RS2

2D Finite Element Program
for Slope and Excavation Stability Analyses

Slope Stability Verification Manual – Pt 4

Table of Contents

Introduction

This document contains a series of slope stability problems that were used to verify the results of the shear strength reduction technique in *RS2*. The problems focus on the new strength criteria that have been added to *RS2*. Results from *RS2* are compared to the limit equilibrium results from *Slide2*. These verification tests come from *Slide2* verification problems as well as from published reports.

The document consists of problems with simple geometries that show that the new strength models have been implemented correctly in *RS2* and that they give accurate results. The document also presents more complex problems from literature that show how these new models can be applied to real-life problems. References for the verification problems are included at the end of the document.

The *RS2* files for these problems can be found in your *RS2* installation folder.

Verification Problem #1

Slope, homogeneous

1.1 Introduction

In 1988 a set of 5 basic slope stability problems, together with 5 variants, was distributed both in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Giam & Donald (1989)). This is the ACADS 1(a) problem.

1.2 Problem Description

This problem as shown in Figure 1.1 is the simple case of a total stress analysis without considering pore water pressures. It represents a homogenous slope with soil properties given in Table 1.1. The factor of safety and its corresponding critical circular failure is calculated.

1.3 Geometry and Material Properties

Table 1.1 – Material Properties

c′ (kN/m²)	ϕ′ (⁰)	γ (kN/m³)
3.0	19.6	20.0

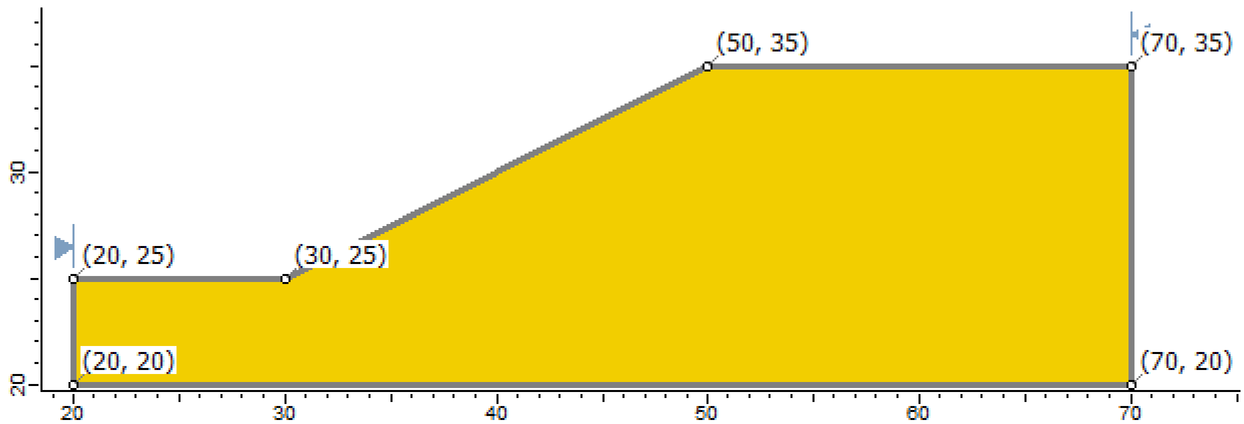


Figure 1.1 – *Slide2* Geometry

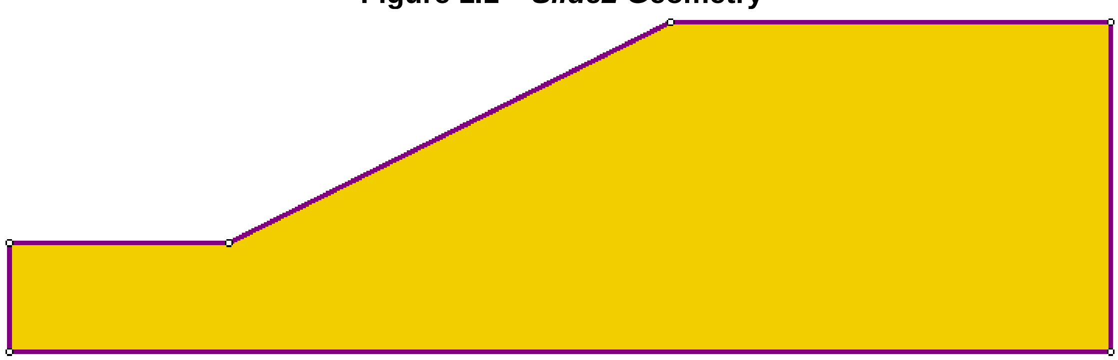


Figure 1.2 – *RS2* Geometry

1.4 Results

Table 1.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	0.986
	GLE	0.986
RS2	SSR	0.98

Note: Reference Factor of Safety = Reference factor of safety = 1.00 [Giam]
Mean Bishop FOS (18 samples) = 0.993
Mean FOS (33 samples) = 0.991

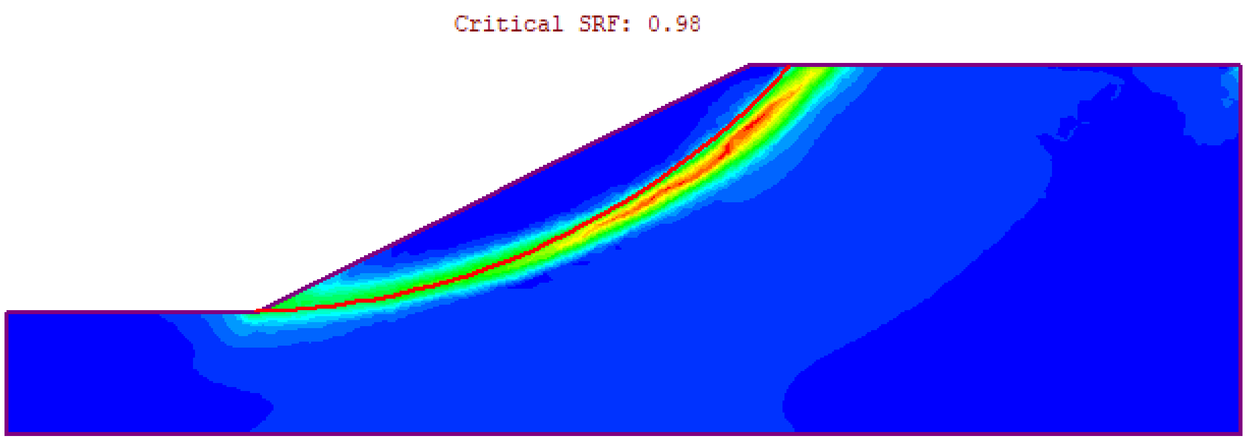


Figure 1.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #2

Slope, homogeneous, tension crack

2.1 Introduction

In 1988 a set of 5 basic slope stability problems, together with 5 variants, was distributed both in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Giam & Donald (1989)). This is the ACADS 1(b) problem.

2.2 Problem Description

Problem #2 has the same slope geometry as verification problem #1, with the addition of a tension crack zone, as shown in Figure 2.1. For this problem, a suitable tension crack depth is required and water is assumed to have filled the tension crack. The tension crack depth can be estimated from the following equations [Craig (1997)].

$$Depth = \frac{2c}{\gamma\sqrt{k_a}} \qquad , k_a = \frac{1-\sin\varphi}{1+\sin\varphi}$$

2.3 Geometry and Material Properties

Table 2.1 – Material Properties

c' (kN/m²)	ϕ' (°)	γ (kN/m³)
32.0	10.0	20.0

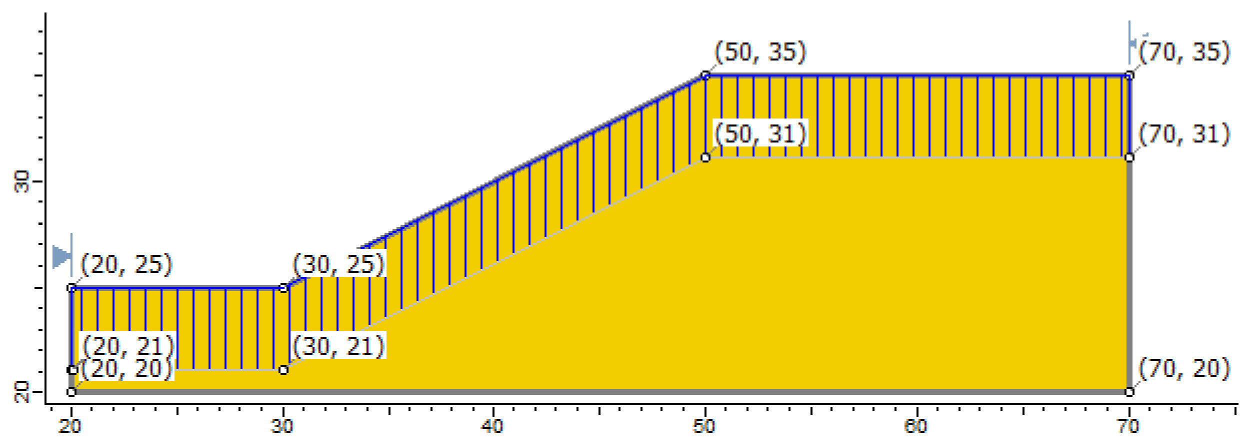


Figure 2.1 – *Slide2* Geometry

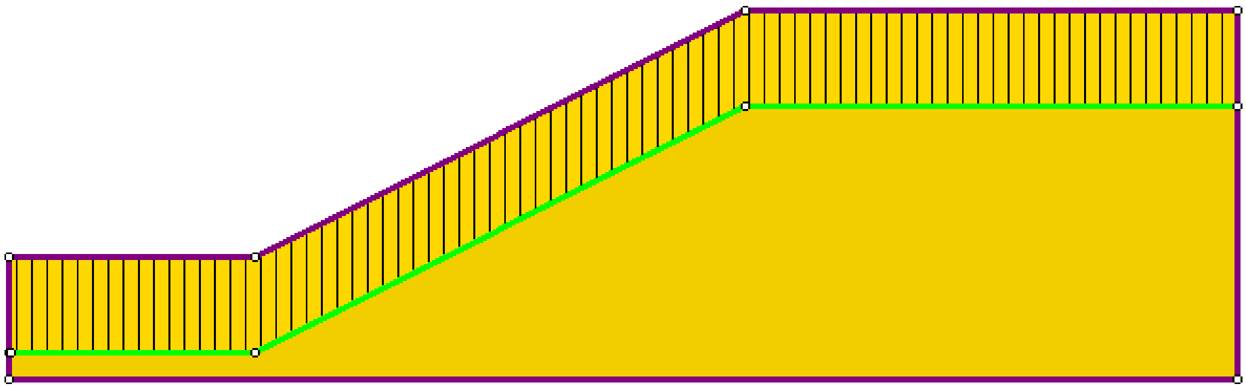


Figure 2.2 – *RS2* Geometry

Note: The Tension Cracks were recreated in *RS2* by setting the Tensile Strength of the material to 0, where the cracks are expressed.

2.4 Results

Table 2.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.592
	GLE	1.592
RS2	SSR	1.63

Note: Reference Factor of Safety = 1.65 [Giam]

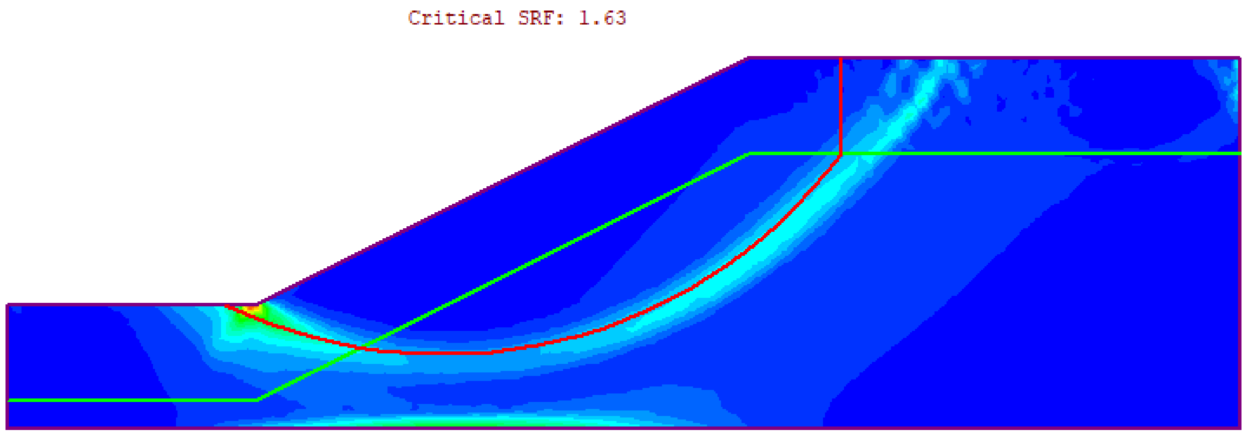


Figure 2.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #3

Slope, (3) materials

3.1 Introduction

In 1988 a set of 5 basic slope stability problems, together with 5 variants, was distributed both in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Giam & Donald (1989)). This is the ACADS 1(c) problem.

3.2 Problem Description

Problem #3 is a non-homogeneous, three layer slope with material properties given in Table 3.1. The factor of safety and its corresponding critical circular failure surface is calculated.

Table 3.1 – Material Properties

	c′ (kN/m²)	ϕ′ (°)	γ (kN/m³)
Soil #1	0.0	38.0	19.5
Soil #2	5.3	23.0	19.5
Soil #3	7.2	20.0	19.5

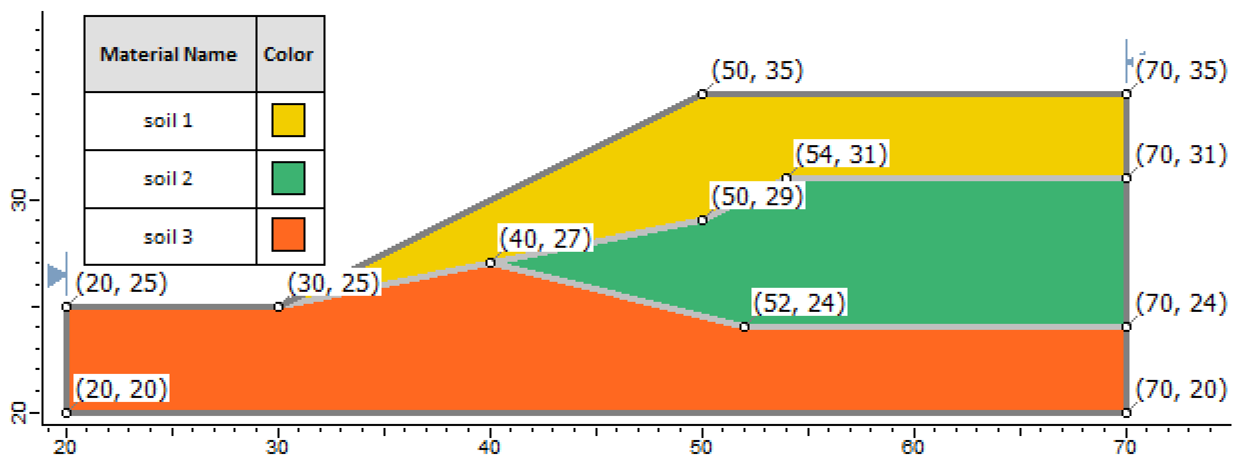


Figure 3.1 – *Slide2* Geometry

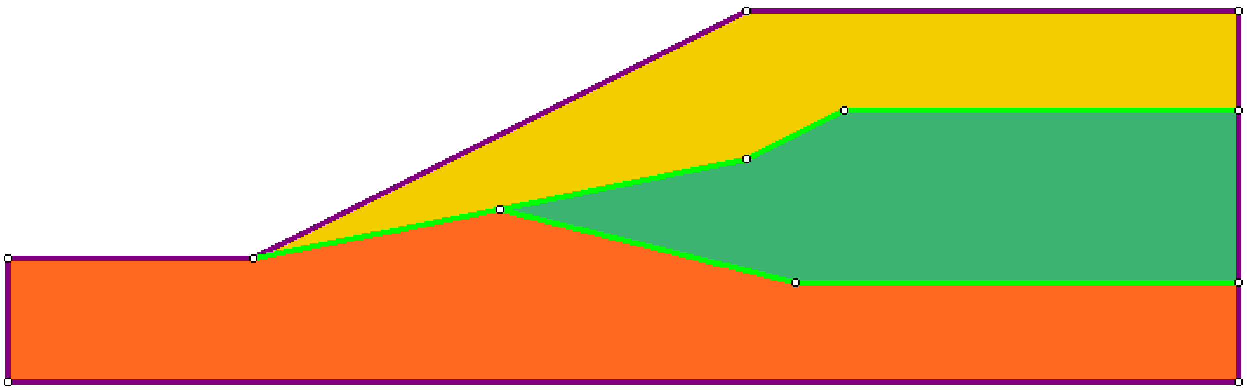


Figure 3.2 – *RS2* Geometry

3.4 Results

Table 3.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.375
	GLE	1.374
RS2	SSR	1.34

Note: Reference factor of safety = 1.39 [Giam]

Mean Bishop FOS (16 samples) = 1.406

Mean FOS (31 samples) = 1.381

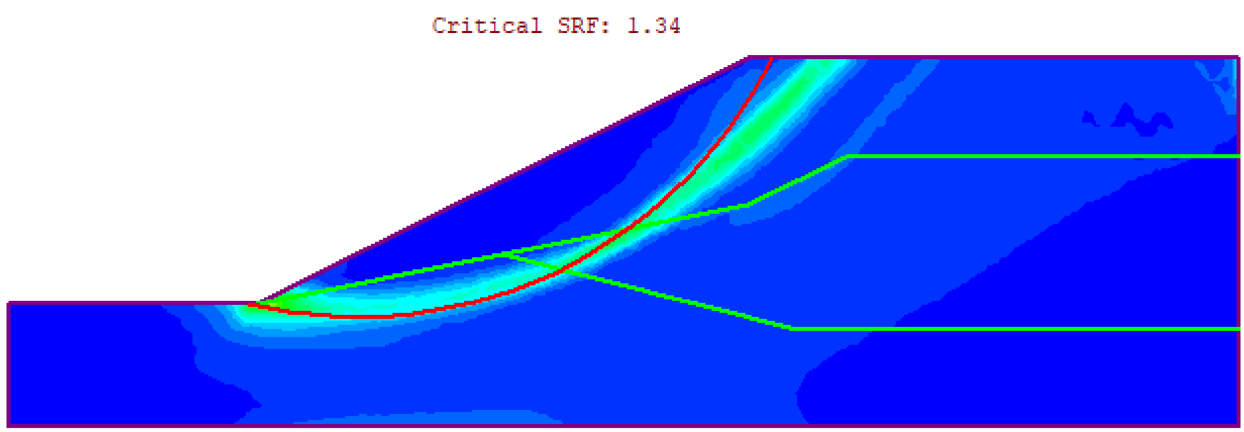


Figure 3.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #4

Slope, (3) materials, seismic

4.1 Introduction

In 1988 a set of 5 basic slope stability problems, together with 5 variants, was distributed both in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Giam & Donald (1989)). This is the ACADS 1(d) problem.

4.2 Problem Description

This Problem #4 is a non-homogeneous, three layer slope with material properties given in Table 4.1 and geometry as shown in Figure 4.1. This problem is identical to #3, but with a horizontal seismically induced acceleration of 0.15g included in the analysis. The factor of safety and its corresponding critical circular failure surface is calculated.

4.3 Geometry and Material Properties

Table 4.1 – Material Properties

	c' (kN/m²)	ϕ' (°)	γ (kN/m³)
Soil #1	0.0	38.0	19.5
Soil #2	5.3	23.0	19.5
Soil#3	7.2	20.0	19.55

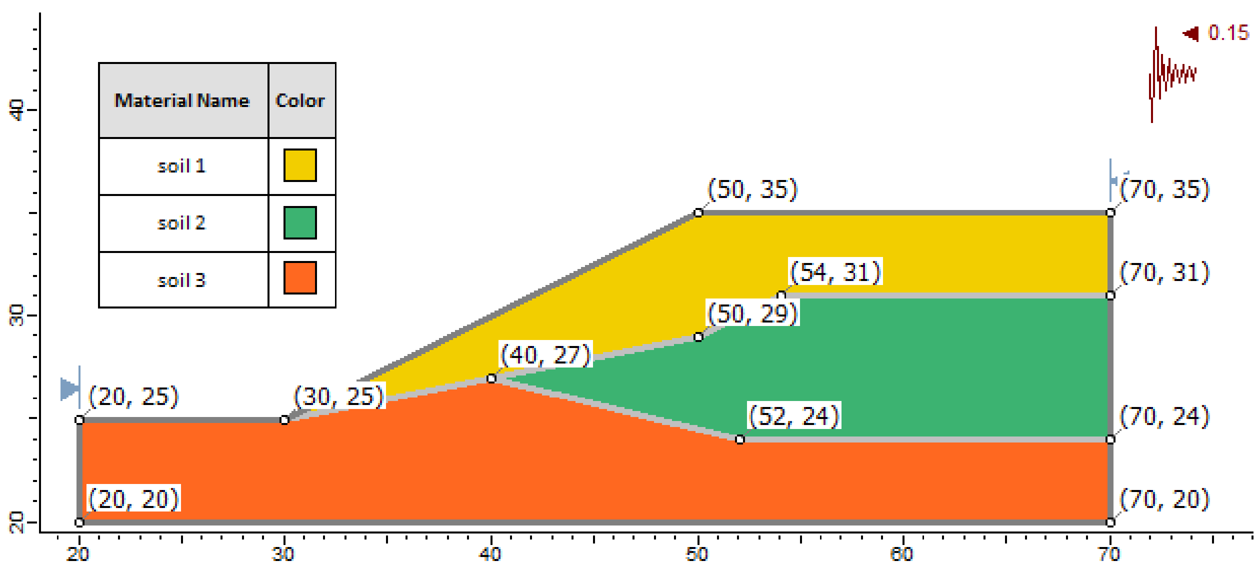


Figure 4.1 – *Slide2* Geometry

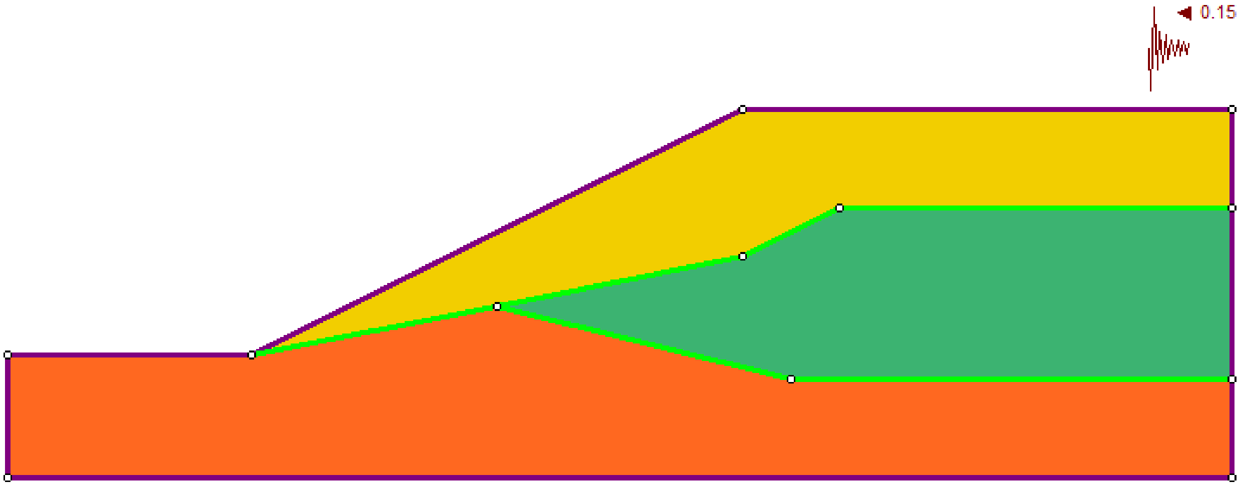


Figure 4.2 – *RS2* Geometry

4.4 Results

Table 4.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	0.991
	GLE	0.989
RS2	SSR	0.95

Note: Reference factor of safety = 1.00 [Giam]

Mean FOS (15 samples) = 0.973

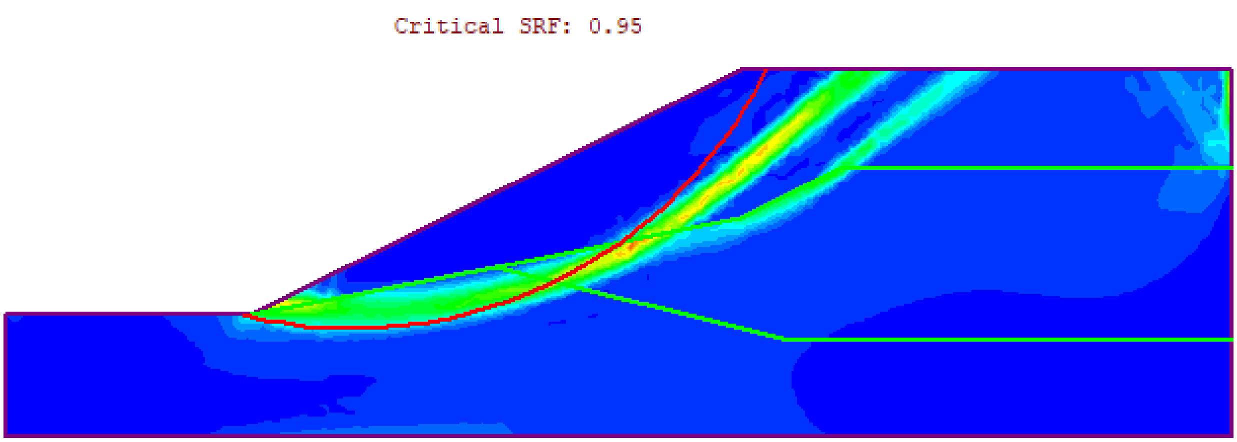


Figure 4.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #5

Dam, (4) materials

5.1 Introduction

In 1988 a set of 5 basic slope stability problems, together with 5 variants, was distributed both in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Giam & Donald (1989)). This is the ACADS 2(a) problem.

5.2 Problem Description

Problem #5 is Talbingo Dam as shown in Figure 5.2. The material properties at the end of construction stage are given in Table 5.1, while the geometrical data are given in Table 5.2. The factor of safety and its corresponding critical circular failure surface is calculated.

5.3 Geometry and Material Properties

Table 5.1 – Material Properties

	c′ (kN/m²)	ϕ′ (⁰)	γ (kN/m³)
Rockfill	0	45	20.4
Transitions	0	45	20.4
Filter	0	45	20.4
Core	85	23	18.1

Table 5.2 – Geometry Data

Pt.#	Xc (m)	Yc (m)	Pt.#	Xc (m)	Yc (m)	Pt.#	Xc (m)	Yc (m)
1	0	0	10	515	65.3	19	307.1	0
2	315.5	162	11	521.1	65.3	20	331.3	130.6
3	319.5	162	12	577.9	31.4	21	328.8	146.1
4	321.6	162	13	585.1	31.4	22	310.7	0
5	327.6	162	14	648	0	23	333.7	130.6
6	386.9	130.6	15	168.1	0	24	331.3	146.1
7	394.1	130.6	16	302.2	130.6	25	372.4	0
8	453.4	97.9	17	200.7	0	26	347	130.6
9	460.6	97.9	18	311.9	130.6	-	-	-

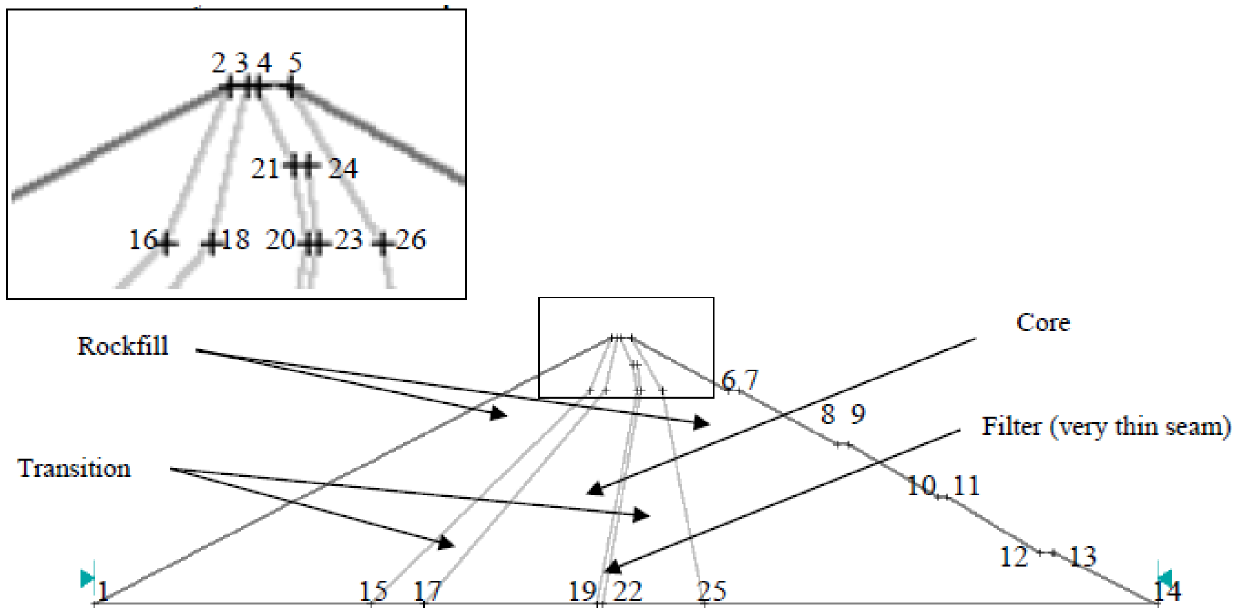


Figure 5.1 – Geometry

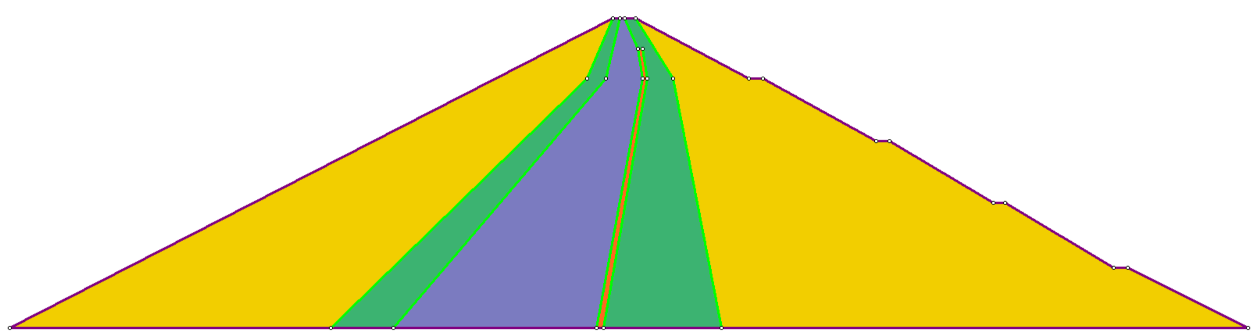


Figure 5.2 – *RS2* Geometry

5.4 Results

Table 5.3 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	1.948
	GLE	1.948
RS2	SSR	1.9

Note: Reference factor of safety = 1.95 [Giam]

Mean FOS (24 samples) = 2.0

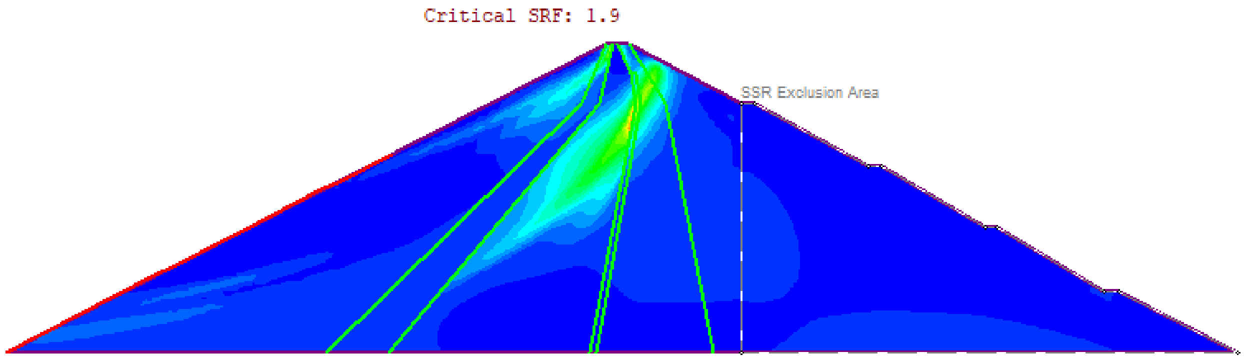


Figure 5.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #6

Dam, (4) materials, predefined slip surface

6.1 Introduction

In 1988 a set of 5 basic slope stability problems, together with 5 variants, was distributed both in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Giam & Donald (1989)). This is the ACADS 2(b) problem.

6.2 Problem Description

Problem #6 is identical to verification problem #5, except a single circular slip surface of known center and radius, is analyzed. See problem #5 for material properties and boundary coordinates

6.3 Geometry and Predefined Slip Surface

Table 6.1 – Data for Slip Circle

Xc (m)	Yc (m)	Radius (m)
100.3	291.0	278.8

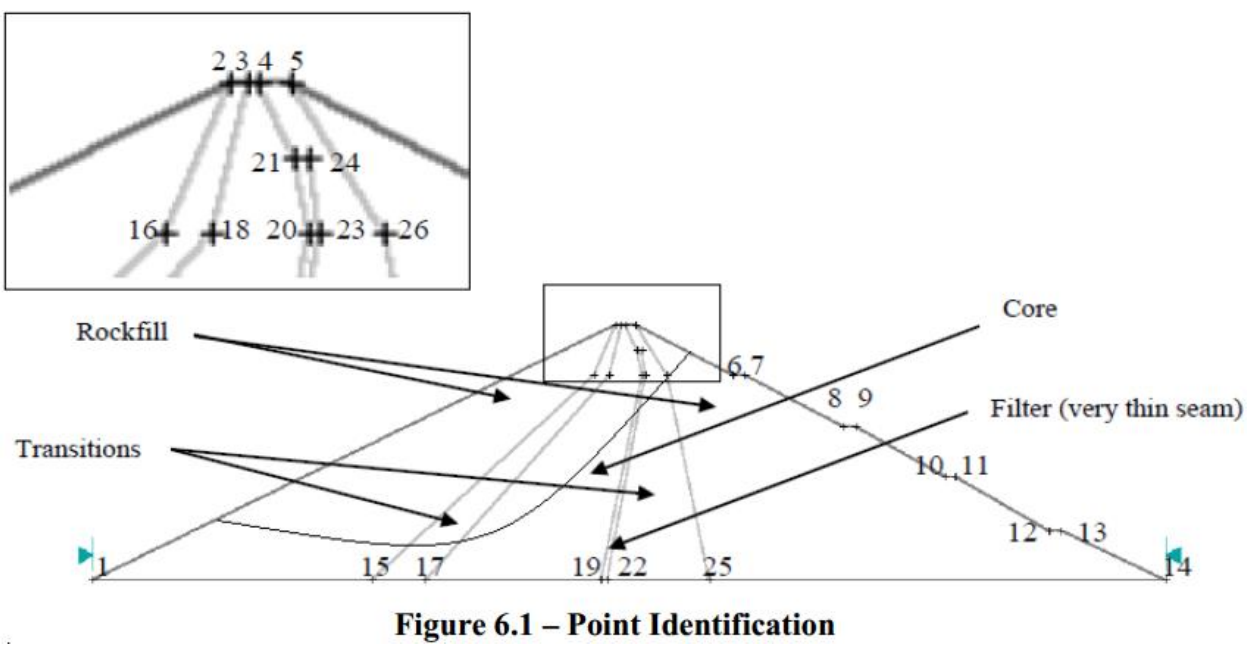


Figure 6.1 – Geometry

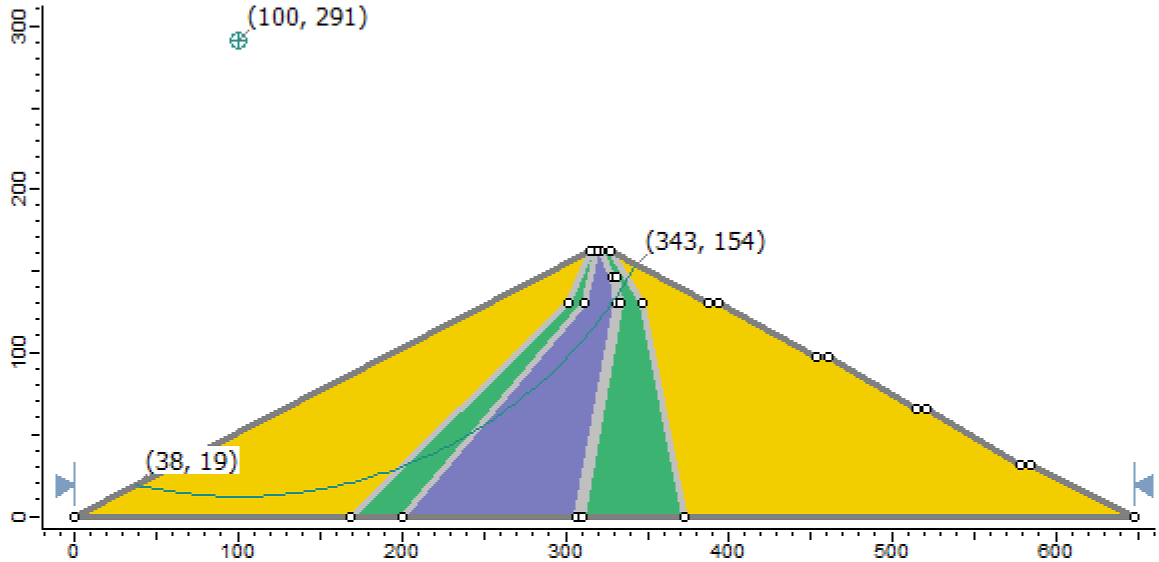


Figure 6.2 – *Slide2* Geometry

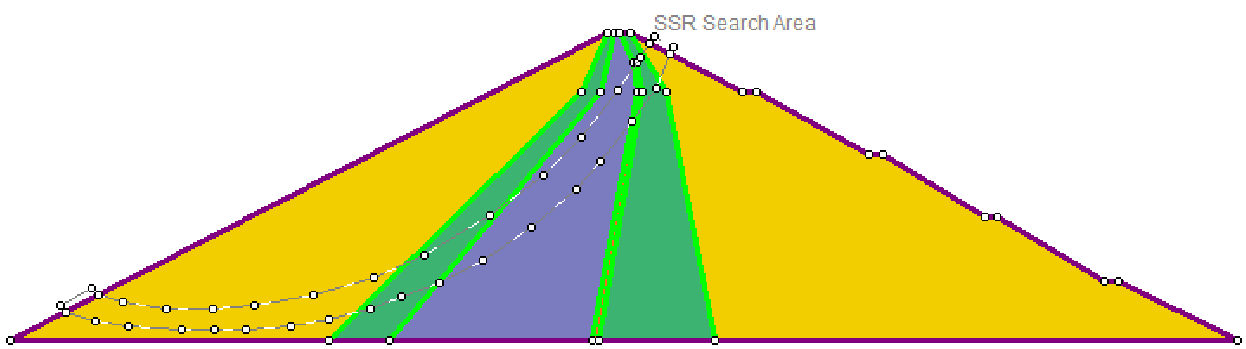


Figure 6.3 – *RS2* Geometry

Note: An SSR Search Area was used to define the slope failure surface in *RS2*.
Soil properties in Problem #6 are the same as Problem #5.

6.4 Results

Table 6.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	2.292
	GLE	2.301
RS2	SSR	2.15

Note: Reference factor of safety = 2.29 [Giam]

Mean Bishop FOS (11 samples) = 2.204

Mean FOS (24 samples) = 2.239

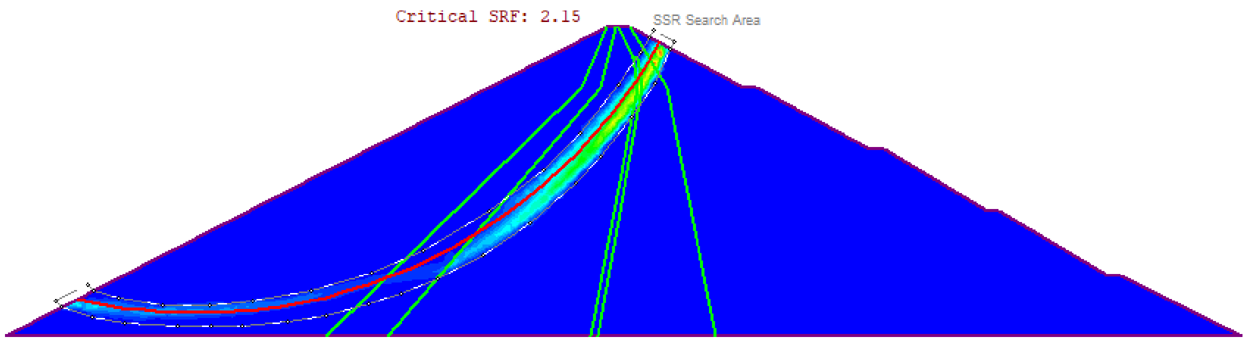


Figure 6.4 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #7

Slope, (2) materials, weak layer

7.1 Introduction

In 1988 a set of 5 basic slope stability problems, together with 5 variants, was distributed both in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Giam & Donald (1989)). This is the ACADS 3(a) problem.

7.2 Problem Description

This problem has material properties given in Table 7.1, and the geometry is shown in Figure 7.1. The water table is assumed to coincide with the base of the weak layer. The effect of negative pore water pressure above the water table is to be ignored (i.e. u=0 above water table). The effect of the tension crack is also to be ignored in this problem. The factor of safety and its corresponding critical non-circular failure surface is calculated.

Note: Values of 45, 65 and 135,155 degrees are used for the block search line projection angles. Line should be in the middle of the seam.

7.3 Geometry and Material Properties

Table 7.1 – Material Properties

	c' (kN/m²)	ϕ' (⁰)	γ (kN/m³)
Soil #1	28.5	20.0	18.84
Soil #2	0	10.0	18.84

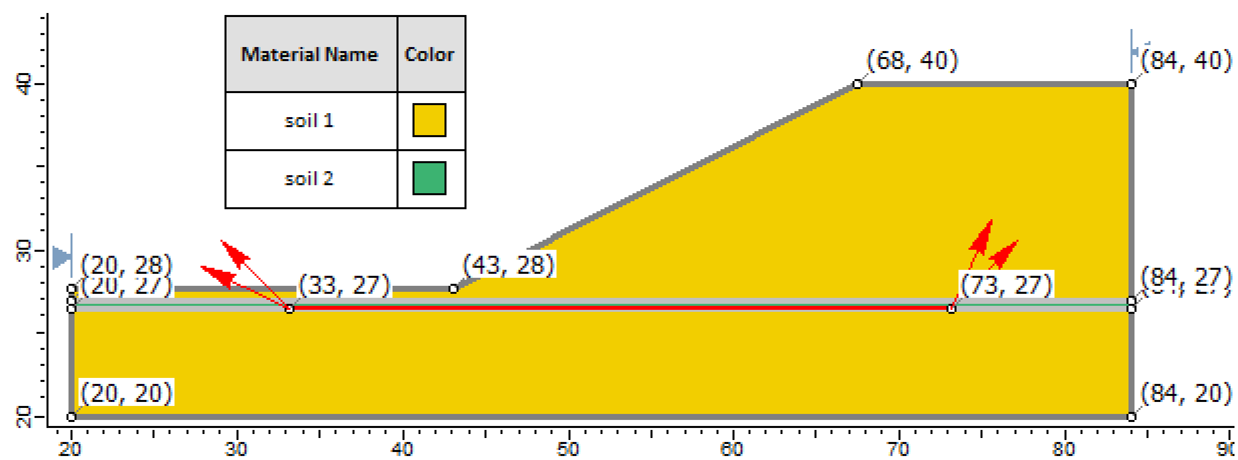


Figure 7.1 – *Slide2* Geometry

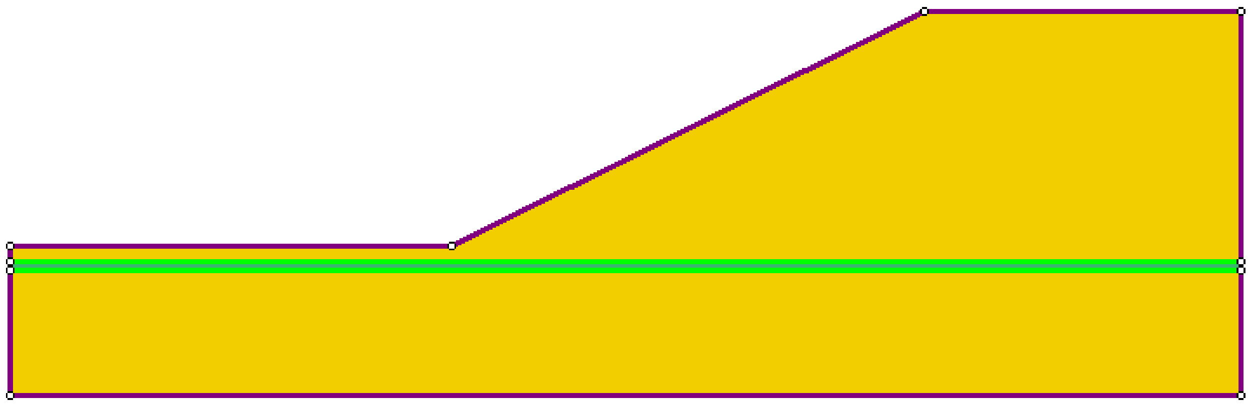


Figure 7.2 – *RS2* Geometry

7.4 Results

Table 7.2 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	1.257
	GLE	1.246
RS2	SSR	1.24

Note: Reference factor of safety = 1.24 – 1.27 [Giam]
Mean Non-circular FOS (19 samples) = 1.293

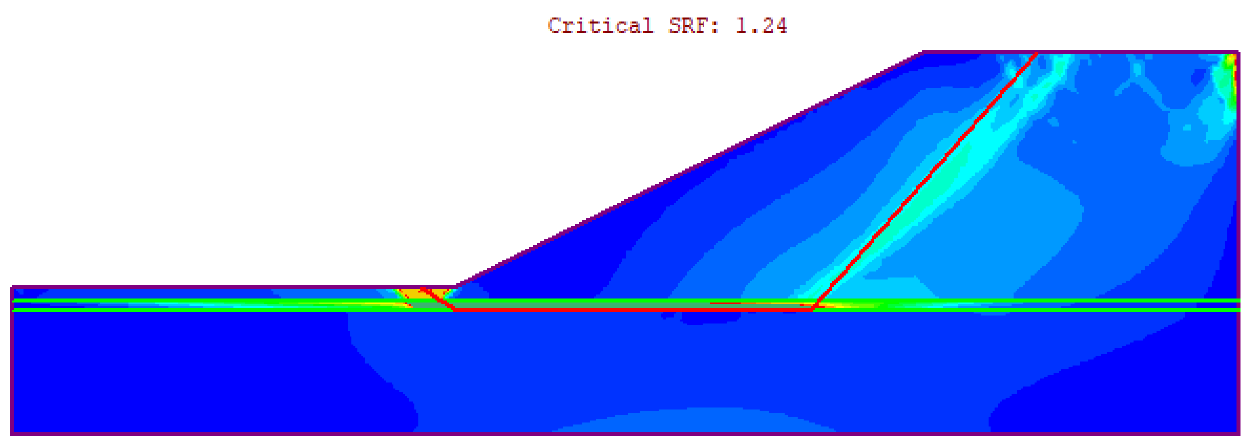


Figure 7.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #9

Slope, (2) materials, weak layer, water table, distributed load

9.1 Introduction

In 1988 a set of 5 basic slope stability problems, together with 5 variants, was distributed both in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Giam & Donald (1989)). This is the ACADS 4 problem.

9.2 Problem Description

Problem #9 is shown in Figure 9.1. The soil properties, external loadings and piezometric surface are shown in Table 9.1, Table 9.2 and Table 9.3 respectively. The effect of a tension crack is to be ignored. The noncircular critical slip surface and corresponding factor of safety is calculated.

A block search for the critical non-circular failure surface was carried out by defining a block search polyline object within the weak layer, and variable projection angles from the weak layer to the slope surface.

