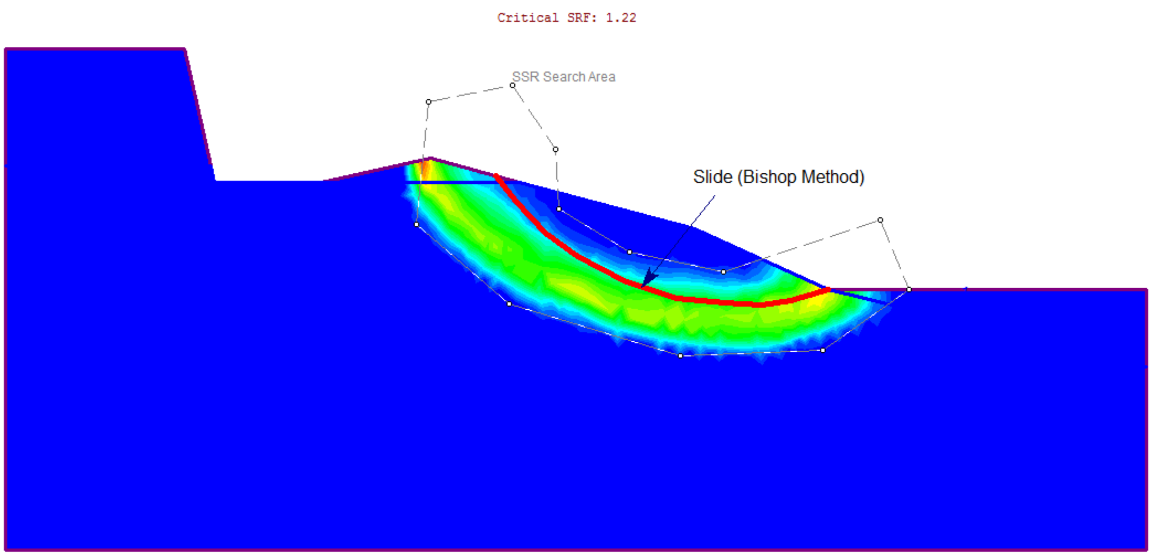


Figure 17 – Maximum Shear Strain Plot of Case 12

Introduction

This problem is taken from the slope stability problem in "Stability Analysis of a Tailings dam: Existing State and Planned Heightening", a paper by Anton D. Tzenkov (2008).

Description

Figure 1 shows the slope geometry for the Padina tailings dam. Mohr-Coulomb (M-C) failure criterion was used in the analysis. The material properties of the soils are given in Table 1. The results of this study are compared to Slide2 results as well as those of Tzenkov (2008).

Geometry and Properties

Table 1 – Material Properties

No.	Material	Mass Density (g/cm^3)	Poisson's Ratio v	Cohesion, c (kPa)	Friction angle, ϕ (^{0})	Modulus of Elasticity E (kPa)
1	Rockfill – Lyulyaka Quarry	1.86	0.30	20.00	38.0	75 000
2	Fill	1.89	0.31	22.50	33.70	70 000
3	Rockfill – G. Sakar Quarry	1.86	0.30	20.00	38.00	75 000
4	Counterfill	1.89	0.31	22.50	33.70	70 000
5	Tailings	1.33	0.35	0.00	34.80	16 100
6	Alluvial Clay	1.98	0.34	0.00	24.65	16 300
7	Marly Clay	2.22	0.33	0.00	19.50	38 000
8	Marl	2.40	0.30	30.00	24.50	75 000

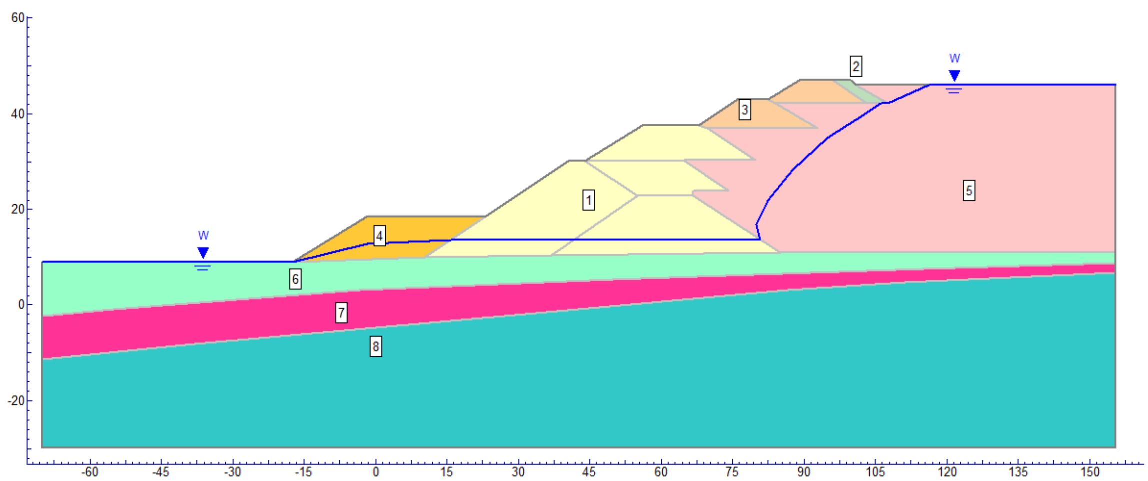


Figure 1 - Geometry

Results:

Slide2 (circular)	Slide2 (non-circular)	RS2	Reference (LEM)	Reference (FEM)
1.41	1.33	1.29	1.39	1.41