9.3 Geometry and Material Properties

Table 9.1 – Material Properties

	c' (kN/m²)	ϕ' (⁰)	γ (kN/m³)
Soil #1	28.5	20.0	18.84
Soil #2	0	10.0	18.84

Table 9.2 – External Loadings

Xc (m)	Yc (m)	Normal Stress (kN/m²)
23.00	27.75	20.00
43.00	27.75	20.00
70.00	40.00	20.00
80.00	40.00	40.00

Table 9.3 – Data for Piezometric Surface

Pt.#	Xc (m)	Yc (m)
1	20.0	27.75
2	43.0	27.75
3	49.0	29.8
4	60.0	34.0
5	66.0	35.8
6	74.0	37.6
7	80.0	38.4
8	84.0	38.4

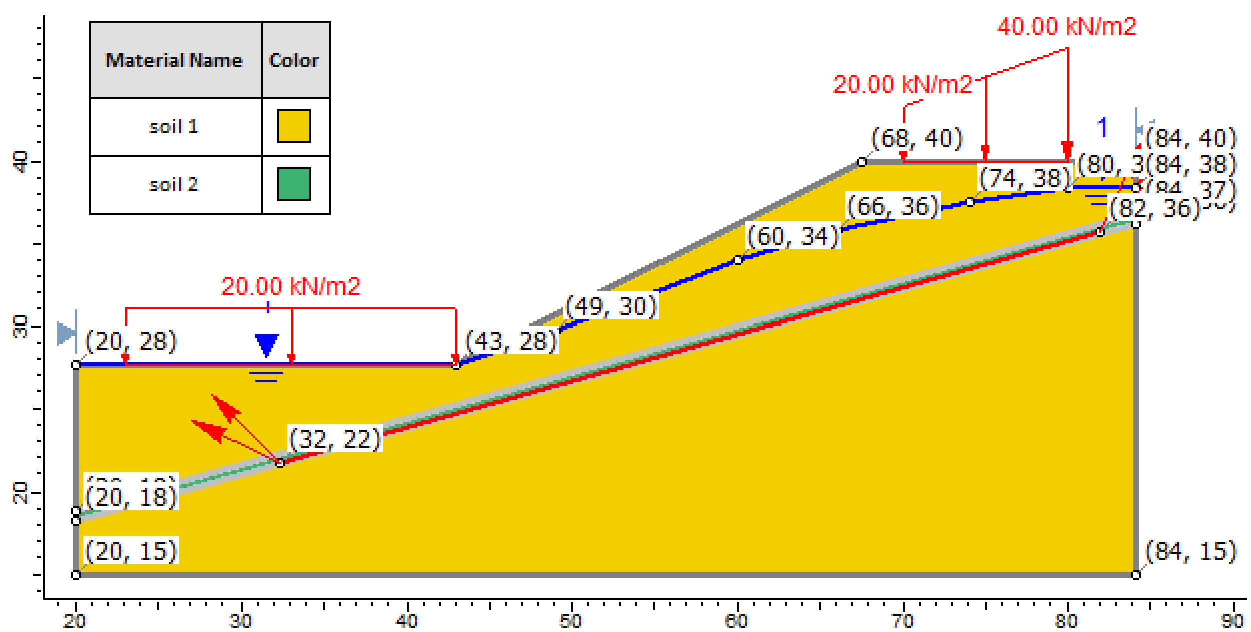


Figure 9.1 – *Slide2* Geometry

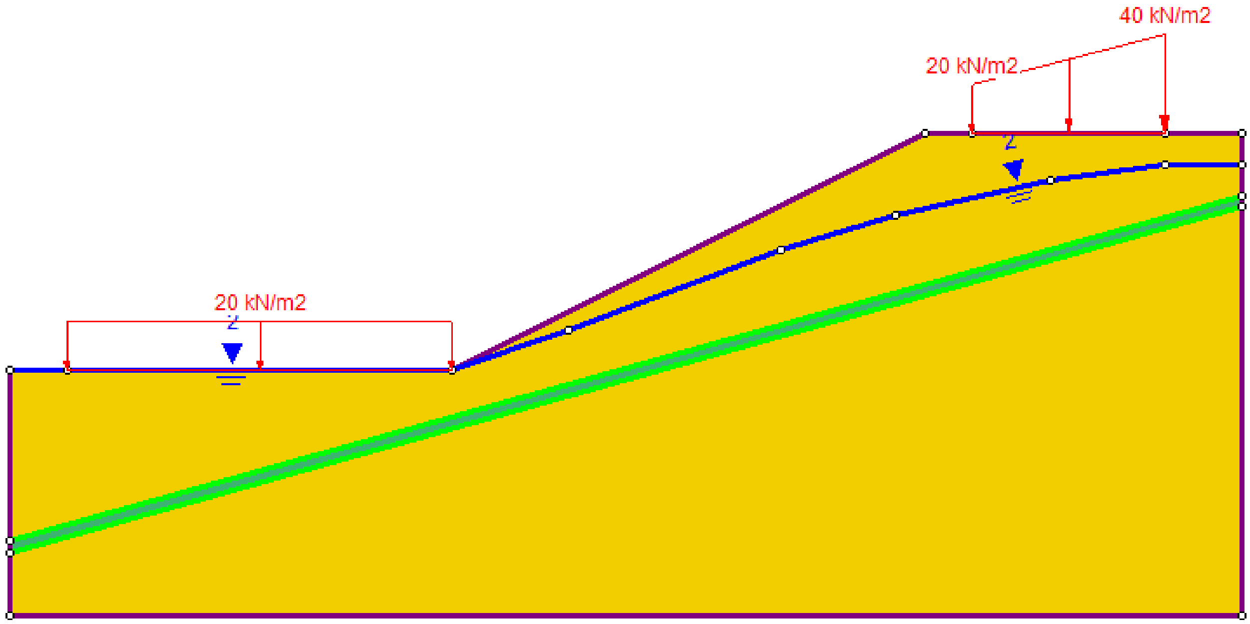


Figure 9.2 – *RS2* Geometry

9.4 Results

Table 9.4 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	0.761
	GLE	0.721
RS2	SSR	0.76

Note: Reference factor of safety = 0.78 [Giam]
Mean Non-circular FOS (20 samples) = 0.808
Reference GLE Factor of Safety = 0.6878 [Slope 2000]

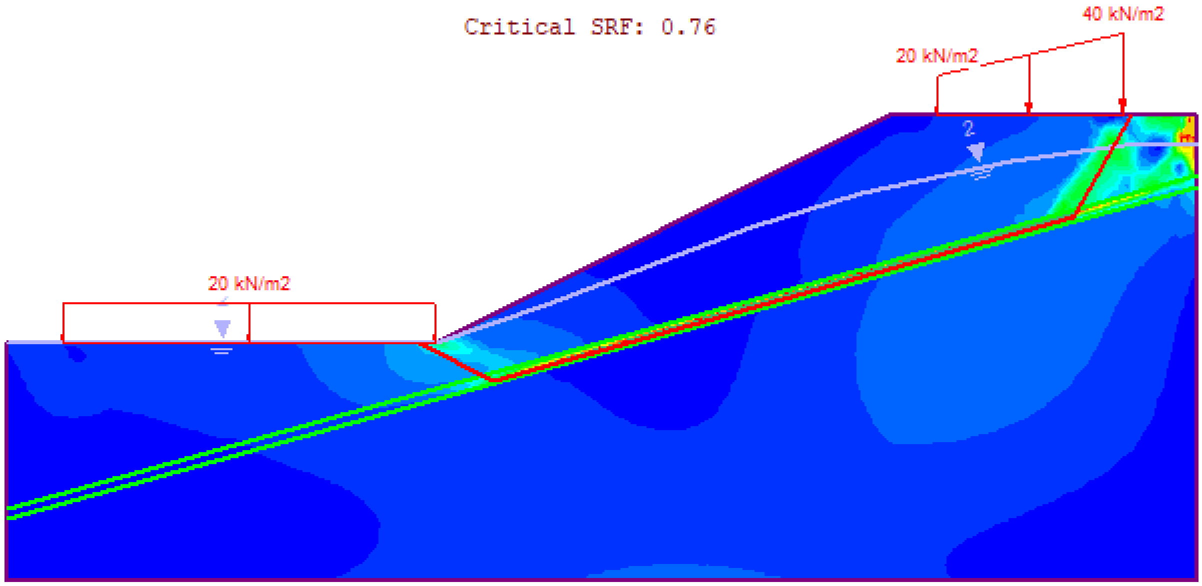


Figure 9.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #10

Slope, homogeneous, pore pressure grid, ponded water

10.1 Introduction

In 1988 a set of 5 basic slope stability problems, together with 5 variants, was distributed both in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Giam & Donald (1989)). This is the ACADS 5 problem.

10.2 Problem Description

Problem #10 is shown in Figure 10.1. The soil properties are given in Table 10.1. This slope has been excavated at a slope of 1:2 (β=26.56˚) below an initially horizontal ground surface. The position of the critical slip surface and the corresponding factor of safety are required for the long term condition, i.e. after the ground water conditions have stabilized. Pore water pressure may be derived from the given boundary conditions or from the approximate flow net provided in Figure 10.2. If information is required beyond the geometrical limits of Figure 10.2, the flow net may be extended by the user. Grid interpolation is done with TIN triangulation. The critical slip surface (circular) and the corresponding factor of safety is calculated.

10.3 Geometry and Material Properties

Table 20.1 – Material Properties

c' (kN/m²)	ϕ' (⁰)	γ (kN/m³)
11.0	28.0	20.00

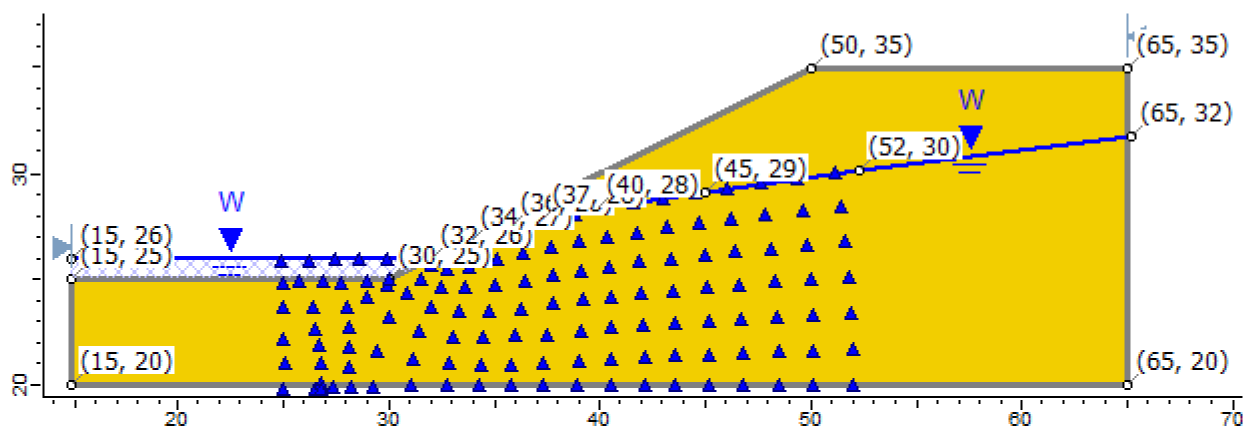


Figure 20.1 – *Slide2* Geometry

Note: Grid used to draw waterline (which comes from Figure 10.2) is identical to the data used in *Slide2* tutorial 5 (tutorial5.sli). The data can be imported from *Slide2* tutorial5.sli or *Slide2* verification#10.sli.

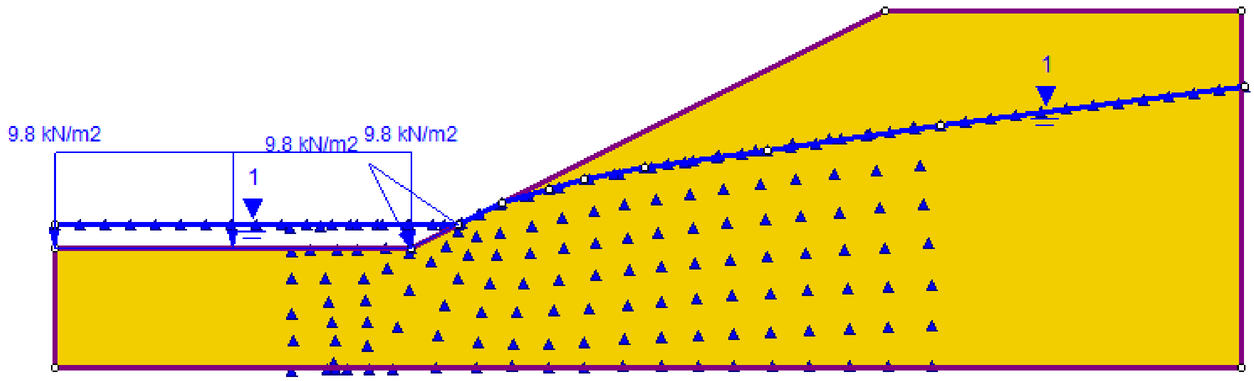


Figure 10.2 – *RS2* Geometry

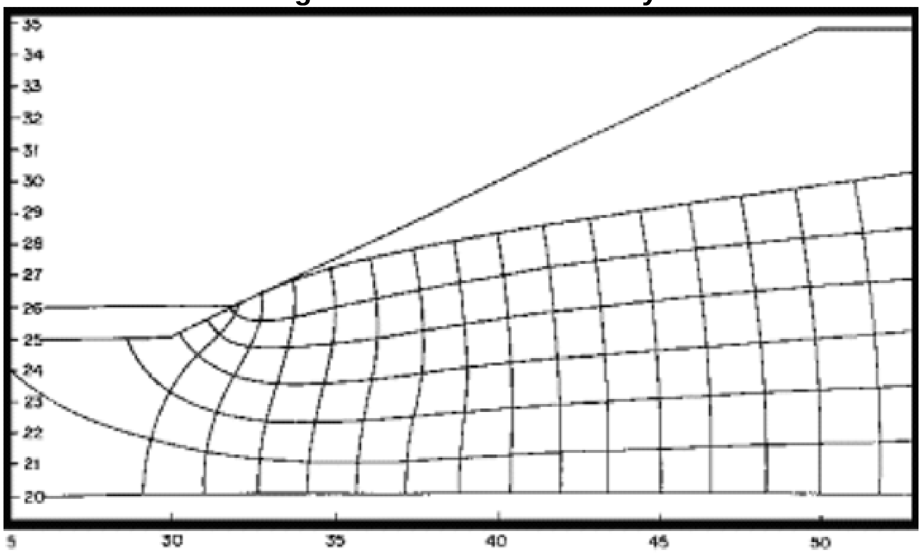


Figure 10.3 – *Approximate Flow Net*

10.4 Results

Table 10.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.500
	GLE	1.500
RS2	SSR	1.46

Note: Reference factor of safety = 1.53 [Giam]

Mean FOS (23 samples) = 1.464

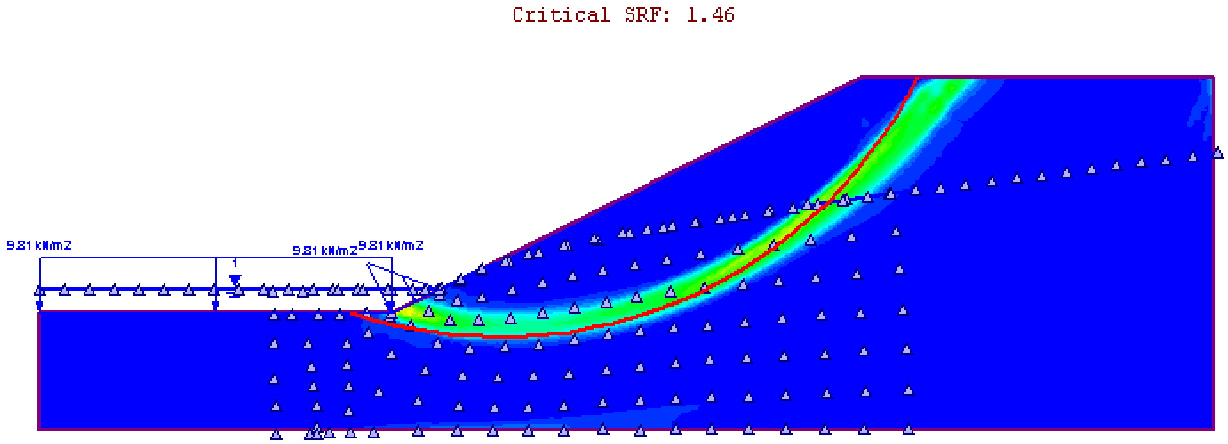


Figure 10.4 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #14

Slope Homogenous

14.1 Introduction

This model is taken from Arai and Tagyo (1985) example #1 and consists of a simple slope of homogeneous soil with zero pore pressure.

14.2 Problem Description

Verification problem #14 is shown in Figure 14.1. The soil properties are given in Table 14.1. The position of the critical slip surface and the corresponding factor of safety is calculated for both a circular and noncircular slip surface. There are no pore pressures in this problem.

14.3 Geometry and Material Properties

Table 34.1 – Material Properties

c' (kN/m²)	φ' (⁰)	γ (kN/m³)
41.65	15	18.82

Case 1

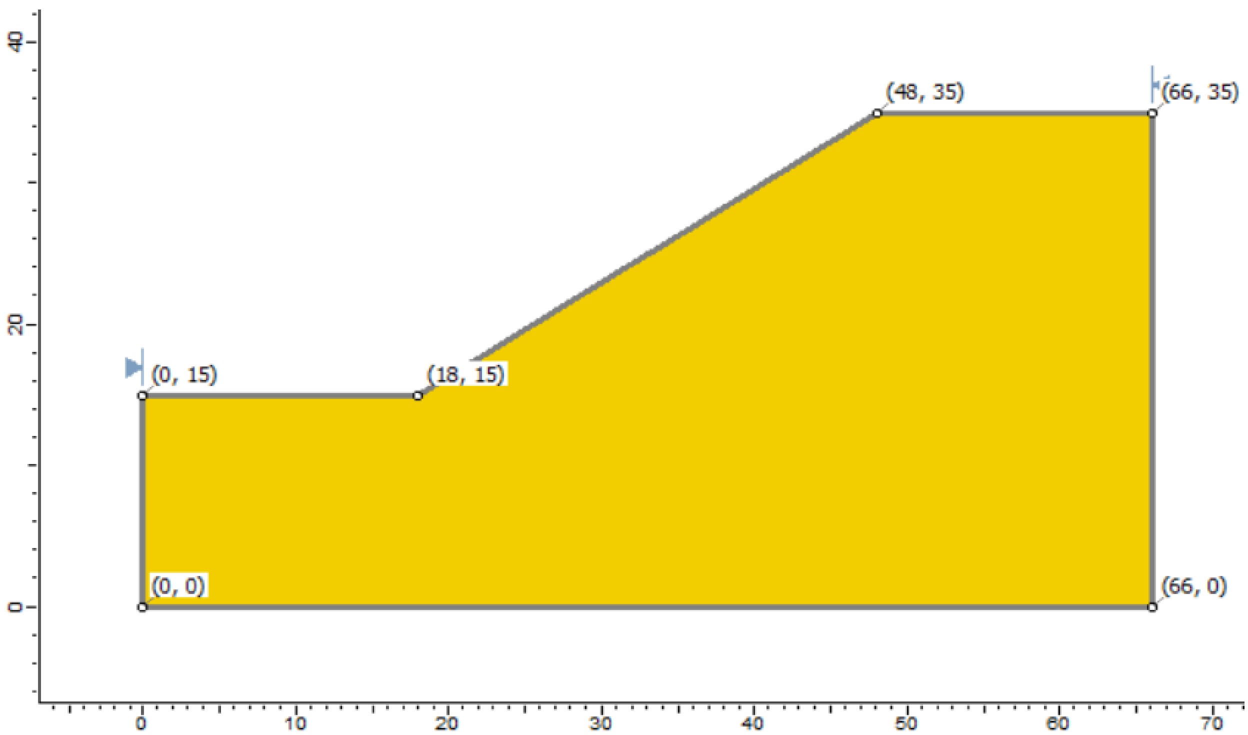


Figure 34.1 – *Slide2* Geometry

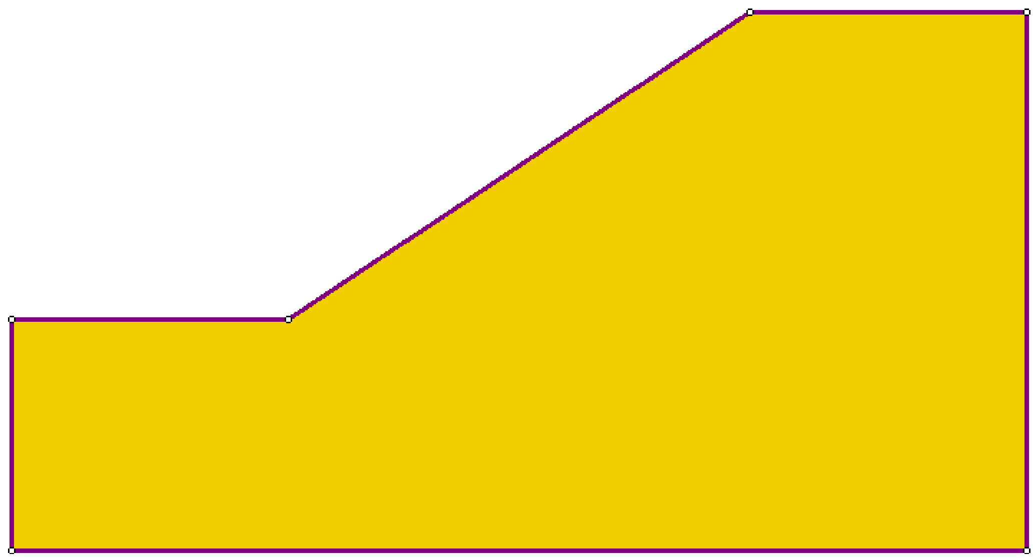


Figure 14.2 – *RS2* Geometry

Case 2 (with tension crack)

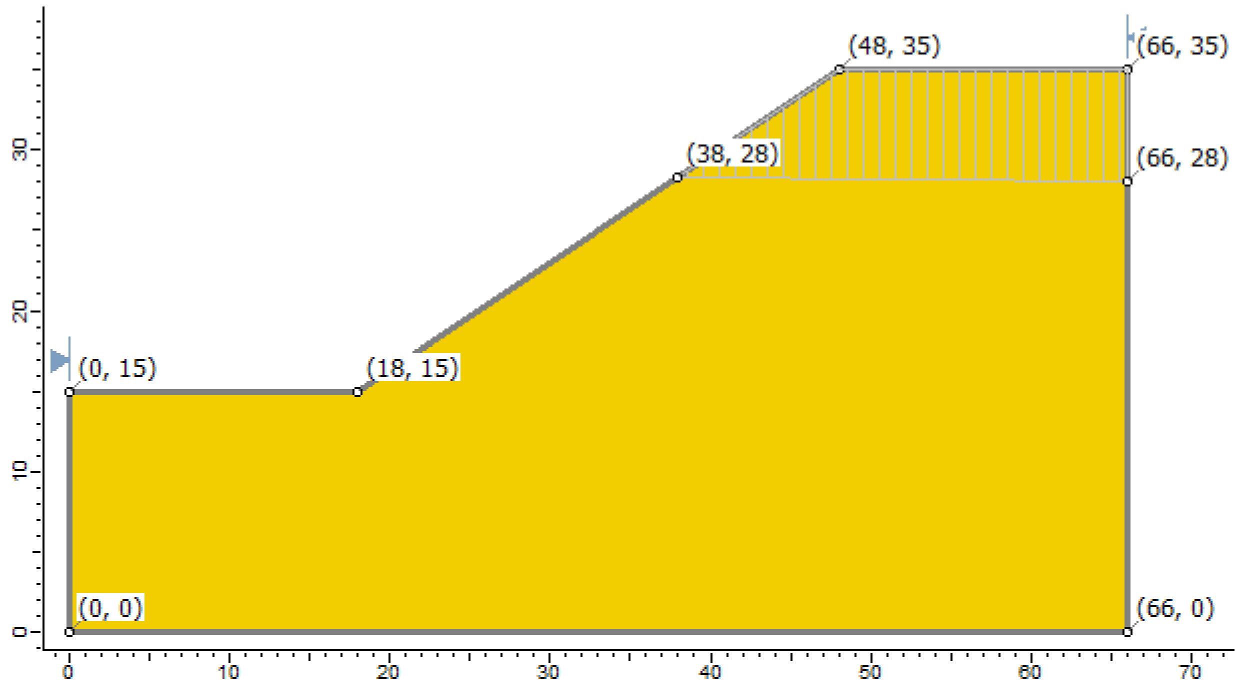


Figure 44.3 – *Slide2* Geometry

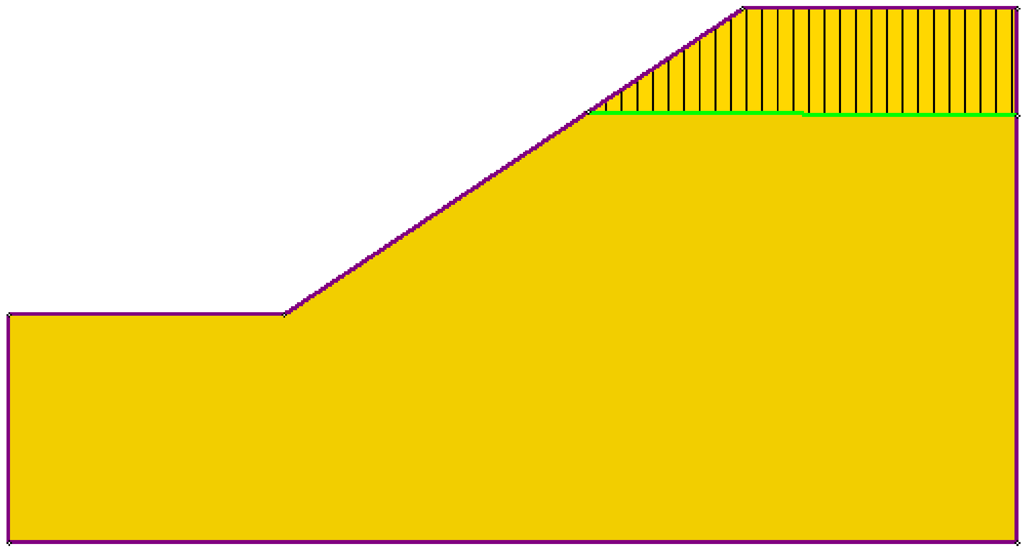


Figure 14.4 – *RS2* Geometry

Note: To simulate tension cracks in *RS2* the materials Tensional Strengths were set to zero in the afflicted regions

14.4 Results

Case 1

Table 14.2 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.405	1.386
	GLE	1.404	1.368
RS2	SSR	1.39	

Note: Circular Arai and Tagyo (1985) Bishops Simplified Factor of Safety = 1.451

Non-circular Arai and Tagyo (1985) Janbu Simplified Factor of Safety = 1.265

Non-circular Arai and Tagyo (1985) Janbu Corrected Factor of Safety = 1.357

Case 2 (With Tension Crack)

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	1.377
	GLE	1.363
RS2	SSR	1.37

Case 1

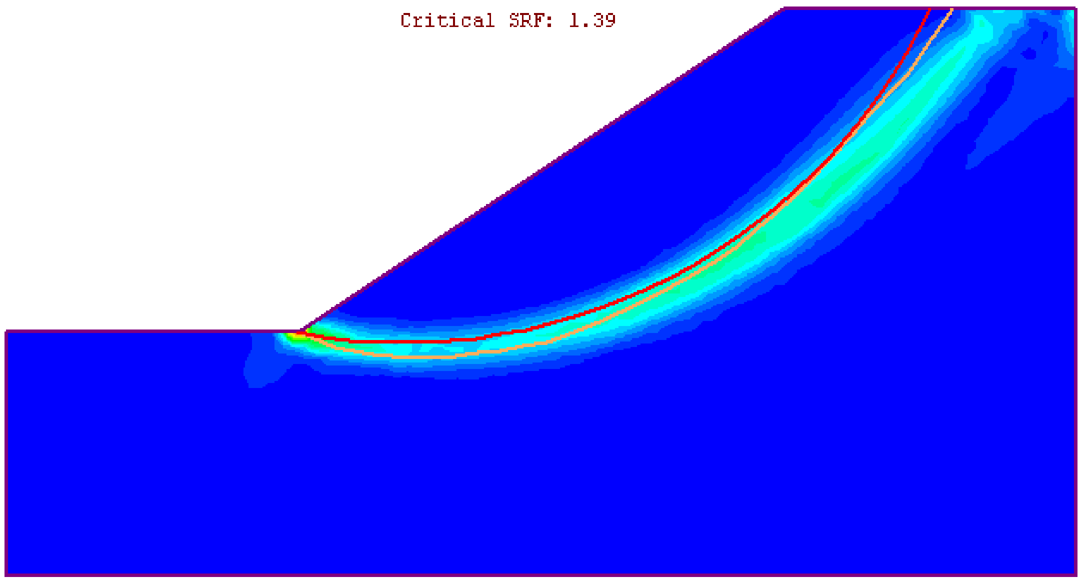


Figure 14.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 2 (With Tension Crack)

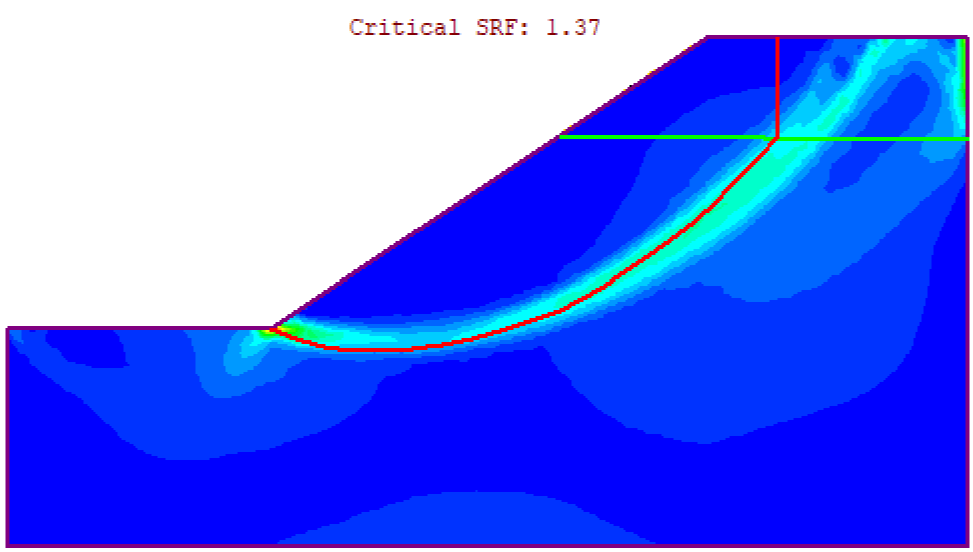


Figure 14.4 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #15

Slope, (3) materials, weak layer

15.1 Introduction

This model is taken from Arai and Tagyo (1985) example #2 and consists of a layered slope where a layer of low resistance is interposed between two layers of higher strength. A number of other authors have also analyzed this problem, notably Kim et al. (2002), Malkawi et al. (2001), and Greco (1996).

15.2 Problem Description

Verification problem #15 is shown in Figure 15.1. The soil properties are given in Table 15.1. The position of the critical slip surface and the corresponding factor of safety are calculated for both a circular and noncircular slip surface. There are no pore pressures in this problem.

15.3 Geometry and Material Properties

Table 45.1 – Material Properties

	c′ (kN/m²)	ϕ′ (°)	γ (kN/m³)
Upper Layer	29.4	12	18.82
Middle Layer	9.8	5	18.82
Lower Layer	294	40	18.82

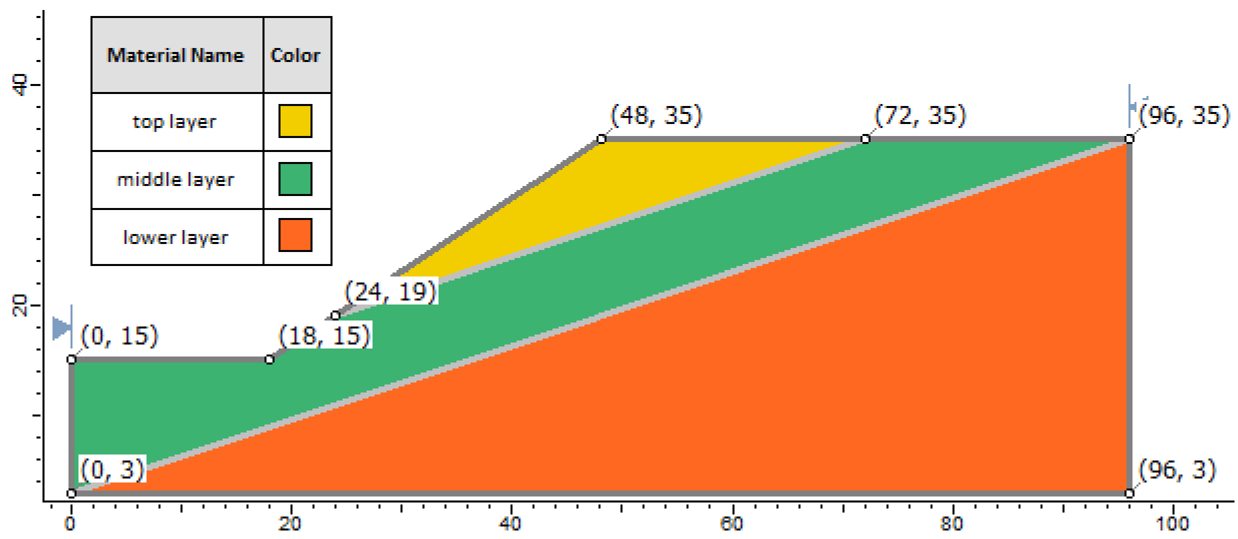


Figure 55.1 – *Slide2* Geometry

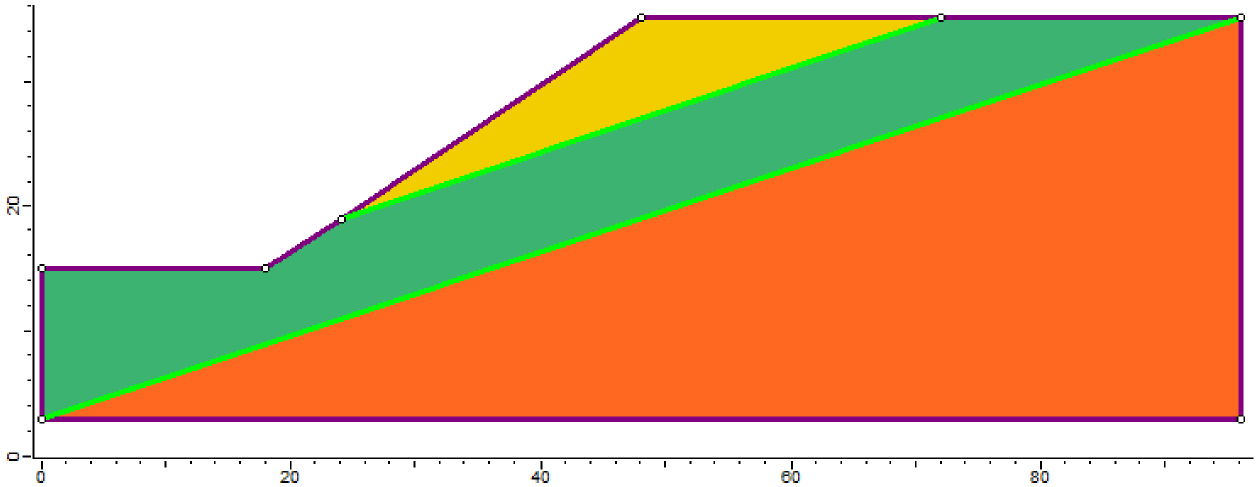


Figure 15.2 – *RS2* Geometry

15.4 Results

Table 15.2 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	0.423	0.413
	GLE	0.420	0.407
RS2	SSR	0.41	

Note: Circular Arai and Tagyo (1985) Bishops Simplified factor of safety = 0.417
Circular Kim et al. (2002) Bishops Simplified factor of safety = 0.43
Non-circular Greco (1996) Spencers method using monte carlo searching = 0.39
Non-circular Kim et al. (2002) Spencers method using random search = 0.44
Non-circular Kim et al. (2002) Spencers method using pattern search = 0.39
Non-circular Arai and Tagyo (1985) Janbu Simplified Factor of Safety = 0.405
Non-circular Arai and Tagyo (1985) Janbu Corrected Factor of Safety = 0.430

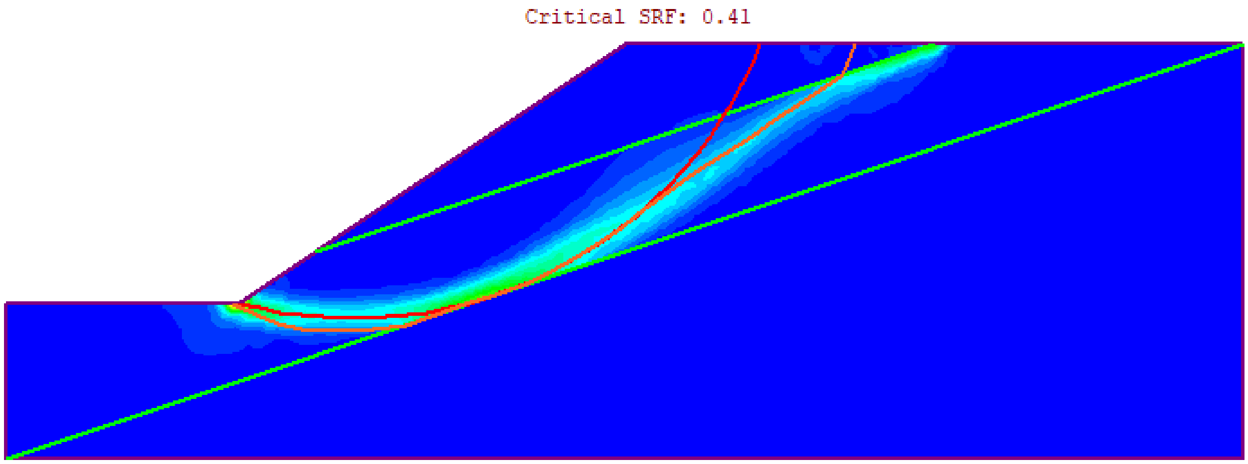


Figure 15.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #16

Slope, homogeneous, water table

16.1 Introduction

This model is taken from Arai and Tagyo (1985) example#3, and it consists of a simple slope of homogeneous soil with pore pressure.

16.2 Problem Description

Verification problem #16 is shown in Figure 16.1. The material properties are given in Table 16.1. The location for the water table is shown in Figure 16.1. The position of the critical slip surface and the corresponding factor of safety is calculated for both a circular and noncircular slip surface. Pore pressures are calculated assuming hydrostatic conditions. The pore pressure at any point below the water table is calculated by measuring the vertical distance to the water table and multiplying by the unit weight of water. There is zero pore pressure above the water table.

16.3 Geometry and Material Properties

Table 56.1 – Material Properties

c' (kN/m²)	ϕ' (⁰)	γ (kN/m³)
41.65	15	18.82

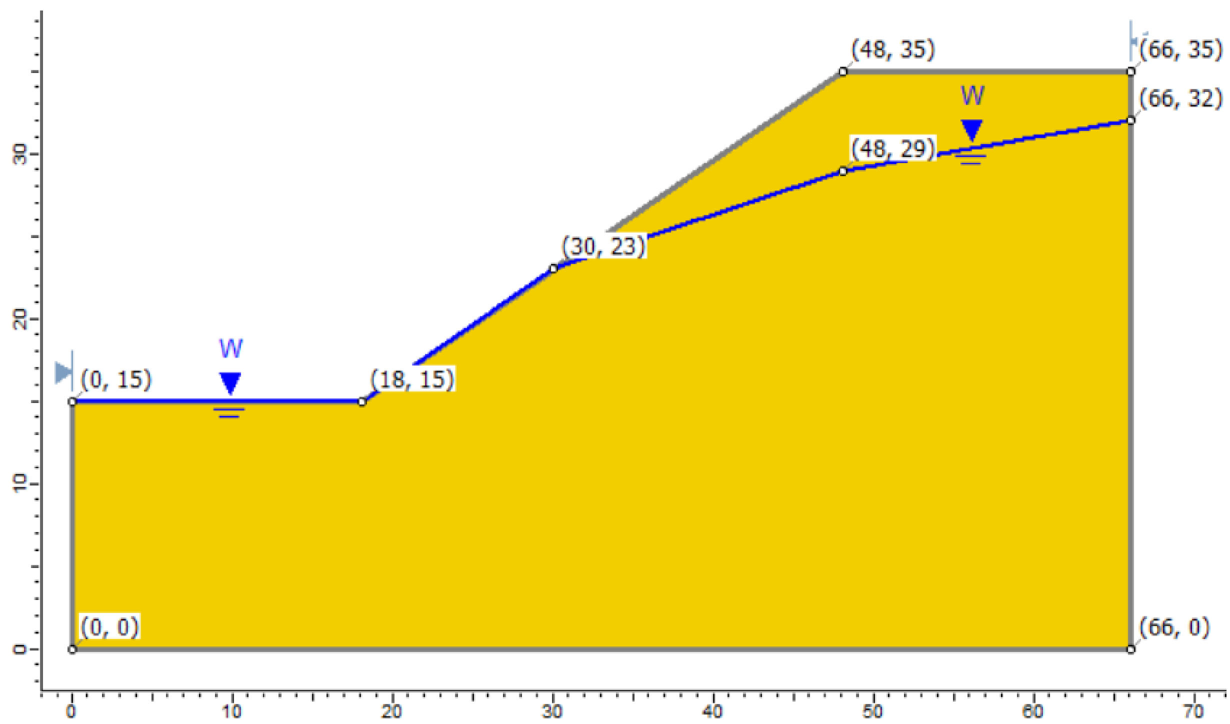


Figure 66.1 – *Slide2* Geometry

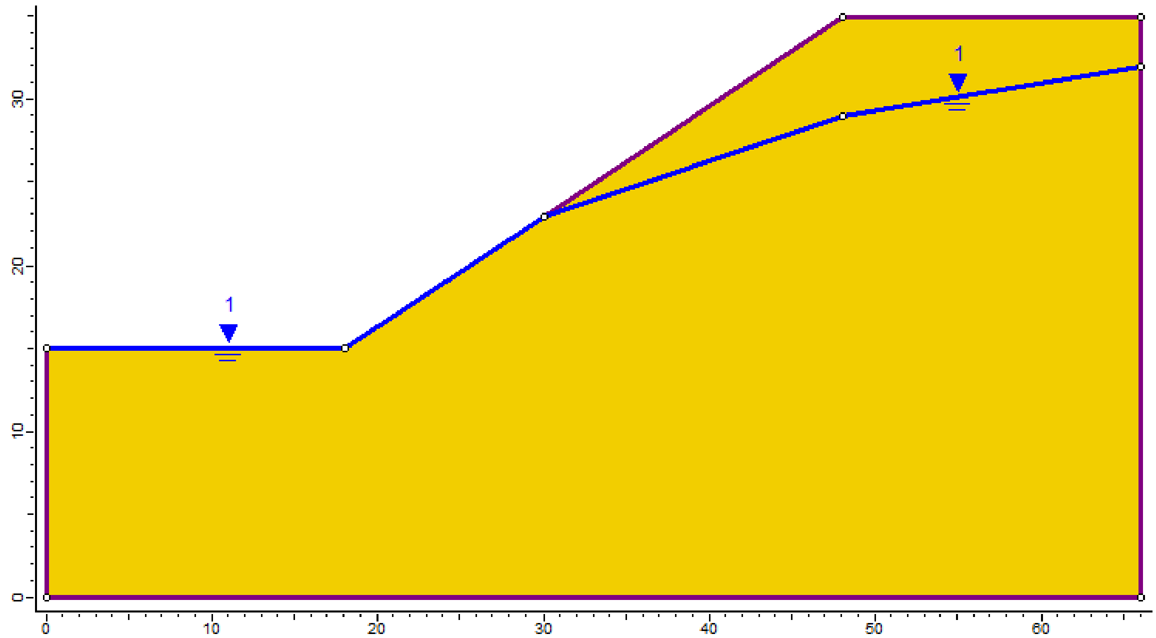


Figure 16.2 – *RS2* Geometry

16.4 Results

Table 16.2 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.117	1.095
	GLE	1.116	1.081
RS2	SSR	1.09	

Note: Arai and Tagyo (1985) Bishops Simplified factor of safety = 1.138

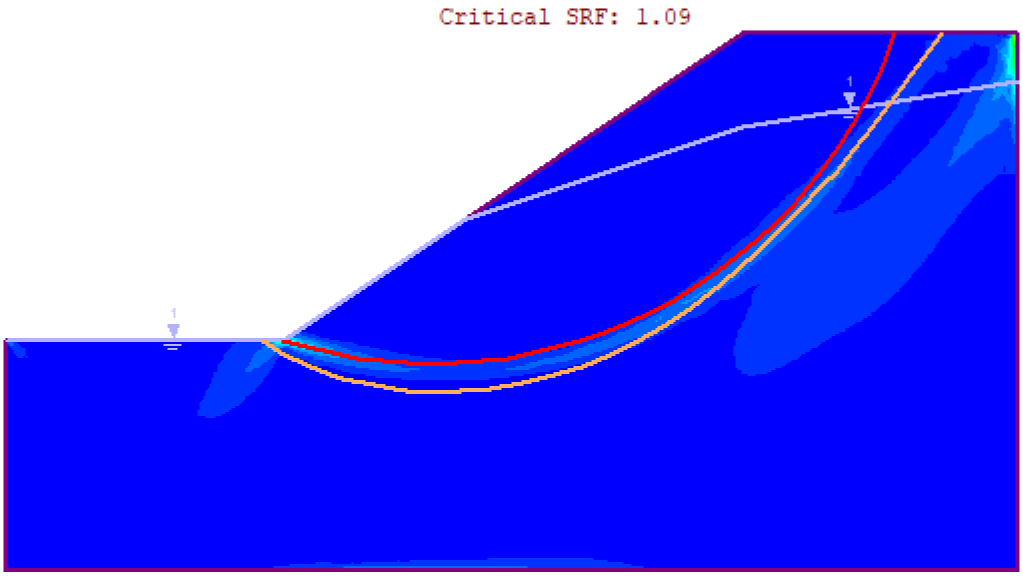


Figure 16.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #17

Slope, homogeneous

17.1 Introduction

This model is taken from Yamagami and Ueta (1988), and it consists of a simple slope of homogeneous soil with zero pore pressure. Greco (1996) has also analyzed this slope.

17.2 Problem Description

Verification problem #17 is shown in Figure 17.1. The material properties are given in Table 17.1. The position of the critical slip surface and the corresponding factor of safety is calculated for both a circular and noncircular slip surface. There are no pore pressures in this problem.

17.3 Geometry and Material Properties

Table 67.1 – Material Properties

c′ (kN/m²)	ϕ′ (⁰)	γ (kN/m³)
9.8	10	17.64

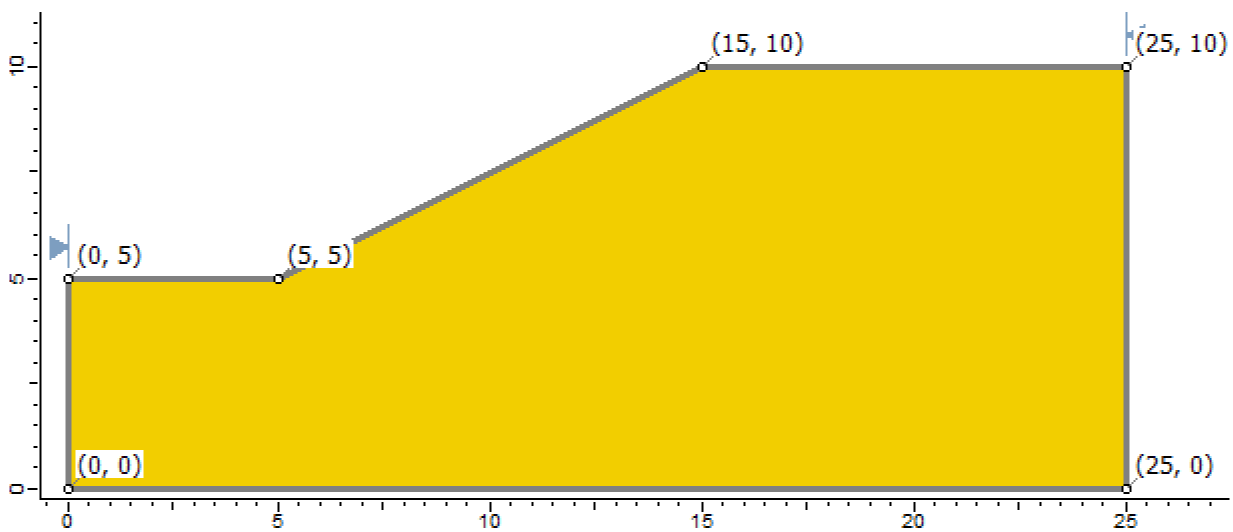


Figure 77.1 – *Slide2* Geometry

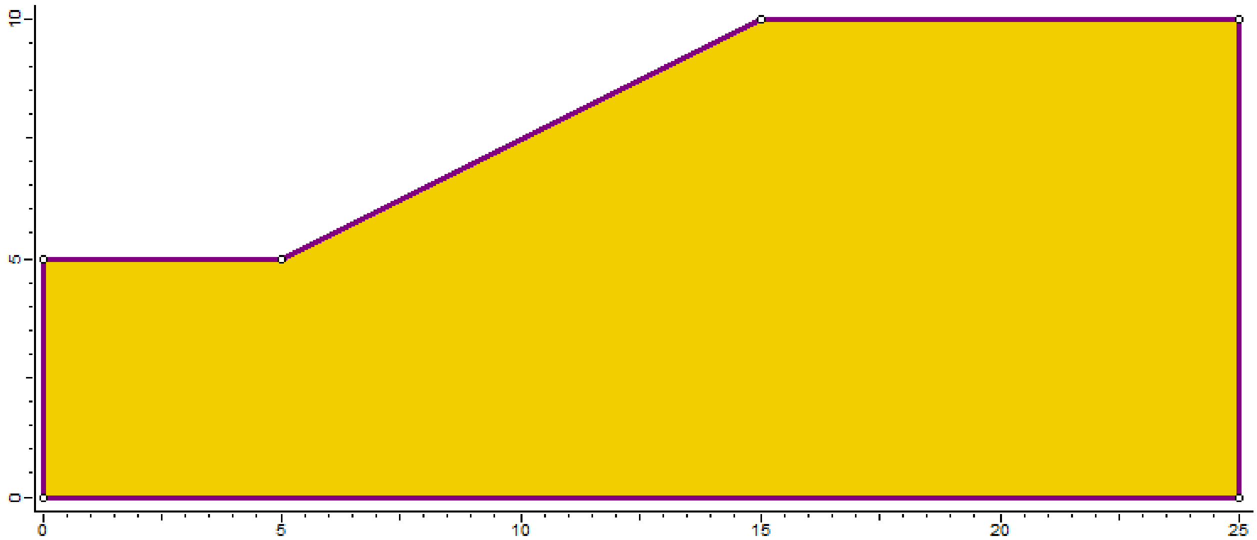


Figure 17.2 – *RS2* Geometry

17.4 Results

Table 1.2 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.342	1.324
	GLE	1.342	1.309
RS2	SSR	1.32	

Note: Yamagami and Ueta (1988) Bishops Simplified factor of safety = 1.348
Yamagami and Ueta (1988) Fellenius/Ordinary factor of safety = 1.282

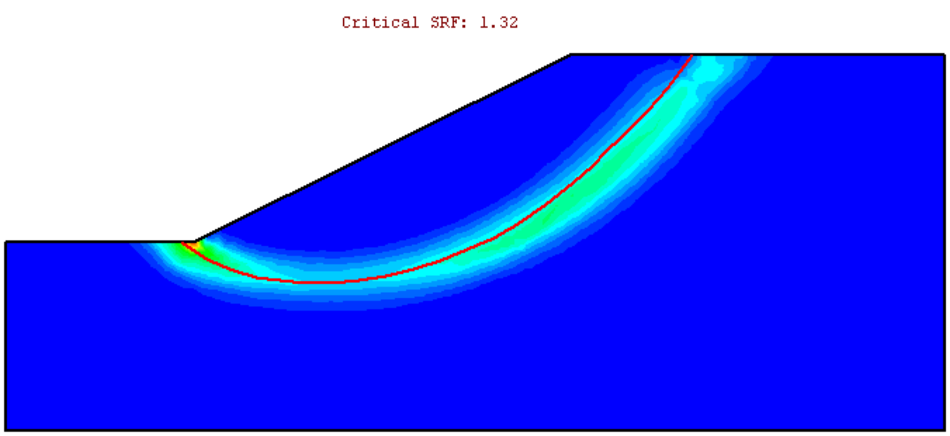


Figure 17.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #19

Slope, (4) materials

19.1 Introduction

This model is taken from Greco (1996) example #4, and it was originally published by Yamagami and Ueta (1988). It consists of a layered slope without pore pressure.

19.2 Problem Description

Verification problem #19 is shown in Figure 19.1. The material properties are given in Table 19.1. The position of the critical slip surface and the corresponding factor of safety are calculated for a noncircular slip surface.

19.3 Geometry and Material Properties

Table 79.1 – Material Properties

	c′ (kN/m²)	ϕ′ (⁰)	γ (kN/m³)
Upper Layer	49	29	20.38
Layer 2	0	30	17.64
Layer 3	7.84	20	20.38
Bottom Layer	0	30	17.64

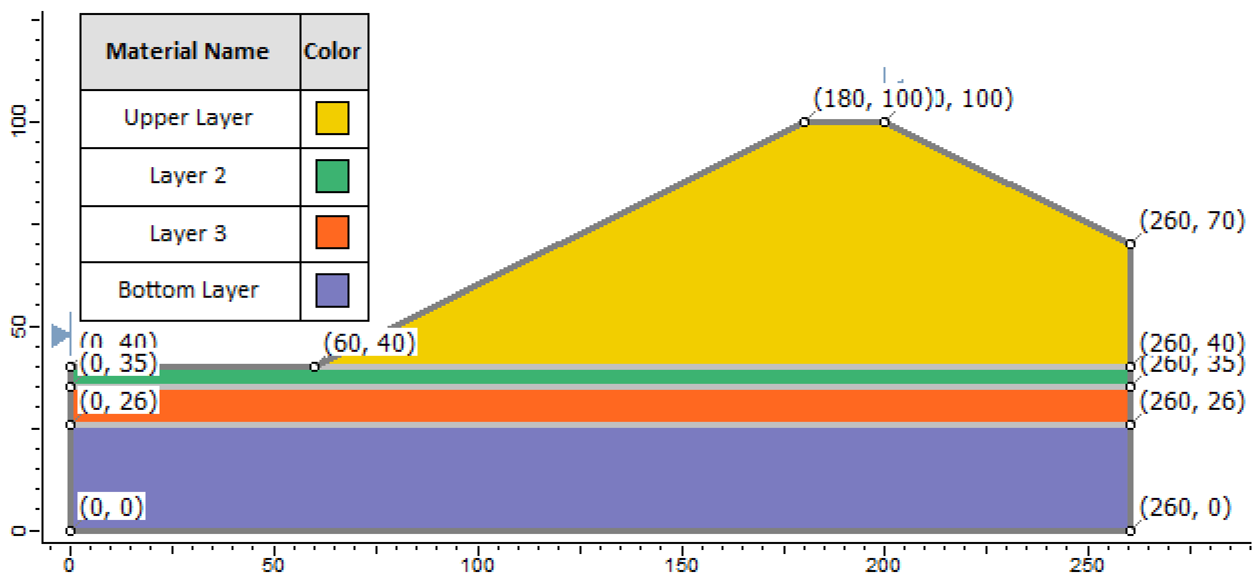


Figure 89.1 – *Slide2* Geometry

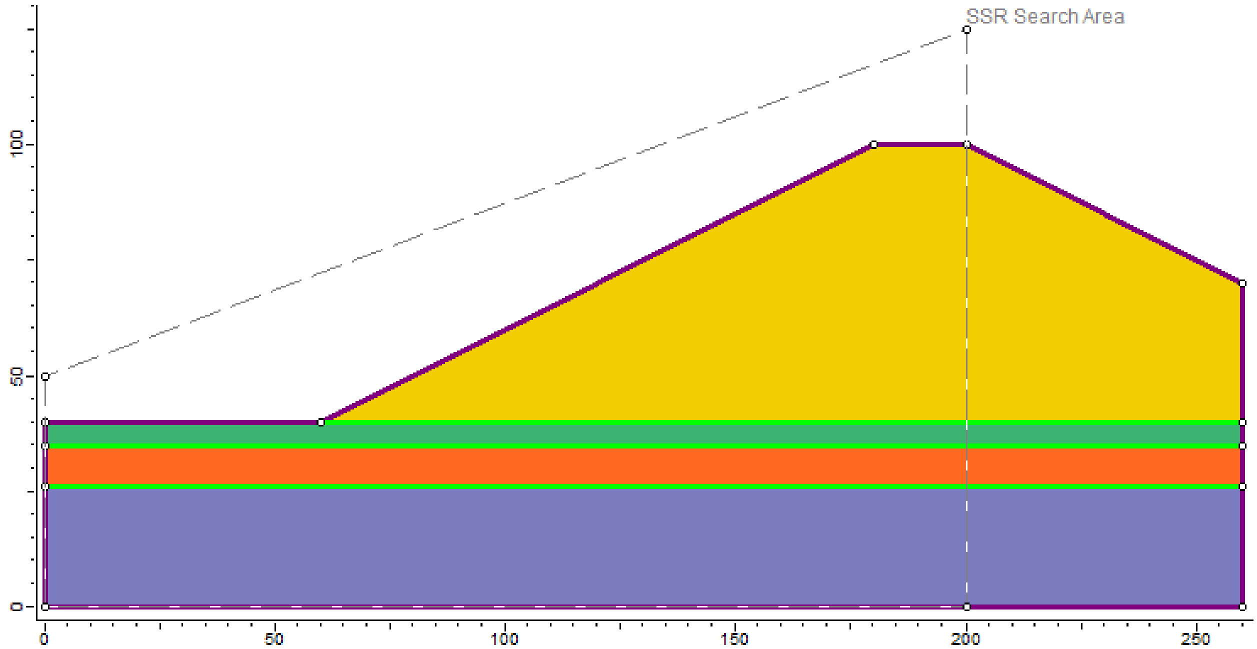


Figure 19.2 – *RS2* Geometry

Note: SSR Search Area was used to define the slope limits in *RS2*.

19.4 Results

Table 19.2 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	1.405
	GLE	1.398
RS2	SSR	1.38

Note: Greco (1996) Spencer factor of safety = 1.40 - 1.42
Spencer (1969) Spencer factor of safety = 1.40 - 1.42

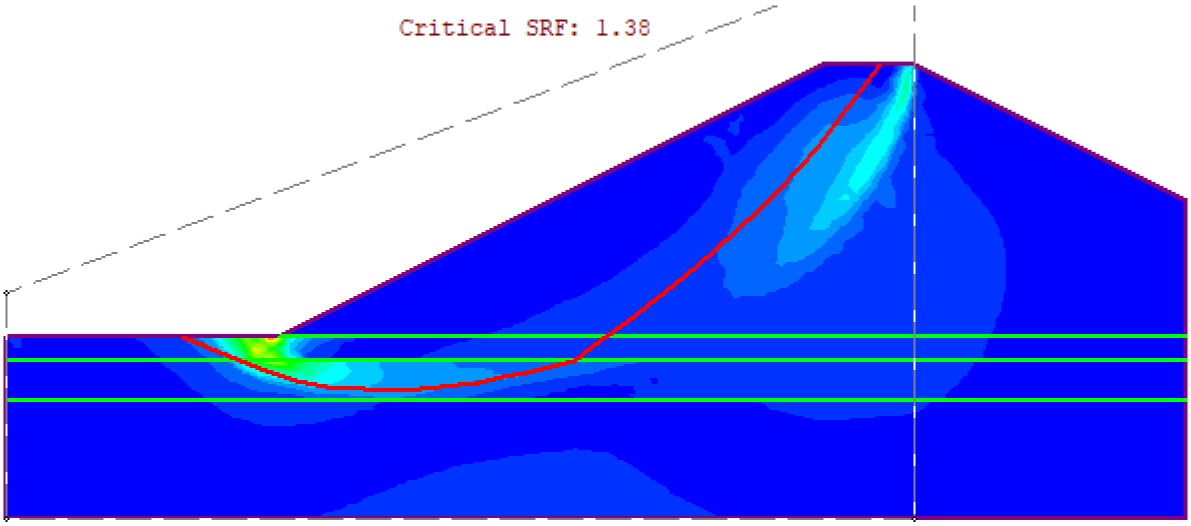


Figure 19.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #21

Slope, homogeneous, ru pore pressure

21.1 Introduction

This model is taken from Fredlund and Krahn (1977). It consists of a homogeneous slope with three separate water conditions, 1) dry, 2) Ru defined pore pressures, 3) pore pressures defined using a water table. The model is done in imperial units to be consistent with the original paper. Quite a few other authors, such as Baker (1980), Greco (1996), and Malkawi (2001) have also analyzed this slope.

21.2 Problem Description

Verification problem #21 is shown in Figure 21.1. The material properties are given in Table 21.1. The position of the circular slip surface is given in Fredlund and Krahn as being xc=120, yc=90, radius=80. The GLE/Discrete Morgenstern and Price method was run with the half sine interslice force function.

Table 28.1 – Material Properties

c' (psf)	φ' (°)	γ (pcf)	Ru (case 2)
600	20	20.0	0.25

Case 1, 2 (Dry, Ru)

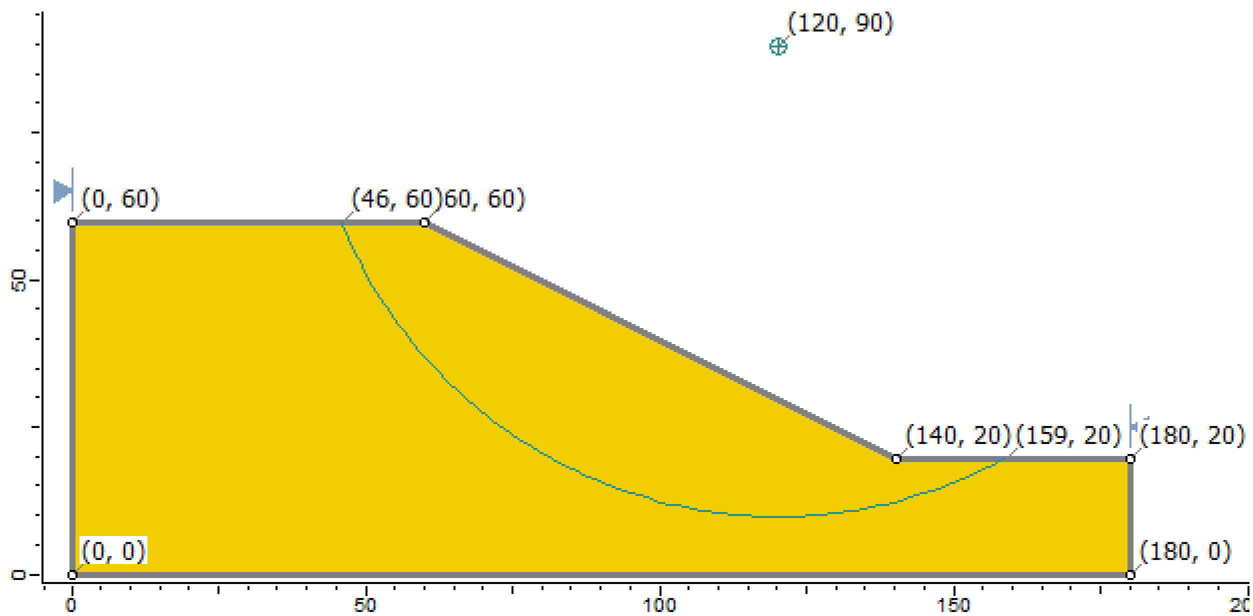


Figure 29.1 – *Slide2* Geometry

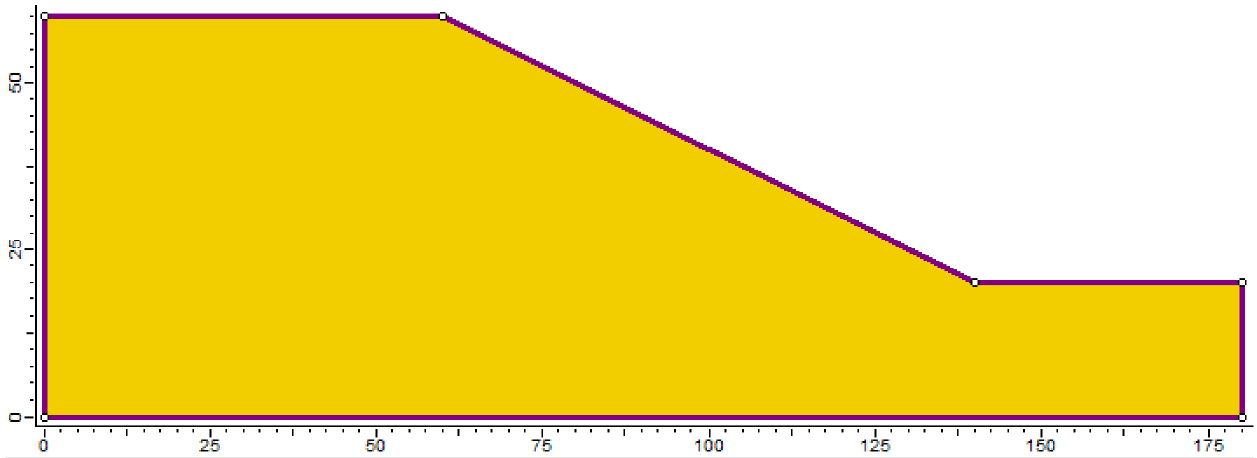


Figure 21.2 – *RS2* Geometry

Case 3 (WT)

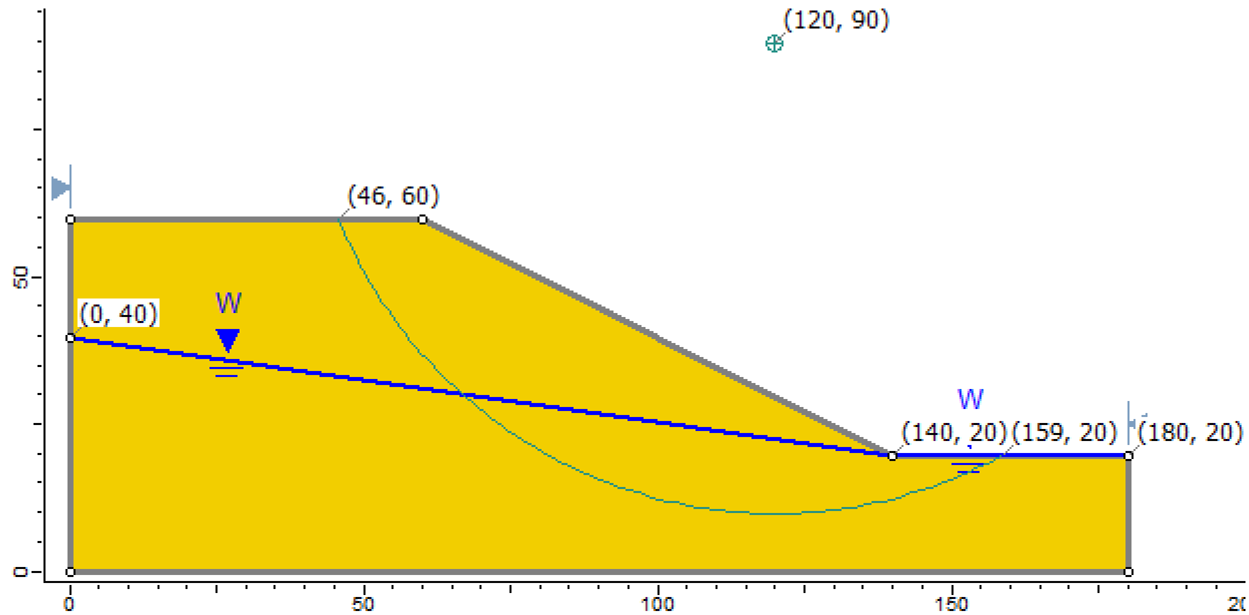


Figure 210.3 – *Slide2* Geometry

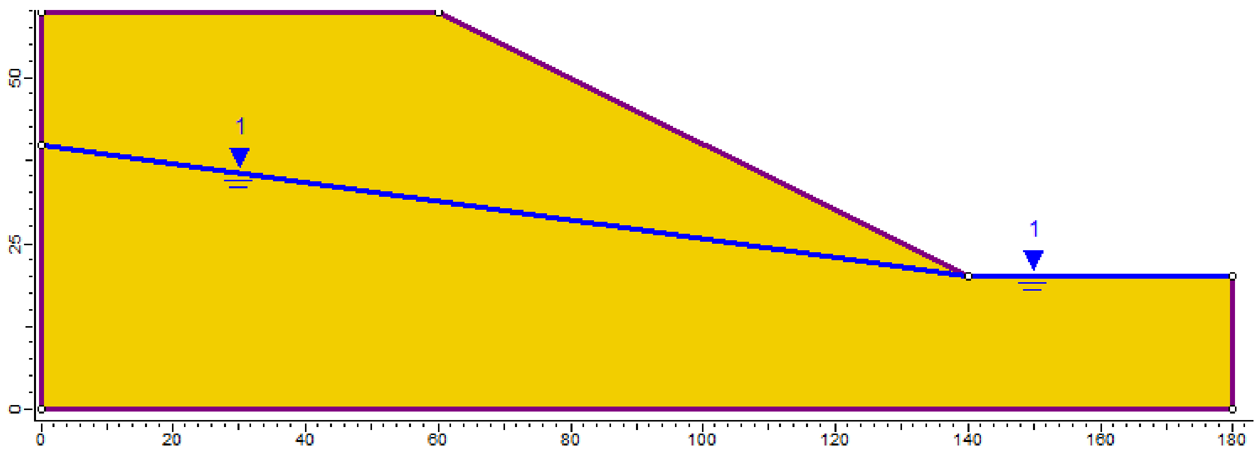


Figure 211.4 – *Slide2* Geometry

21.4 Results

Table 21.2 – Comparison of Results

Program	Method	Factor of Safety Case 1 (Dry)	Factor of Safety Case 2 (Ru)	Factor of Safety Case 3 (WT)
Slide2	Spencer	2.075	1.760	1.831
	GLE	2.075	1.760	1.831
RS2	SSR	1.98	1.68	1.77

Note: Case 1 Reference Factor of Safety = 2.075 Spencer [F&K]
Case 1 Reference Factor of Safety = 2.075 GLE [F&K]
Case 2 Reference Factor of Safety = 1.761 Spencer [F&K]
Case 2 Reference Factor of Safety = 1.764 GLE [F&K]
Case 3 Reference Factor of Safety = 1.830 Spencer [F&K]
Case 3 Reference Factor of Safety = 1.832 GLE [F&K]

Case 1 (Dry)

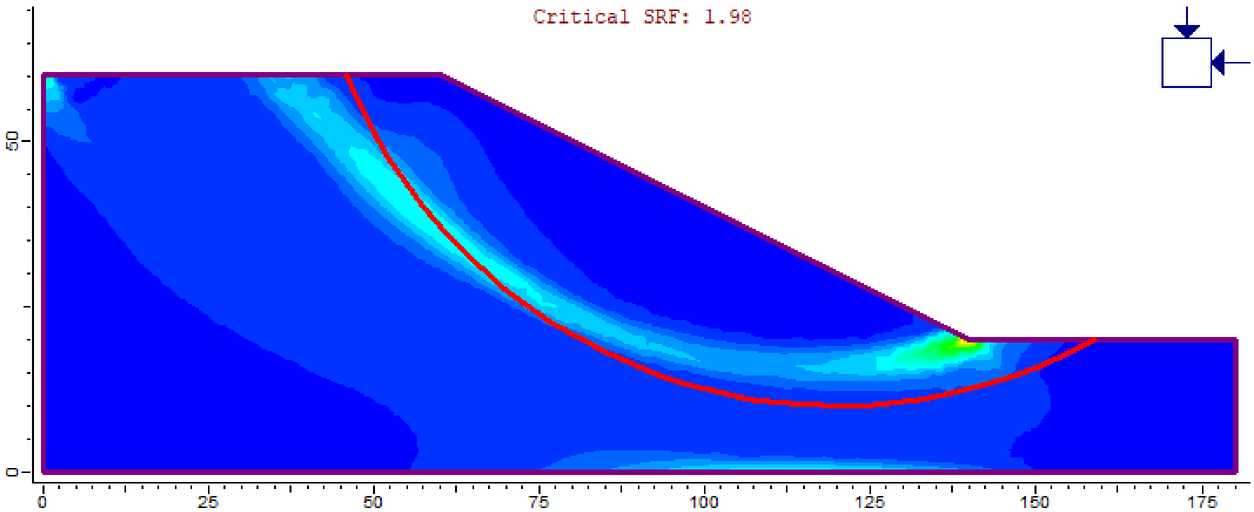


Figure 21.5 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 2 (Ru)

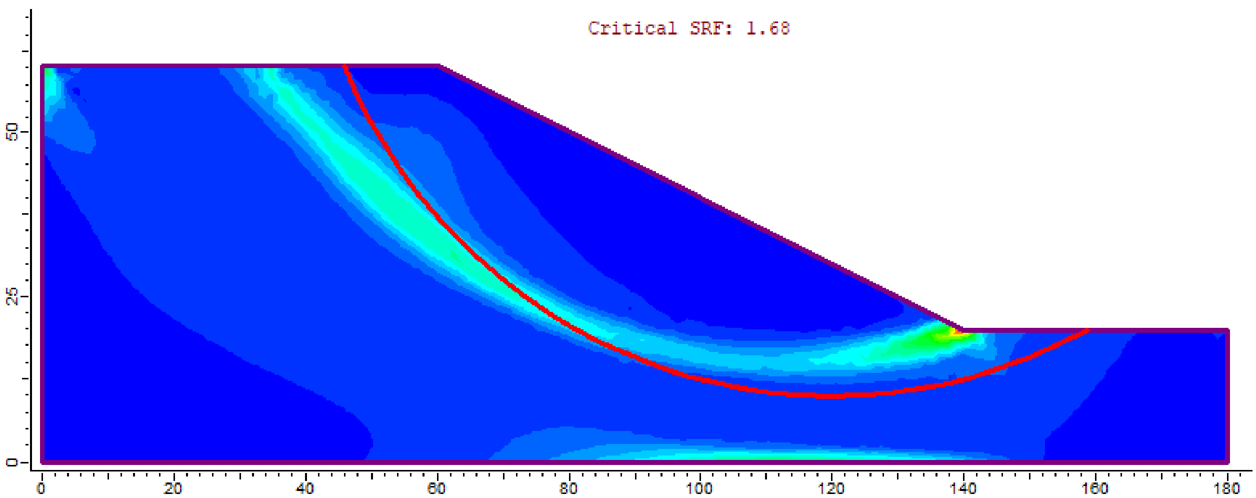


Figure 21.6 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 3 (WT)

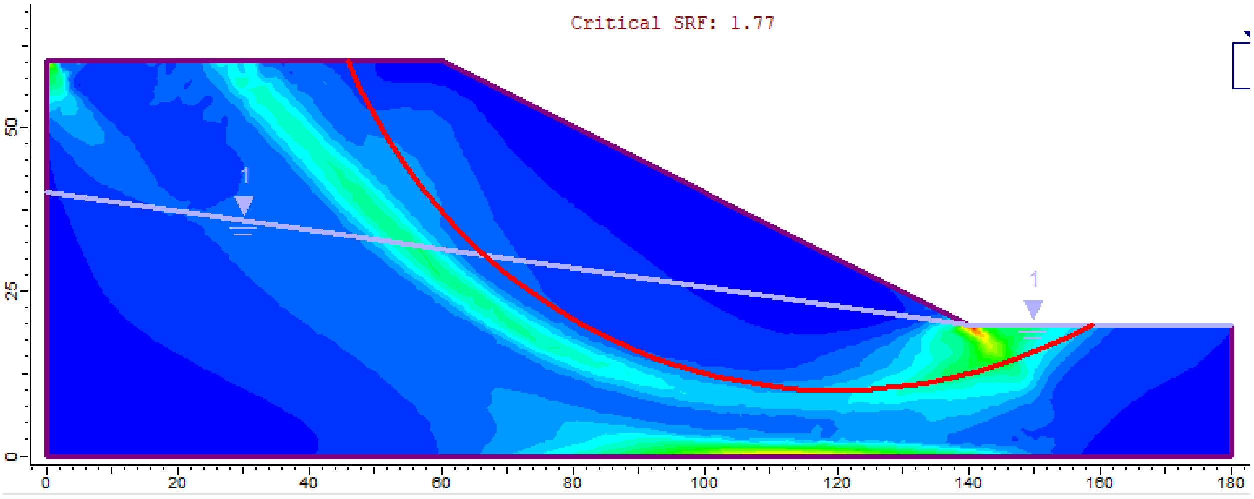


Figure 21.7 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #22

Slope, (2) materials, weak layer, ru pore pressure

22.1 Introduction

This model is taken from Fredlund and Krahn (1977). It consists of a slope with a weak layer and three separate water conditions, 1) dry, 2) Ru defined pore pressures, 3) pore pressures defined using a water table. The model is done in imperial units to be consistent with the original paper. Quite a few other authors, such as Kim and Salgado (2002), Baker (1980), and Zhu, Lee, and Jiang (2003) have also analyzed this slope. Unfortunately, the location of the weak layer is slightly different in all the above references. Since the results are quite sensitive to this location, results routinely vary in the second decimal place.

22.2 Problem Description

Verification problem #22 is shown in Figure 22.1. The material properties are given in Table 22.1. The position of the composite circular slip surface is given in Fredlund and Krahn as being xc=120, yc=90, radius=80. The GLE/Discrete Morgenstern and Price method was run with the half sine interslice force function.

22.3 Geometry and Material Properties

Table 22.1 – Material Properties

	c' (psf	ϕ' (^{0})	γ (pcf)	Ru (Case 2)
Upper Soil	600	20	120	0.25
Weak Layer	0	10	120	0.25

Case 1, 2 (Dry, Ru)

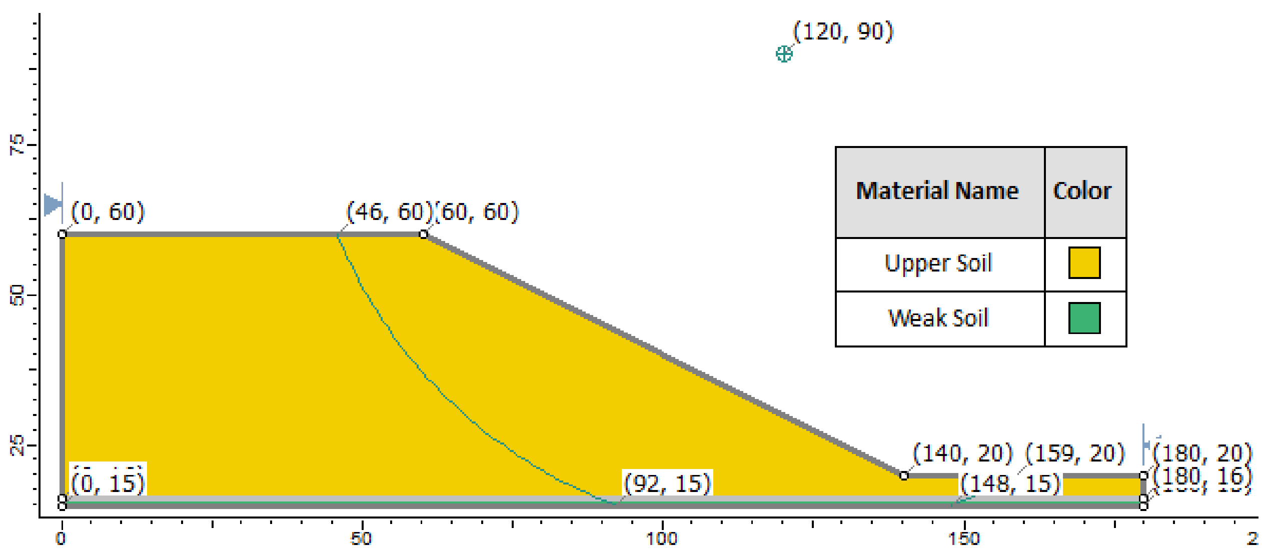


Figure 22.1 – *Slide2* Geometry

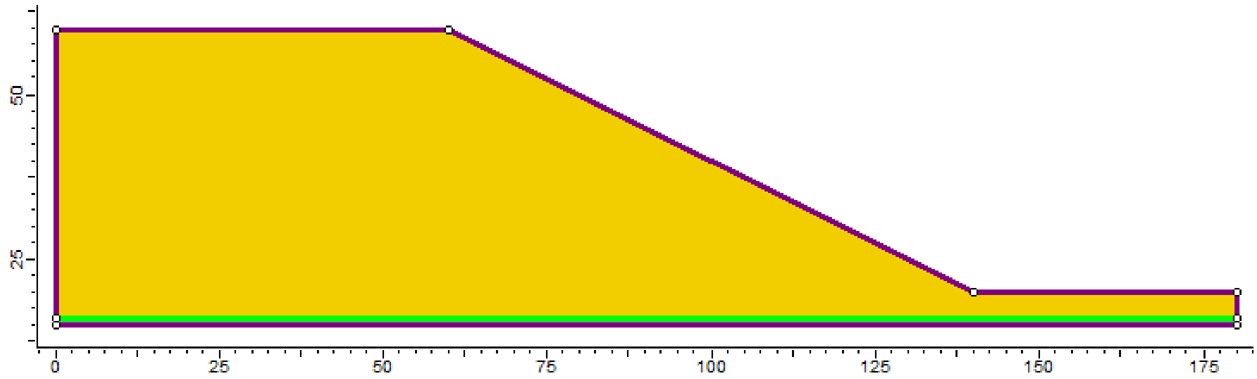


Figure 22.2 – *RS2* Geometry

Case 3 (WT)

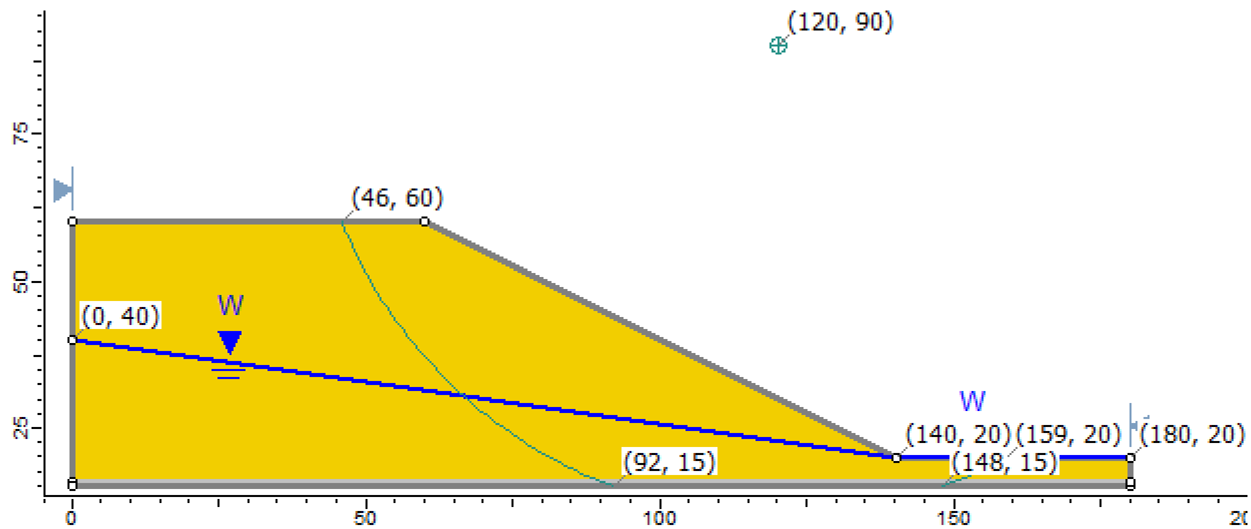


Figure 22.3 – *Slide2* Geometry

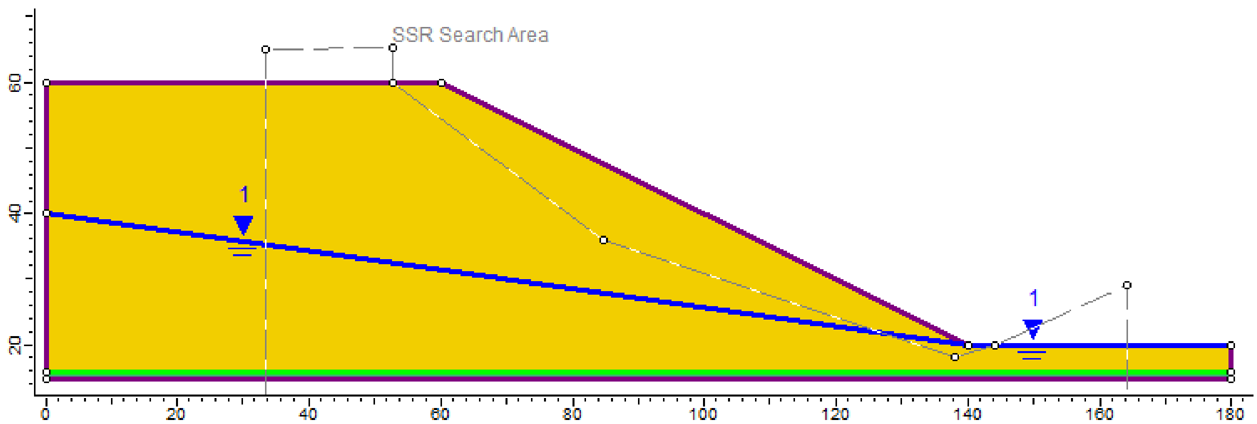


Figure 22.4 – *RS2* Geometry

22.4 Results

Table 22.2 – Comparison of Results

Program	Method	Factor of Safety Case 1 (Dry)	Factor of Safety Case 2 (Ru)	Factor of Safety Case 3 (WT)
Slide2	Spencer	1.382	1.124	1.244
	GLE	1.372	1.114	1.237
RS2	SSR	1.26	0.99	1.15

Note: Case 1 Referee Factor of Safety = 1.373 Spencer [Fredlund & Krahn]
Case 1 Referee Factor of Safety = 1.381 Spencer [Zhu, Lee, and Jiang]
Case 1 Referee Factor of Safety = 1.370 GLE [Fredlund & Krahn]
Case 1 Referee Factor of Safety = 1.371 GLE [Zhu, Lee, and Jiang]
Case 2 Referee Factor of Safety = 1.118 Spencer [Fredlund & Krahn]
Case 2 Referee Factor of Safety = 1.119 Spencer [Zhu, Lee, and Jiang]
Case 2 Referee Factor of Safety = 1.118 GLE [Fredlund & Krahn]
Case 2 Referee Factor of Safety = 1.109 GLE [Zhu, Lee, and Jiang]
Case 3 Referee Factor of Safety = 1.245 Spencer [Fredlund & Krahn]
Case 3 Referee Factor of Safety = 1.261 Spencer [Zhu, Lee, and Jiang]
Case 3 Referee Factor of Safety = 1.245 GLE [Fredlund & Krahn]
Case 3 Referee Factor of Safety = 1.254 GLE [Zhu, Lee, and Jiang]

Case 1 (Dry)

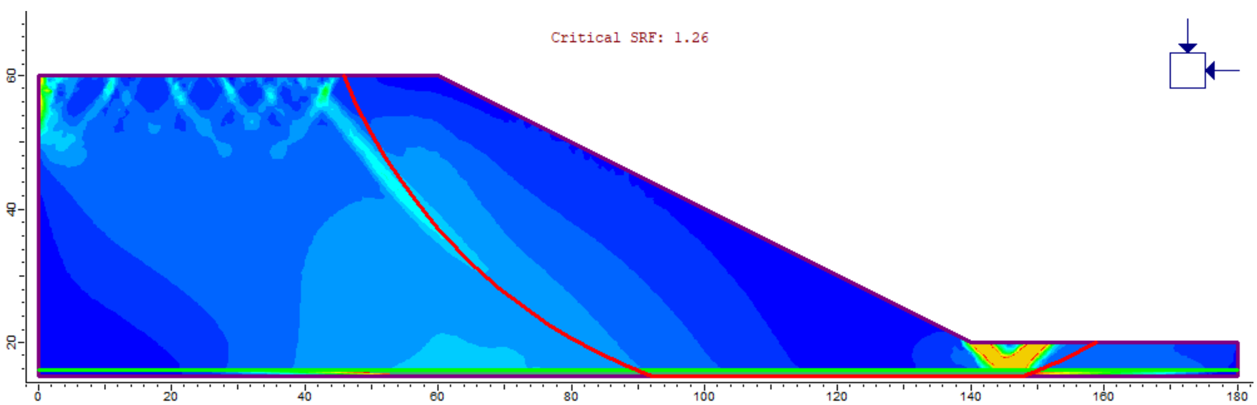


Figure 22.5 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 2 (Ru)

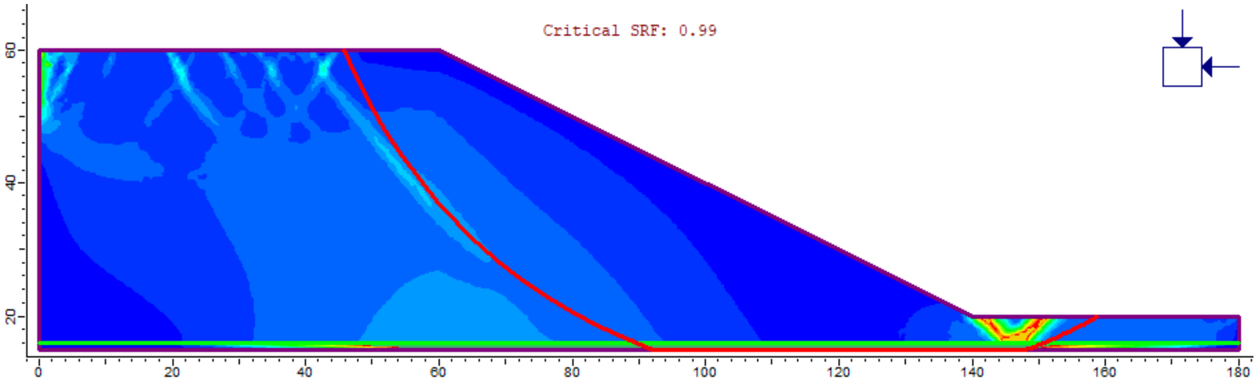


Figure 22.6 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 3 (WT)

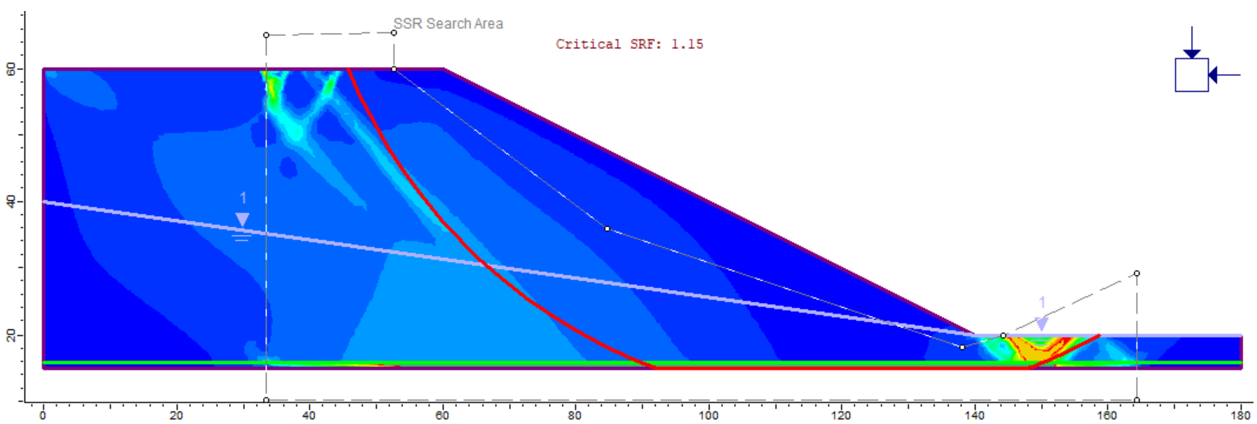


Figure 22.7 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #24

Slope, (3) materials

24.1 Introduction

This model is taken from Low (1989). It consists of a slope with three layers with different undrained shear strengths.

24 .2 Problem Description

Verification problem #24 is shown in Figure 24.1. The soil properties are given in Table 24.1. The position of the critical slip surface and the corresponding factor of safety is calculated for a circular slip surface.

24.3 Geometry and Material Properties

Table 24.1 – Material Properties

	Cu (kN/m²)	γ (kN/m³)
Upper Layer	30	18
Middle Layer	20	18
Bottom Layer	150	18

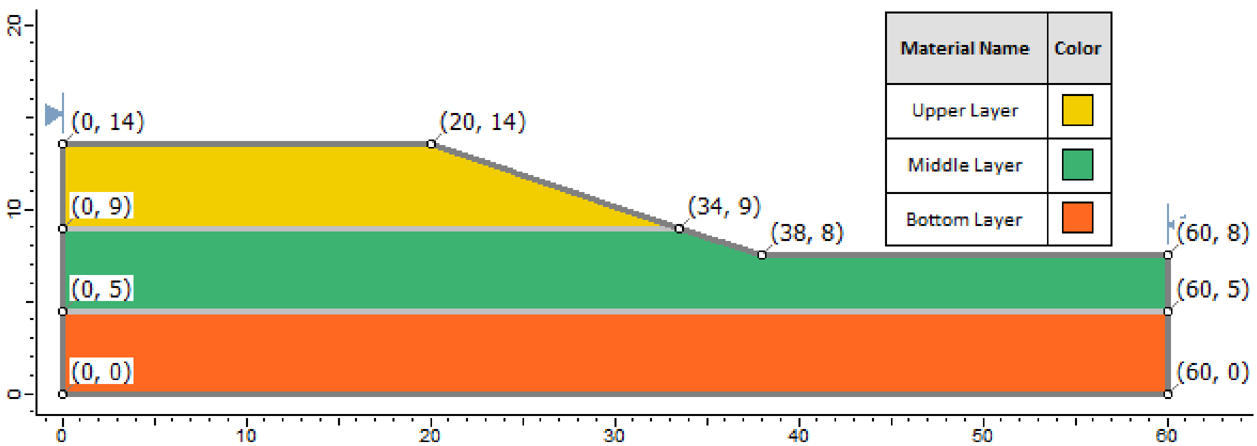


Figure 24.1 – *Slide2* Geometry

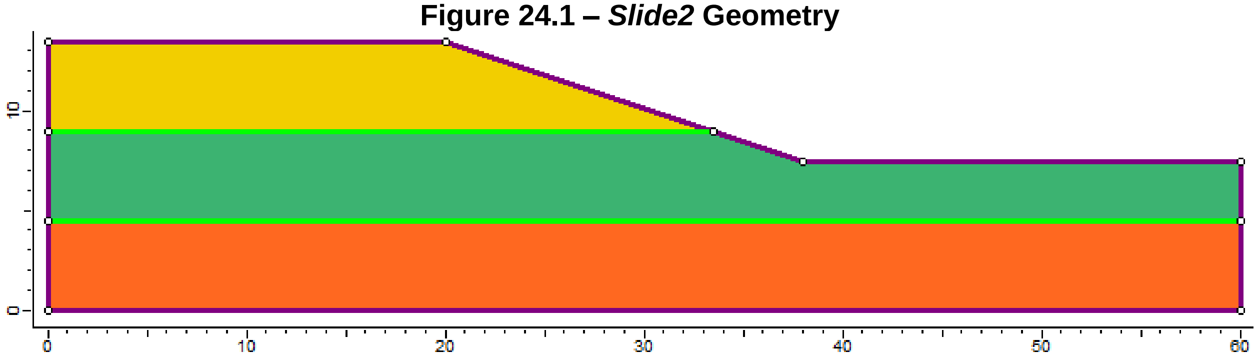


Figure 24.2 – *RS2* Geometry

24.4 Results

Table 24.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.439
	GLE	1.439
RS2	SSR	1.42

Note: Low(1989) Ordinary factor of safety=1.44
Low(1989) Bishop factor of safety=1.44

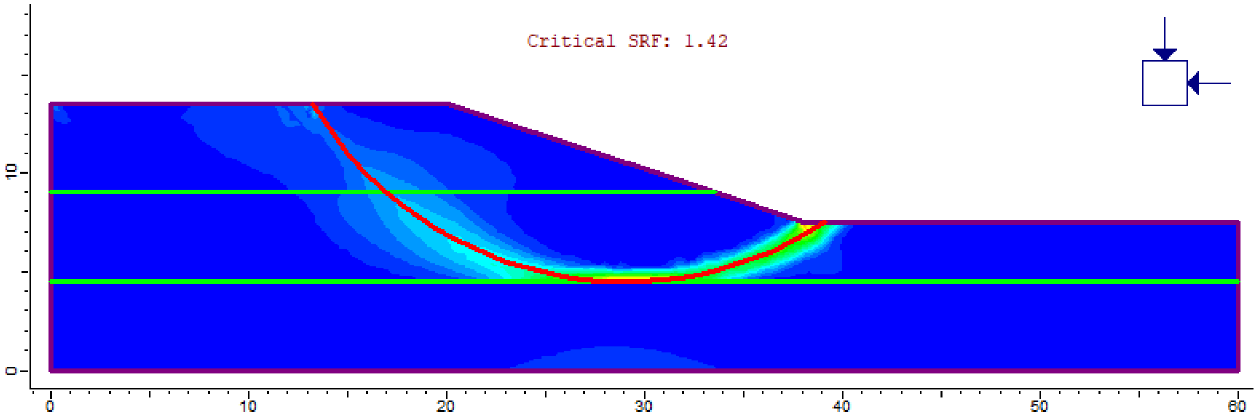


Figure 24.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #25

Bearing capacity test slope, homogenous, distributed load, predefined slip surface

25.1 Introduction

This model is taken from Chen and Shao (1988). It analyses the classical problem in the theory of plasticity of a weightless, frictionless slope subjected to a vertical load. This problem was first solved by Prandtl (1921).