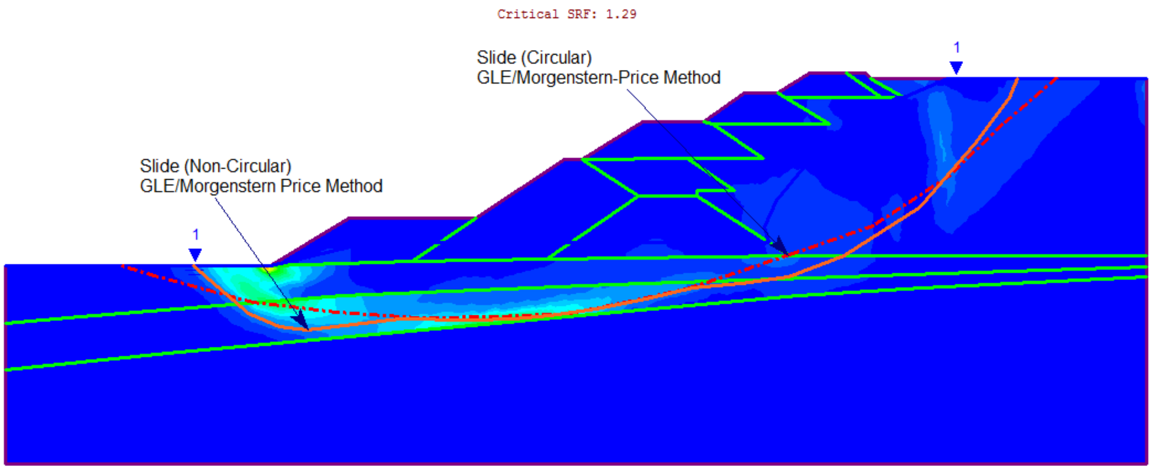


Figure 2 – Maximum Shear Strain Plot

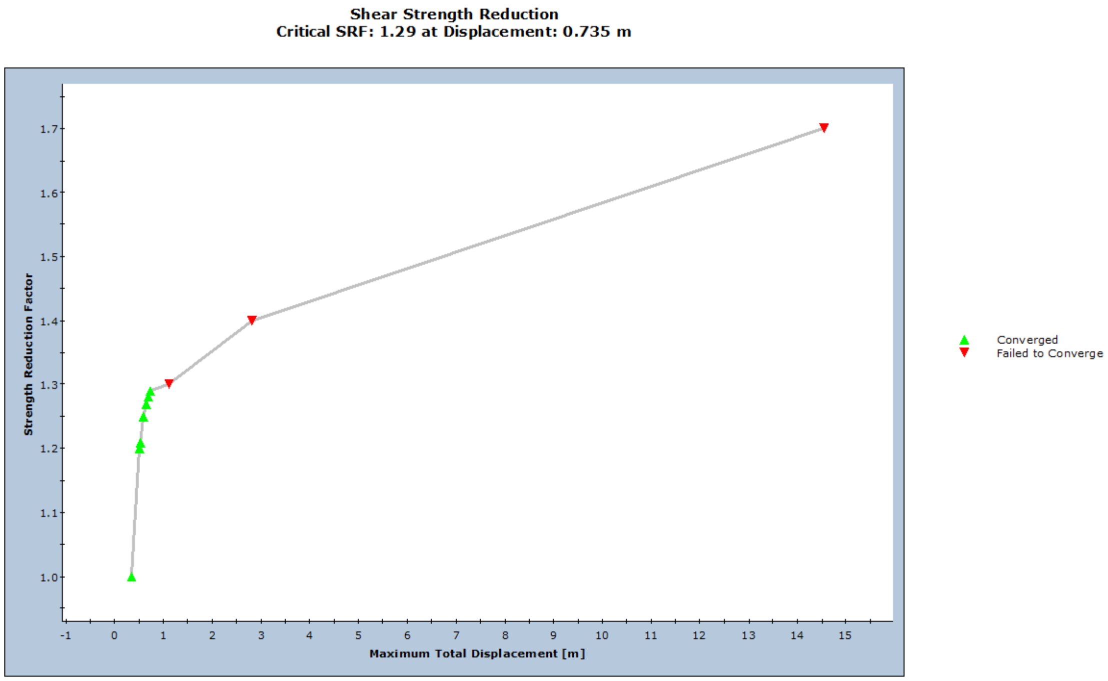


Figure 3 – Graph of Shear Strength Reduction

Introduction

This problem is taken from the paper "Embankment basal stability analysis using shear strength reduction finite element method" by Nakamura, A., Cai, F. & Ugai, K. (2008).

Description

The embankment is constructed over layered soil strata with upper layer being soft, while the lower one is hard bearing stratum. The thickness of the upper softer strata is varied, while that of lower bearing strata and the embankment dimensions are kept constant. The analysis is carried out for different thicknesses both with SSR and LEM techniques and the results obtained are compared with the published ones. The exact geometry is as given in Figure 1. The soil properties of the embankment layers are given in Table 1.

Geometry and Properties

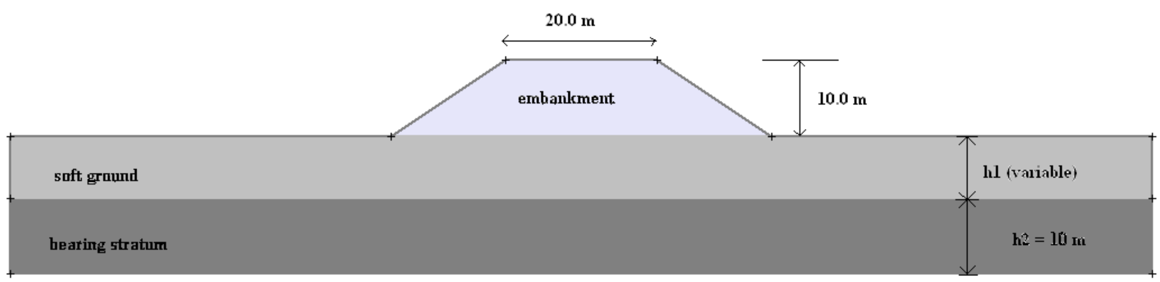


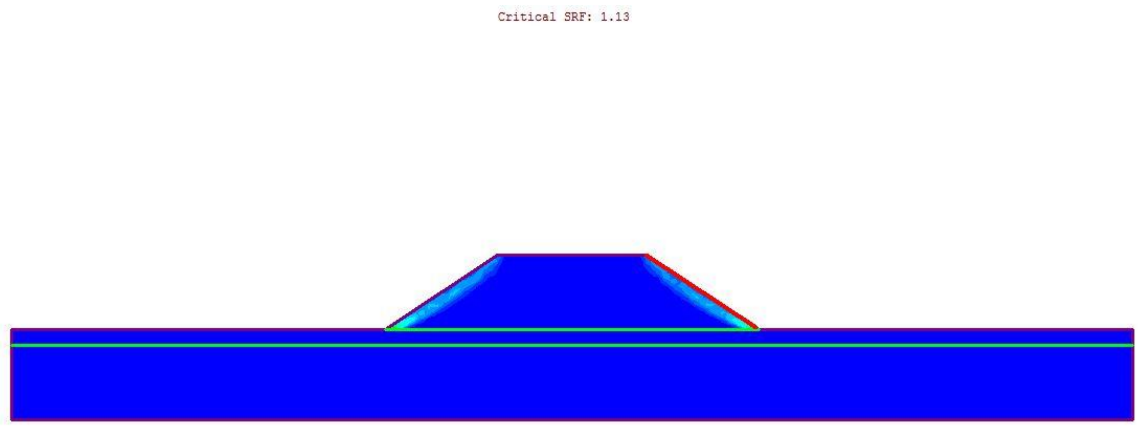
Figure 1 - Embankment geometry

Table 1 - Material properties

Layer	φ (Deg)	c (kN/m²)
Embankment	35.0	0.00
Soft ground	0.0	35.0
Bearing stratum	0.0	100.0

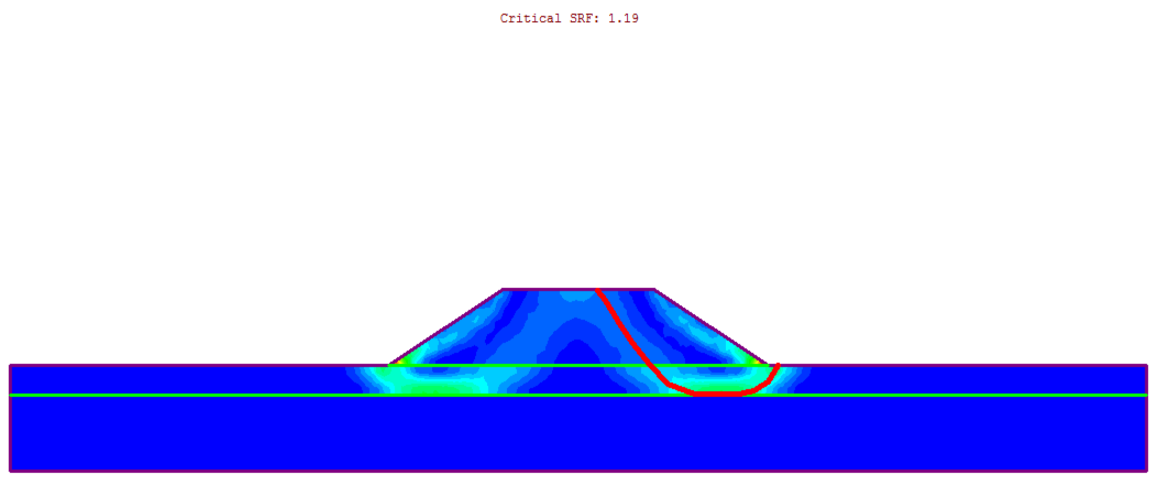
For all soils the Dilation angle (ψ) = Friction angle (φ).

Results: Case 1 (h1 = 2m)



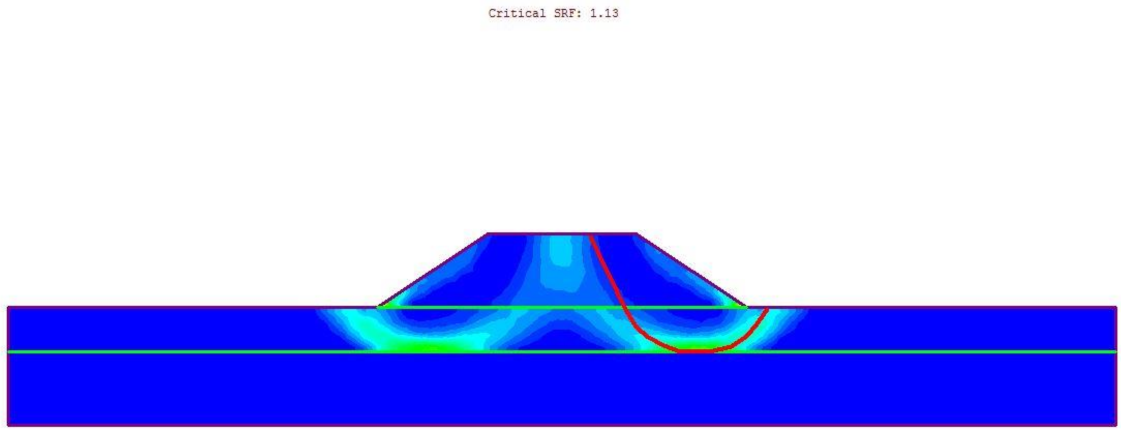
RESULTS OBTAINED (FS)		REFERENCE	
Slide2 (Spencer)	**RS2 (SSR)**	**LEM**	**FEM**
1.05	1.13	1.21	1.24