25.2 Problem Description

Verification problem #25 is shown in Figure 25.2. The slope geometry, equation for the critical load, and position of the critical slip surface is defined by Prandtl and they are shown in Figure 25.1. The critical failure surface has a theoretical factor of safety of 1.0. The analysis uses the input data of Chen and Shao and is shown in Table 25.1. The geometry, shown in Figure 25.2, is generated assuming a 10m high slope with a slope angle of 60 degrees. The critical uniformly distributed load for failure is calculated to be 149.31 kN/m, with a length equal to the slope height, 10m.

Note: The GLE/discrete Morgenstern-Price results used the following custom inter-slice force function. This function was chosen to approximate the theoretical force distribution shown in Chen and Shao.

Table 25.1 – Interslice Force Function

x	F(x)
0	1
0.3	1
0.6	0
1.0	0

25.3 Geometry and Material Properties

Table 25.2 – Material Properties

c’ (kN/m²)	ϕ’ (⁰)	γ (kN/m³)
49	0	1e-6

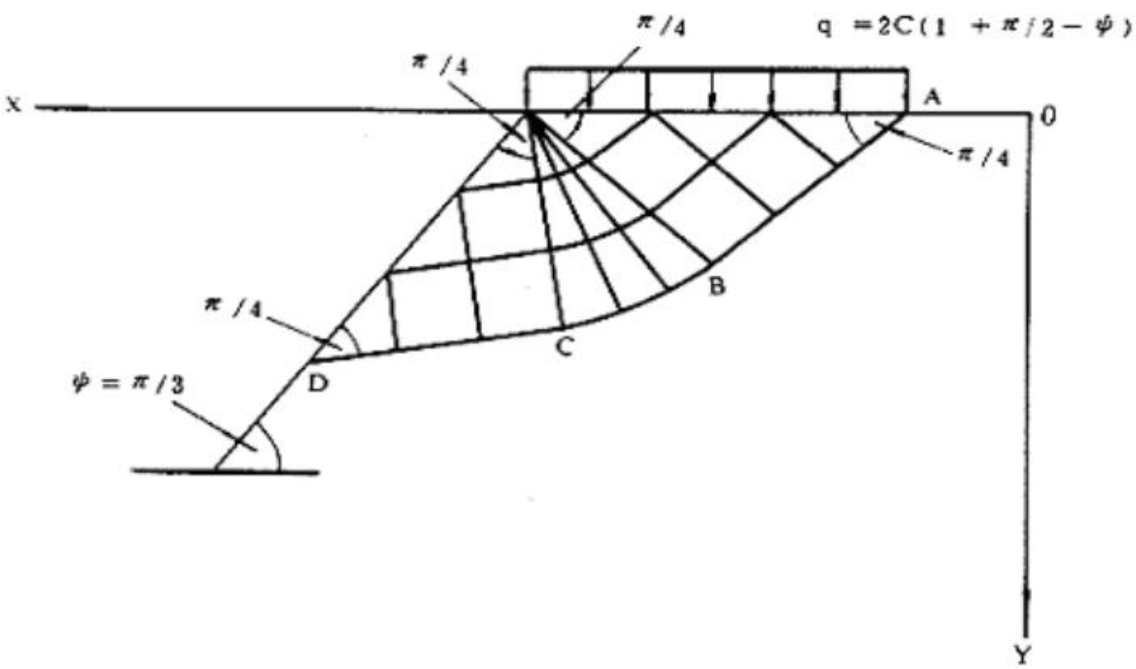


Figure 25.1 – ***Closed-form solution (from Chen and Shao (1988))***

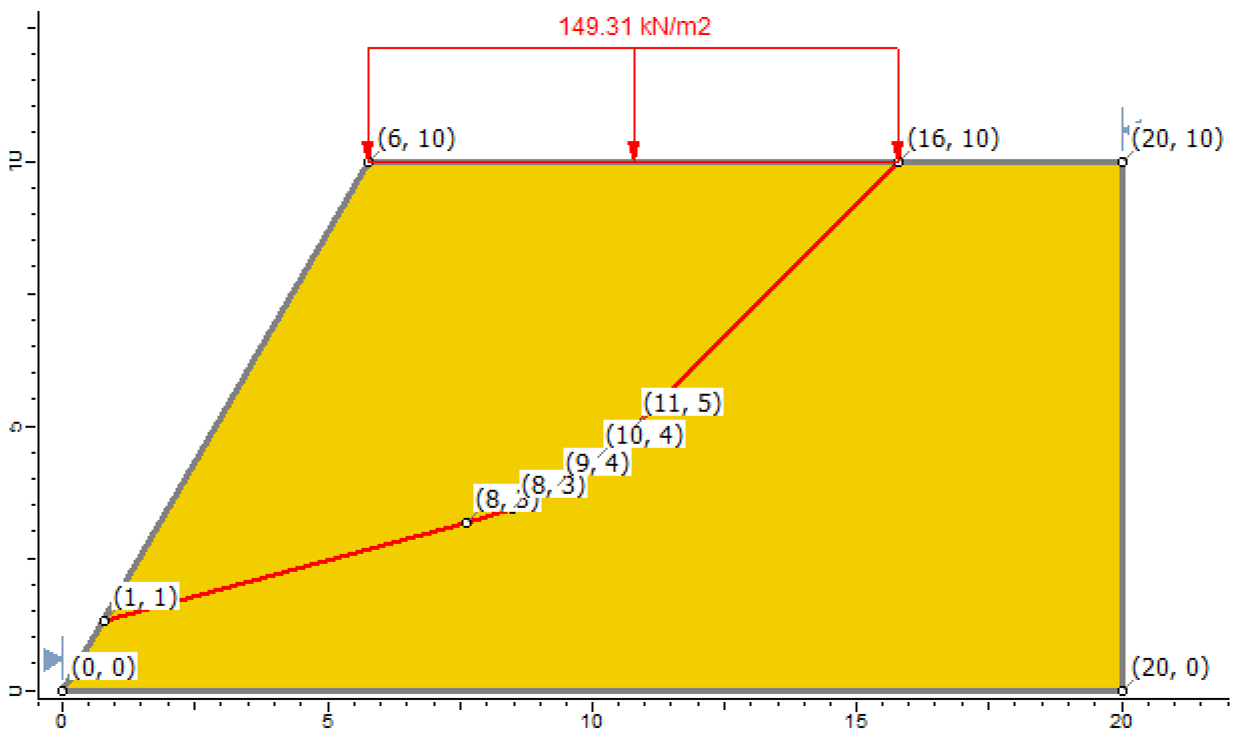


Figure 25.2 – ***Slide2*** **Geometry**

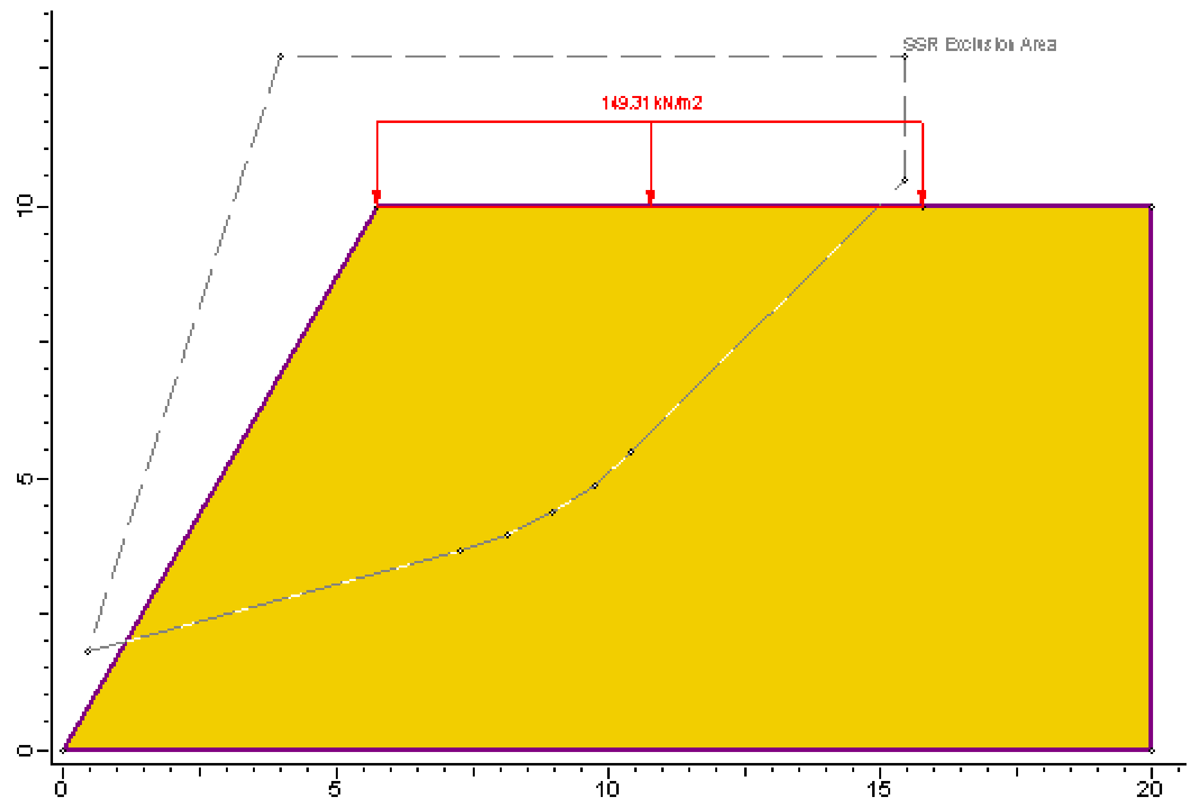


Figure 25.3 – *RS2* Geometry

25.4 Results

Table 25.2 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	1.051
	GLE	1.009
RS2	SSR	1.01

Note: Chen and Shao (1988) Spencer factor of safety = 1.05

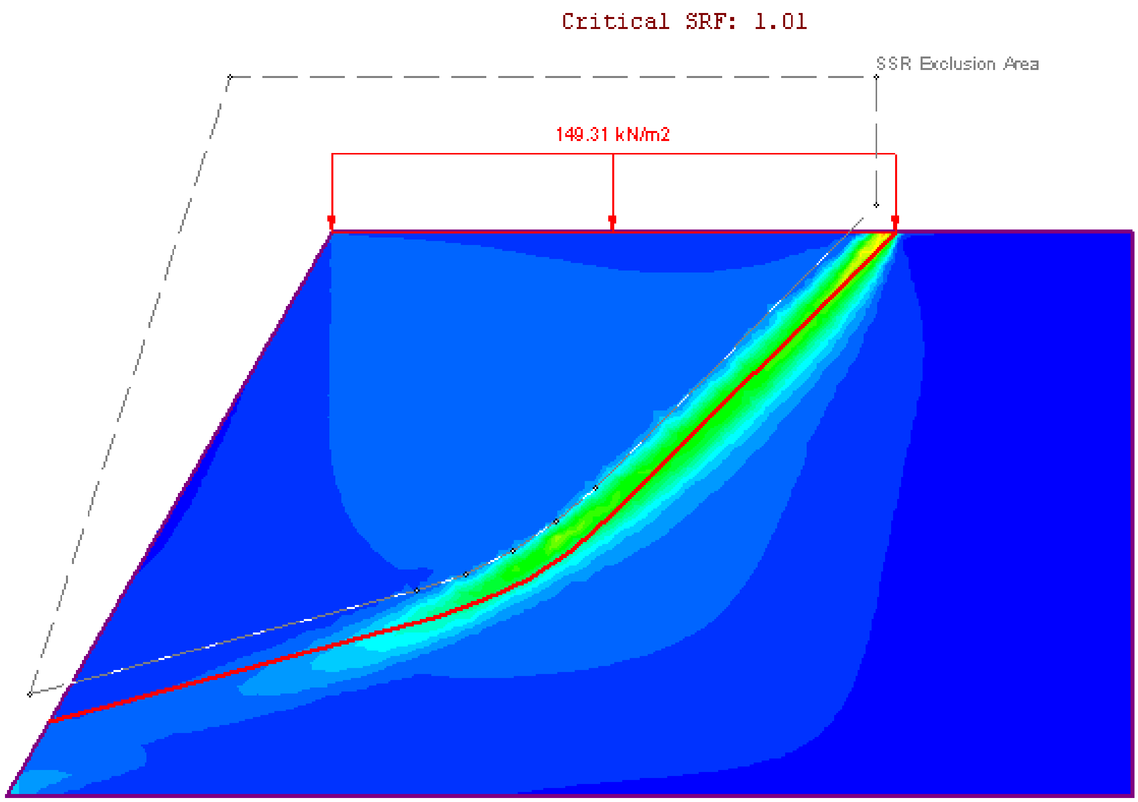


Figure 25.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #26

Bearing capacity test prism, homogenous, distributed load, predefined slip surface

26.1 Introduction

This verification test models the well-known Prandtl solution of bearing capacity: $qc=2C(1+\pi/2)$

26.2 Problem Description

Verification problem #26 is shown in Figure 26.1. The soil properties are given in Table 26.1. With cohesion of 20kPa, qc is calculated to be 102.83 kN/m. A uniformly distributed load of 102.83kN/m was applied over a width of 10m as shown in the figure below. The theoretical noncircular critical failure surface was used.

26.3 Geometry and Material Properties

Table 26.1 – Material Properties

c' (kN/m^2)	ϕ' (^{0})	γ (kN/m^3)
20	0	1e-6

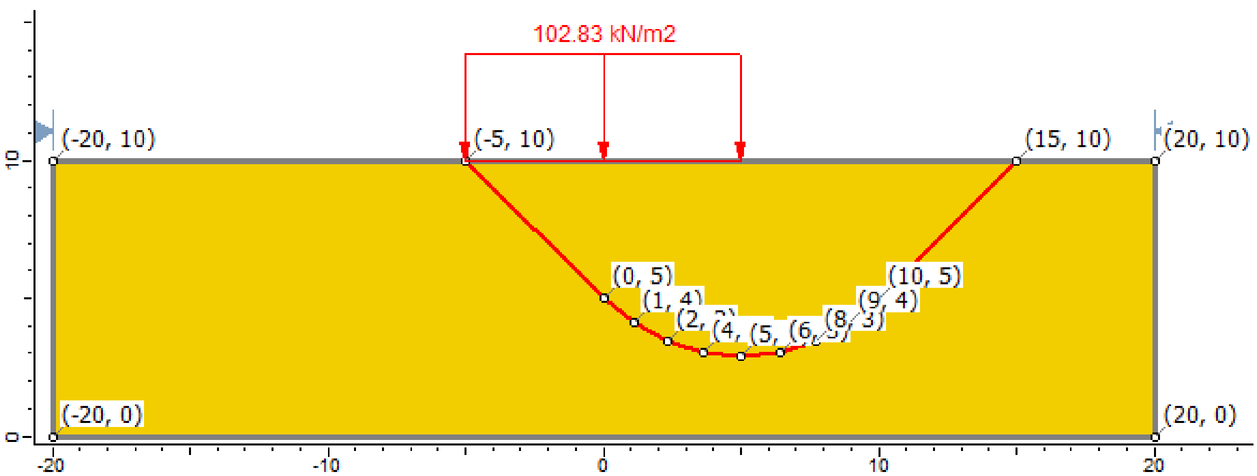


Figure 26.1 – *Slide2* Geometry

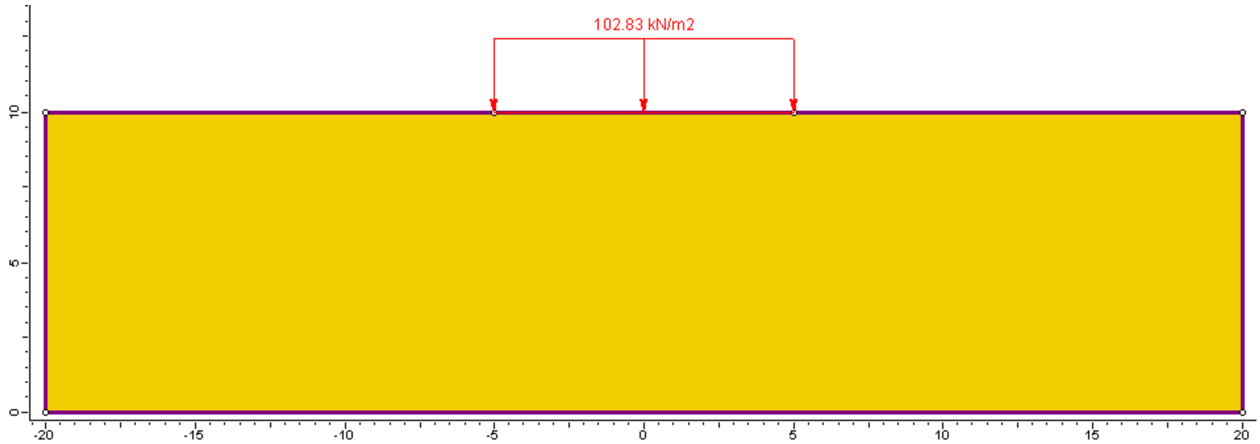


Figure 26.2 – *RS2* Geometry

Note: SSR Search Area was used in the *RS2* model to ensure the predetermined *Slide2* geometry

26.4 Results

Table 26.2 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	0.940
	GLE	0.955
RS2	SSR	1.00

Note: Theoretical factor of safety=1.0

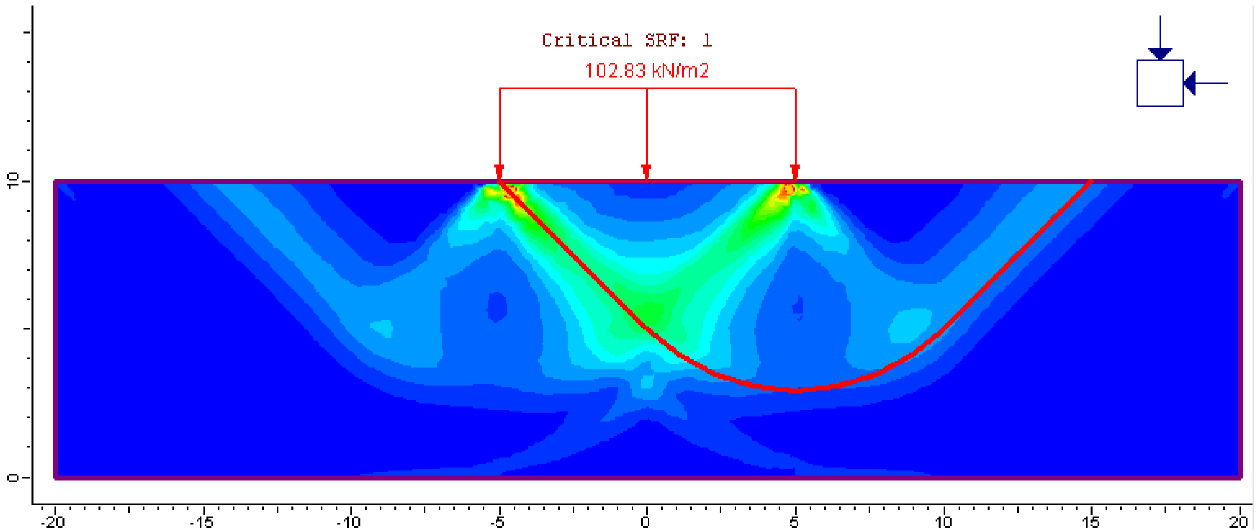


Figure 26.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #32

Reinforced Embankment, (7) materials, geosynthetic

32.1 Introduction

This model is taken from Borges and Cardoso (2002), their case 3 example. It looks at the stability of a geosynthetic-reinforced embankment on soft soil.

32.2 Problem Description

Verification problem #32 is shown in Figure 32.1 through Figure 32.6 The sand embankment is modeled as a Mohr-Coulomb material while the foundation material is a soft clay with varying undrained shear strength. The geosynthetic has a tensile strength of 200 kN/m, and frictional resistance against slip of 30.96 degrees. The reinforcement force is assumed to be parallel with the reinforcement. The Bishop simplified analysis method is used since this best simulates the moment based limit-equilibrium method the authors use. The reinforcement is modeled as a passive force since this corresponds to how the authors implement the reinforcement force in their limit-equilibrium implementation. There are two embankment materials, the lower embankment material is from elevation 0 to 1 while the upper embankment material is from elevation 1 to either 7 (Case 1) or 8.75m (Case 2). The geosynthetic is at elevation 0.9, just inside the lower embankment material.

32.3 Geometry and Material Properties

Table 32.1 – Embankment Properties

	c' (kN/m²)	ϕ' (⁰)	γ (kN/m³)
Upper Embankment	0	35	21.9
Lower Embankment	0	33	17.2

Table 32.2 – Soil Properties

	Cu (kN/m²)	γ (kN/m³)
Clay 1	43	18
Clay 2	31	16.6
Clay 3	30	13.5
Clay 4	32	17
Clay 5	32	17.5

Case 1 – Embankment Height = 7m

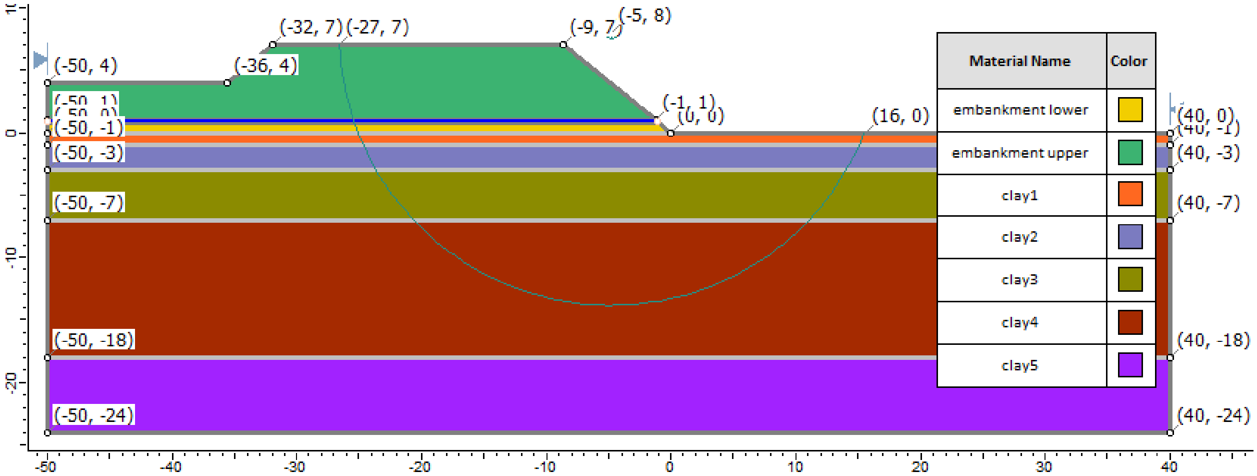


Figure 32.1 – *Slide2* Geometry

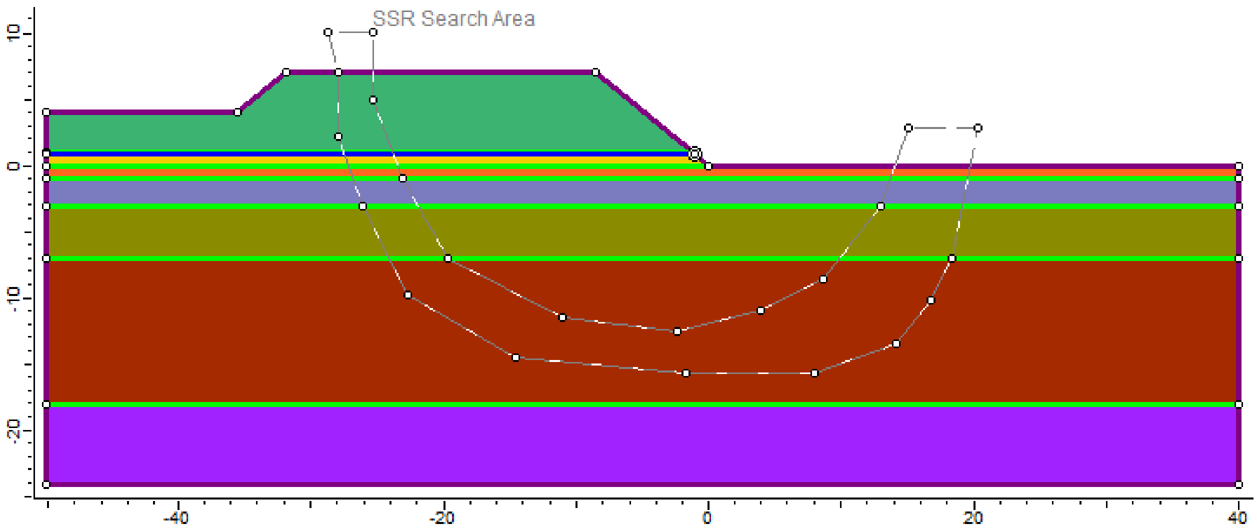


Figure 32.2 – *RS2* Geometry

Case 2 – Embankment Height = 7m

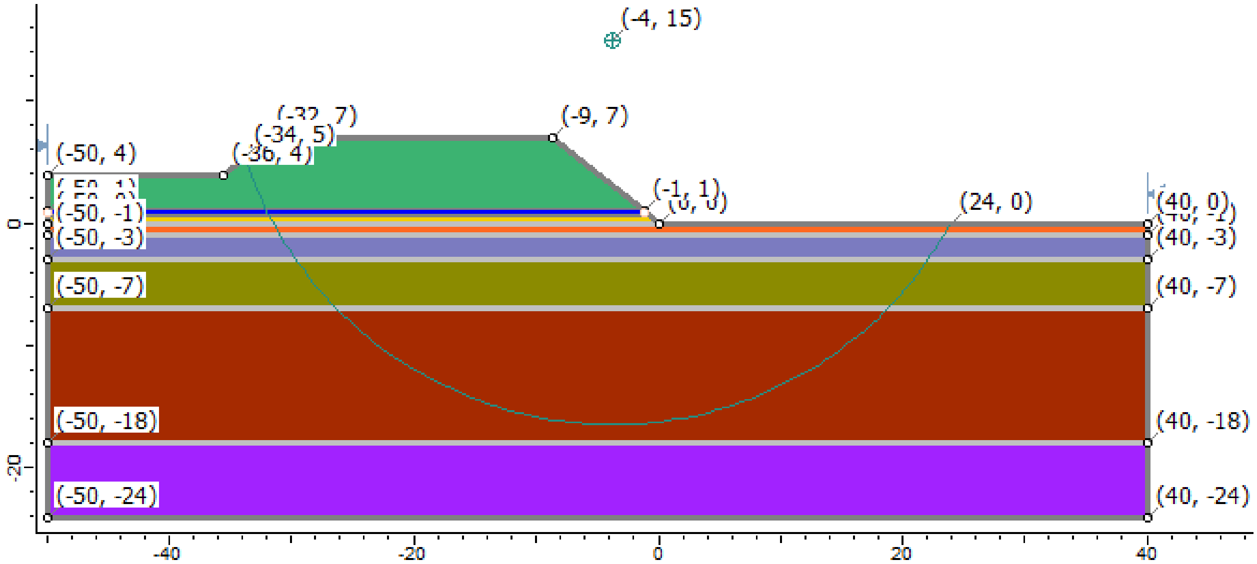


Figure 32.3 – *Slide2* Geometry

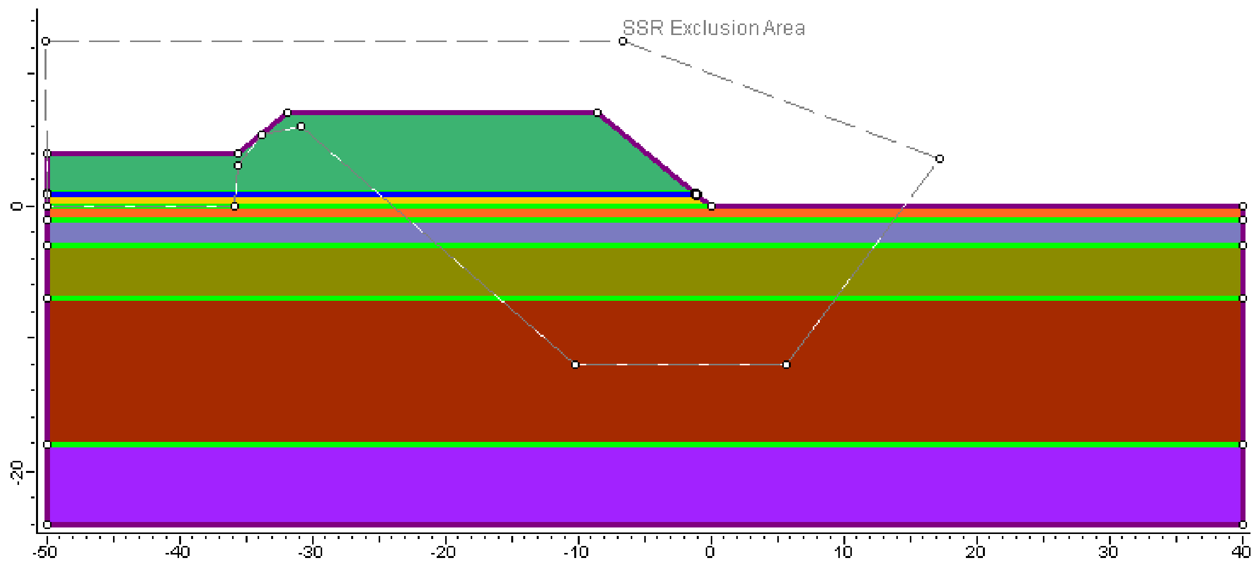


Figure 32.4 – *RS2* Geometry

Case 3 – Embankment Height = 8.75m

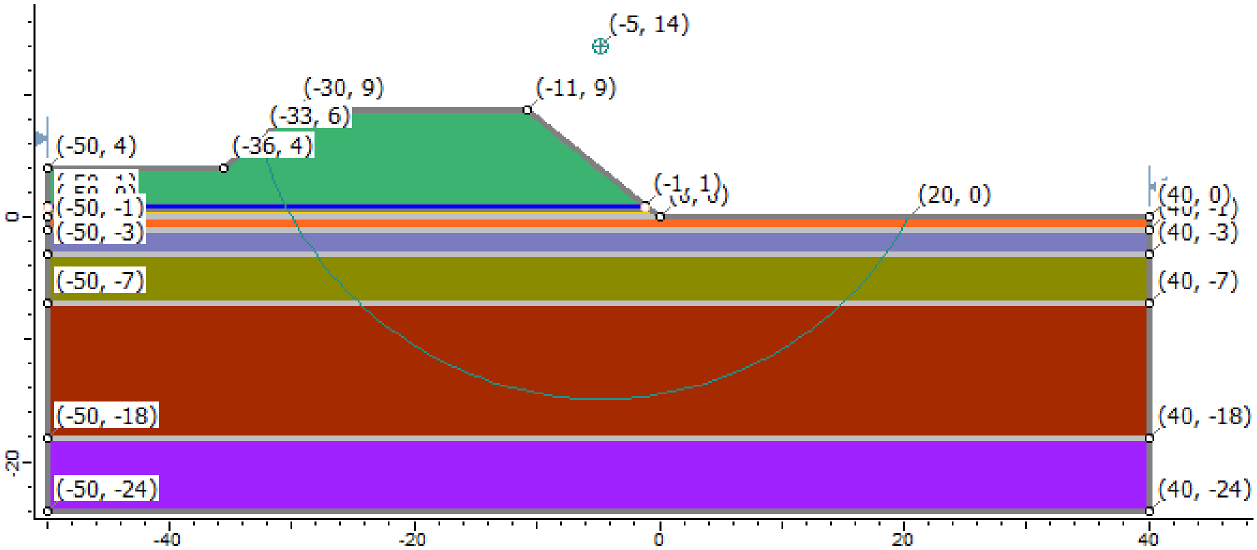


Figure 32.5 – *Slide2* Geometry

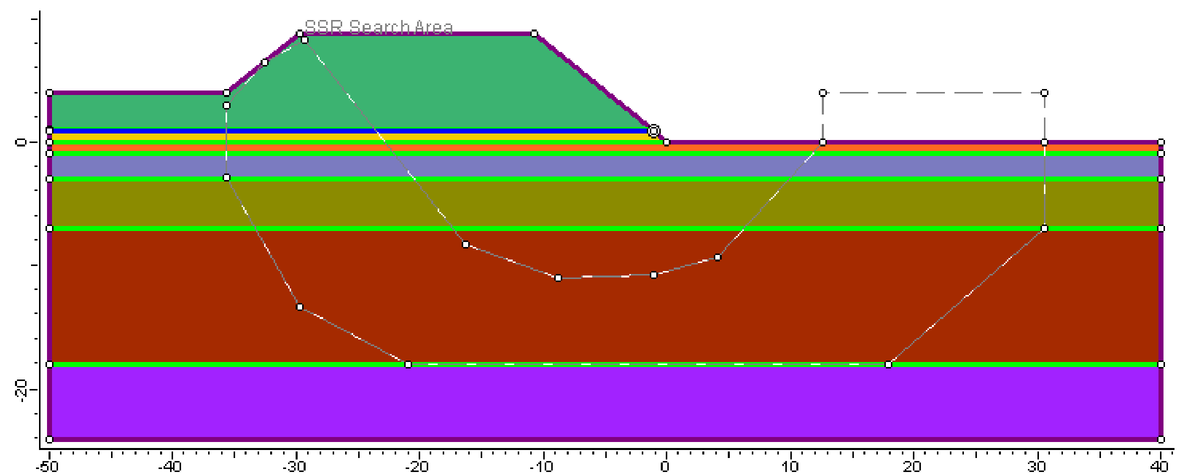


Figure 32.6 – *RS2* Geometry

32.4 Results

Case 1 – Embankment Height = 7m

Table 32.3 – Comparison of Results Case 1

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.226
	GLE	1.225
RS2	SSR	1.24

Note: Reference Factor of Safety = 1.25 [Borges]

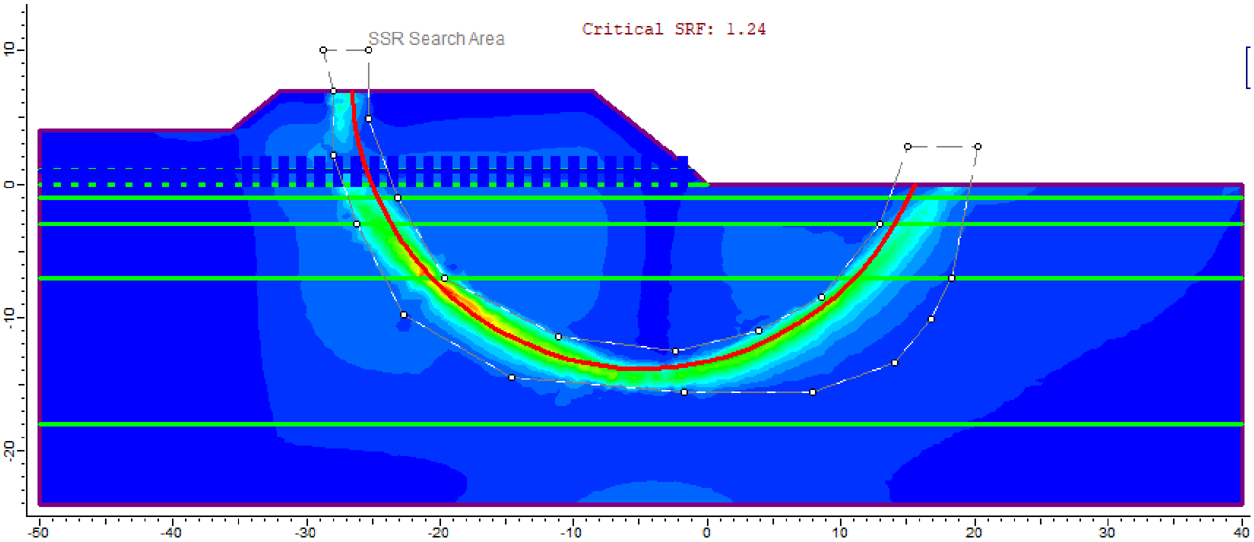


Figure 37.7 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 2 – Embankment Height = 7m

Table 32.4 – Comparison of Results Case 2

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.220
	GLE	1.221
RS2	SSR	1.21

Note: Reference Factor of Safety = 1.19 [Borges]

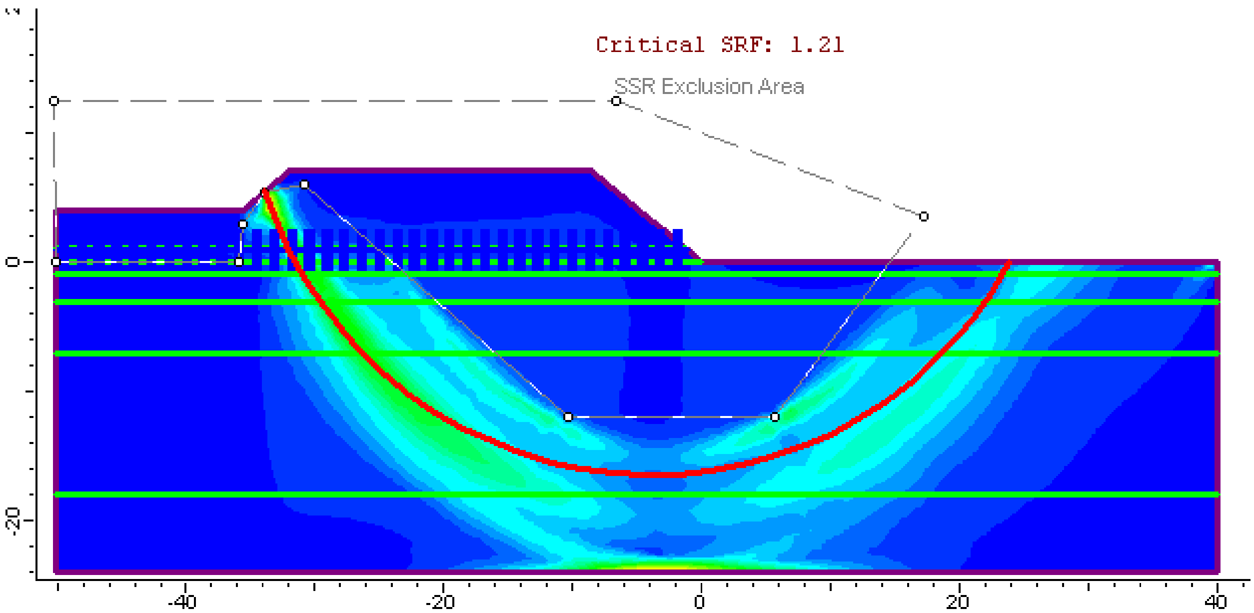


Figure 32.8 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 3 – Embankment Height = 8.75m

Table 32.5 – Comparison of Results Case 3

Program	Method	Factor of Safety (circular)
Slide2	Spencer	0.987
	GLE	0.984
RS2	SSR	0.98

Note: Reference Factor of Safety = 0.99 [Borges]

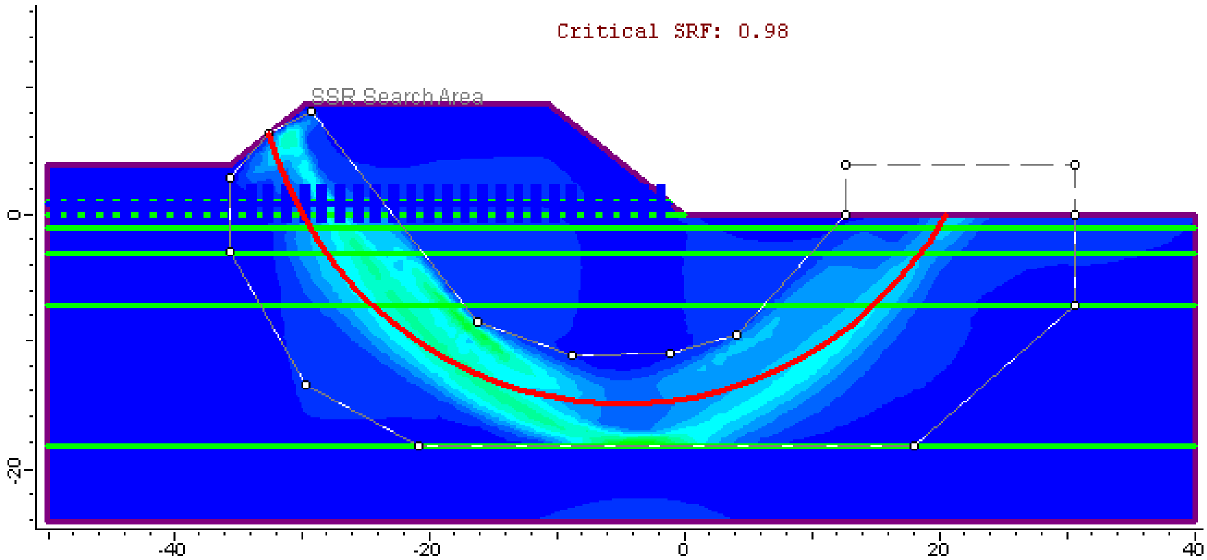


Figure 32.9 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #38

Excavated slope, homogeneous, finite element groundwater seepage analysis, matric suction

38.1 Introduction

Verification #38 models a typical steep cut slope in Hong Kong. The example is taken from Ng and Shi (1998). It illustrates the use of finite element groundwater analysis and conventional limit equilibrium slope stability in the assessment of the stability of the cut.

38.2 Problem Description

The cut has a slope face angle of 28o and it consists of a 24m thick soil layer, underlain by a 6m thick bedrock layer. Figure 38.1 describes the slope model in *Slide2*.

Steady-state groundwater analysis is conducted using the finite element module in *Slide2*. Initial conditions of constant total head are applied to both sides of the slope. Three different initial hydraulic boundary conditions (H=61m, H=62m, H=63m) for the right side of the slope are considered for the analyses in this section, shown in Figure 38.1. Constant hydraulic boundary head of 6m is applied on the left side of the slope. A mesh of 1621 six-noded triangular elements was used to model the problem. Figure 38.2 shows the soil permeability function used to model the hydraulic conductivity of the soil, Ng (1998).

The negative pore water pressure, which is commonly referenced to as the matric suction of soil, above the water table influences the soil shear strength and hence the factor of safety. Ng and Shi used the modified Mohr-Coulomb failure criterion for the unsaturated soils, which can be written as

$$\tau = c' + (\sigma_n - u_a) \tan\varphi' + (ua - uw) \tan\varphi_b$$

where σ_n is the normal stress, φ_b is an angle defining the increase in shear strength for an increase in matric suction of the soil. Table 38.1 shows the material properties for the soil.

Both positive and negative pore water pressures predicted from groundwater analysis engine were used in the stability analysis.