Results: Case 2 (h1 = 4m)



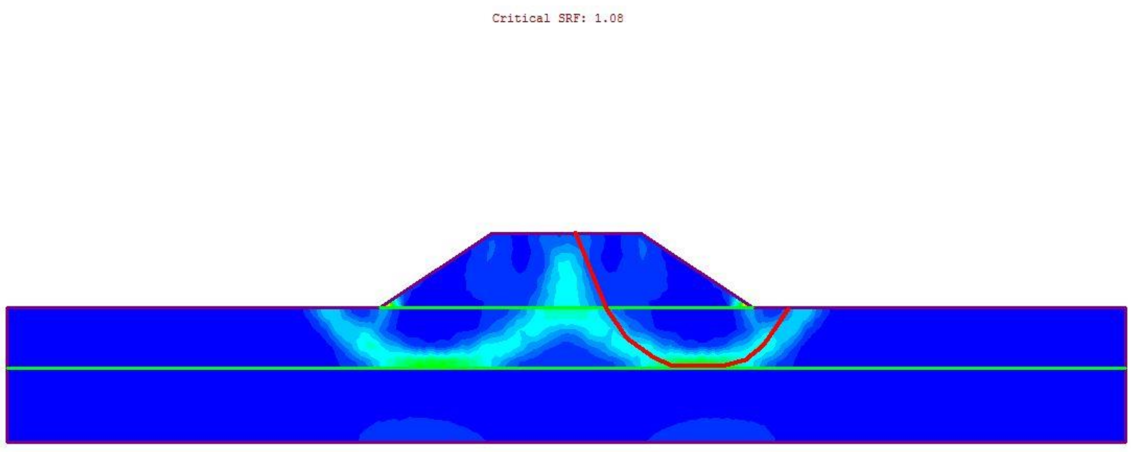
RESULTS OBTAINED (FS)		REFERENCE	
Slide2 (Spencer)	**RS2 (SSR)**	**LEM**	**FEM**
1.16	1.19	1.22	1.16

Results: Case 3 (h1 = 6m)



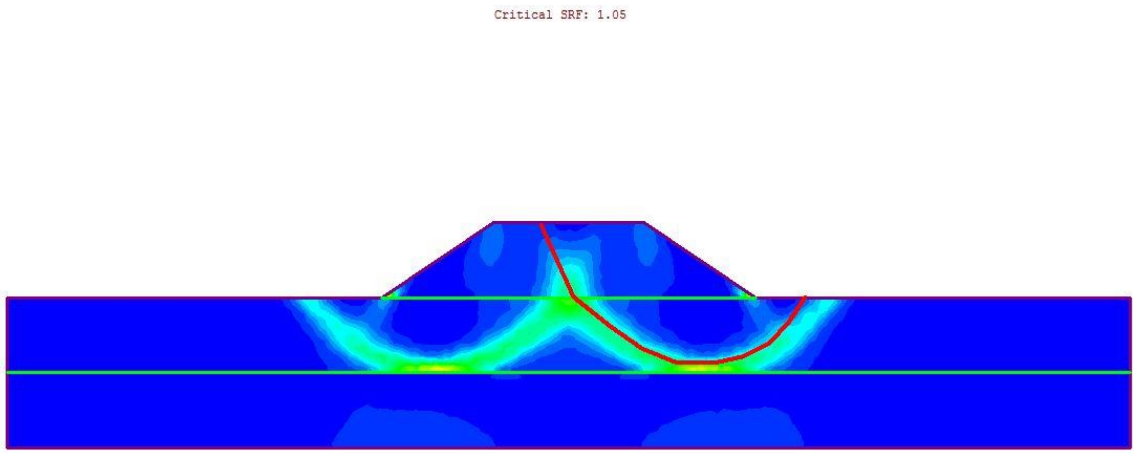
RESULTS OBTAINED (FS)		REFERENCE	
Slide2 (Spencer)	RS2 (SSR)	LEM	FEM
1.10	1.13	1.22	1.16

Results: Case 4 (h1 = 8m)



RESULTS OBTAINED (FS)		REFERENCE	
Slide2 (Spencer)	RS2 (SSR)	LEM	FEM
1.13	1.08	1.10	1.10

Results: Case 5 (h1 = 10m)



RESULTS OBTAINED (FS)		REFERENCE	
Slide2 (Spencer)	**RS2 (SSR)**	**LEM**	**FEM**
1.05	1.05	1.08	1.08

Introduction

This problem is taken from the paper "Strength reduction FEM in stability analysis of soil slopes subjected to transient unsaturated seepage" by Huang, M. and Jia, Cang-Qin (2009).

Description

The problem involves the stability analysis of an earth dam subjected to steady & transient unsaturated seepage. The geometry of the earth dam under consideration is given in Figure 1.