38.3 Geometry and Material Properties

Table 38.1 – Material Properties

c' (kN/m²)	ϕ' (⁰)	ϕb (⁰)	γ (kN/m³)
10	38	15	16

Case 1 – Total Head 61m

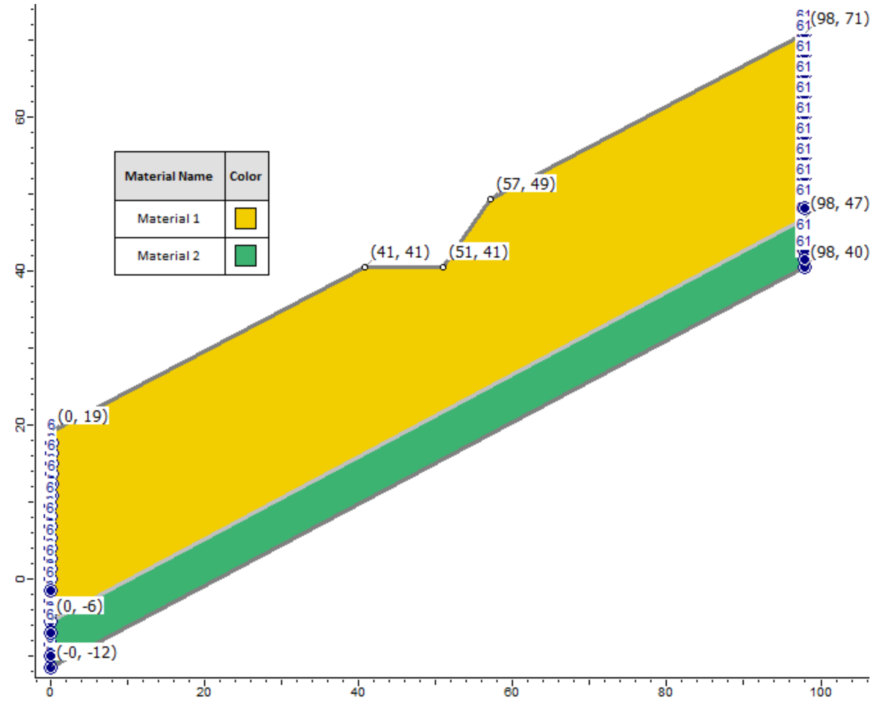


Figure 38.1 – *Slide2* Geometry

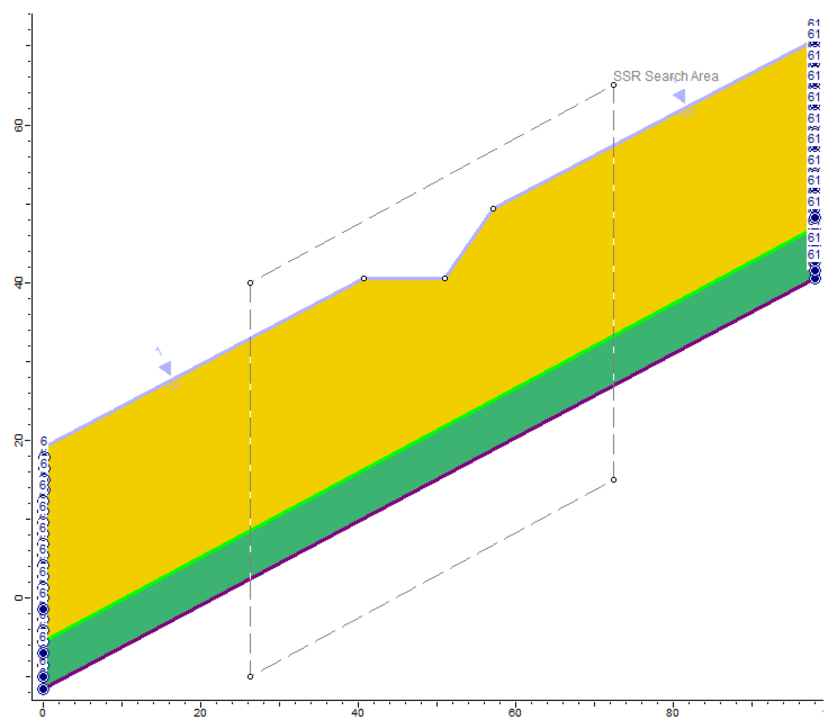


Figure 38.2 – *RS2* Geometry

Case 2 – Total Head 62m

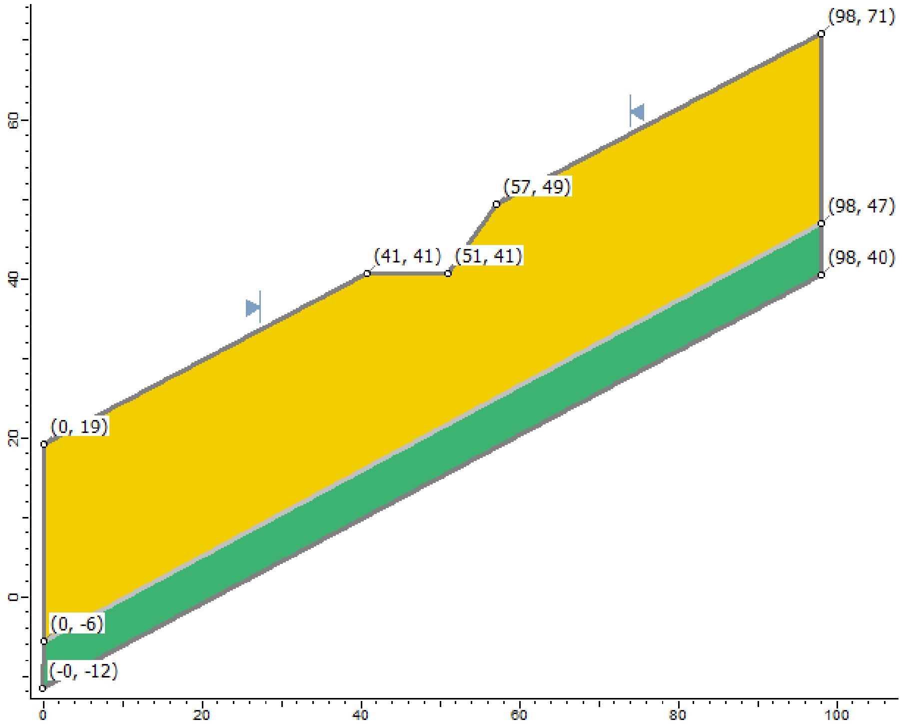


Figure 38.3 – *Slide2* Geometry

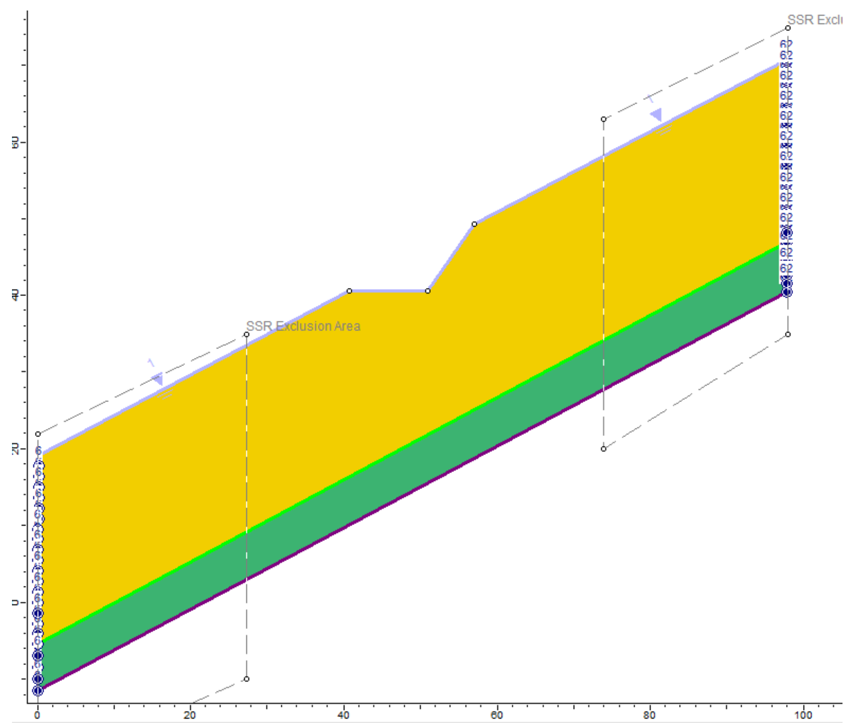


Figure 38.4 – *RS2* Geometry

Case 3 – Total Head 63m

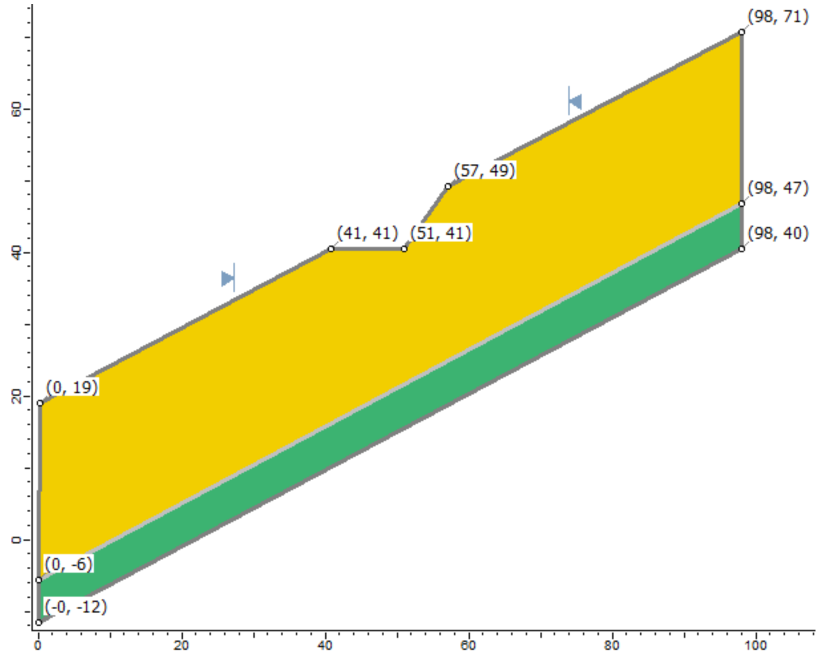


Figure 38.5 – *Slide2* Geometry

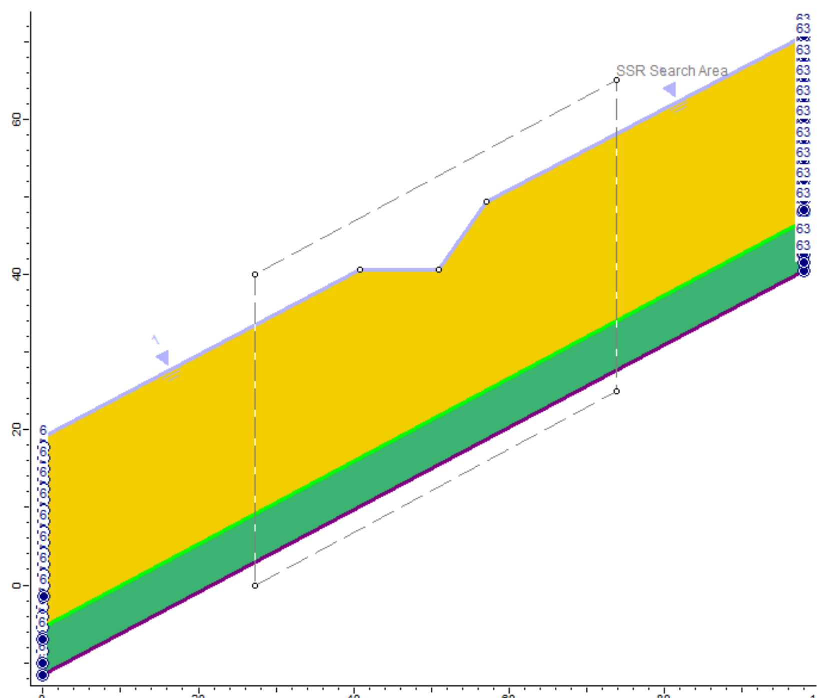


Figure 38.6 – *RS2* Geometry

38.4 Results

Case 1 – Total Head 61m

Table 38.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.619
	GLE	1.619
RS2	SSR	1.56

Note: Reference Factor of Safety = 1.636 [Ng. & Shi (1998)]

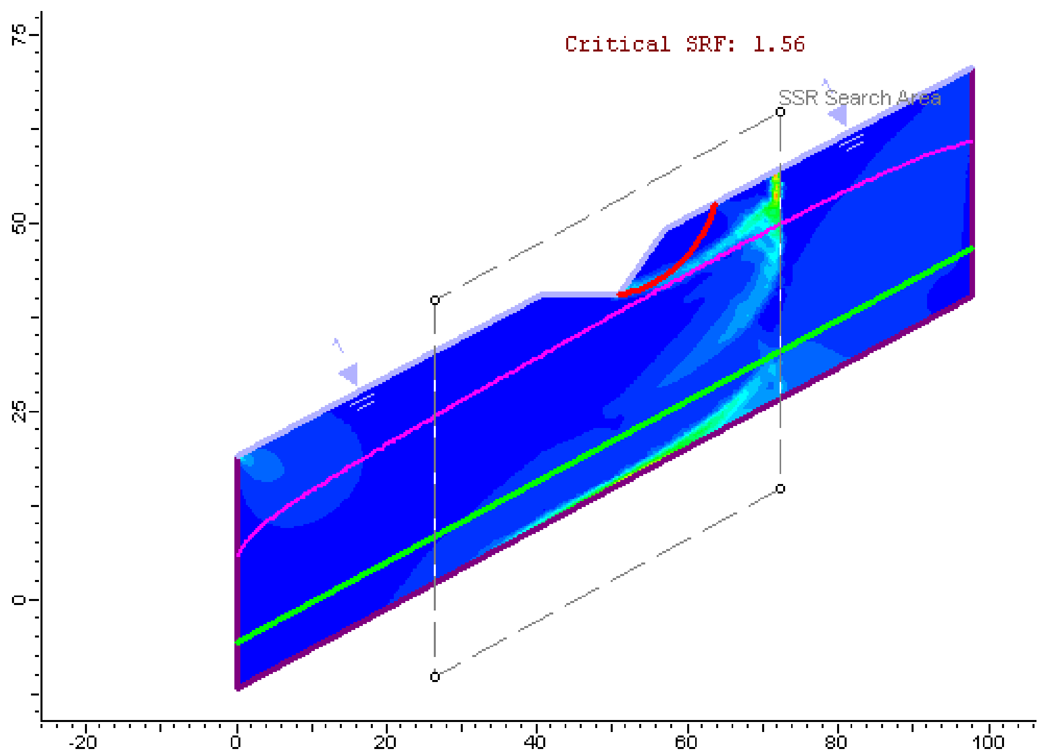


Figure 38.7 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 2 – Total Head 62m

Table 38.3 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	1.534
	GLE	1.534
RS2	SSR	1.46

Note: Reference Factor of Safety = 1.527 [Ng. & Shi (1998)]

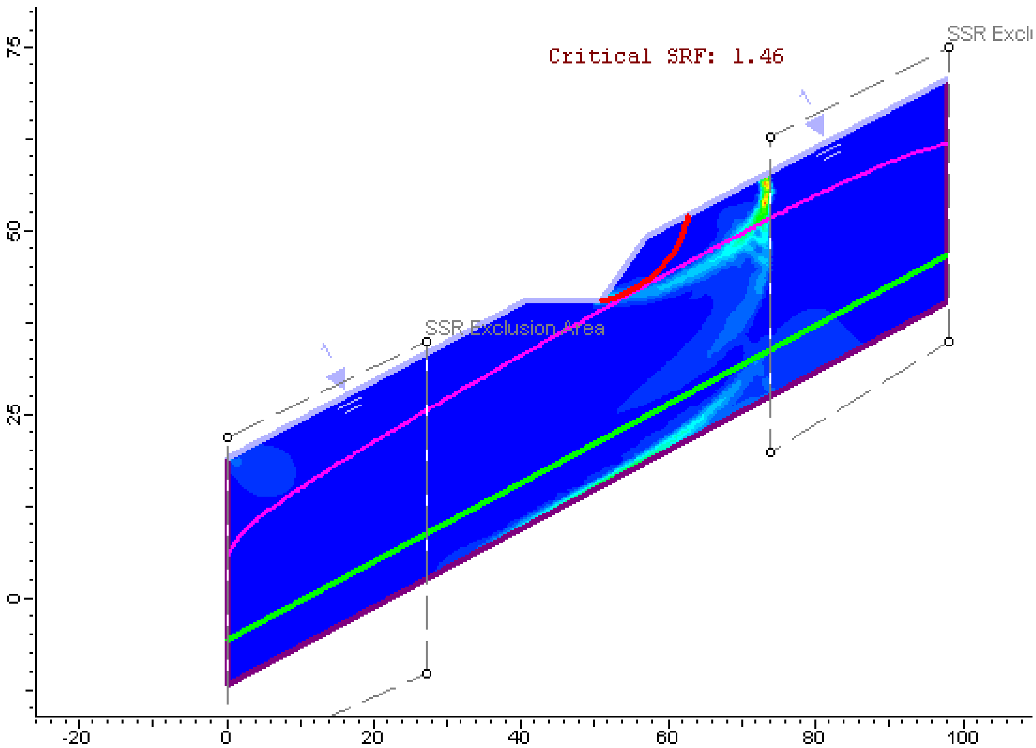


Figure 38.8 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 3 – Total Head 63m

Table 38.3 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	1.401
	GLE	1.403
RS2	SSR	1.32

Note: Reference Factor of Safety = 1.407 [Ng. & Shi (1998)]

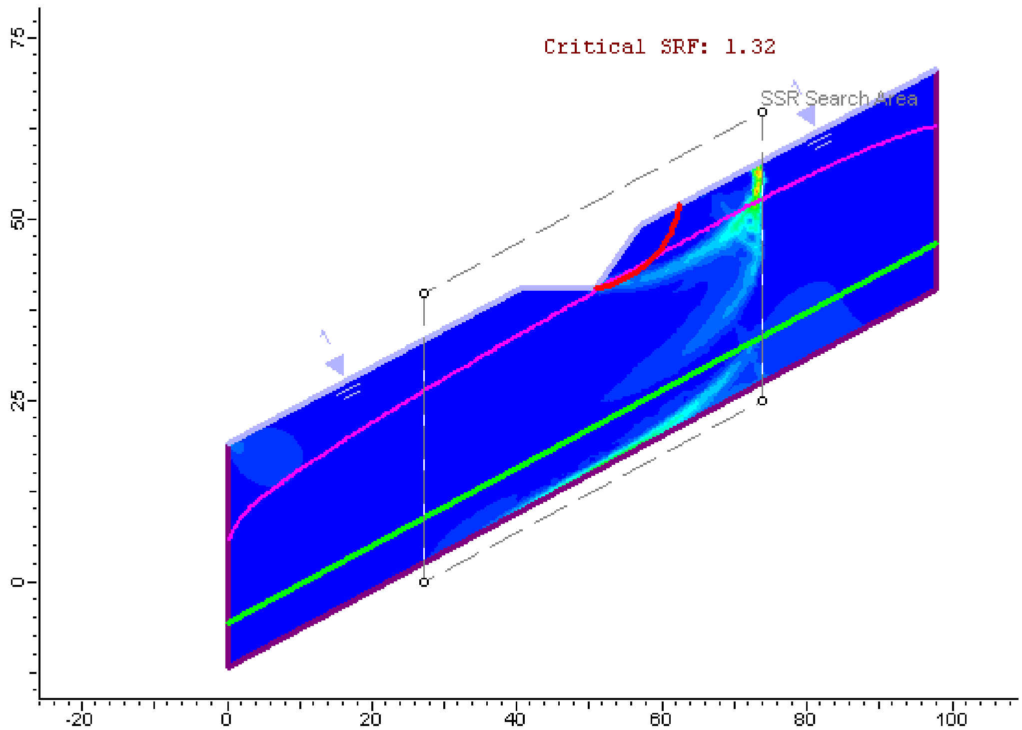


Figure 38.9 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #39

Reinforced embankment, (2) materials, tension crack, geosynthetic

39.1 Introduction

This model is taken from Tandjiria (2002), their problem 1. It looks at the stability of a geosynthetic-reinforced embankment on soft soil. The problem looks at the stability of the embankment if it consists of either a sand fill or an undrained clayey fill. Both are analyzed.

39.2 Problem Description

Verification problem #39 is shown in Figures 39.1 and 39.2. The purpose of this example is to compute the required reinforcement force to yield a factor of safety of 1.35. Both circular and non-circular surfaces are looked at. In each case, the embankment is modeled without the reinforcement; the critical slip surface is located, and then used in the reinforced model to determine the reinforcement force to achieve a factor of safety of 1.35. This is done for a sand or clay embankment, circular and non-circular critical slip surfaces. Both cases incorporate a tension crack in the embankment. In the case of the clay embankment, a water-filled tension crack is incorporated into the analysis. The reinforcement is located at the base of the embankment. The model was analyzed with both Spencer and GLE (half-sine interslice function) but Spencer was used for the force computation. The reinforcement is modeled as an active force since this is how Tandjiria et.al. modelled the force.

39.3 Geometry and Material Properties

Table 39.1 – Material Properties

	c' (kPa)	ϕ' (⁰)	γ (kN/m³)
Sand Fill	20	0	19.4
Soft Clay	20	0	19.4

Case 1 – Clay – No Reinforcement

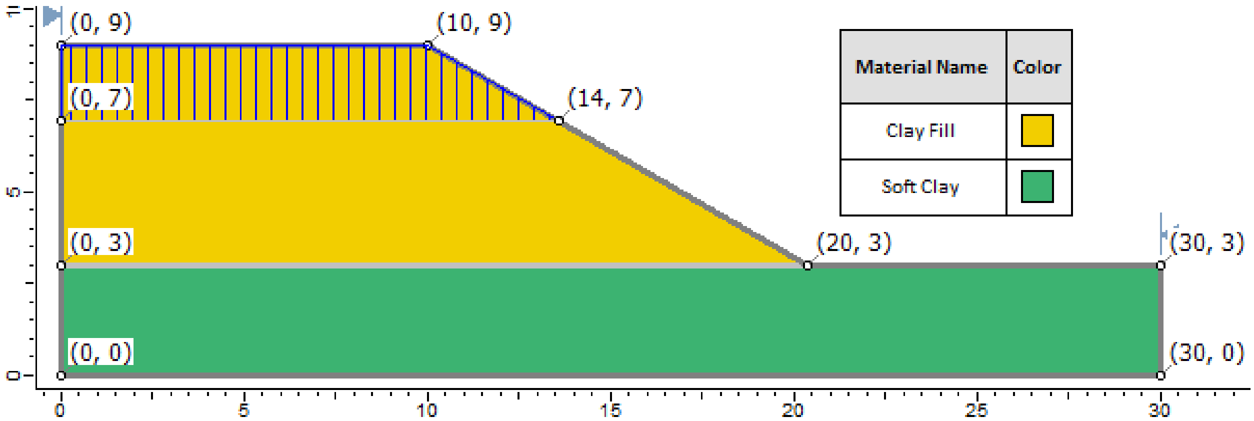


Figure 39.1 – *Slide2* Geometry

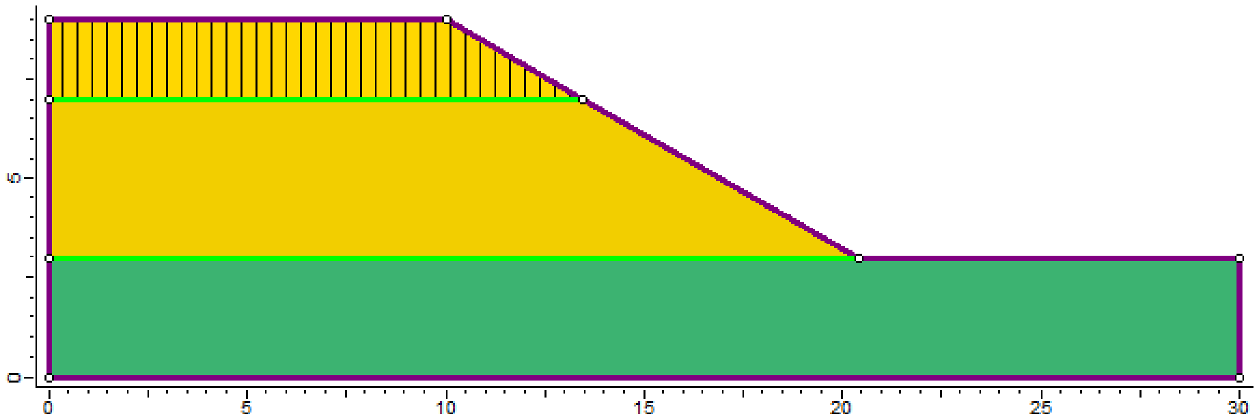


Figure 39.2 – *RS2* Geometry

Case 2 – Clay – Reinforcement

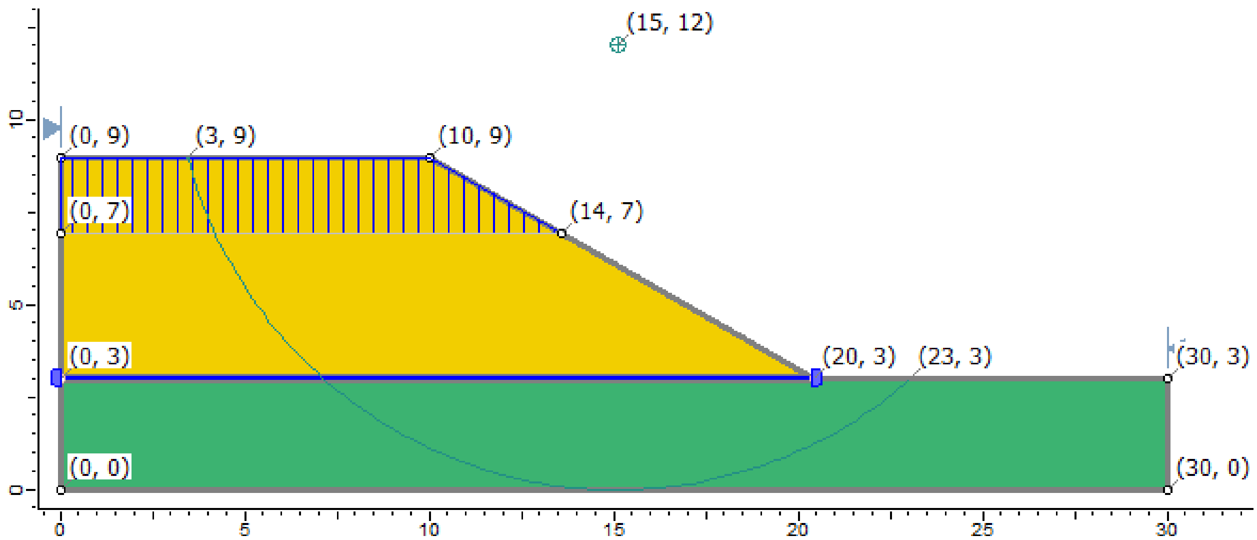


Figure 39.3 – *Slide2* Geometry

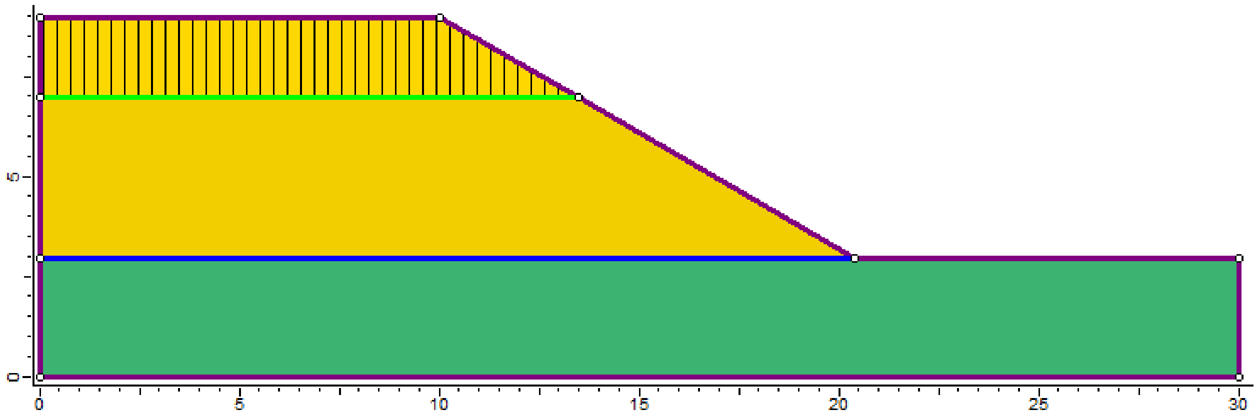


Figure 39.4 – *RS2* Geometry

Case 3 – Sand – No Reinforcement

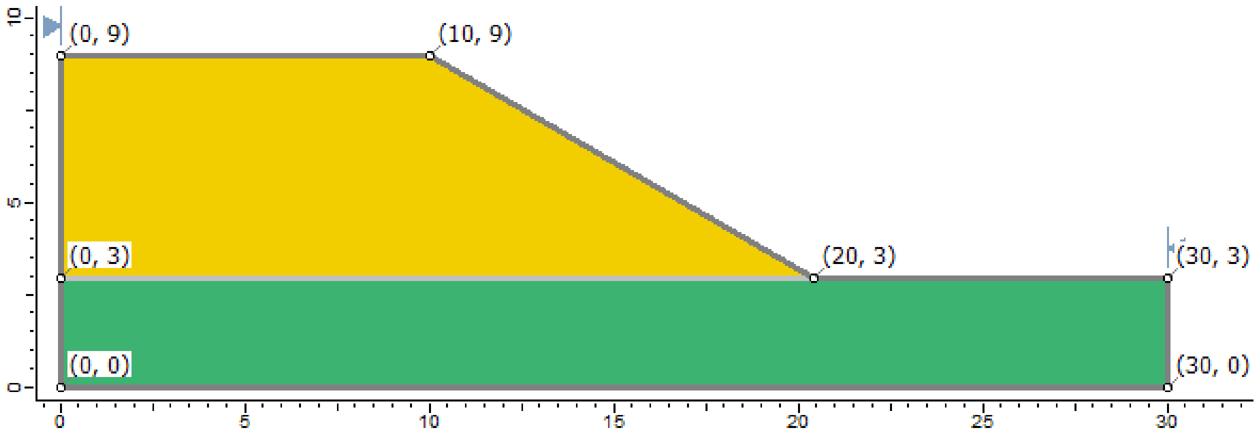


Figure 39.5 – *Slide2* Geometry

Figure 39.6 – *RS2* Geometry

Case 4 – Sand – Reinforcement

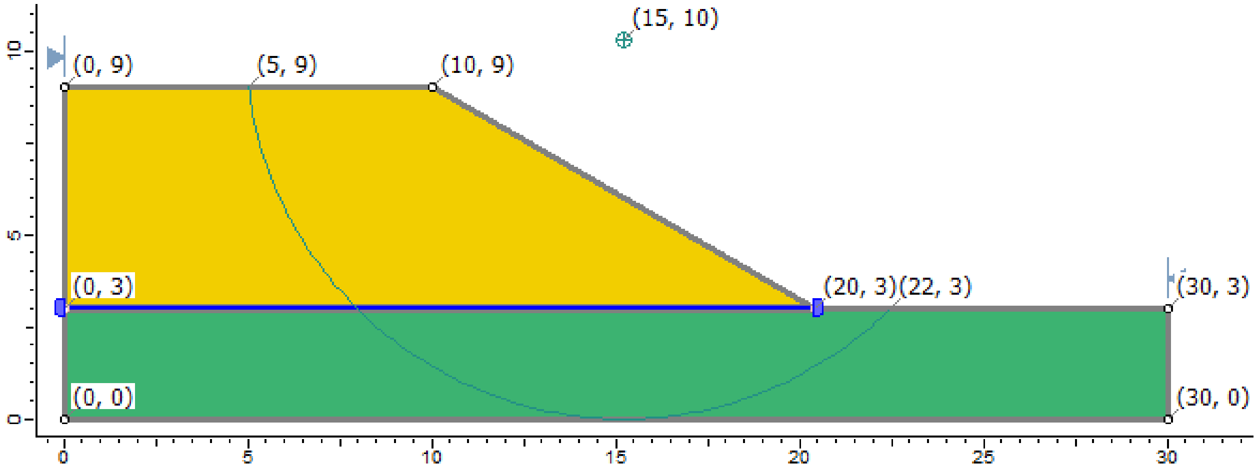


Figure 39.7 – *Slide2* Geometry

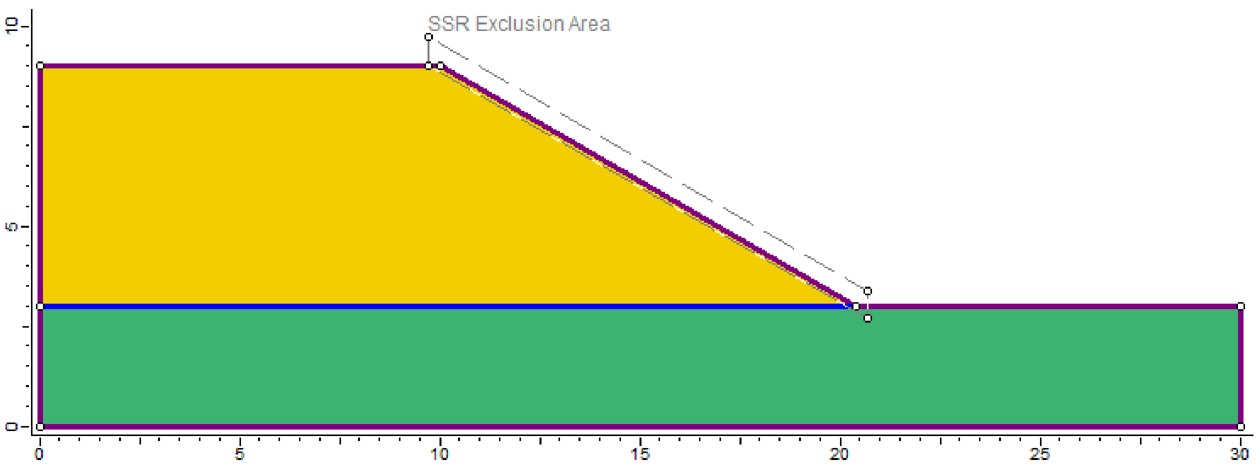


Figure 39.8 – *RS2* Geometry

39.4 Results

Case 1 – Clay – No Reinforcement

Table 39.2 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	0.975	0.936
	GLE	0.975	0.939
RS2	SSR	0.97	

Note: Circular Tandjiria (2002) Spencer factor of safety = 0.981
Non-Circular Tandjiria (2002) Spencer factor of safety = 0.941

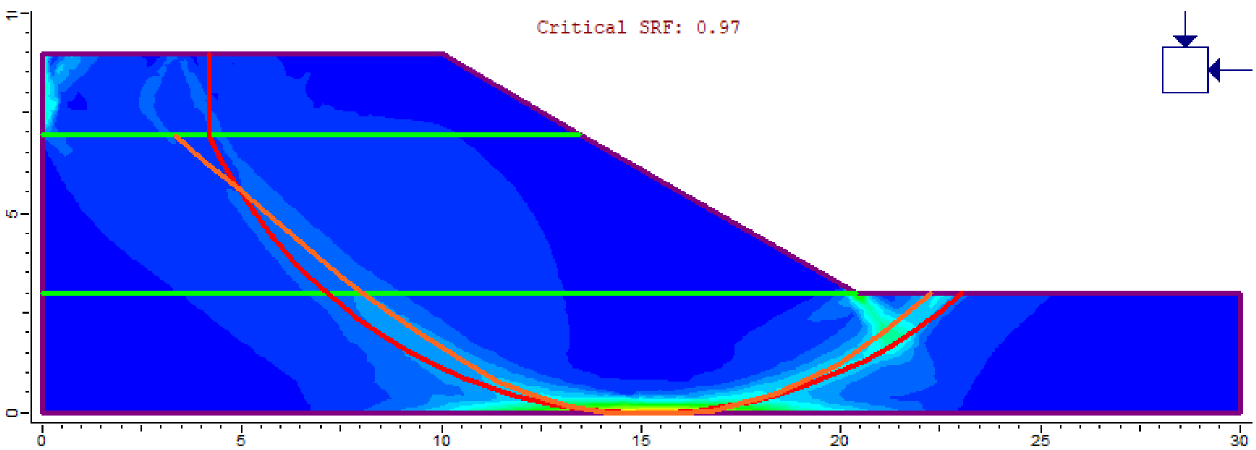


Figure 39.9 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 2 – Clay – Reinforcement

Table 39.3 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.350	1.352
	GLE	1.350	1.366
RS2	SSR	1.42	

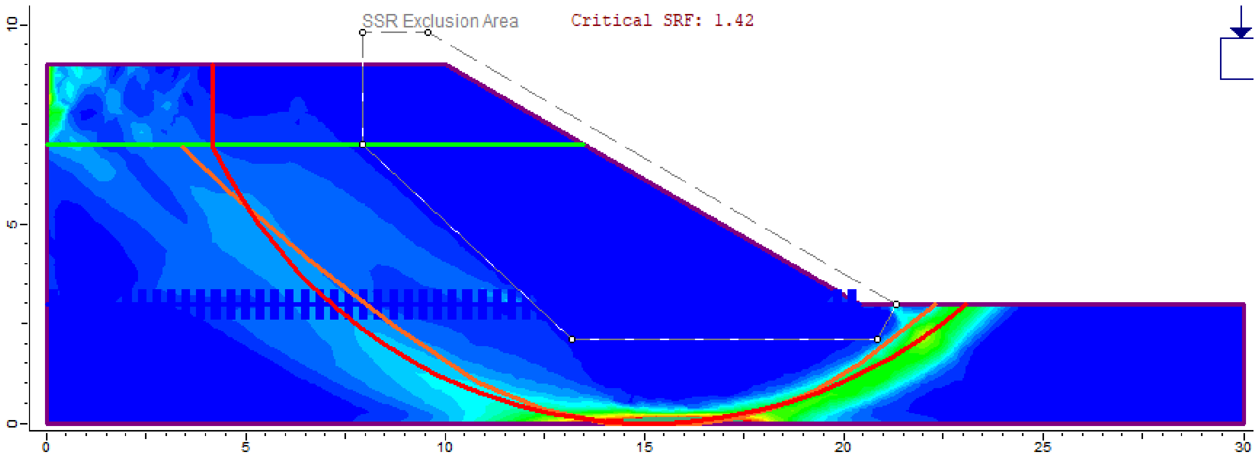


Figure 39.10 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 3 – Sand – No Reinforcement

Table 39.4 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.209	1.184
	GLE	1.218	1.188
RS2	SSR	1.22	

Note: Circular Tandjiria (2002) Spencer factor of safety = 1.219
Non-Circular Tandjiria (2002) Spencer factor of safety = 1.192

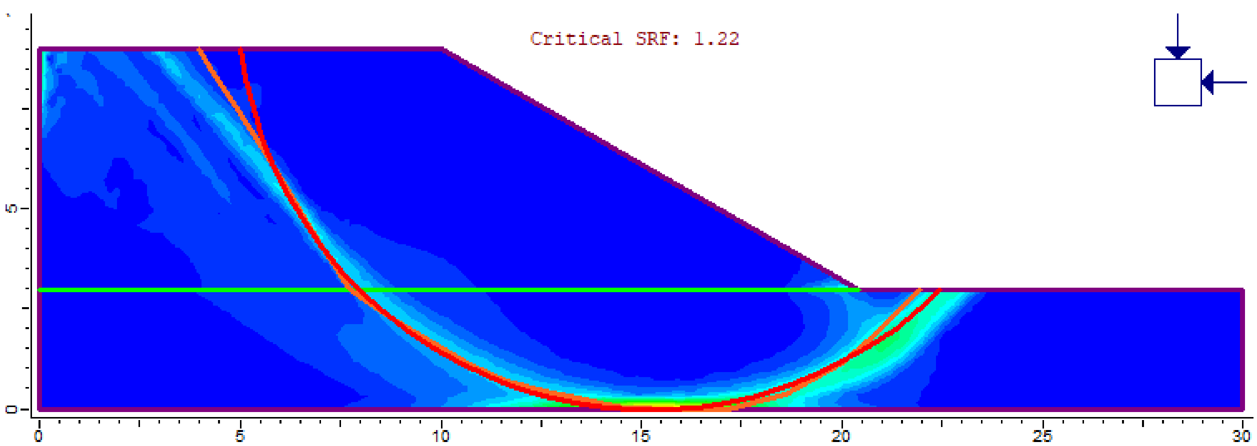


Figure 39.11 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 4 – Sand – Reinforcement

Table 39.5 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.350	1.350
	GLE	1.357	1.359
RS2	SSR	1.39	

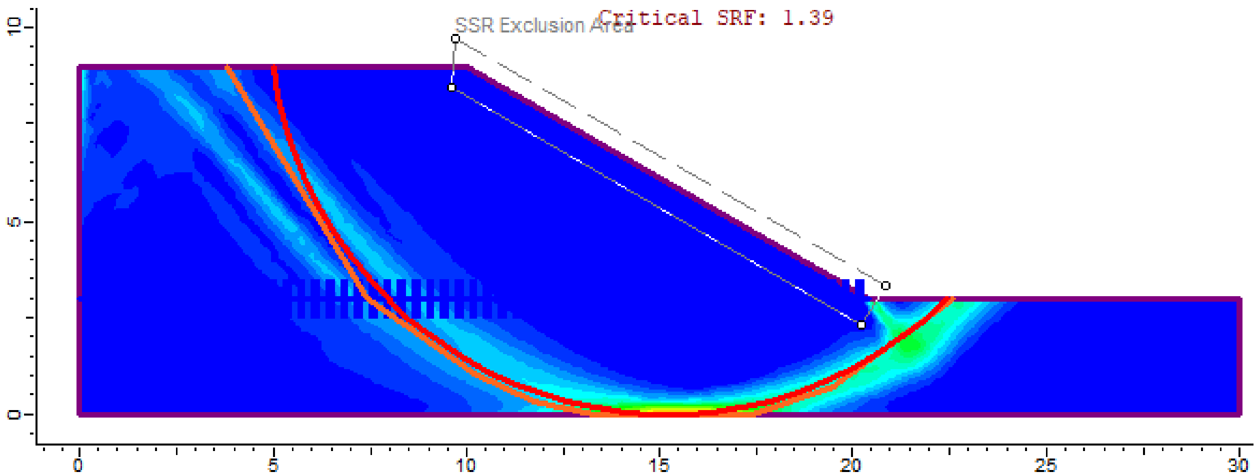


Figure 39.12 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #40

Slope, homogeneous, sensitivity analysis

40.1 Introduction

This problem was taken from J. Perry (1993), Fig. 10. It looks at the non-linear power curve relation of effective normal stress to shear stress.

40.2 Problem Description

This problem consists of a simple homogeneous slope with 5 slices (Figure 40.1). The nonlinear failure surface has been defined. The dry soil is assumed to follow non-linear power curve strength parameters. The factor of safety for the specified failure surface is required. A sensitivity analysis must also be carried out for parameters A and b.

40.3 Geometry and Material Properties

Table 40.1 – Material Properties

	A	b	γ (kN/m³)
Mean	2	0.7	20.0
Rel. max/min	0.3	0.105	N/a

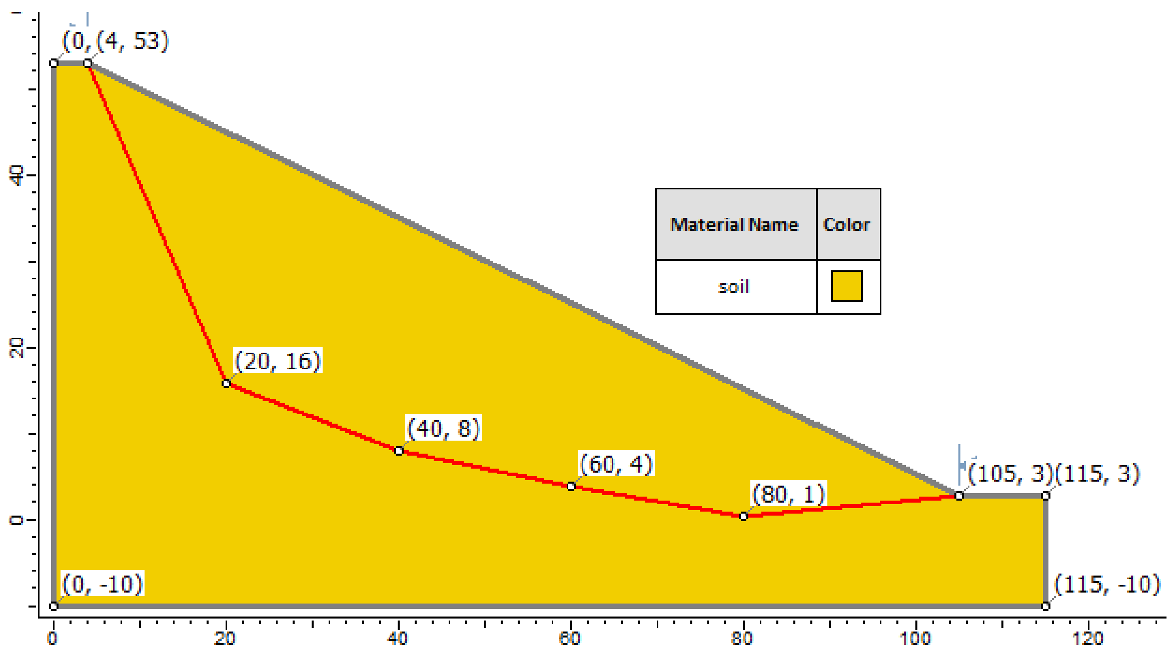


Figure 40.1 – *Slide2* Geometry

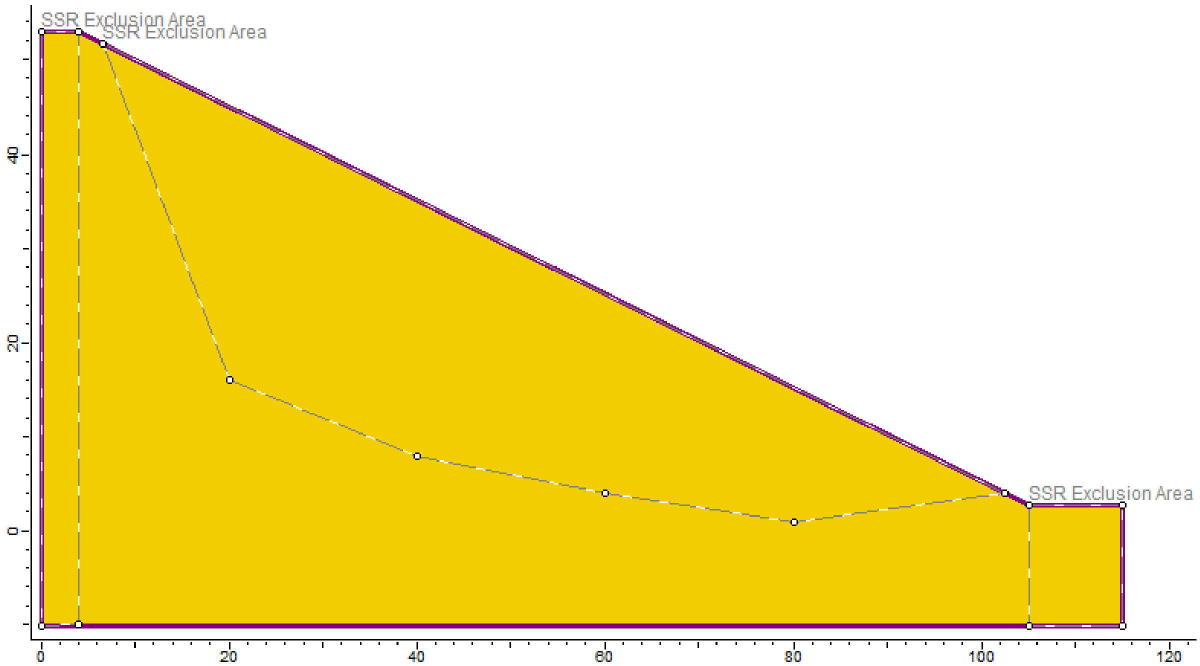


Figure 40.2 – *RS2* Geometry

40.4 Results

Table 40.2 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	1.088
	GLE	1.064
RS2	SSR	0.97

Note: Reference Factor of Safety = 0.98 [Perry]

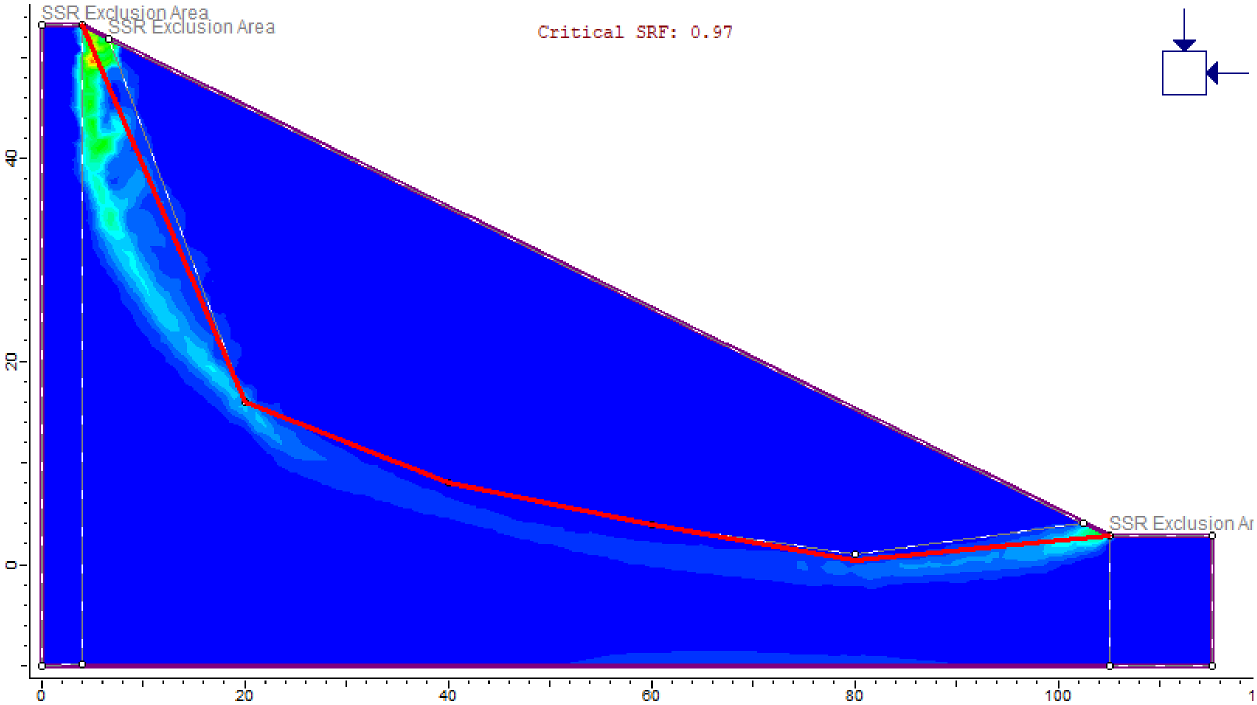


Figure 40.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #41

Slope, homogeneous, ru pore pressure

41.1 Introduction

This problem was taken from Jiang, Baker, and Yamagami (2003). It examines a homogeneous slope with non-linear strength properties.

41.2 Problem Description

The slope geometry is shown in Fig. 41.1. The material strength is modeled with a power curve. Using the path search, the factor of safety and non-linear failure surface is calculated. Pore pressure ratio (Ru) for the clay is 0.3.