Geometry and Properties

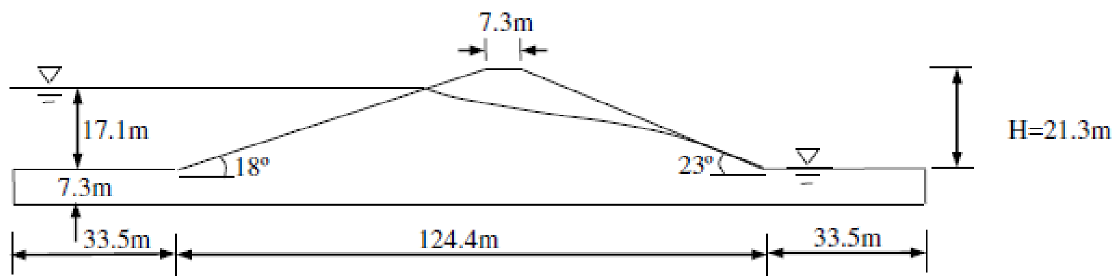


Figure 1 - Dam Geometry

Table 1 – Soil Properties

Cohesion, c (kPa)	Friction angle, ϕ (^{0})	Unit weight, γ (kN/m^3)	Elastic modulus, E (kPa)	Poisson ratio, ν
13.8	37	18.2	$1x10^5$	0.3

Results: Case 1

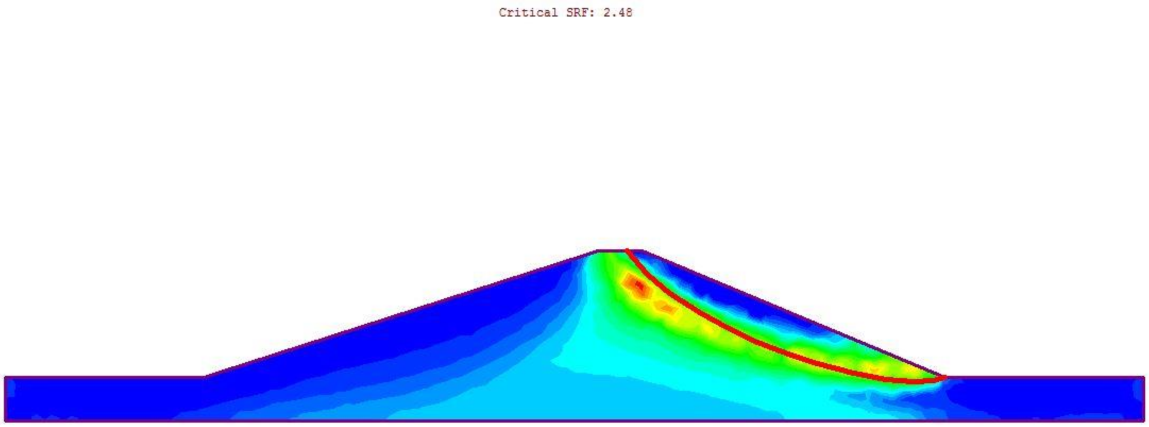


Figure 2 - Dry dam (without a free water surface)

RESULTS OBTAINED					REFERENCE	
Slide2 (Safety Factors)				RS2 (SSR)	LEM	FEM
Bishop	Janbu	Spencer	GLE/ Morgenstern-Price			
2.45	2.32	2.44	2.42	2.48	2.43	2.50

Results: Case 2

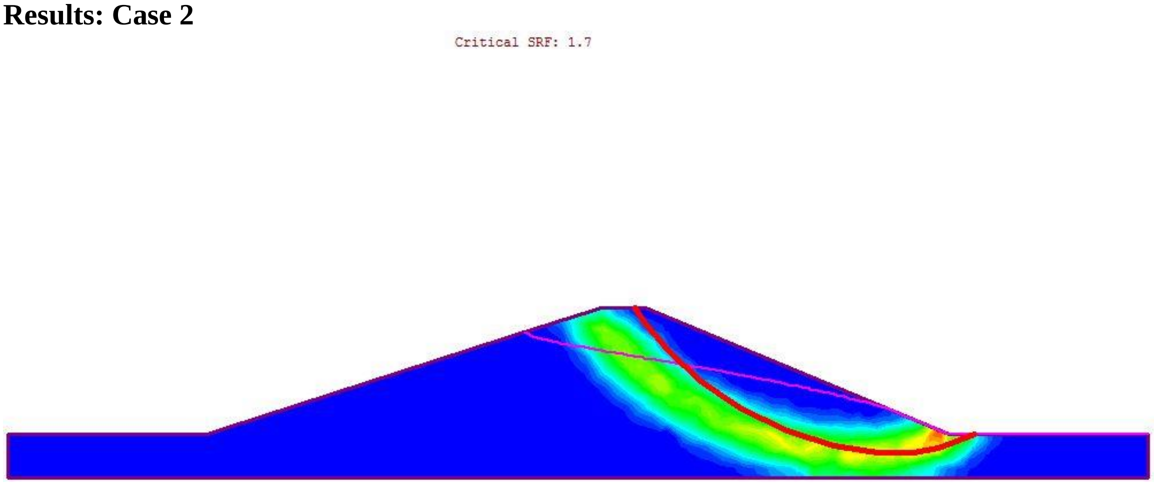


Figure 3 - Dam (downstream) with steady free surface (steady seepage)

	RESULTS OBTAINED					REFERENCE	
	Slide2 (Safety Factors)				RS2 (SSR)	LEM	FEM
	Bishop	Janbu	Spencer	GLE/ Morgenstern-Price			
Downstream	1.64	1.55	1.73	1.71	1.70	1.70	1.78

Results: Case 3

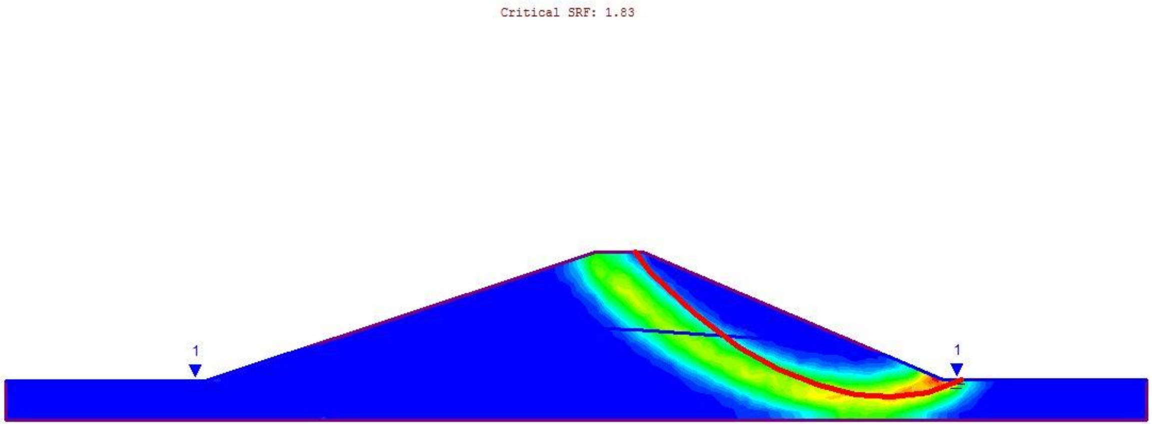


Figure 4 - Dam (downstream) with free surface 90 h after rapid drawdown

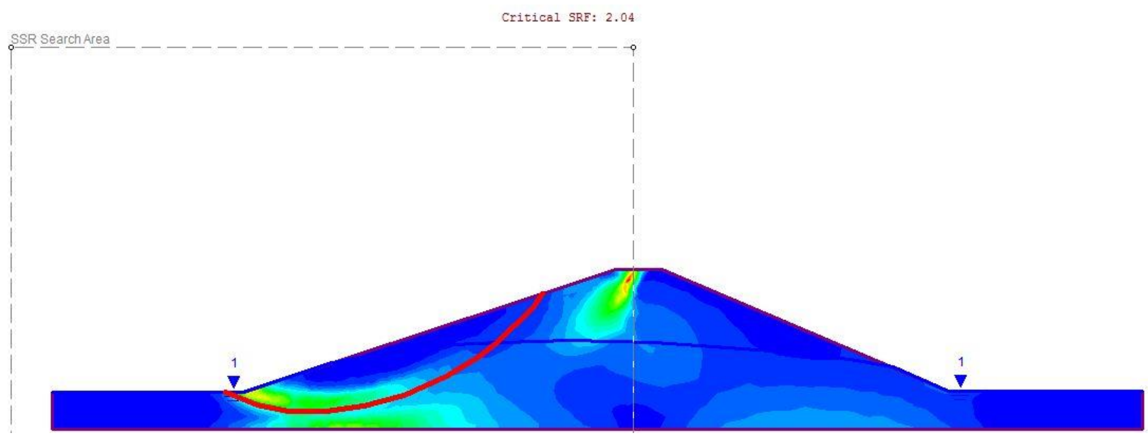


Figure 5 - Dam (upstream) with free surface 90 h after rapid drawdown

	RESULTS OBTAINED					REFERENCE	
	Slide2 (Safety Factors)				RS2 (SSR)	LEM	FEM
	Bishop	Janbu	Spencer	GLE/ Morgenstern-Price			
Downstream	1.77	1.68	1.88	1.85	1.83	1.92	2.08
Upstream	1.99	1.89	2.07	2.06	2.04	2.03	-