41.3 Geometry and Material Properties

Table 49.1 – Material Properties

A	B	γ (kN/m³)
1.4	0.8	20.0

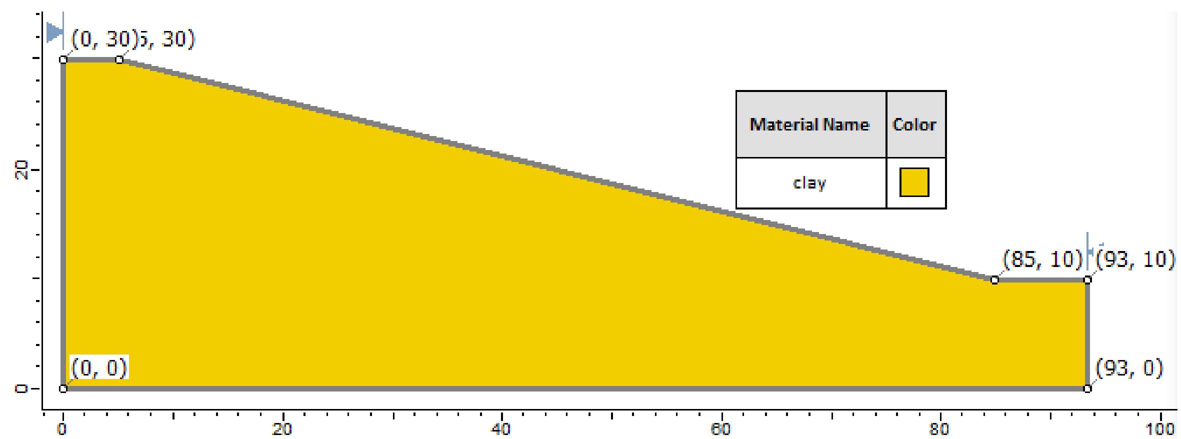


Figure 412.1 – *Slide2* Geometry

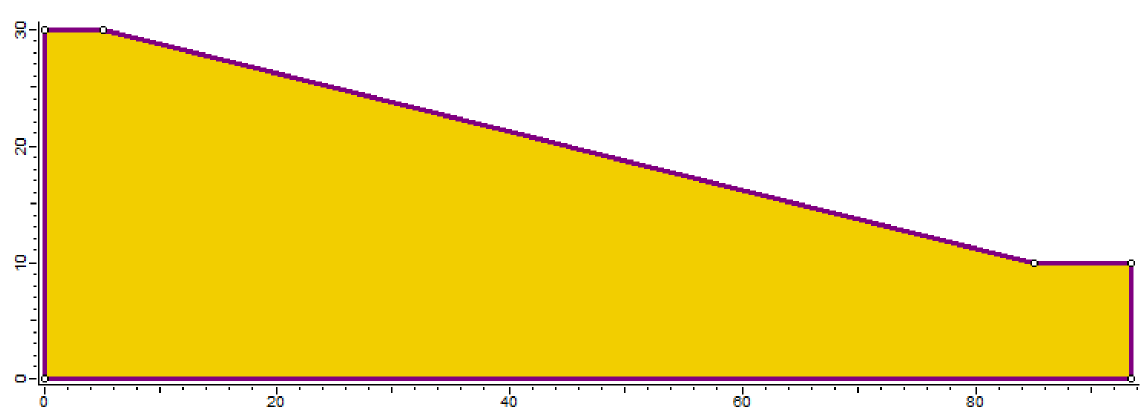


Figure 41.2 – *RS2* Geometry

41.4 Results

Table 41.2 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	1.666
	GLE	1.653
RS2	SSR	1.64

Note: Charles and Soares (1984) Bishop Factor of Safety = 1.66
Baker (2003) Janbu Factor of Safety = 1.60
Baker (2003) 2D dynamic programming search Factor of Safety = 1.56
Perry (1994) rigorous Janbu Factor of Safety = 1.67

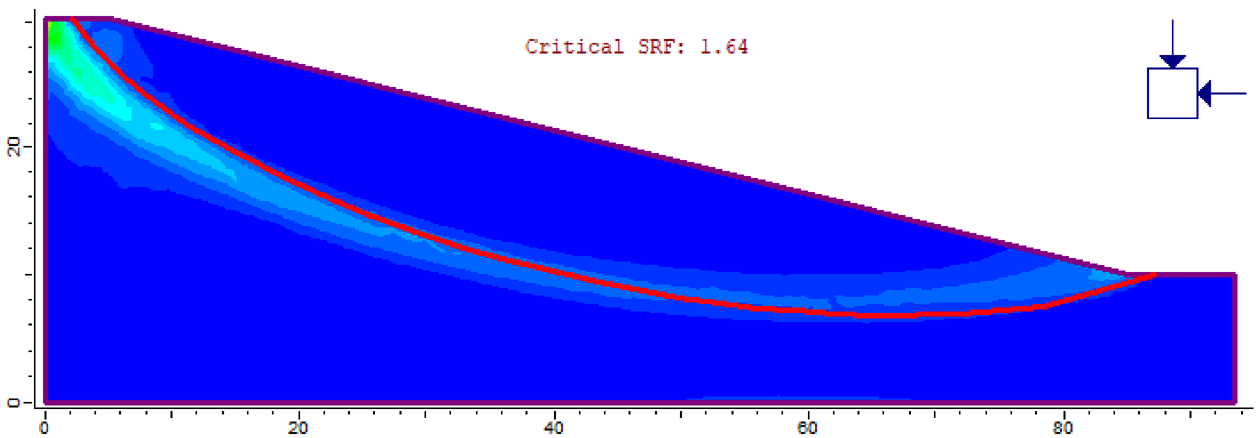


Figure 41.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #42

Dam, (3) materials, water table, ponded water, tension crack

42.1 Introduction

This problem was taken from Baker and Leshchinsky (2001). It is their example question regarding the use of safety maps as practical tools for slope stability analysis.

42.2 Problem Description

The geometry of the dam is shown in Figure 42.1. It consists of a clay core, granular fill surrounding the core, and a solid base. A dry tension crack at the top is included to simulate a 5m thick cracked layer. The circular slip surfaces for all safety factors must be plotted on the dam to obtain a safety map of regional safety factors (use 80x80 grid). The noncircular slip surface and its corresponding factor of safety is also calculated.

42.3 Geometry and Material Properties

Table 42.1 – Material Properties

	c' (kN/m²)	ϕ' (⁰)	γ (kN/m³)
Clay Core	20	20	20
Granular Fill	0	40	21.5
Hard Base	200	45	24

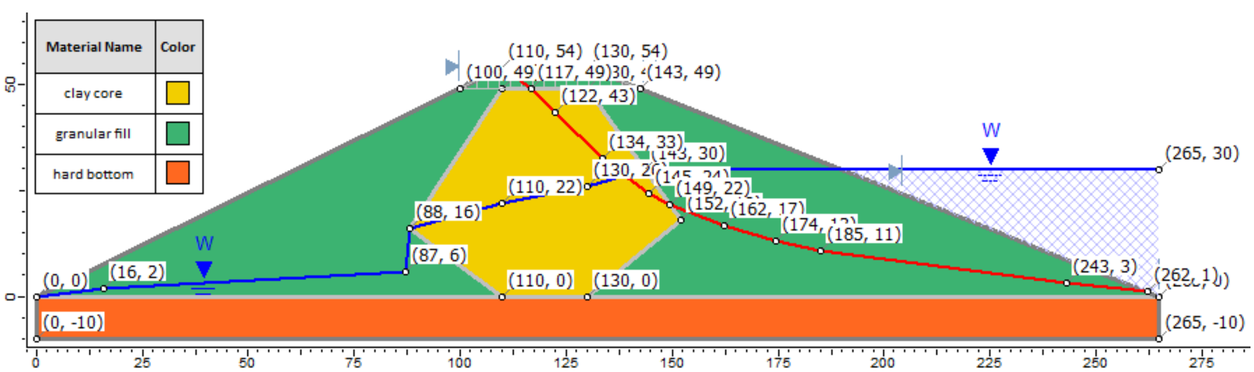


Figure 42.1 – *Slide2* Geometry

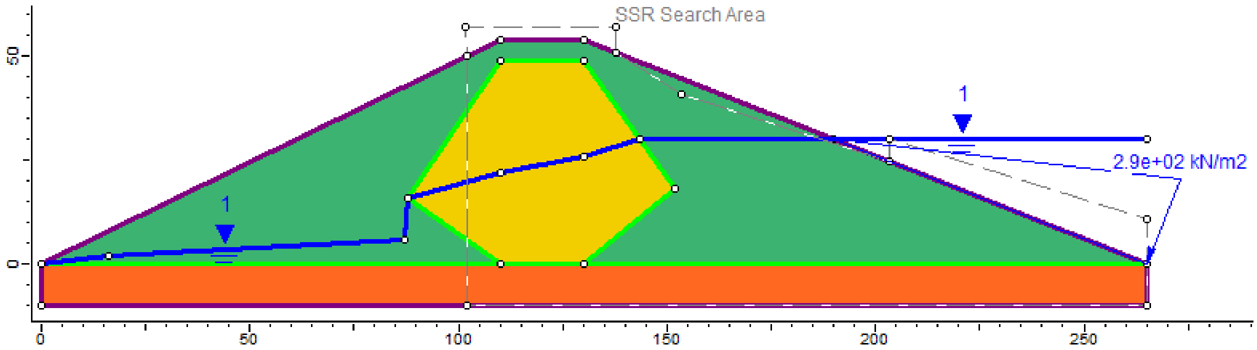


Figure 42.2 – *RS2* Geometry

42.4 Results

Table 42.2 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.925	1.877
	GLE	1.924	1.865
RS2	SSR	1.84	

Note: Baker (2001) Spencer non-circular FS = 1.91

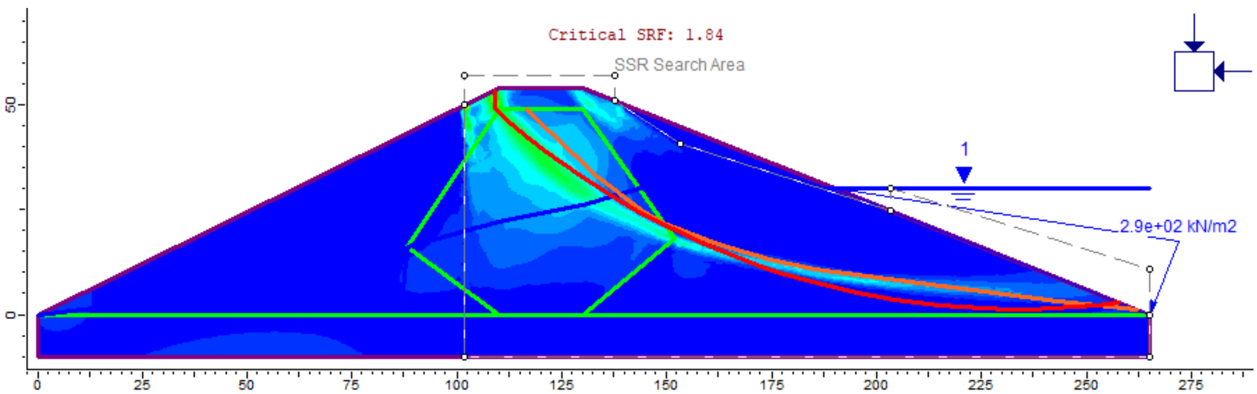


Figure 42.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #44

Slope, homogeneous

44.1 Introduction

This problem was taken from Baker (2003). It is his first example problem comparing linear and non-linear Mohr envelopes.

44.2 Problem Description

Verification problem #44 compares two homogeneous slopes of congruent geometry (Figure 44.1) under different strength functions (Table 44.1). The critical circular surface factor of safety and maximum effective normal stress must be determined for both MohrCoulomb strength criterion and Power Curve criterion. The power curve criterion was derived from Baker's own non-linear function:

$$\tau \;=\; P_a A\left(\frac{\sigma}{P_a} + T\right)^n \ldots P_a = 101.325\ kPa$$

The power curve variables are in the form:

$$\tau = a(\sigma_n + d)^b + c$$

Finally, the critical circular surface factor of safety and maximum effective normal stress must be determined using the soil properties that Baker derives from his iterative process; these values should be compared to the accepted values.

44.3 Geometry and Material Properties

Table 44.1 – Material Properties

	c' (kN/m²)	ϕ' (⁰)	γ (kN/m³)	A	N	T	A	B	c
Clay	11.64	24.7	18	0.58	0.86	0	1.107	0.86	0
Clay, iterative results	0.39	38.6	18	-	-	-	-	-	-

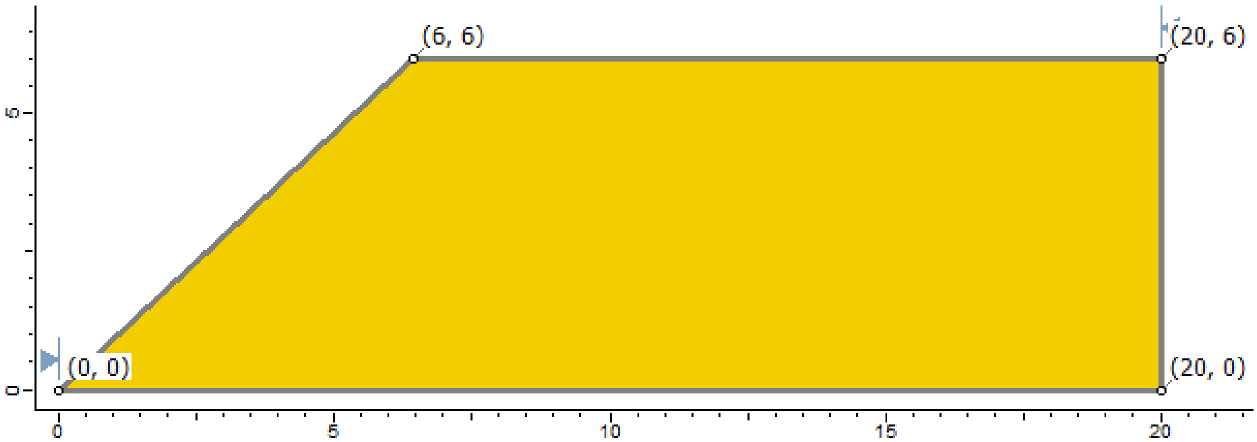


Figure 44.1 – *Slide2* Geometry

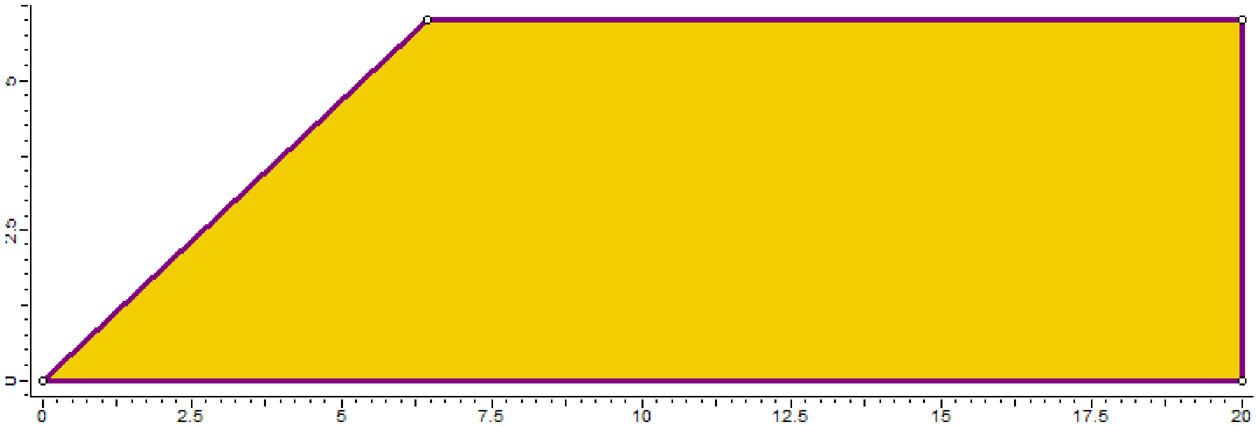


Figure 44.2 – *RS2* Geometry

44.4 Results

Table 44.2 – Comparison of Results

Program	Method	Factor of Safety (circular): M-C with iteration	Factor of Safety (circular): M-C	Factor of Safety (circular): Power Curve
Slide2	Spencer	0.981	1.536	0.960
	GLE	0.981	1.535	0.959
RS2	SSR	0.96	1.5	0.93

Note: Baker (2003) non-linear results: FS = 0.97, σmax = 8.7

Baker (2003) M-C results: FS = 1.50, σmax = 40.2

Case 1 – Mohr-Coulomb with iteration results

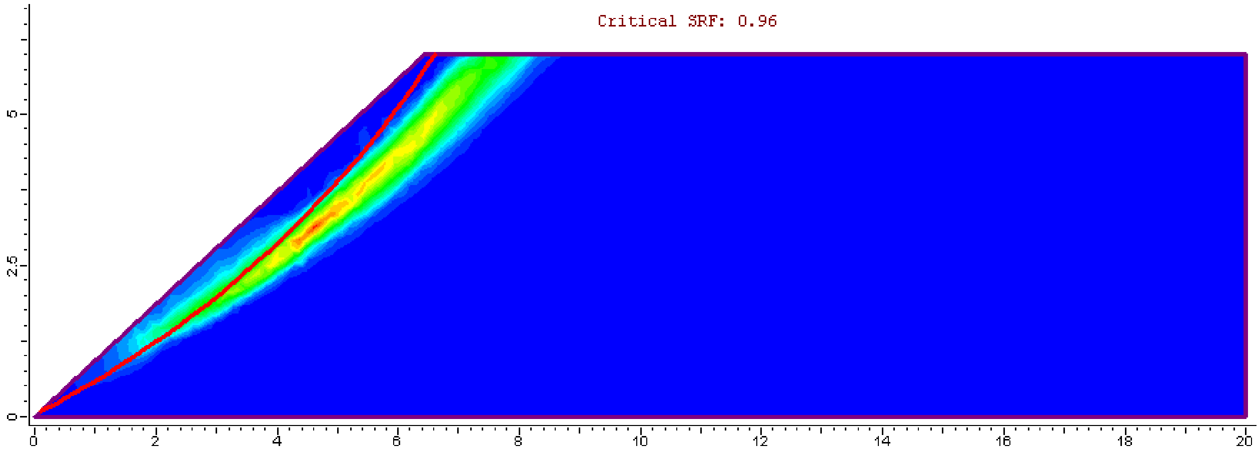


Figure 44.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Circular Failure Surface Overlay)

Case 2 – Mohr-Coulomb

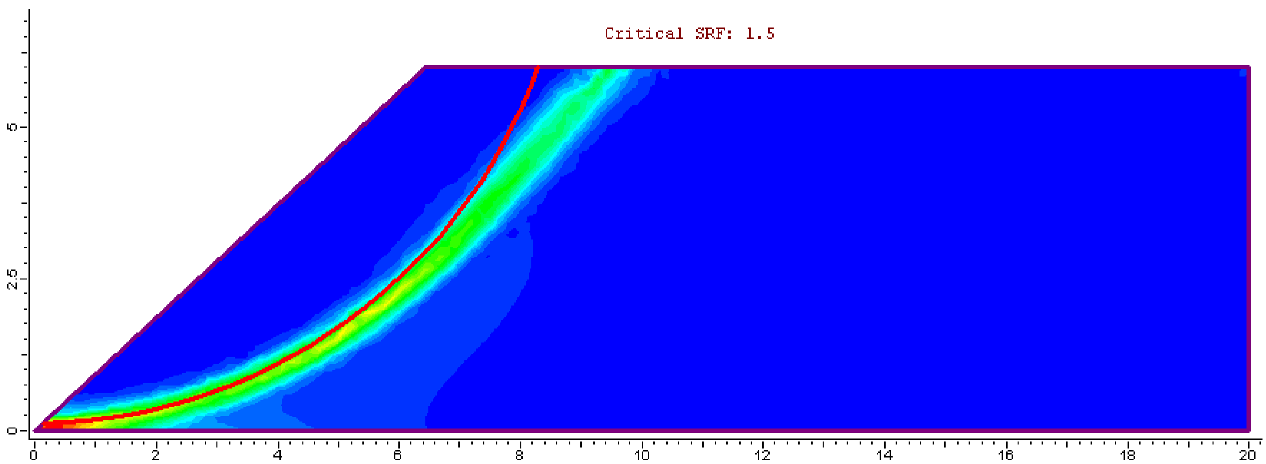


Figure 44.4 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Circular Failure Surface Overlay)

Case 3 – Power Curve

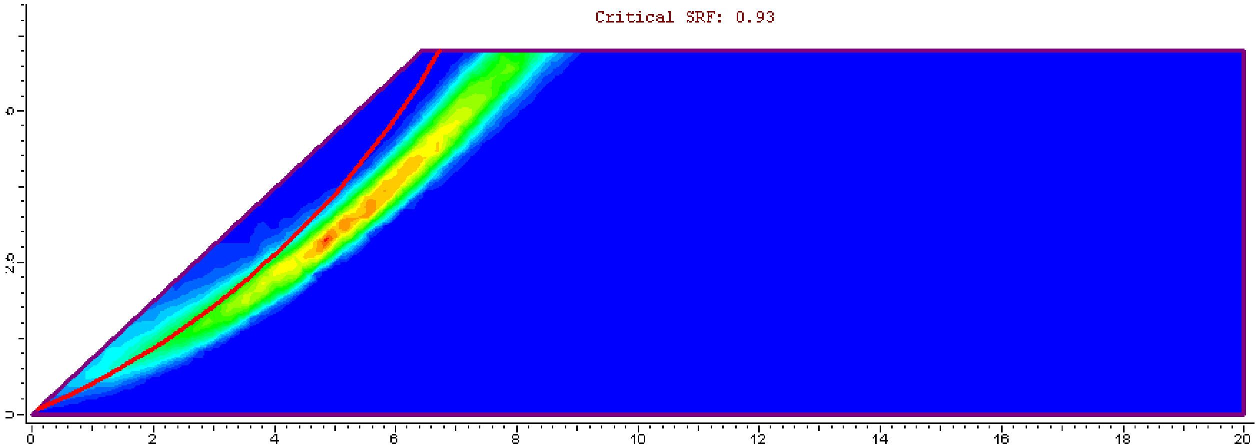


Figure 44.5 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Circular Failure Surface Overlay)

Verification Problem #45

Slope, homogeneous

45.1 Introduction

This problem was taken from Baker (2003). It is his second example problem comparing linear and non-linear Mohr envelopes.

45.2 Problem Description

Verification problem #45 compares two homogeneous slopes of congruent geometry (Figure 45.1) under different strength functions (Table 45.1). The critical circular surface factor of safety and maximum effective normal stress must be determined for both Mohr-Coulomb strength criterion and Power Curve criterion. The power curve criterion was derived from Baker's own non-linear function:

$$\tau \ = \ P_a A(\frac{\sigma}{P_a} + T)^n \ldots P_a \ = 101.325 \ kPa$$

The power curve variables are in the form:

$$\tau = a(\sigma_n + d)^b + c$$

Finally, the critical circular surface factor of safety and maximum effective normal stress must be determined using the material properties that Baker derives from his iterative process; these values should be compared with the accepted values.

45.3 Geometry and Material Properties

Table 45.1 – Material Properties

	c' (kN/m²)	φ' (⁰)	γ (kN/m³)	A	N	T	A	B	c
Clay	11.64	24.7	18	0.58	0.86	0	1.107	0.86	0
Clay, iterative results	2.439	30.392	18	-	-	-	-	-	-

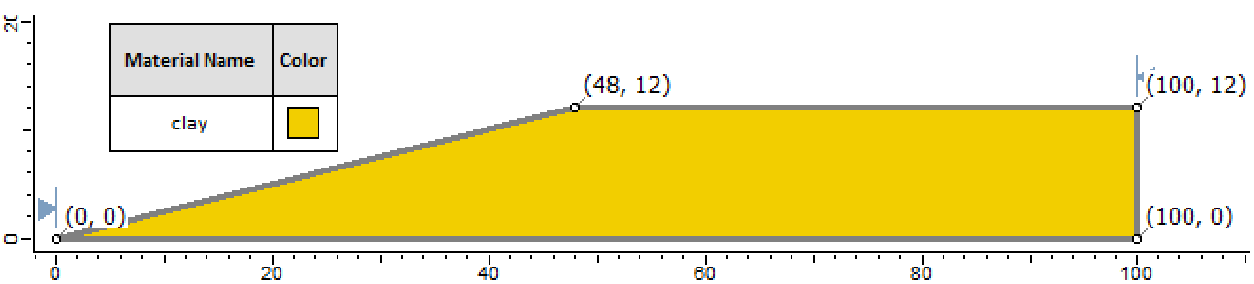


Figure 45.1 – *Slide2* Geometry

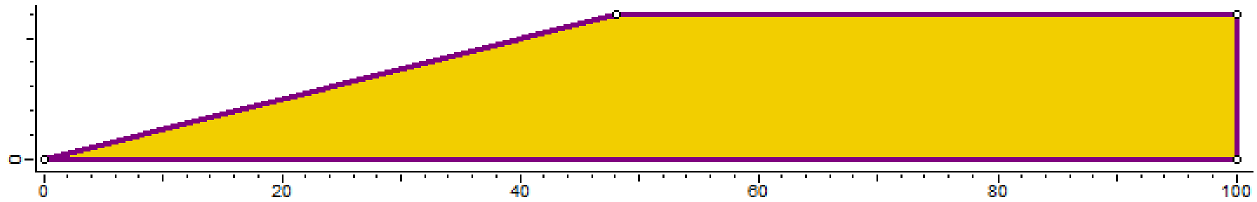


Figure 45.2 – *RS2* Geometry

45.4 Results

Table 45.2 – Comparison of Results

Program	Method	Factor of Safety (circular): M-C with iteration	Factor of Safety (circular): M-C	Factor of Safety (circular): Power Curve
Slide2	Spencer	2.696	2.794	2.662
	GLE	2.696	2.797	2.663
RS2	SSR	2.65	2.78	2.63

Note: Baker (2003) non-linear results: FS = 2.64, σmax = 78.1

Baker (2003) M-C results: FS = 2.66, σmax = 140.3

Case 1 – Mohr-Coulomb with iteration results

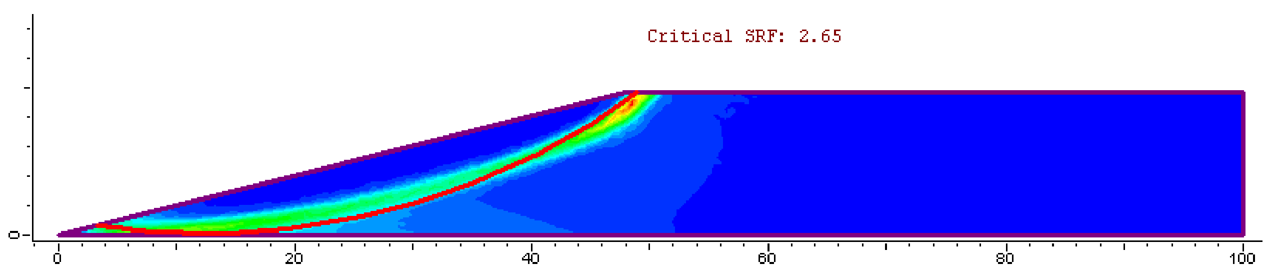


Figure 45.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Circular Failure Surface Overlay)

Case 2 – Mohr-Coulomb

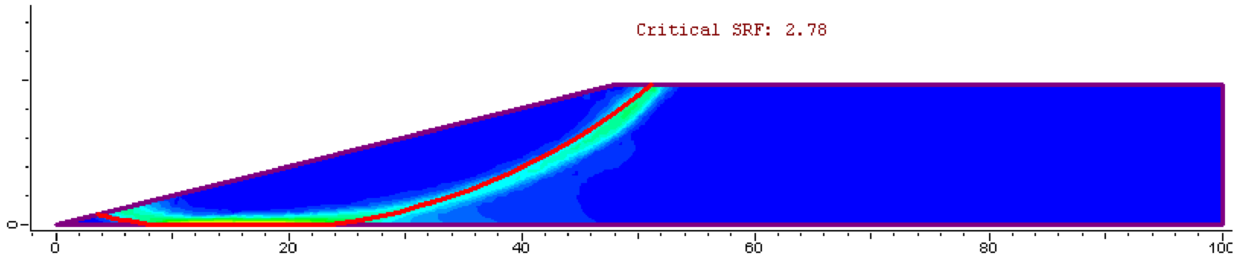


Figure 45.4 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Circular Failure Surface Overlay)

Case 3 – Power Curve

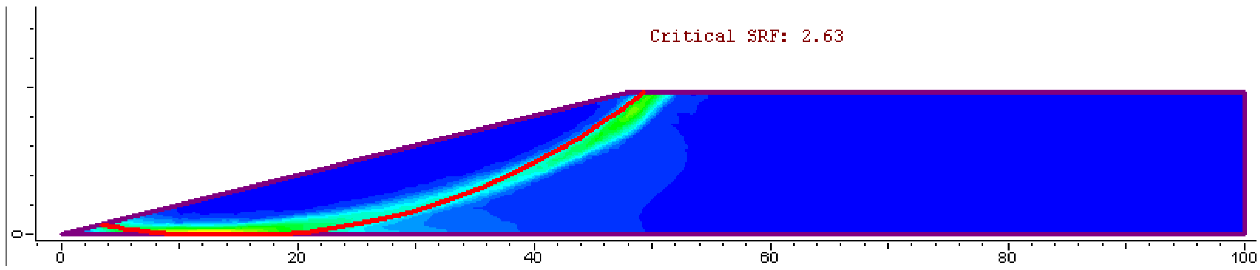


Figure 45.5 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Circular Failure Surface Overlay)

Verification Problem #51

Slope, (4) materials, water table, tension crack, seismic

51.1 Introduction

This problem was taken from Zhu (2003). It analyzes a four layered slope with a given failure surface, using twelve different methods.

51.2 Problem Description

Verification problem #51 examines a multiple layer slope with a circular failure surface. A tension crack is included in the top layer. The slope is also assumed to be under earthquake conditions, with a seismic coefficient of 0.1. The factor of safety for this surface - with 100 slices - is required. A tolerance of 0.001 is used

51.3 Geometry and Material Properties

Table 510.1 – Material Properties

	c′ (kN/m²)	ϕ′ (⁰)	γ (kN/m³)
Layer 1 (top)	20	32	18.2
Layer 2	25	30	18
Layer 3	40	18	18.5
Layer 4 (bottom)	40	28	18.8

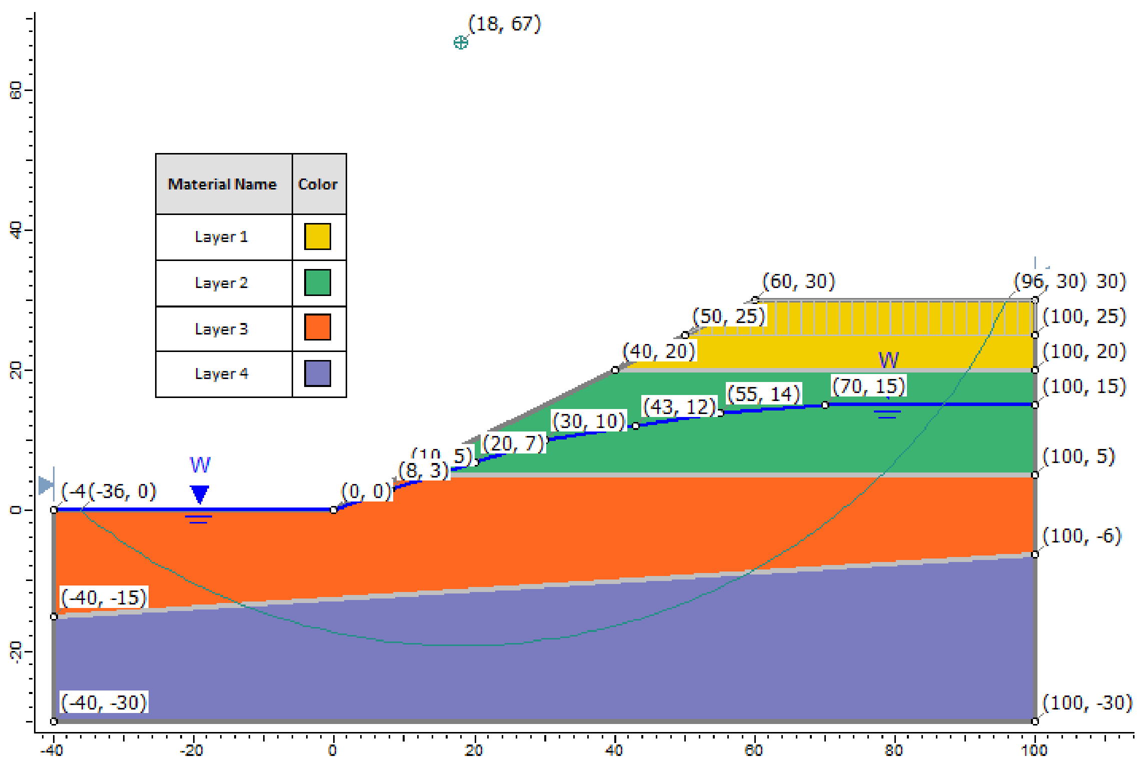


Figure 513.1 – *Slide2* Geometry

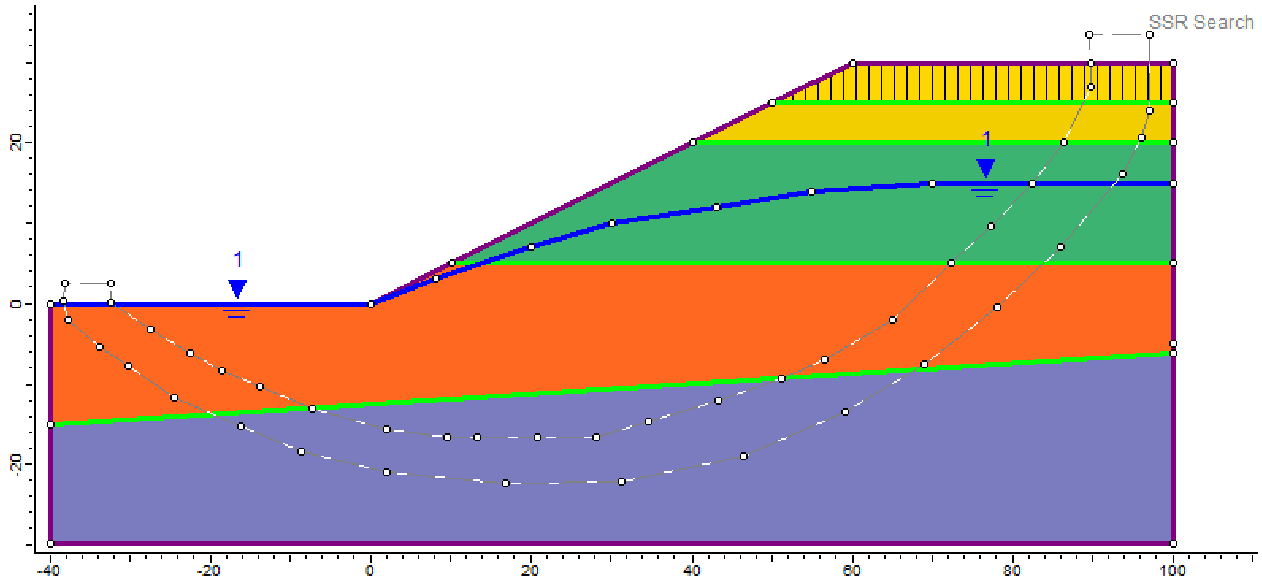


Figure 51.2 – *RS2* Geometry

51.4 Results

Table 51.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.293
	GLE	1.304
RS2	SSR	1.22

Note: Ordinary = 1.066 [Zhu]

Bishop Simplified = 1.278 [Zhu]

Janbu Simplified = 1.112 [Zhu]

Corps of Engineers = 2 1.377 [Zhu]

Lowe & Karafiath = 1.29 [Zhu]

Spencer = 1.293 [Zhu]

GLE/Morgenstern & Price = 1.303 [Zhu]

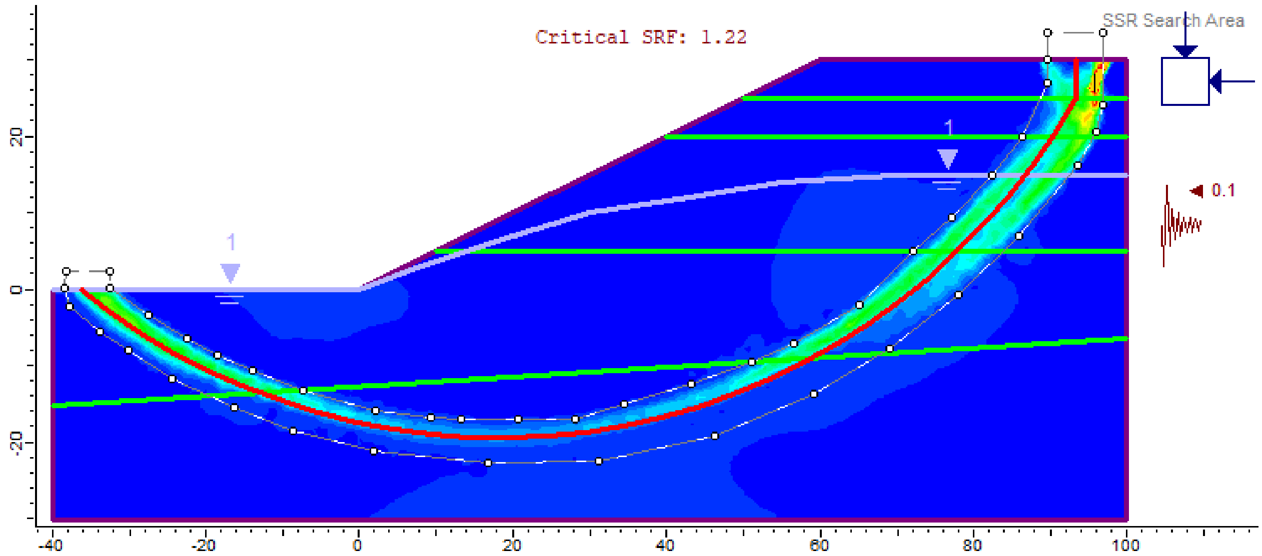


Figure 51.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #56

Slope, homogeneous, water table, tension crack

56.1 Introduction

In December 2000, Pockoski and Duncan released a paper comparing eight different computer programs for analysis of reinforced slopes. This is their second test slope.

56.2 Problem Description

Verification Problem #56 analyses an unreinforced homogeneous slope. A water table is present, as is a dry tension crack (Figure 56.1). The circular critical failure surface and factor of safety for this slope is calculated (40x40 grid).

56.3 Geometry and Material Properties

Table 56.1 – Material Properties

c' (psf)	ϕ' (^{0})	γ (pcf)
300	30	120

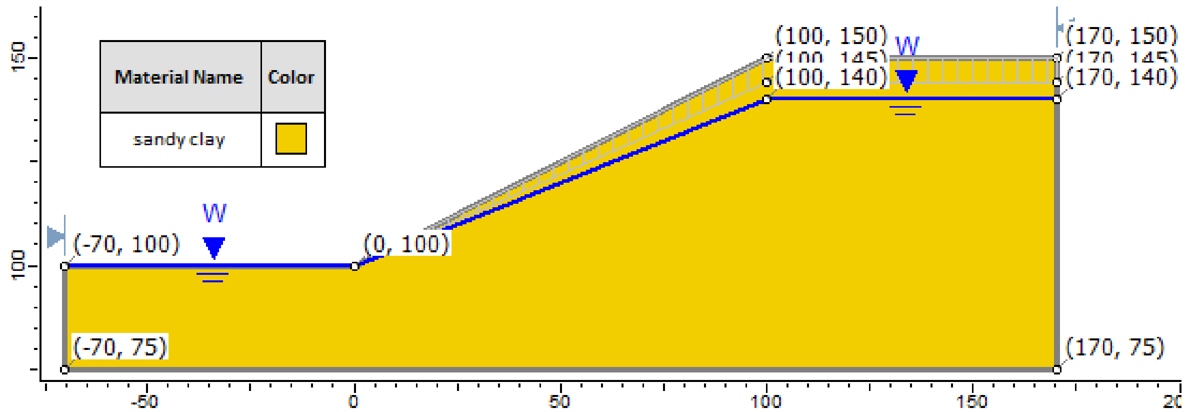


Figure 56.1 – *Slide2* Geometry

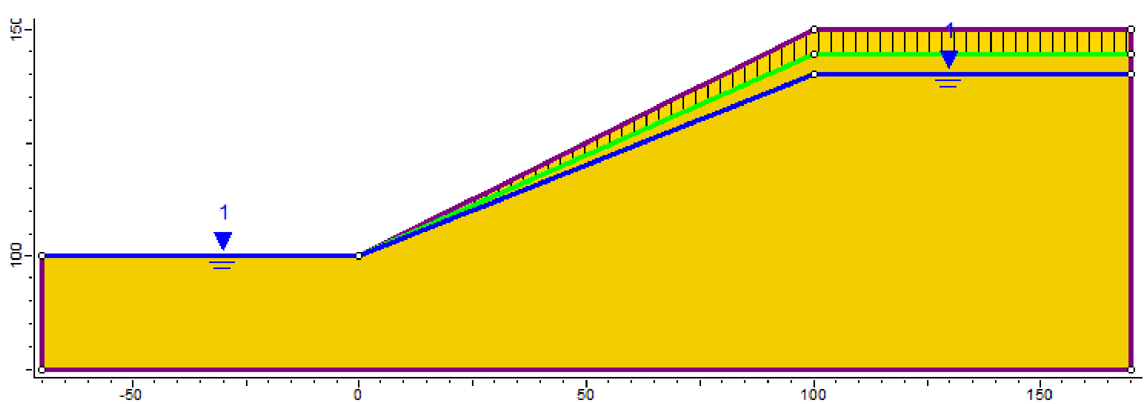


Figure 56.2 – *RS2* Geometry

56.4 Results

Table 56.2 – Comparison of Results

Program	Method	Factor of Safety (Circular)
Slide2	Spencer	1.293
	GLE	1.291
RS2	SSR	1.26

Note: SNAIL Factor of Safety = 1.18 (Wedge method)
GOLD-NAIL Factor of Safety = 1.30 (Circular Method)
UTEX AS4 Factor of Safety = 1.29 (Spencer)
UTEX AS4 Factor of Safety = 1.28 (Bishop Simplified)
UTEX AS4 Factor of Safety = 1.14 (Janbu Simplified)
UTEX AS4 Factor of Safety = 1.31 (Lowe-Karafiath)
SLOPE/W Factor of Safety = 1.29 (Spencer)
SLOPE/W Factor of Safety = 1.28 (Bishop Simplified)
SLOPE/W Factor of Safety = 1.14 (Janbu Simplified)
SLOPE/W Factor of Safety = 1.02 (Ordinary)
WINSTABL Factor of Safety = 1.32 (Spencer)
WINSTABL Factor of Safety = 1.31 (Bishop Simplified)
WINSTABL Factor of Safety = 1.18 (Janbu Simplified)
XSTABL Factor of Safety = 1.28 (Bishop SImplified)
XSTABL Factor of Safety = 1.23 (Janbu SImplified)
RSS Factor of Safety = 1.28 (Bishop SImplified)
RSS Factor of Safety = 1.13 (Janbu SImplified)

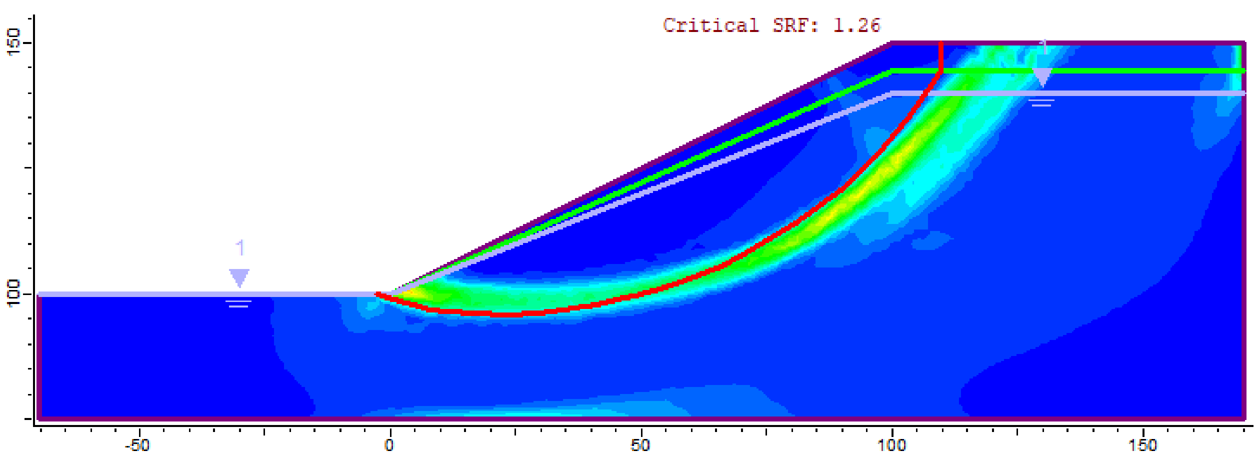


Figure 56.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #57

Slope, homogeneous

57.1 Introduction

In December 2000, Pockoski and Duncan released a paper comparing eight different computer programs for analysis of reinforced slopes. This is their third test slope.

57.2 Problem Description

Verification problem #57 analyses an unreinforced layered slope with a dry tension crack at the surface. A water table is also present. The circular critical failure surface and factor of safety are required. This slope was analyzed with and without composite surfaces in order to compare results with programs that either have this option or do not.

57.3 Geometry and Material Properties

Table 57.1 – Material Properties

	c' (psf)	ϕ' (^{0})	γ (pcf)
Sandy Clay	300	35	130
Highly Plastic Clay	0	25	130

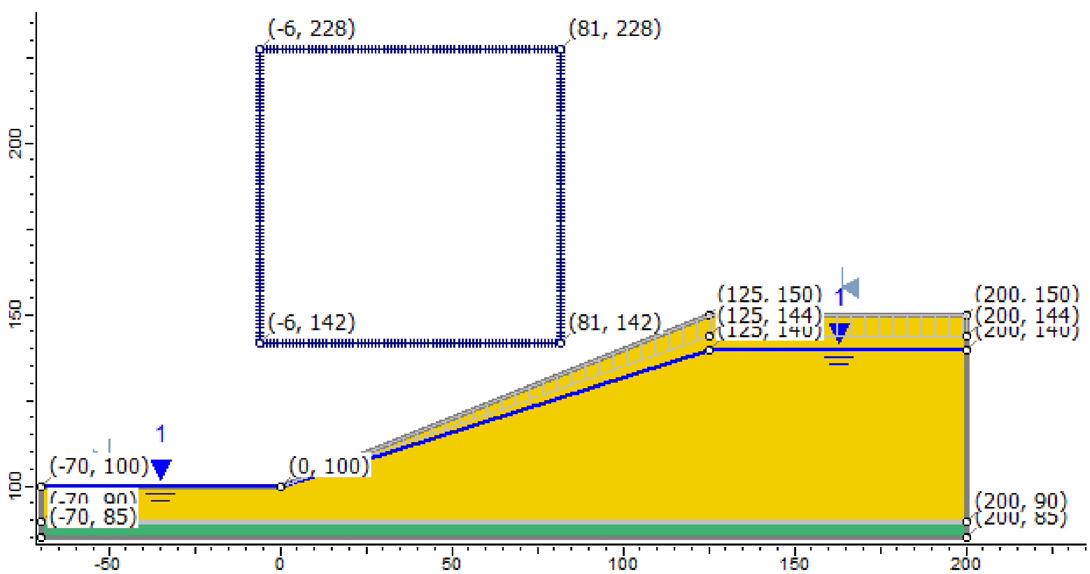


Figure 57.1 – *Slide2* Geometry

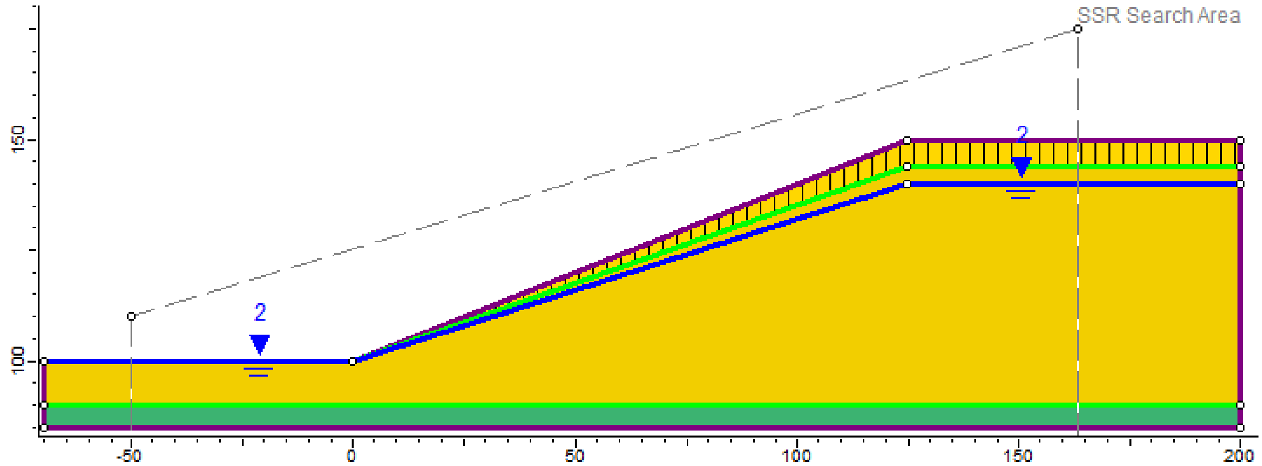


Figure 57.2 – *RS2* Geometry

57.4 Results

Table 57.2 – Comparison of Results

Program	Method	Factor of Safety (Composite)	Factor of Safety (Not Composite)
Slide2	Spencer	1.400	1.422
	GLE	1.376	1.406
RS2	SSR	1.32	

Note: Composite SNAIL Factor of Safety = 1.39 (Wedge Method)
Composite SLOPE/W Factor of Safety = 1.40 (Spencer)
Composite SLOPE/W Factor of Safety = 1.39 (Bishop Simplified)
Composite SLOPE/W Factor of Safety = 1.21 (Janbu Simplified)
Composite SLOPE/W Factor of Safety = 0.85 (Ordinary)
Composite XSTABL Factor of Safety = 1.41 (Bishop Simplified)
Composite XSTABL Factor of Safety = 1.34 (Janbu Simplified)
Not Composite GOLD-NAIL Factor of Safety = 1.40 (Circular Method)
Not Composite UTEXAS4 Factor of Safety = 1.42 (Spencer)
Not Composite UTEXAS4 Factor of Safety = 1.41 (Bishop Simplified)
Not Composite UTEXAS4 Factor of Safety = 1.20 (Janbu Simplified)
Not Composite UTEXAS4 Factor of Safety = 1.12 (Lowe-Karafiath)
Not Composite WINSTABL Factor of Safety = 1.45 (Spencer)
Not Composite WINSTABL Factor of Safety = 1.39 (Bishop Simplified)
Not Composite WINSTABL Factor of Safety = 1.23 (Janbu Simplified)
Not Composite RSS Factor of Safety = 1.41 (Bishop Simplified)
Not Composite RSS Factor of Safety = 1.24 (Janbu Simplified)

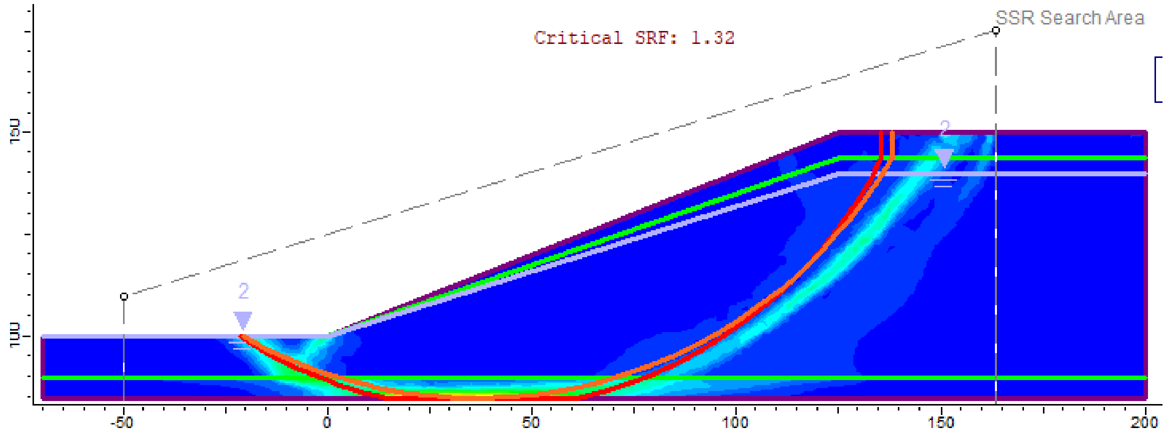


Figure 57.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #60

Retaining wall, (2) materials, tension crack, distributed load, soil nails

60.1 Introduction

In December 2000, Pockoski and Duncan released a paper comparing eight different computer programs for analysis of reinforced slopes. This is their seventh test slope.