Results: Case 4

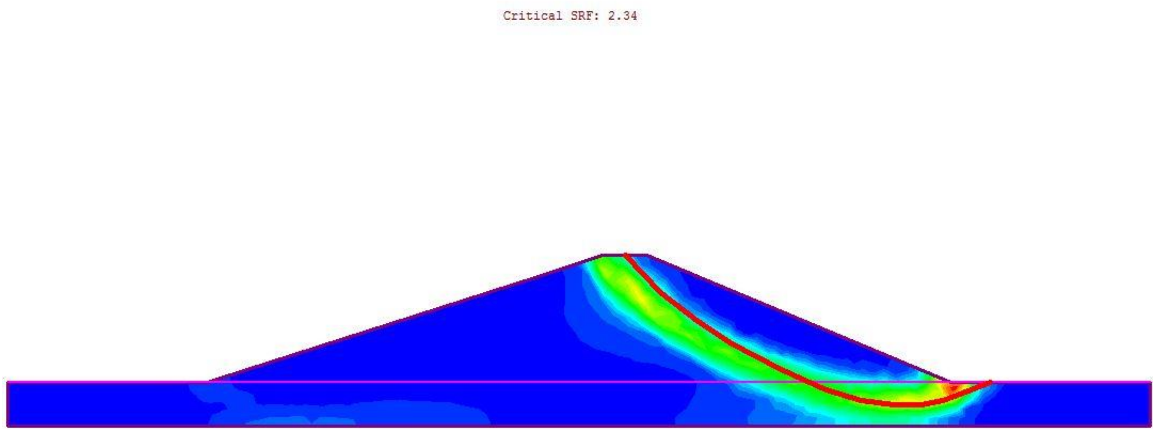


Figure 6 - Dam (downstream) with free surface 1500 h after rapid drawdown

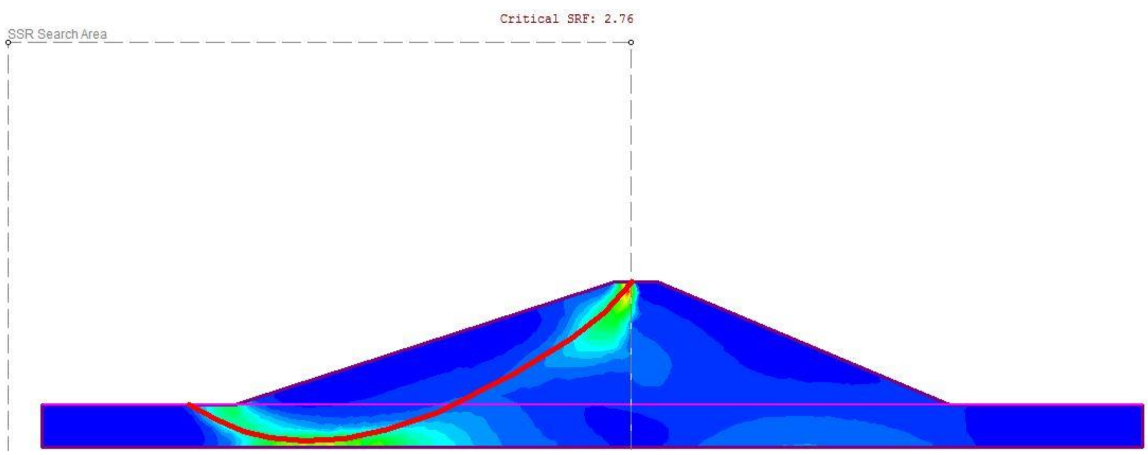


Figure 7 - Dam (upstream) with free surface 1500 h after rapid drawdown

	RESULTS OBTAINED					REFERENCE	
	Slide2 (Safety Factors)				RS2 (SSR)	LEM	FEM
	Bishop	Janbu	Spencer	GLE/ Morgenstern-Price			
Downstream	2.22	2.09	2.35	2.31	2.34	2.38	2.42
Upstream	2.66	2.52	2.79	2.76	2.76	2.80	-

Introduction

This problem is taken from the paper "Stability of Seismically Loaded Slopes Using Limit Analysis" by Loukidis, D., Bandini, P., and Salgado, R. (2003).

Description

The problem involves determination of the critical seismic load coefficient (K_c) for both homogeneous (Figure 1) and non-homogeneous slopes (Figure 2). The results from finite element method are compared to those from limit equilibrium.

Geometry and Properties

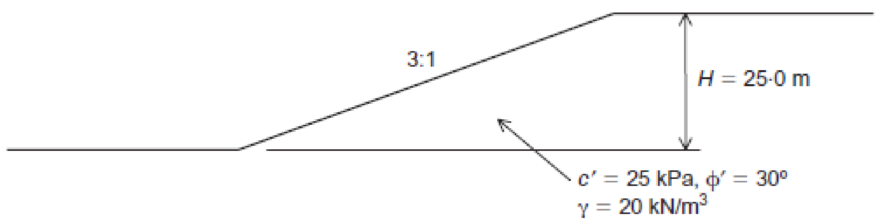


Figure 1 - Homogeneous slope geometry

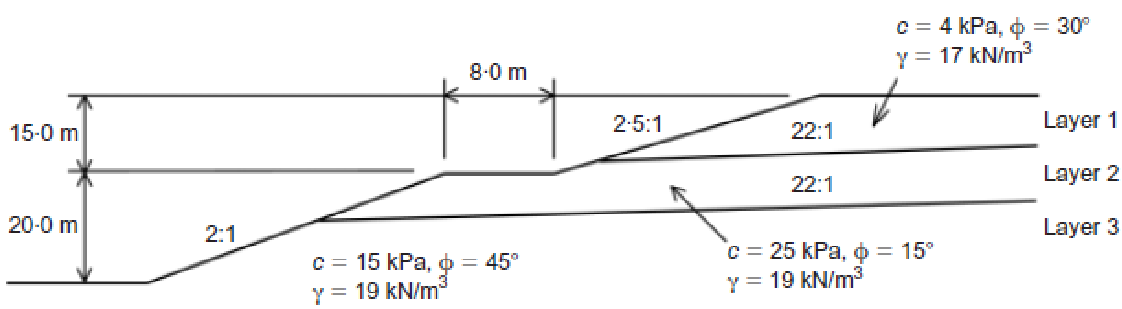


Figure 2 - Non-homogeneous slope geometry

K_c is defined as the ratio between critical horizontal acceleration and acceleration due to gravity (g), where critical horizontal acceleration is that horizontal acceleration for which any given slope is just stable (i.e. safety factor = 1).

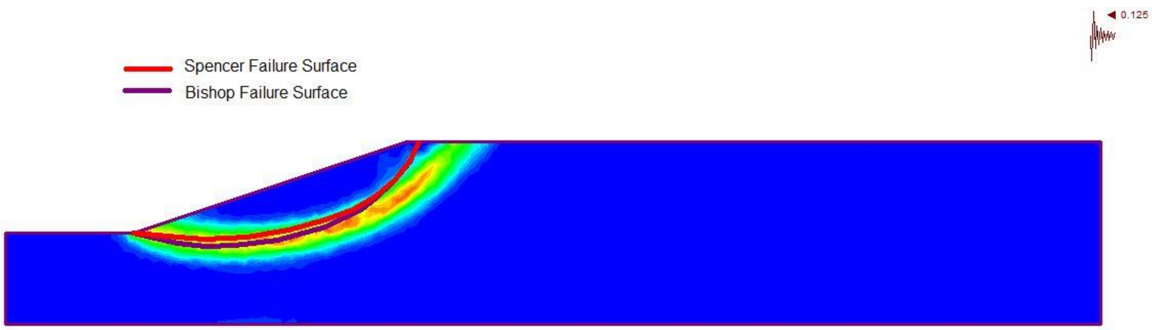
Analytical Solutions

Limit analysis uses the lower and upper bound theorems of plasticity theory to find the rigorous lower and upper bound solutions of a stability problem. The lower bound theorem states that the load carried by a statically admissible stress field is not greater than the actual collapse load. A statically admissible stress field must not violate the yield criterion at any point of the soil mass, and must satisfy the equilibrium equations and the stress boundary conditions. On the other hand, the upper bound theorem states that collapse is imminent or already under way for a kinematically admissible velocity field (or strain rate field), meaning that the true collapse load is always less than, or at most equal to, the calculated load for such a condition. A kinematically admissible velocity field satisfies compatibility, the flow rule of the material, and the velocity boundary conditions.

The finite element method can also be employed to analyze pseudo-statically the two-dimensional seismic slope stability problem and obtain an accurate approximation of the exact collapse load.

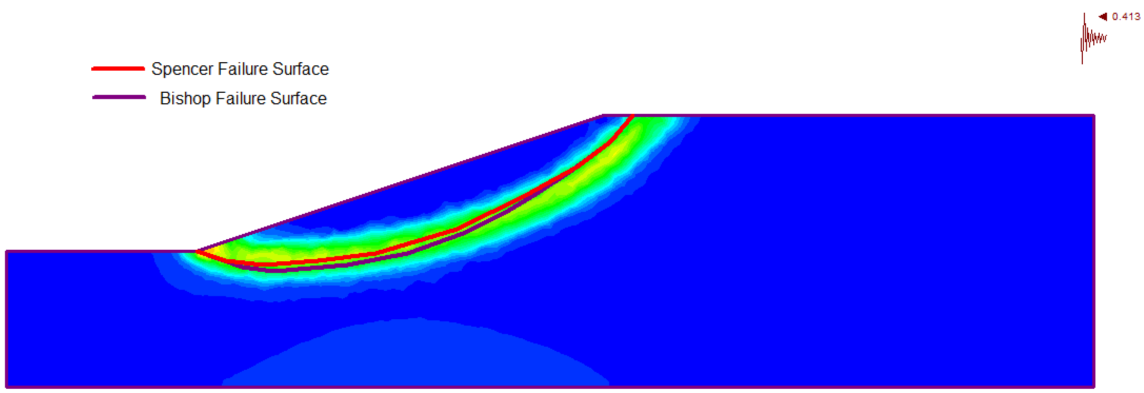
Results: Case 1 (Ru = 0.5)

Slide2		RS2 (SSR)	Reference					
Bishop	Spencer		Upper Bound	Lower Bound	FEM	Bishop	Spencer	Log spiral
0.118	0.132	0.125	0.145	0.126	0.132	0.127	0.131	0.132



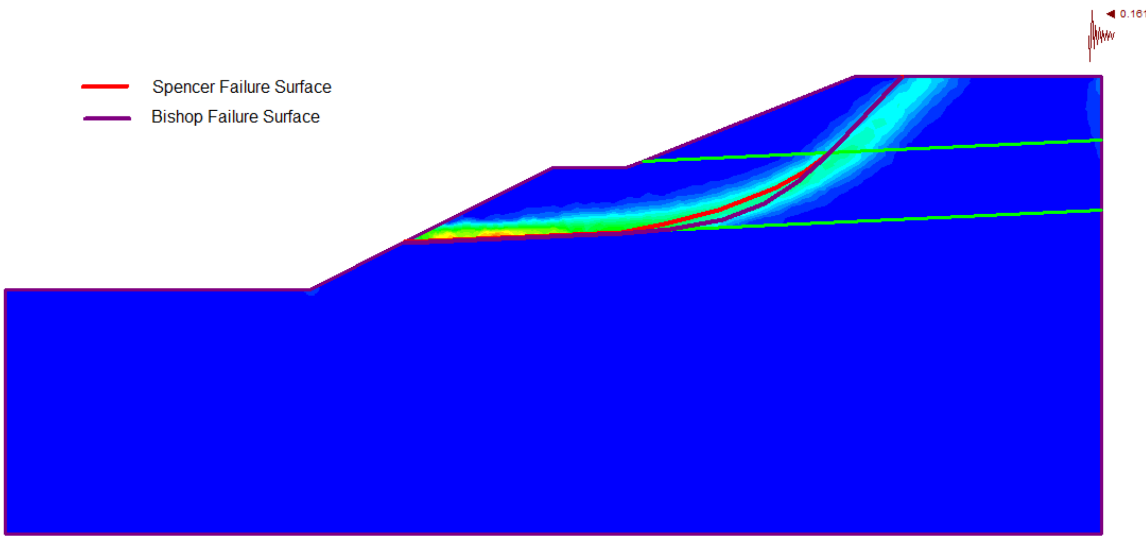
Results: Case 2 (Ru = 0)

Slide2		RS2 (SSR)	Reference					
Bishop	Spencer		Upper Bound	Lower Bound	FEM	Bishop	Spencer	Log spiral
0.425	0.431	0.413	0.454	0.423	0.433	0.426	0.431	0.432



Results: Case 3 (Ru = 0)

Slide2		RS2 (SSR)	Reference					
Bishop	Spencer		Upper Bound	Lower Bound	FEM	Bishop	Spencer	Log spiral
0.155	0.151	0.161	0.172	0.148	0.161	0.155	-	-



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6. Nakamura, A., Cai, F. & Ugai, K. (2008). "Embankment basal stability analysis using shear strength reduction finite element method." 10th International Symposium on Landslides and Engineered Slopes, Xi'an, China.

7. Huang, M. and Jia, Cang-Qin (2009) "Strength reduction FEM in stability analysis of soil slopes subjected to transient unsaturated seepage." Computers and Geotechnics 36(1-2), 93-101.

8. Loukidis, D., Bandini, P., and Salgado, R. (2003). "Stability of Seismically Loaded Slopes Using Limit Analysis." Geotechnique, 53(5), 463-479.