60.2 Problem Description

Verification problem #60 analyzes a soil nailed wall in homogeneous clay. There is a dry tension crack down to the first nail. Two uniformly distributed loads of 500 lb/ft and 250 lb/ft are applied to the high bench (Figure 60.1). Five parallel rows of passive soil nails reinforce the wall; each row has identical strength characteristics. The circular critical surface (through the toe) and corresponding factor of safety is calculated.

60.3 Geometry and Material Properties

Table 60.1 – Material Properties

	c' (psf)	ϕ' (°)	γ (pcf)
Sandy Clay	800	0	120

Table 60.2 – Soil Nail Properties

Tensile Cap. (lbs)	Plate Cap. (lbs)	Bond Strength (lb/ft)	Out-of-Plane Spacing (ft)
Sandy Clay	800	0	120

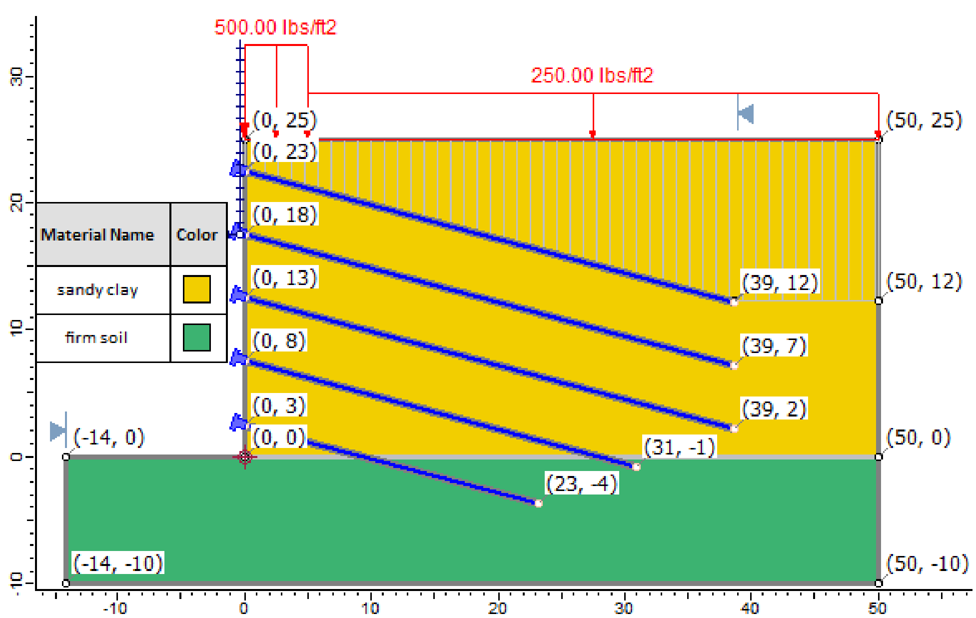


Figure 60.1 – *Slide2* Geometry

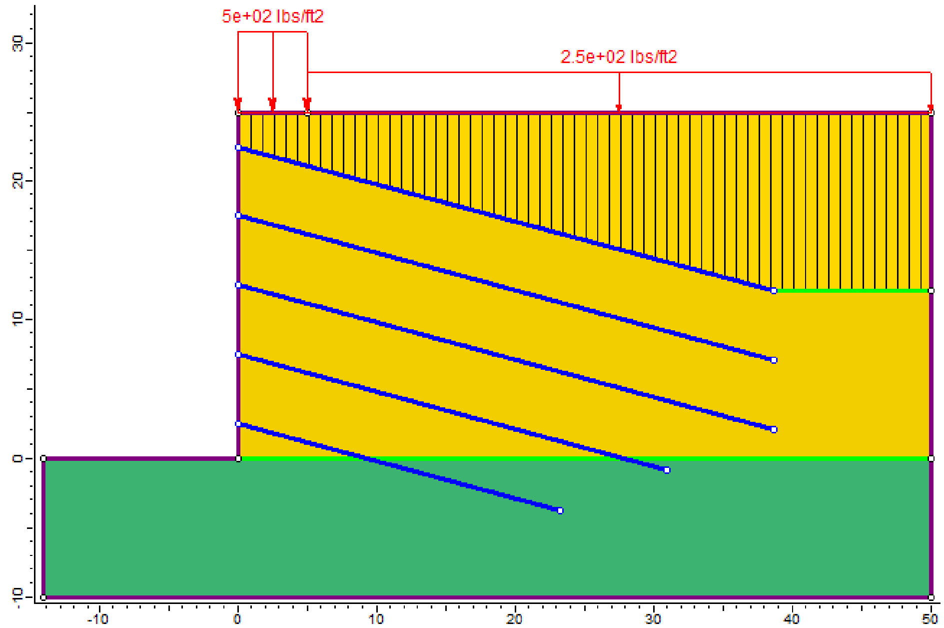


Figure 60.2 – *RS2* Geometry

60.4 Results

Table 60.3 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.009
	GLE	1.005
RS2	SSR	0.98

Note: GOLD-NAIL Factor of Safety = 0.91 (Circular)

SNAIL Factor of Safety = 0.91 (Wedge method – noncircular)

Circular UTEXAS4 Factor of Safety = 1.02 (Spencer)

Circular UTEXAS4 Factor of Safety = 1.00 (Bishop Simplified)

Circular UTEXAS4 Factor of Safety = 1.08 (Janbu Simplified)

Circular UTEXAS4 Factor of Safety = 1.00 (Lowe-Karafiath)

Circular SLOPE/W Factor of Safety = 1.02 (Spencer)

Circular SLOPE/W Factor of Safety = 1.01 (Bishop Simplified)

Circular SLOPE/W Factor of Safety = 1.07 (Janbu Simplified)

Circular SLOPE/W Factor of Safety = 1.00 (Ordinary)

Circular WINSTABL Factor of Safety = 0.99 (Spencer)

Circular WINSTABL Factor of Safety = 1.06 (Bishop Simplified)

Circular WINSTABL Factor of Safety = 1.10 (Janbu Simplified)

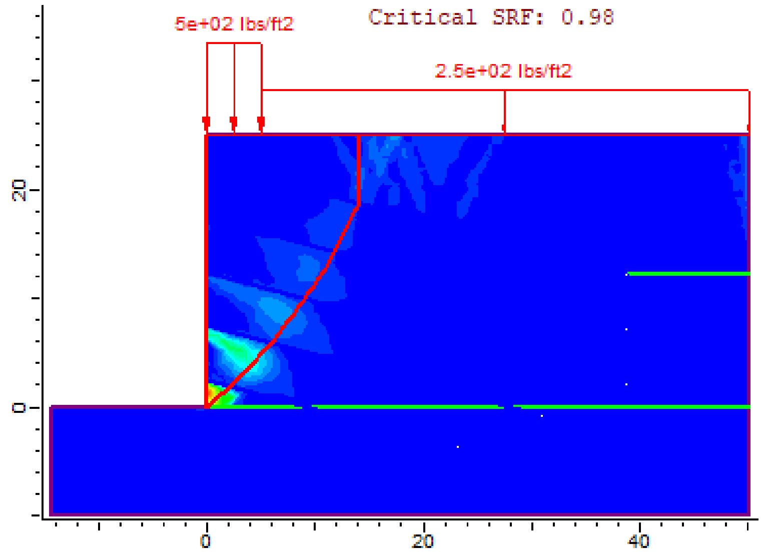


Figure 60.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #61

Slope, homogeneous, composite surfaces

61.1 Introduction

This problem was taken from Baker (2003). It is his third example problem comparing linear and non-linear Mohr envelopes.

61.2 Problem Description

Verification problem #61 compares two homogeneous slopes of congruent geometry (Figure 44.1) under different strength functions (Table 61.1). The critical circular surface factor of safety and maximum effective normal stress must be determined for both Mohr-Coulomb strength criterion and Power Curve criterion. The power curve criterion was derived from Baker's own non-linear function:

$$\tau \ = \ P_a A(\frac{\sigma}{P_a} + T)^n \ldots \ P_a = 101.325\ kPa$$

The power curve variables are in the form:

$$\tau = a(\sigma_n + d)^b + c$$

Finally, the critical circular surface factor of safety and maximum effective normal stress must be determined using the material properties that Baker derives from his iterative process; these values should be compared to the accepted values.

61.3 Geometry and Material Properties

Table 611.1 – Soil Properties – Power Curve

	Baker's Parameter			*Slide2* Parameters			
Material	A	n	T	A	B	C	d
Clay	0.535	0.6	0.0015	3.39344	0.6	0	0.1520

Table 61.2 – Soil Properties – Mohr-Coulomb Criterion

	c' (kN/m²)	ϕ' (⁰)	γ (kN/m³)
Sandy Clay	6.0	32	18

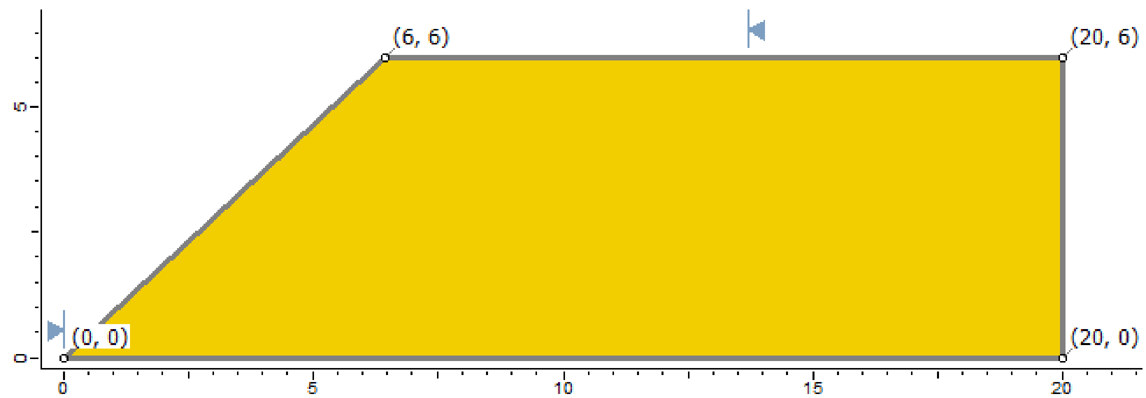


Figure 614.1 – *Slide2* Geometry

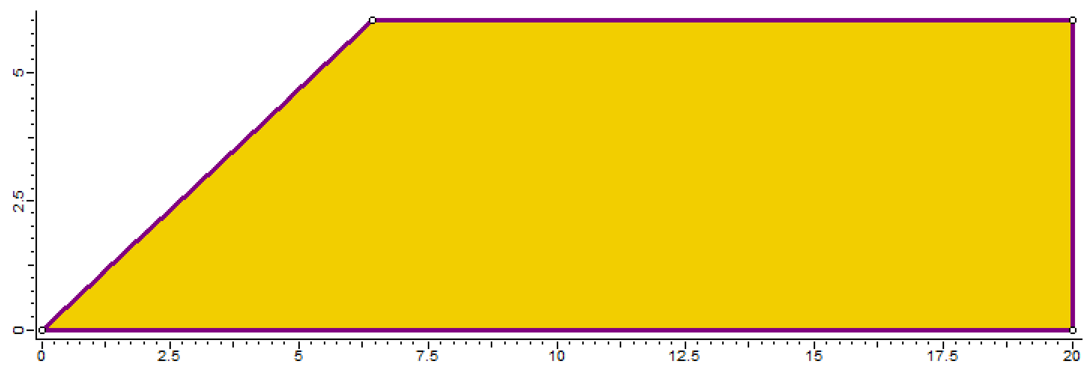


Figure 61.2 – *RS2* Geometry

61.4 Results

Case 1 – Mohr-Coulomb

Table 61.3 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.366
	GLE	1.365
RS2	SSR	1.34

Note: Baker (2003) M-C Factor of Safety = 1.35

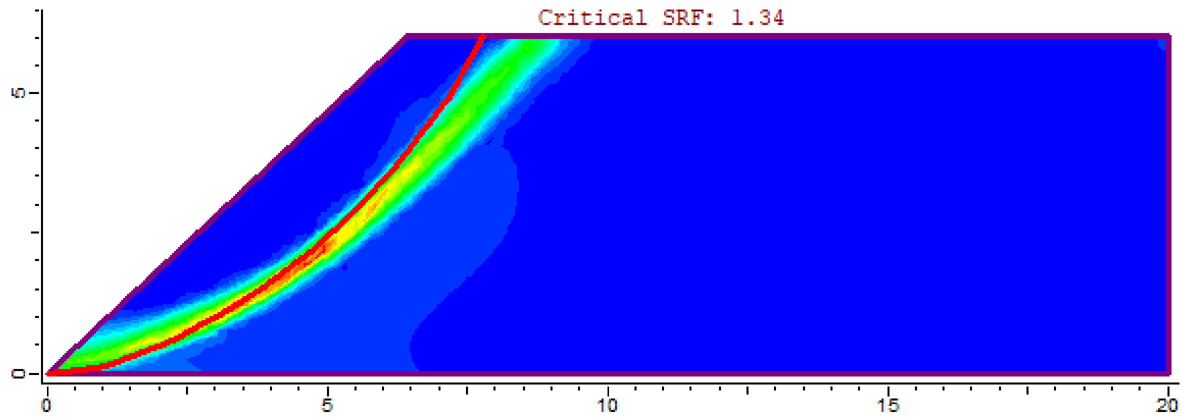


Figure 61.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 2 – Power Curve

Table 61.4 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.468
	GLE	1.460
RS2	SSR	1.45

Note: Baker (2003) non-linear Factor of Safety = 1.48

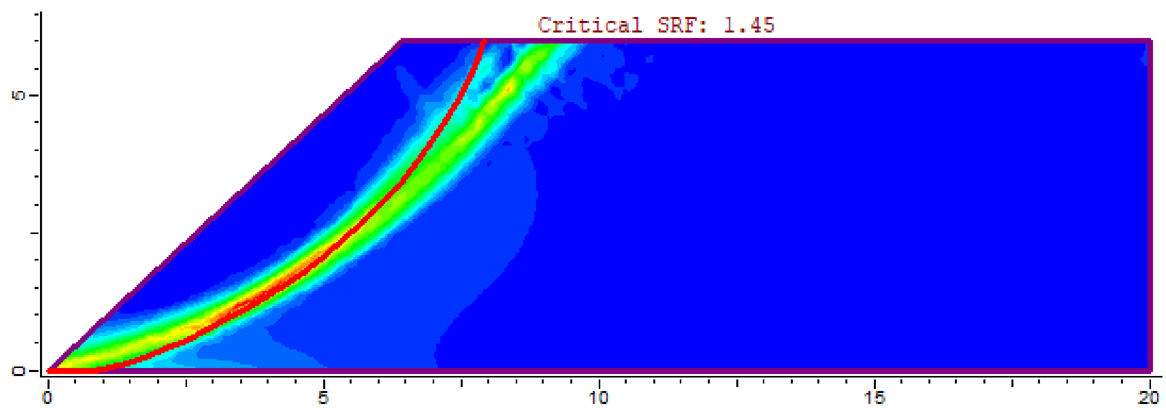


Figure 61.4 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #62

Slope, homogeneous, ru pore pressure, seismic

62.1 Introduction

This problem is taken from Loukidis *et al.* (2003). The paper provides a method for determining the critical seismic coefficient, k_c. This coefficient corresponds to a factor of safety of 1. This is their first example problem.

62.2 Problem Description

Verification problem #62 examines a simple homogeneous slope with seismic loading (Figure 62.1). The slope is analyzed using circular and noncircular* slip surfaces, both of which pass through the toe of the slope. Two pore pressure conditions are also accounted for: a dry slope, and Ru = 0.5. The goal of this verification problem is to reproduce a safety factor of 1 (Spencer) using Loukidis' critical seismic coefficients (Table 62.1).

Note : *Loukidis examines a log-spiral surface.

62.3 Geometry and Material Properties

Table 62.1 – Material Properties

c' (kPa)	ϕ' (°)	γ (kN/m³)
25	30	20

Table 62.1 – Material Properties

Dry Slope	R_u = 0.5
0.432	0.132

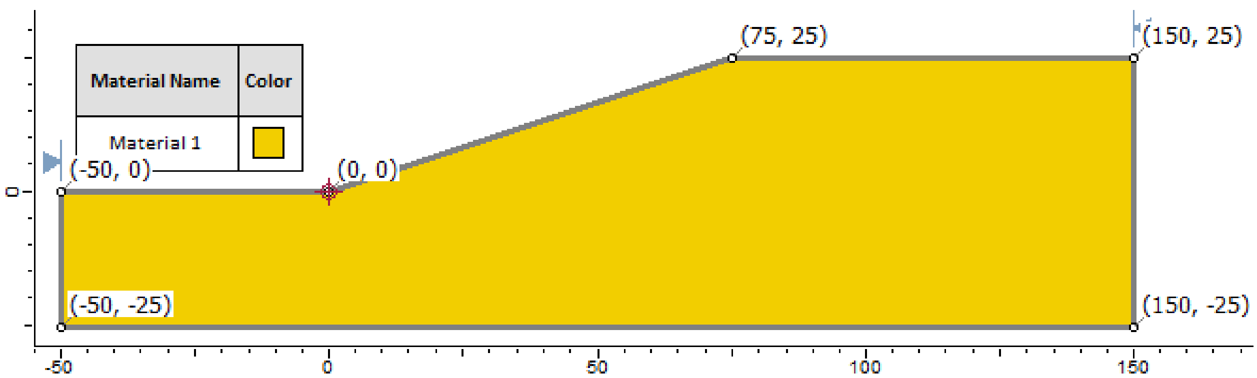


Figure 62.1 – *Slide2* Geometry

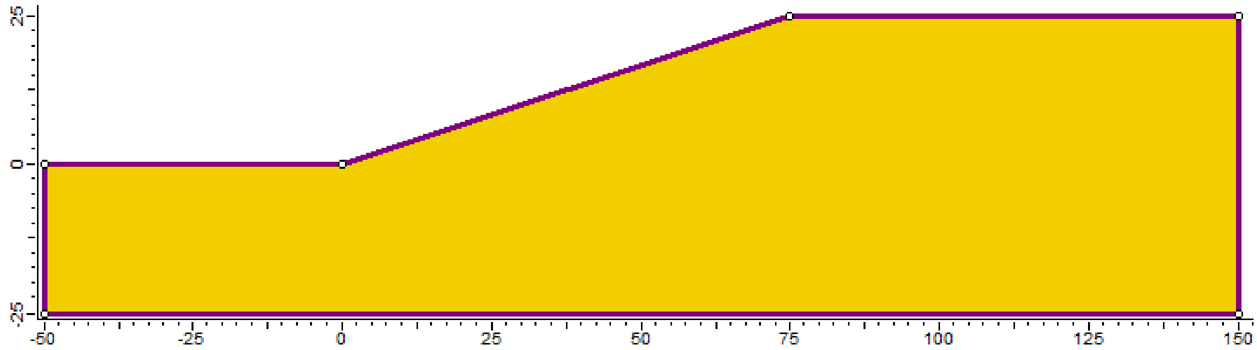


Figure 62.2 – *RS2* Geometry

62.4 Results

Case 1 - Dry

Table 62.3 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.001	0.999
	GLE	1.000	0.986
RS2	SSR	0.96	

Note: Loukidis Factor of Safety (Spencer) = 1.000

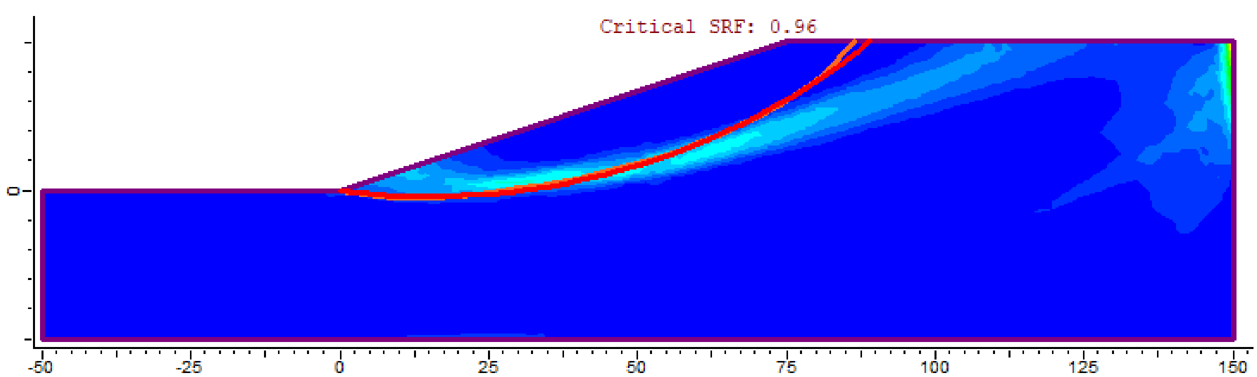


Figure 62.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Case 2 – Wet

Table 62.4 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.001	0.998
	GLE	1.000	0.983
RS2	SSR	0.96	

Note: Loukidis Factor of Safety = 1.000

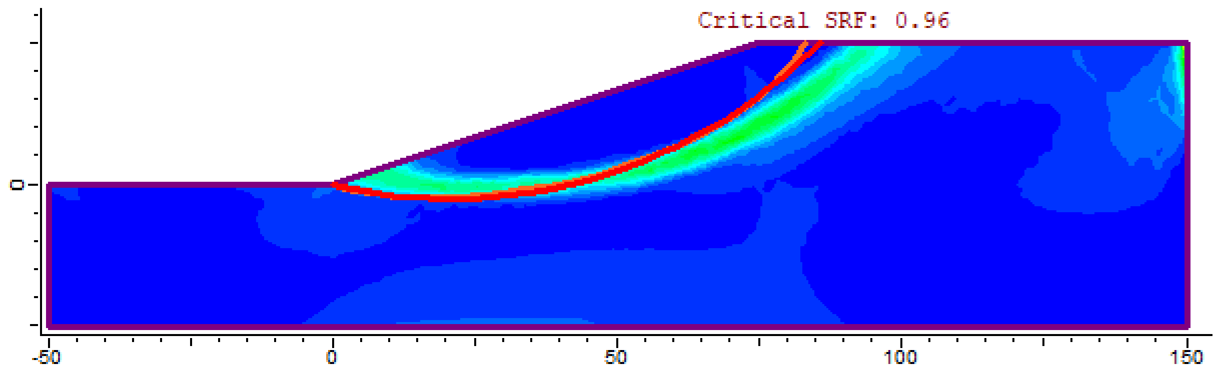


Figure 62.4 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #63

Slope, (3) materials, seismic

63.1 Introduction

This problem is taken from Loukidis *et al.* (2003). The paper provides a method for determining the critical seismic coefficient, k_c. This coefficient corresponds to a factor of safety of 1. This is their second example problem.

63.2 Problem Description

Verification problem #63 analyzes a layered, dry slope under seismic loading conditions. The goal is to duplicate a Spencer safety factor of 1.000 using the author's seismic coefficient of 0.155. A log-spiral surface is analyzed by Loukidis; this is modeled in *Slide2* by doing a path search with Monte-Carlo optimization. The critical slip surface passes through the material boundary point on the slope between the middle and lower layers (limits are included in Figure 63.1).

63.3 Geometry and Material Properties

Table 63.1 – Material Properties

Layer	c′ (kN/m²)	ϕ′ (°)	γ (kN/m³)
Top	4	30	17
Middle	25	15	19
Bottom	15	45	19

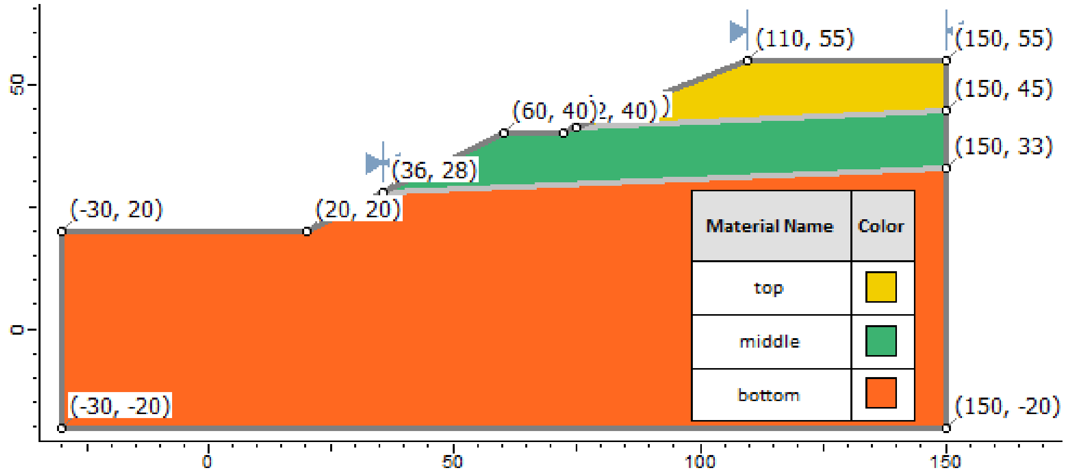


Figure 63.1 – *Slide2* Geometry

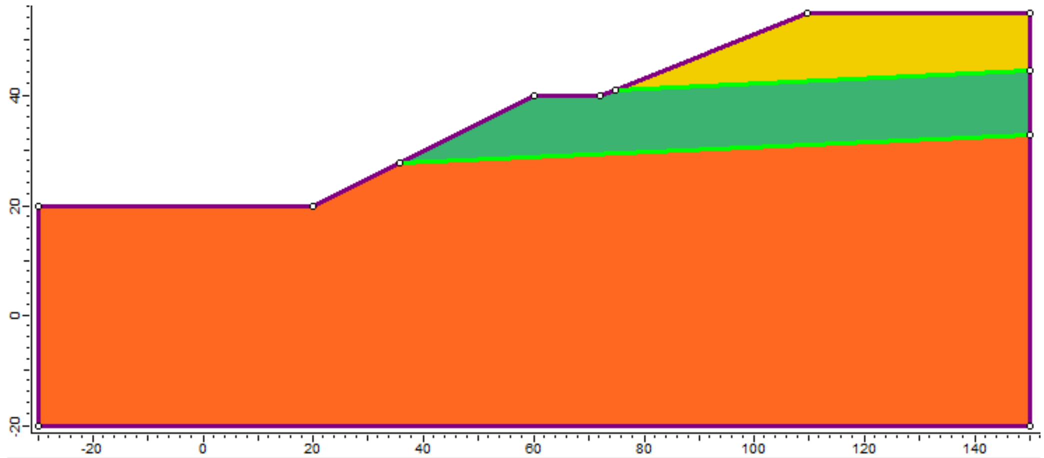


Figure 63.2 – *RS2* Geometry

63.4 Results

Table 63.2 – Comparison of Results

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	0.994
	GLE	0.994
RS2	SSR	0.99

Note: Loukidis Factor of Safety (Spencer) = 1.000

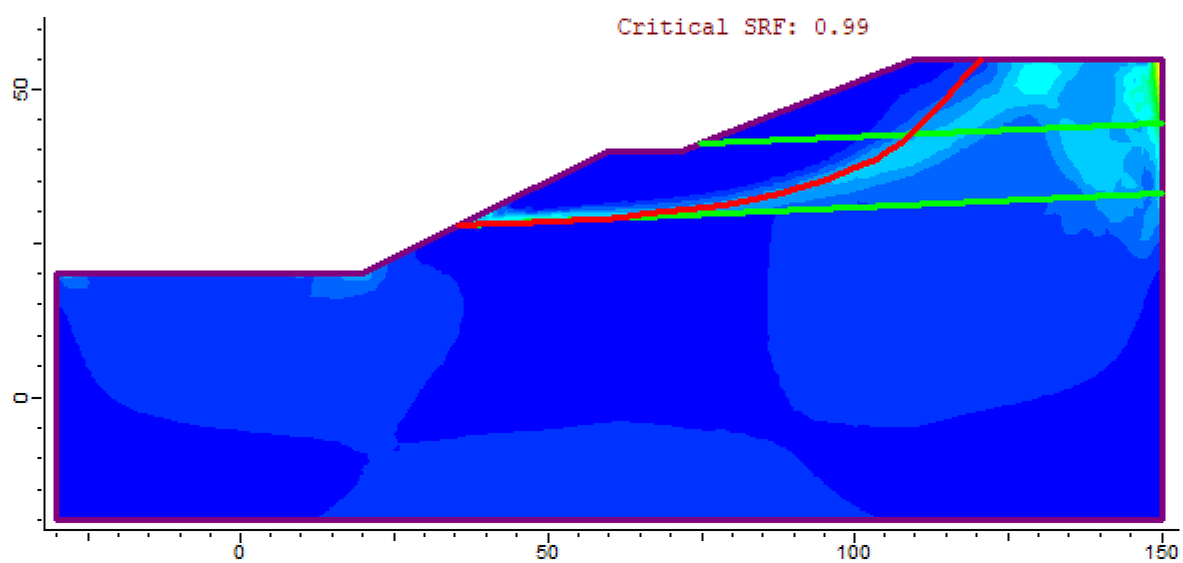


Figure 63.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #64

Embankment, (4) materials, water table, tension crack

64.1 Introduction

This model is taken from Figure 4-1 of USACE (2003).

64.2 Problem Description

The problem as shown in Figure 64.1 is a non-homogeneous three-layer embankment with material properties given in Table 64.1 There is a 7 foot tension crack located at the peak of the embankment, and a groundwater surface between the layer of sand and the embankment. This problem calculates the factor of safety via Spencer's Method using a circular slip surface as shown below.

64.3 Geometry and Material Properties

Table 64.1 – Material Properties

Soil	Unit Weight		Shear Strength	
	Moist γ (pcf)	Sat'd γ (pcf)	c' (psf)	ϕ' (^{0})
Embankment	115	120	1000	5
Sand	125	130	0	35
Foundation Clay	110	115	3000	0
Rock	160	165	0	45

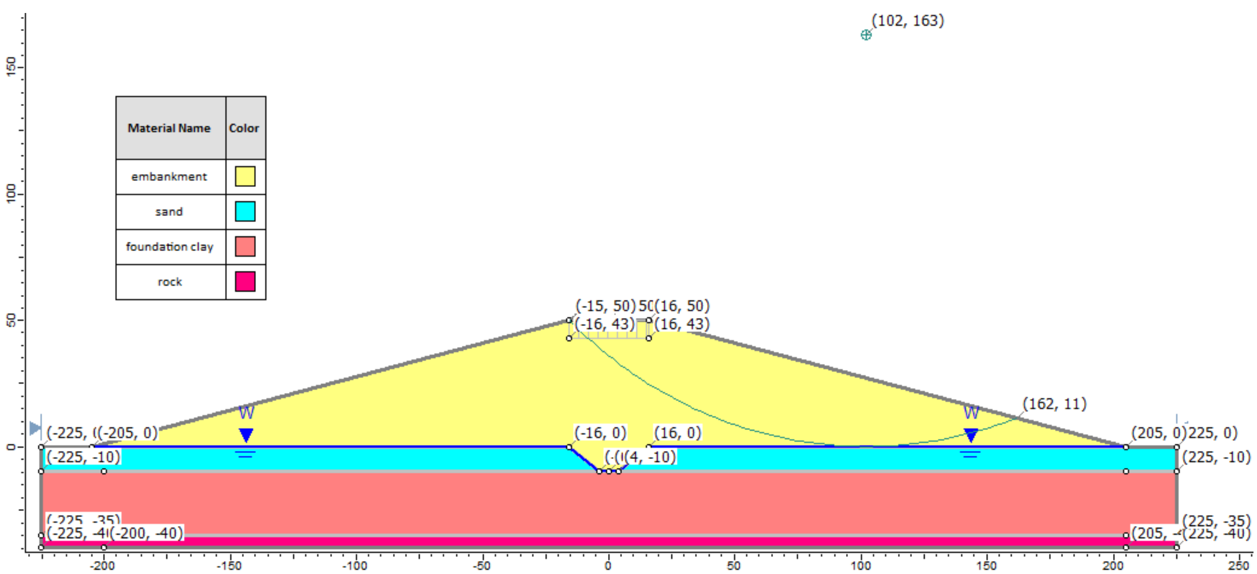


Figure 64.1 – *Slide2* Geometry

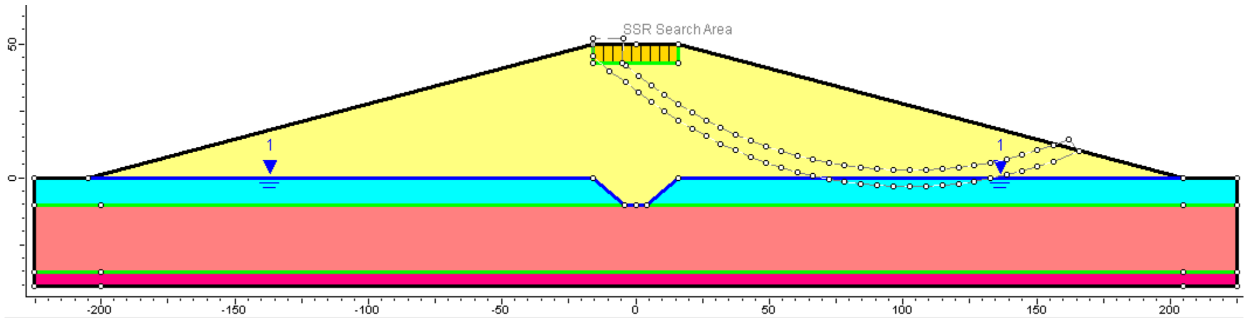


Figure 64.2 – *RS2* Geometry

64.4 Results

Table 64.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	2.445
	GLE	2.447
RS2	SSR	2.37

Note: Reference Factor of Safety (Spencer) = 2.44 [USACE]

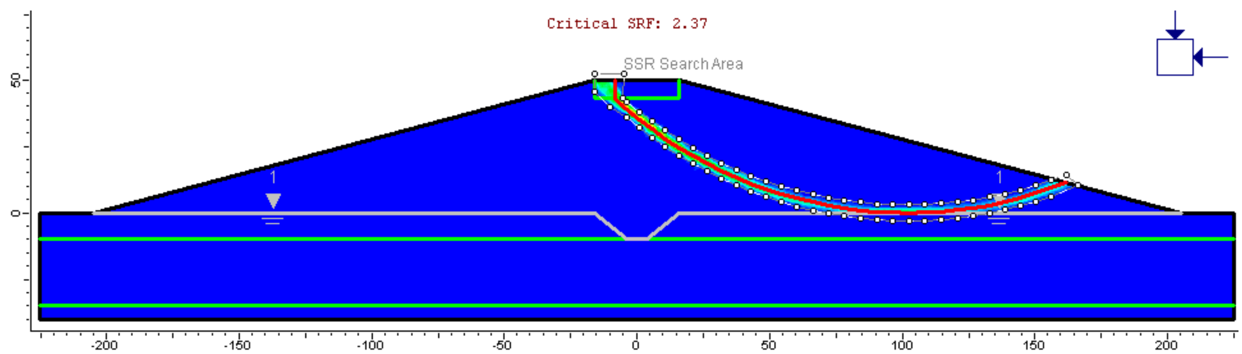


Figure 64.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #65

Embankment, (4) materials, water table, ponded water

65.1 Introduction

This model is taken from Figure 4-2 of USACE (2003)

65.2 Problem Description

The problem as shown in Figure 65.1 is a three-layer slope with material properties given in Table 65.1 This example demonstrates conditions with an upstream slope and a low pool of water. The factor of safety is calculated via the simplified Bishop method using a circular slip surface, located as shown below.

65.3 Geometry and Material Properties

Table 65.1 – Material Properties

Soil	Unit Weight		Shear Strength	
	Moist γ (pcf)	Sat'd γ (pcf)	c' (kN/m²)	ϕ' (°)
Embankment	115	120	100	35
Sand	125	130	0	35
Foundation Clay	110	115	0	28
Rock	160	165	0	45

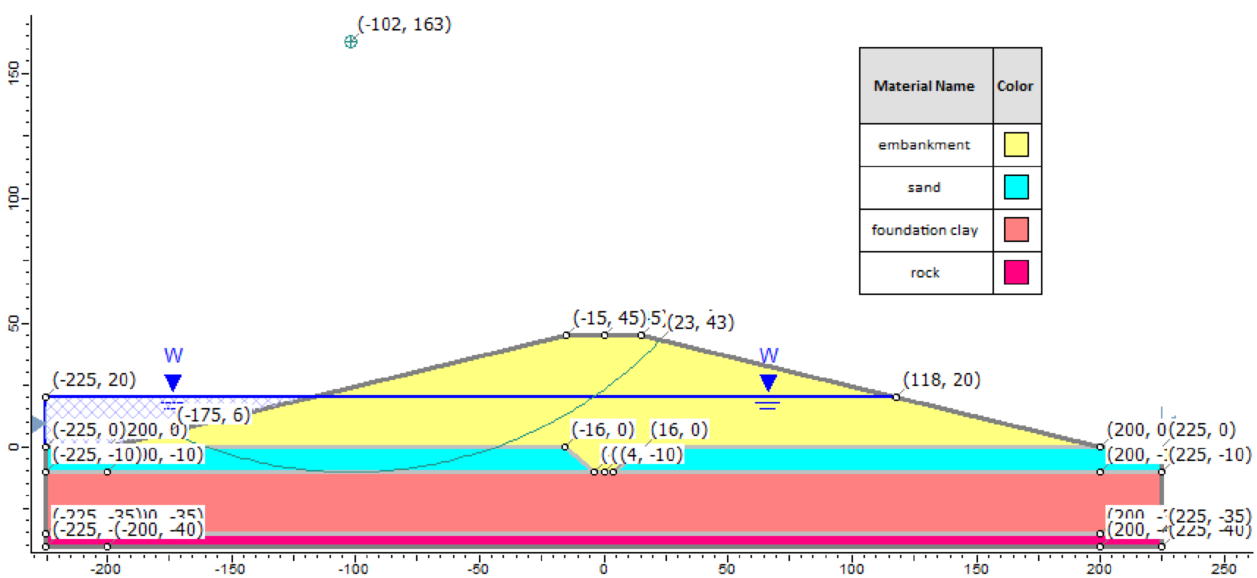


Figure 65.1 – *Slide2* Geometry

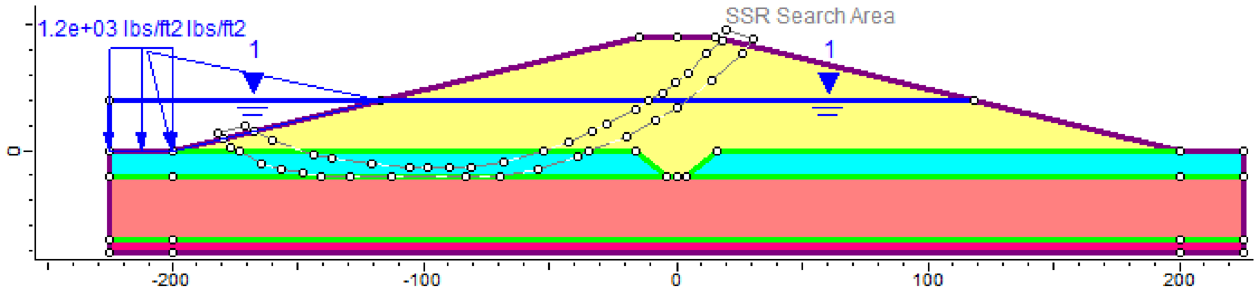


Figure 65.2 – *RS2* Geometry

65.4 Results

Table 65.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	2.744
	GLE	2.750
RS2	SSR	2.60

Note: Reference Factor of Safety = 2.71 [USACE]

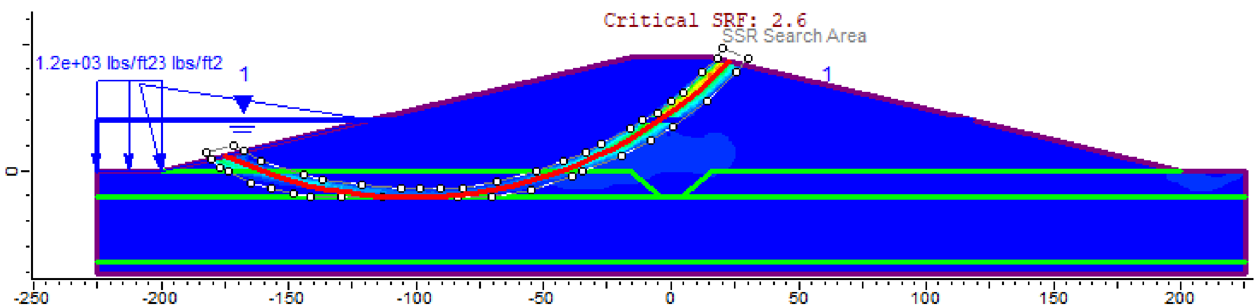


Figure 65.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #66

Embankment, (4) materials, water table, ponded water

66.1 Introduction

This model is taken from Figure 4-3 of USACE (2003).

66.2 Problem Description

The problem as shown in Figure 66.1 is a three-layer slope with material properties given in Table 66.1 This example demonstrates conditions with an upstream slope and a low pool of water. The factor of safety is calculated using a circular slip surface, located as shown below.

66.3 Geometry and Material Properties

Table 66.1 – Material Properties

Soil	c' (kN/m²)	ϕ' (⁰)	γ (kN/m³)
Embankment	115	200	25
Foundation Sand	130	0	35
Foundation Clay	115	0	27

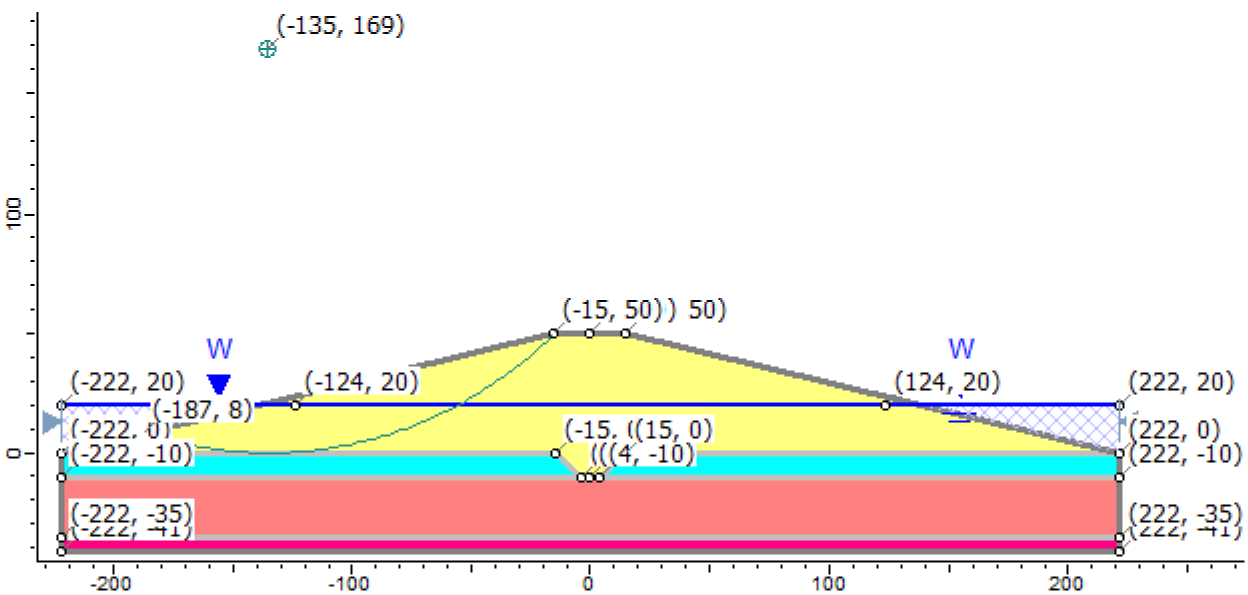


Figure 66.1 – *Slide2* Geometry

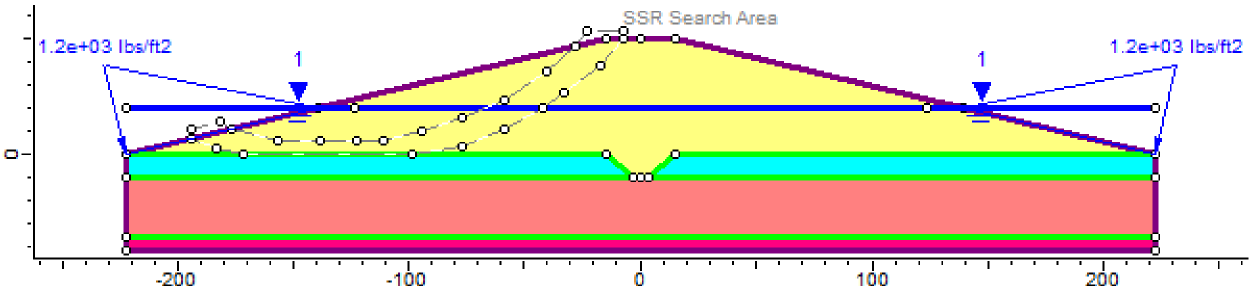


Figure 66.2 – *RS2* Geometry

66.4 Results

Table 66.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	2.307
	GLE	2.309
RS2	SSR	2.22

Note: Referee Factor of Safety = 2.30 [USACE]

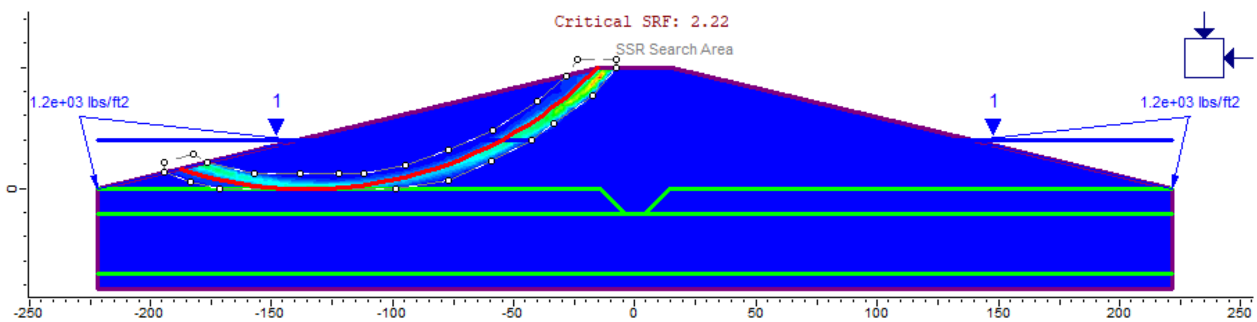


Figure 66.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #67

Embankment, (2) materials

67.1 Introduction

This model is taken from example F-5 of USACE (2003).

67.2 Problem Description

This problem analyzes the stability at the end of construction of the embankment shown in Figure 67.1. The slope is non-homogeneous, consisting of embankment soil and foundation soil. Both soils are fine-grained and undrained during construction. The factor of safety is calculated using a circular slip surface, with center of rotation located 259 feet above and 101 feet to the right of the toe of the slope.

67.3 Geometry and Material Properties

Table 67.1 – Soil Properties

	c′ (psf)	ϕ′ (°)	γ (pcf)
Embankment	1780	5	135
Foundation	1600	2	127

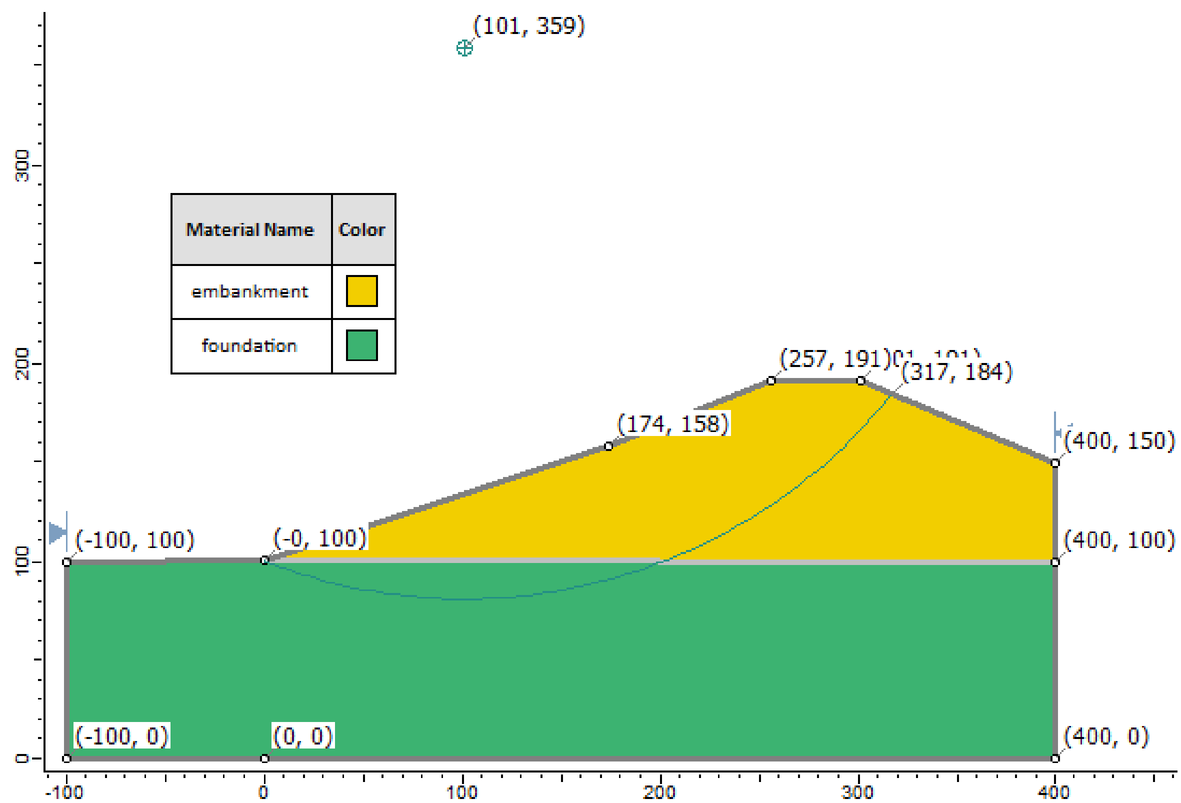


Figure 67.1 – *Slide2* Geometry

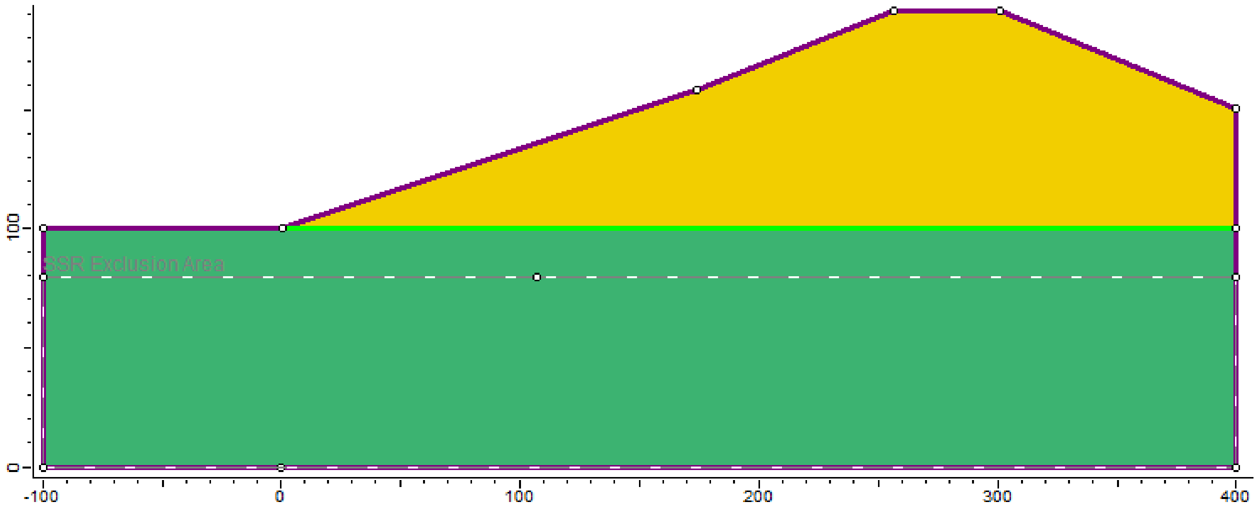


Figure 67.2 – *RS2* Geometry

67.4 Results

Table 67.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.328
	GLE	1.327
RS2	SSR	1.33

Note: Reference Factor of Safety = 1.33 [USACE]

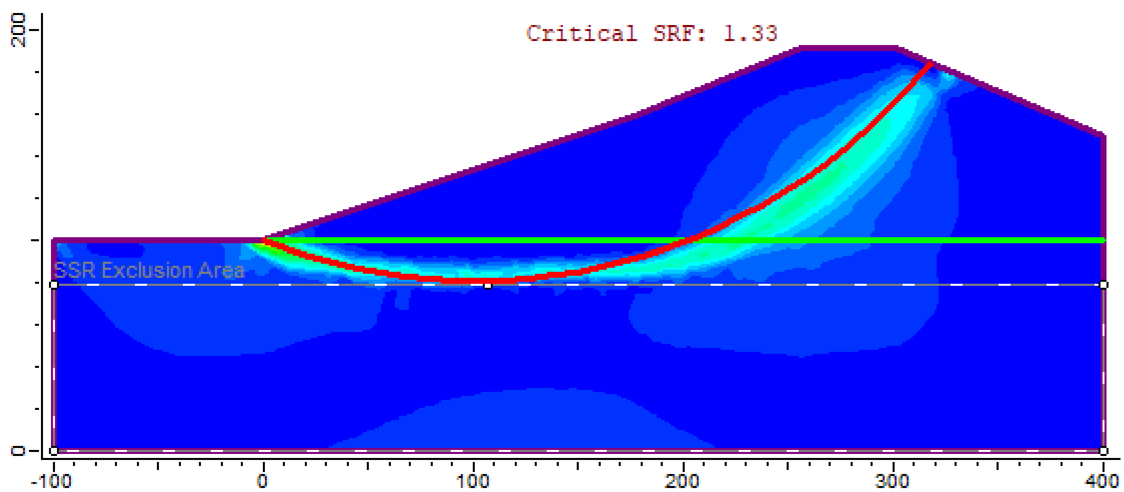


Figure 67.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #68

Slope, homogeneous

68.1 Introduction

This model is taken from example E-10 of USACE (2003).

68.2 Problem Description

This problem analyzes the stability of the undrained ($\phi = 0$) slope in Figure 68.1. The slope consists of three layers with differing material strength and 8 feet of water outside of it. The slip circle used to evaluate the slope, has center of rotation located 8.4 ft to the right and 36 feet above the toe of the slope. The circle is tangent to the base of soil 3.

68.3 Geometry and Material Properties

Table 68.1 – Material Properties

	c' (psf)	γ (pcf)
Soil #1	600	120
Soil #2	400	100
Soil #3	500	105

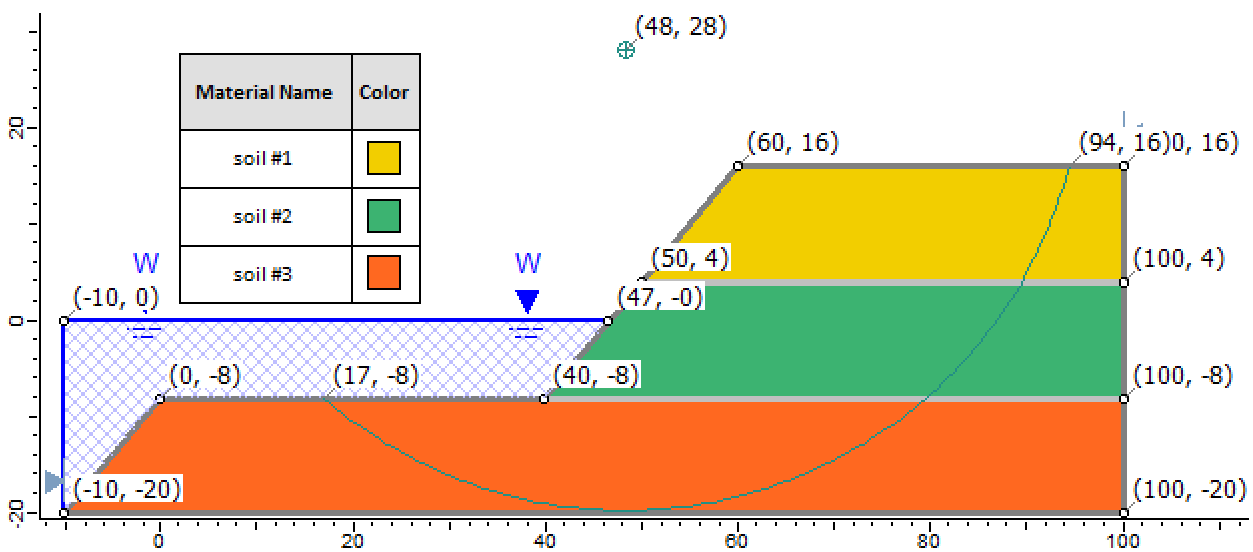


Figure 68.1 – *Slide2* Geometry

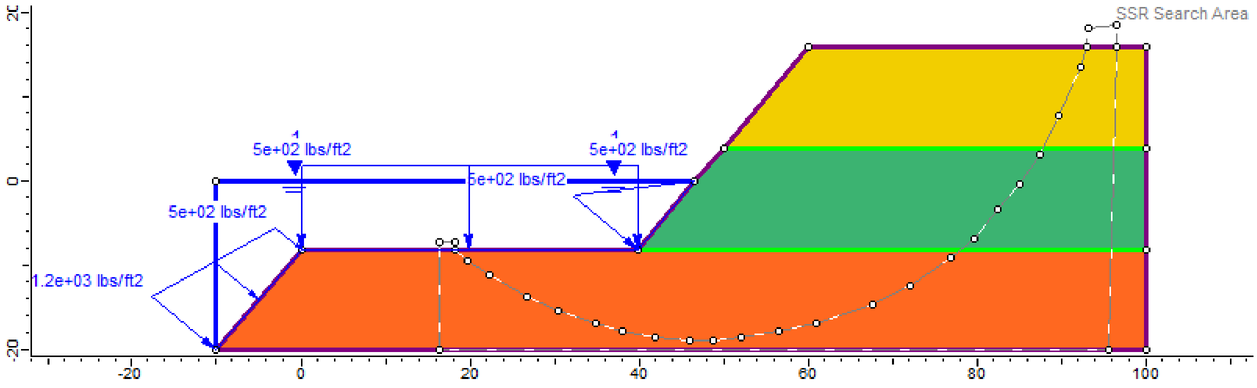


Figure 68.2 – *RS2* Geometry

68.4 Results

Table 68.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	1.241
	GLE	1.241
RS2	SSR	1.17

Note: Reference Factor of Safety = 1.33 [USACE]

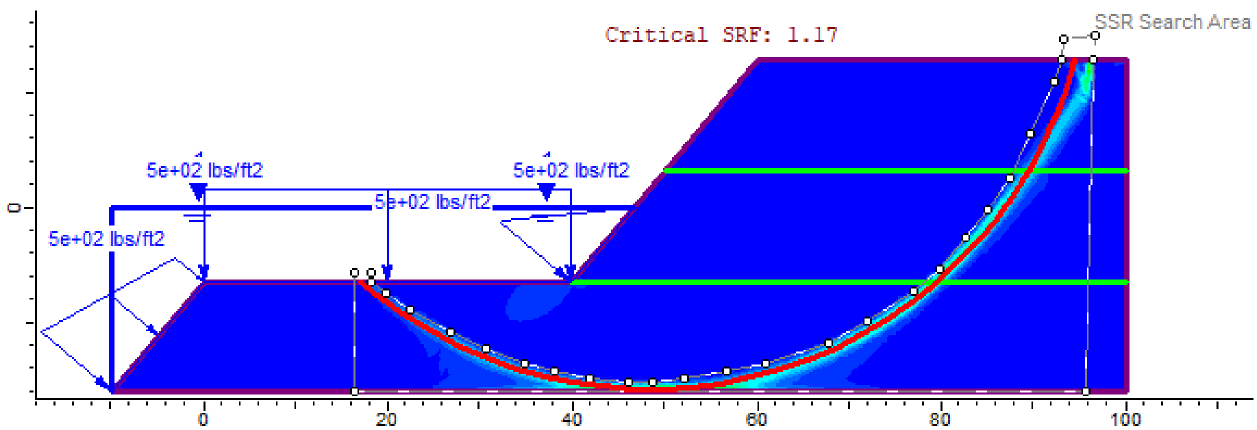


Figure 68.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #69

Embankment, (2) materials, water table, ponded water

69.1 Introduction

This model is taken from example F-6 of USACE (2003).

69.2 Problem Description

Figure 69.1 shows a slope with steady seepage. The two-layered slope is made up of two zones – the embankment fill and the foundation. The stability of the slope is analyzed using a slip circle of radius 280 feet.

69.3 Geometry and Material Properties

Table 69.1 – Material Properties

	c' (kN/m²)	ϕ' (⁰)	γ (kN/m³)
Embankment	0	34	130
Foundation	0	35	125

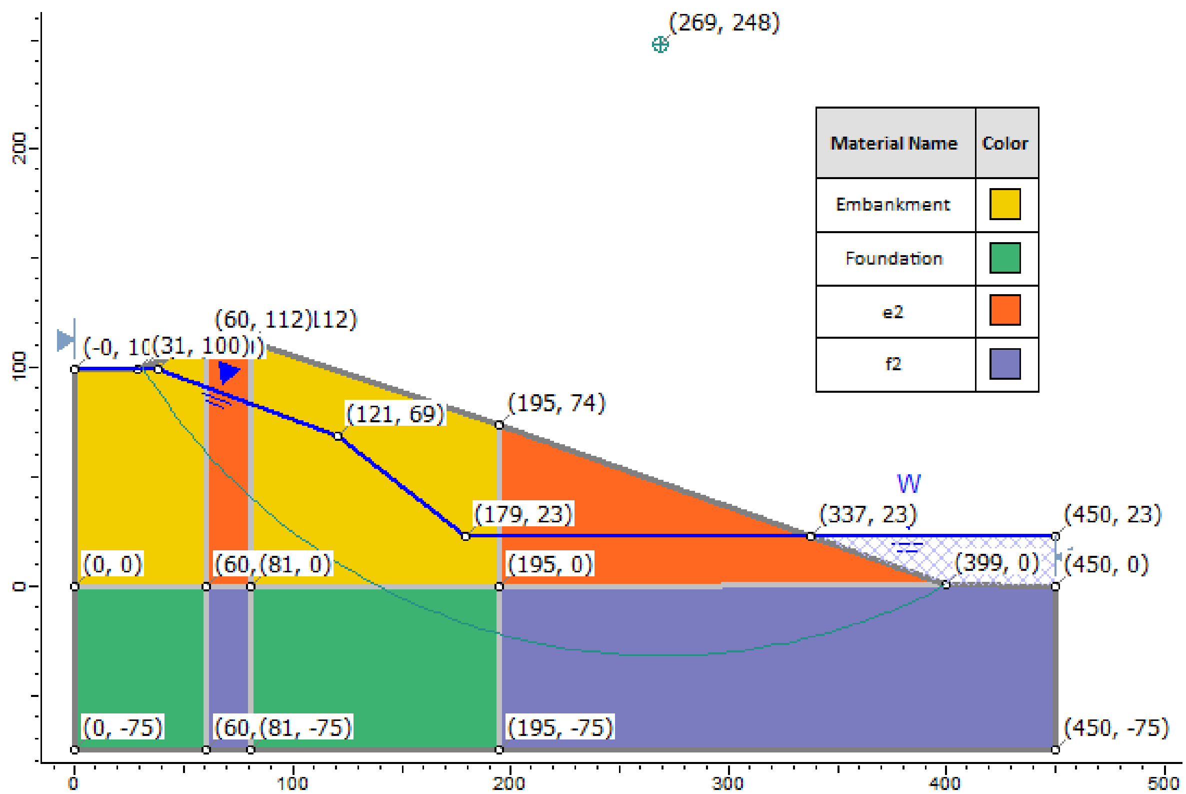


Figure 69.1 – *Slide2* Geometry

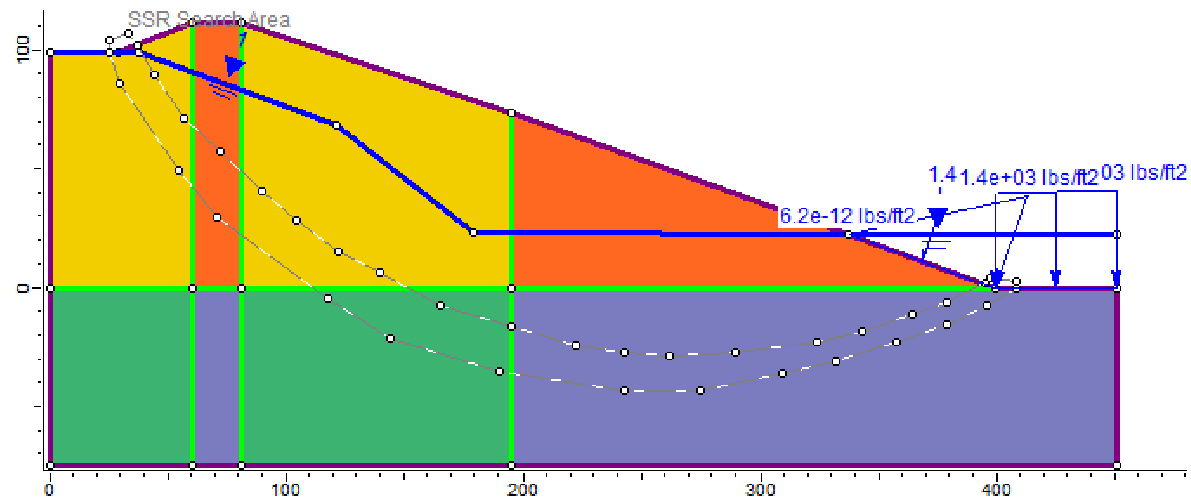


Figure 69.2 – *RS2* Geometry

69.4 Results

Table 69.2 – Comparison of Results

Program	Method	Factor of Safety (circular)
Slide2	Spencer	2.026
	GLE	2.027
RS2	SSR	1.94

Note: Reference Factor of Safety = 2.01 [USACE]

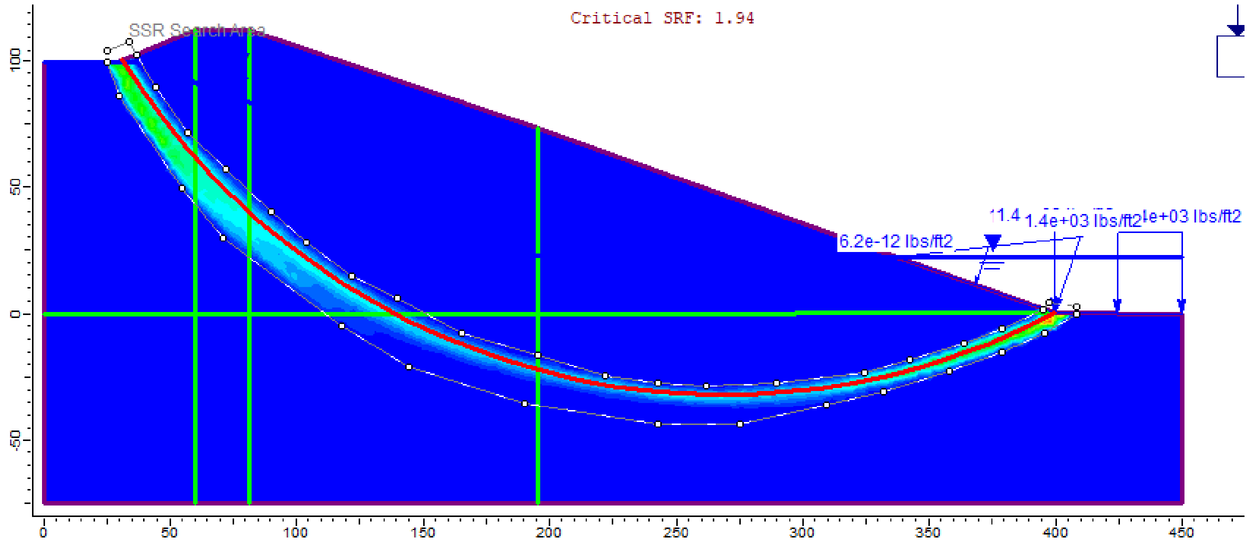


Figure 69.3 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #70

Submerged slope, homogeneous, water table, ponded water

70.1 Introduction

This problem is taken from Figure 6.27 on page 88 of Duncan and Wright (2005).

70.2 Problem Description

Verification problem #70 for ***Slide2***–a submerged slope with water table at 30 feet above the crest (Case 1), and with water table at 60 feet above the crest (Case 2)–are shown in Figure 70.1 through Figure 70.4. The slope is homogeneous with soil properties given in Table 70.1. The factor of safety (Table 70.2 and Table 70.3) and its corresponding slip surface (Figure 70.6 and Figure 70.9) are required.

70.3 Geometry and Material Properties

Table 70.1 – Material Properties

c′ (psf)	ϕ′ (^{0})	γ (pcf)
100	20	128

Case 1

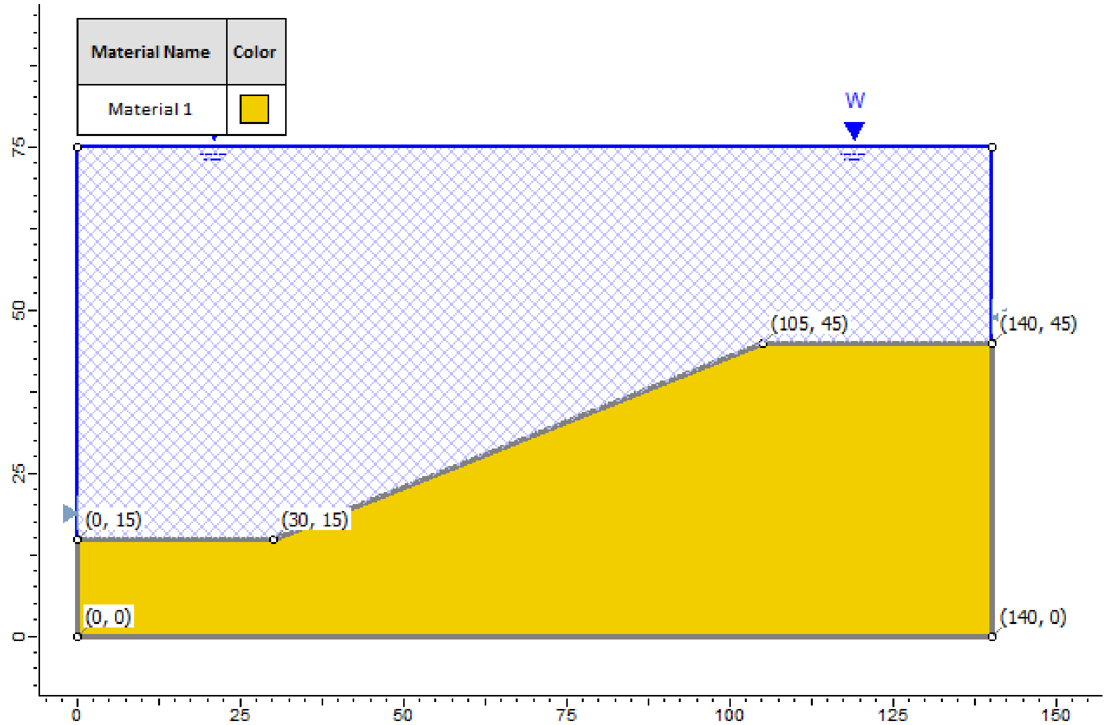


Figure 70.1 – *Slide2* Geometry (Case 1: Water Table 30 ft Above Crest)

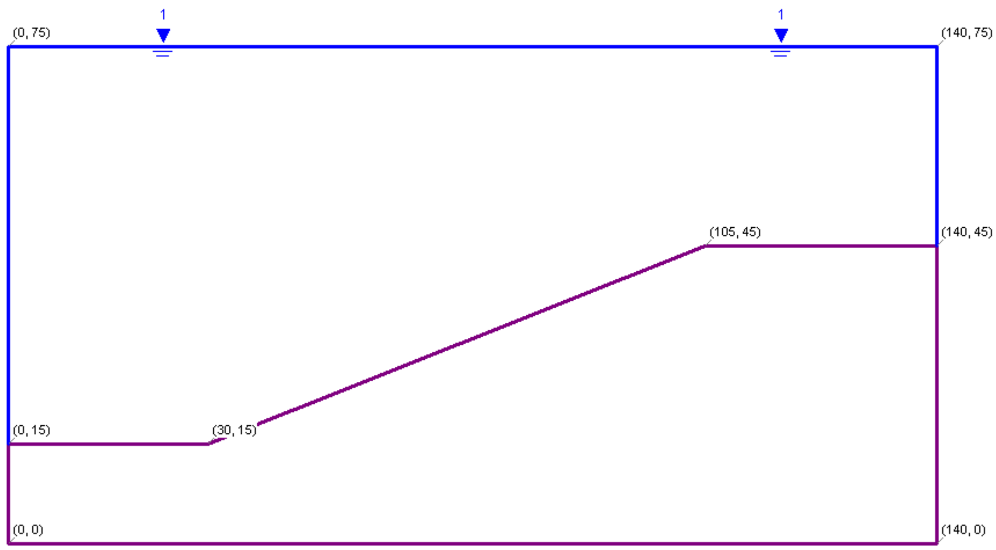


Figure 70.2 – *RS2* Geometry (Case 1: Water Table 30 ft Above Crest)

Case 2

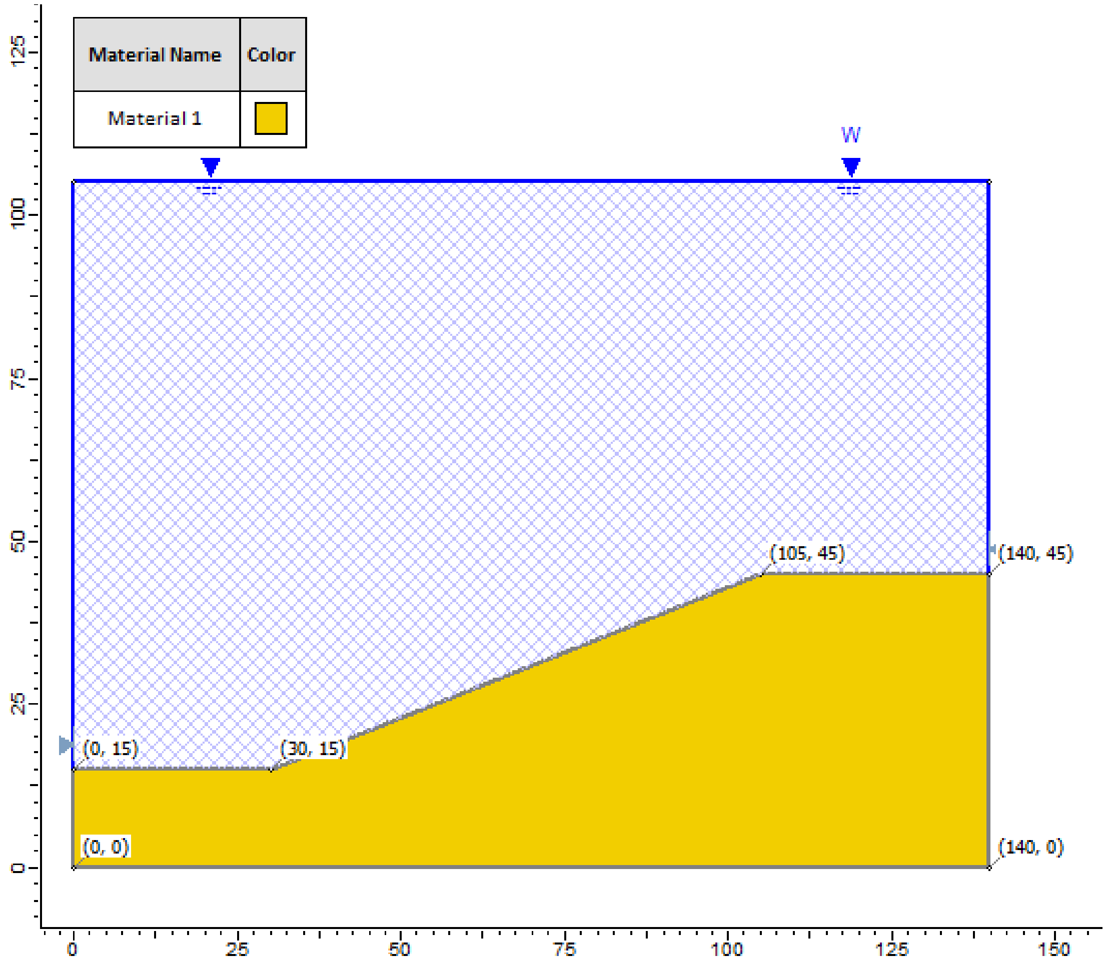


Figure 70.3 – *Slide2* Geometry (Case 2: Water Table 60 ft Above Crest)

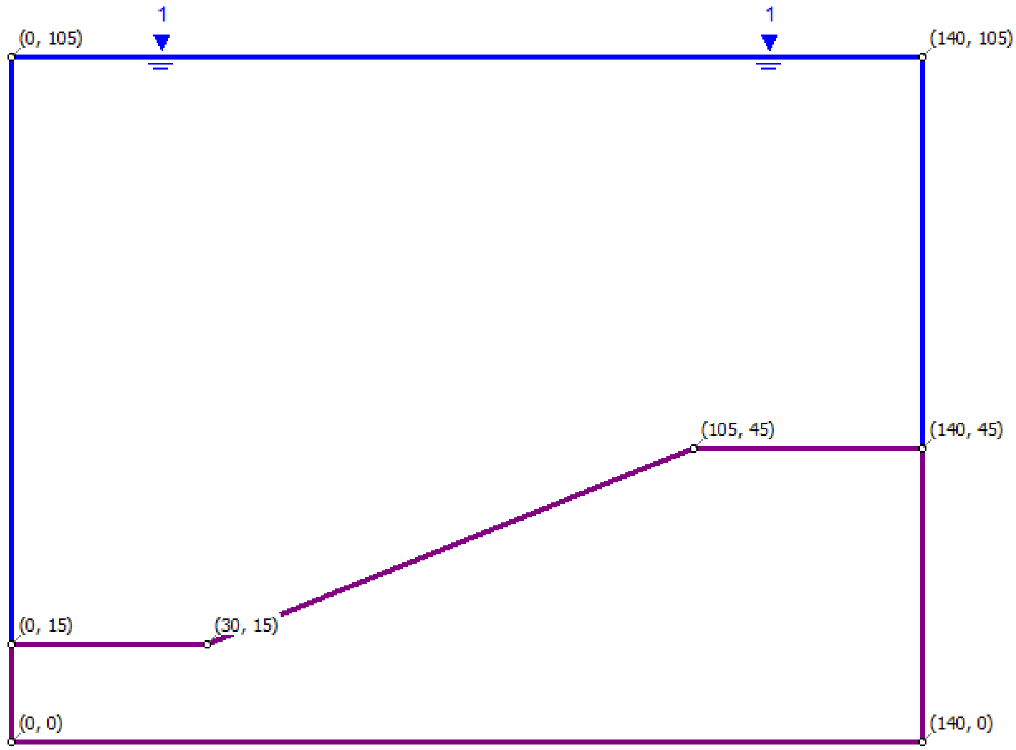


Figure 70.4 – *RS2* Geometry (Case 2: Water Table 60 ft Above Crest)

70.4 Results

Case 1

Figure 70.2 – Comparison of Results (Case 1: Water Table 30 ft Above Crest)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.60	1.59
	GLE	1.60	1.59
RS2	SSR	1.58	

Note: Referee Factor of Safety = 1.60 [Duncan and Wright]

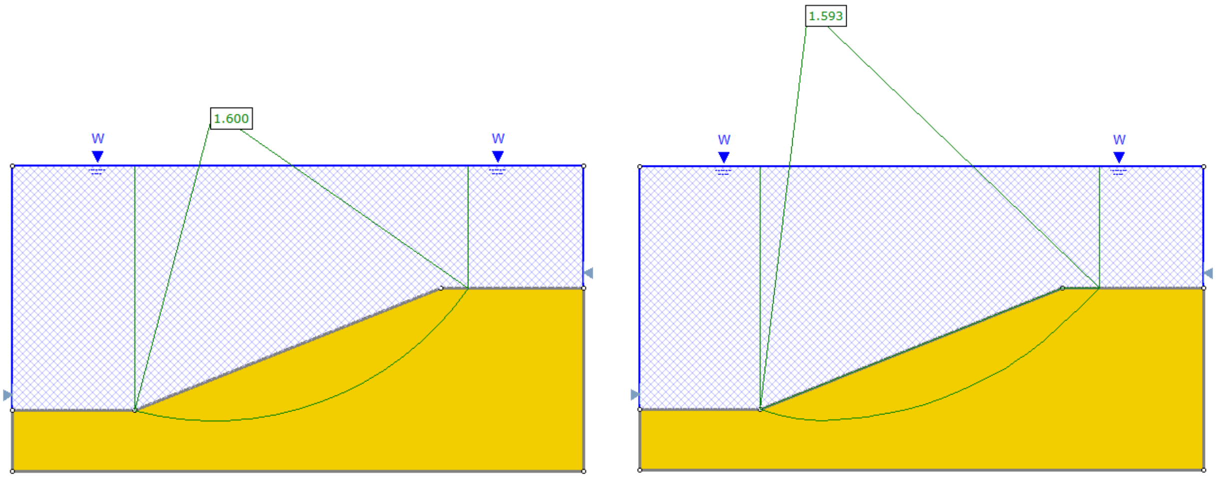


Figure 70.5 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 1: Water Table 30 ft Above Crest)

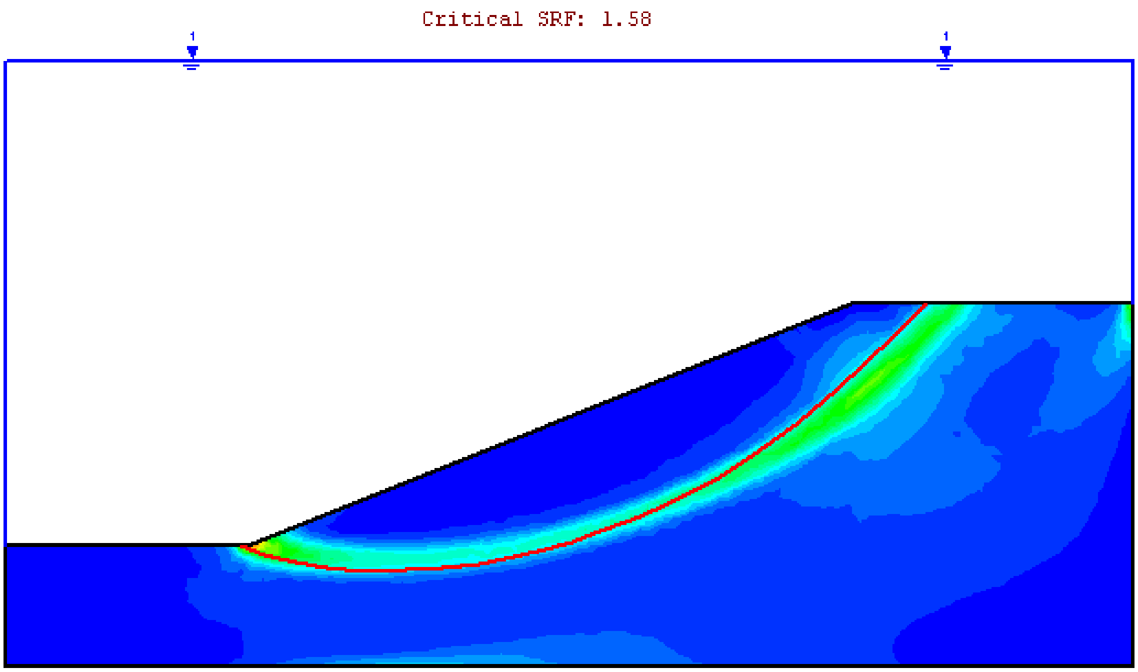


Figure 70.6 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 1: Water Table 30 ft Above Crest)

Case 2

Figure 70.3 – Comparison of Results (Case 2: Water Table 60 ft Above Crest)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.60	1.59
	GLE	1.60	1.58
RS2	SSR	1.58	

Note: Referee Factor of Safety = 1.60 [Duncan and Wright]

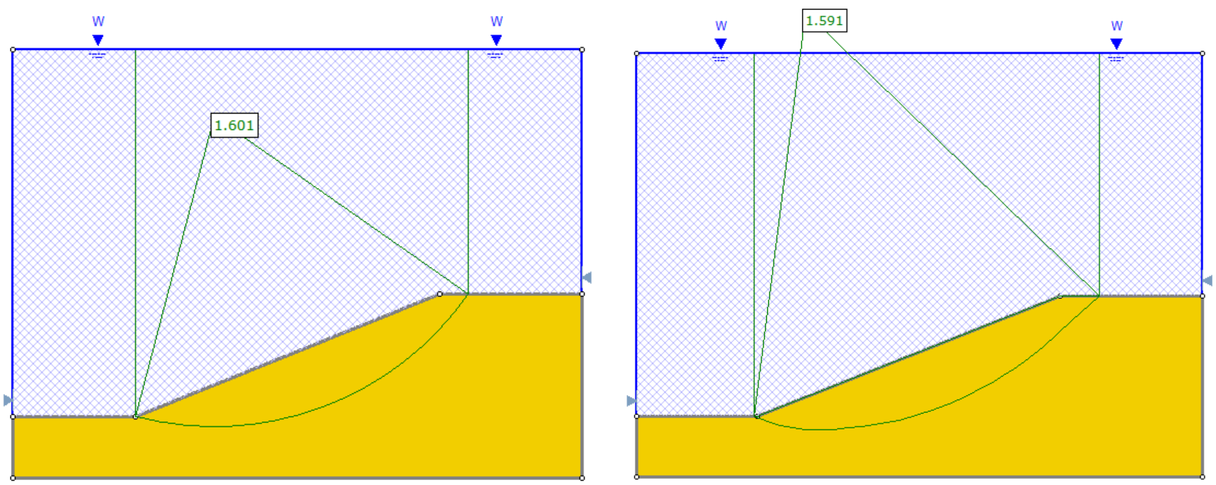


Figure 70.7 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method)
(with *Slide2* Spencer Method Failure Surface Overlay) (Case 2: Water Table 60 ft Above Crest)

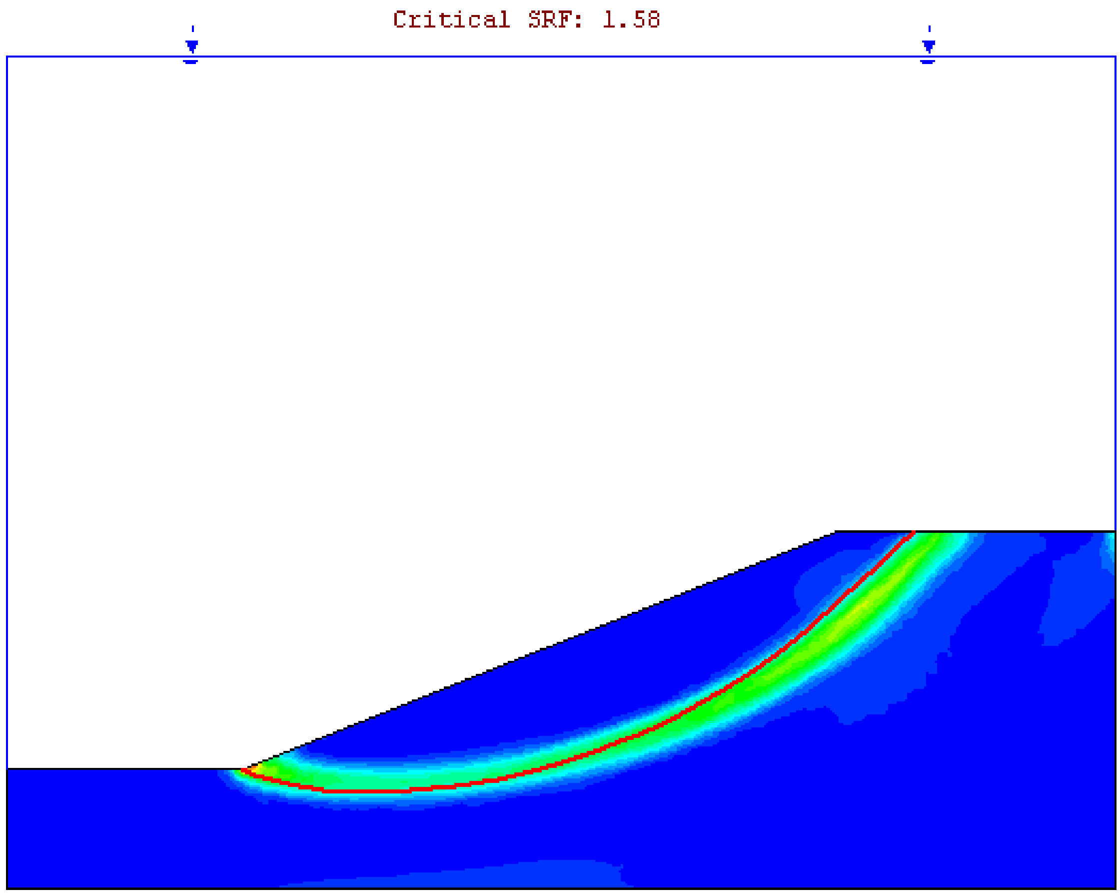


Figure 70.8 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 2: Water Table 60 ft Above Crest)

Verification Problem #71

Slope, homogeneous, finite element groundwater seepage analysis, water table

71.1 Introduction

This problem is taken from Figure 6.37 and 6.38 on page 100 of Duncan and Wright (2005).

71.2 Problem Description

Verification problem #71 for *Slide2*–a homogeneous slope with water level located at 75 feet at the right end–is shown in Figure 71.1 through Figure 71.4. The soil properties are given in Table 71.1. Seepage analysis was carried out using two different methods in this verification problem. The first method was using Finite Element seepage analysis (Case 1) and the second method was using piezometric line approximation (Case 2). The location of the approximated piezometric line is shown in Figure 71.3 and 71.4. The factor of safety (Table 71.2 and Table 71.3) and its corresponding slip surface (Figure 71.7 and Figure 71.10) are required.

71.3 Geometry and Material Properties

Table 71.1 – Material Properties

c' (psf)	ϕ' (⁰)	γ (pcf)
200	20	125

Case 1

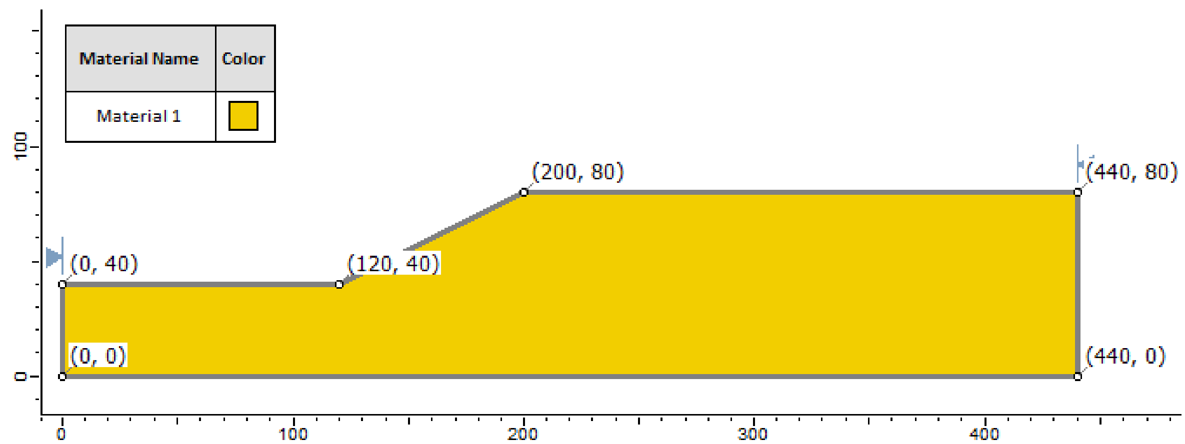


Figure 71.1 – *Slide2* Geometry (Case 1: Finite Element Seepage Analysis)

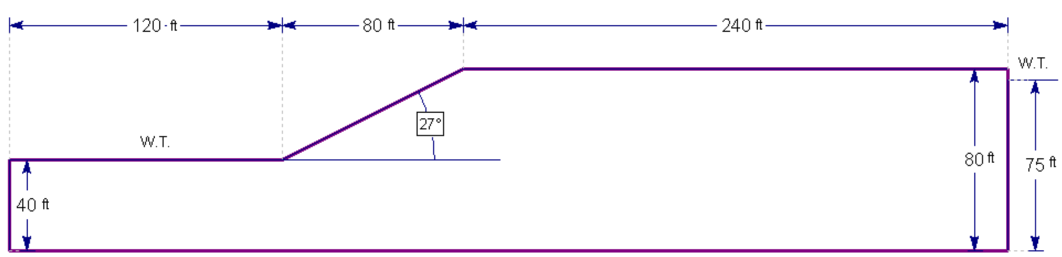


Figure 71.2 – *RS2* Geometry (Case 1: Finite Element Seepage Analysis)

Case 2

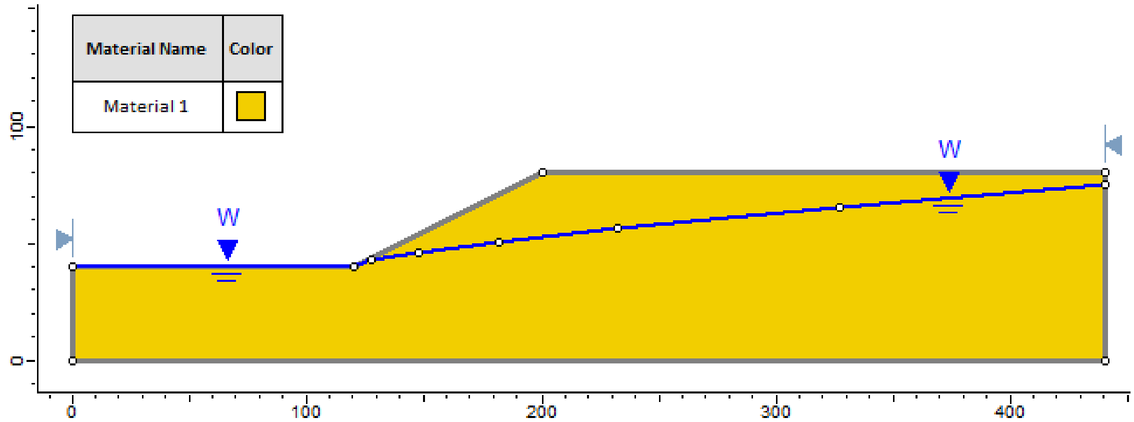


Figure 71.3 – *Slide2* Geometry (Case 2: Piezometric Line Approximation)

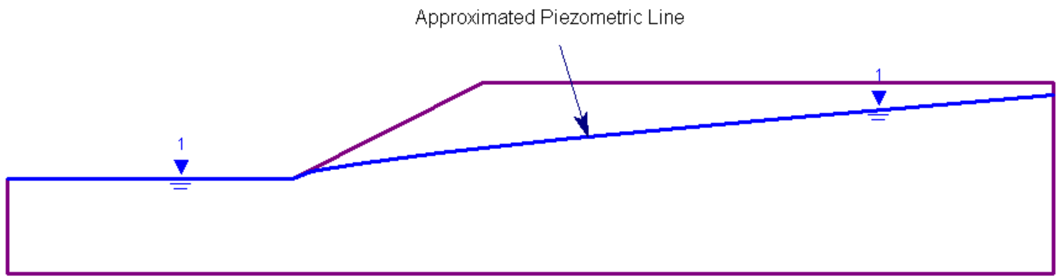


Figure 71.4 – *RS2* Geometry (Case 2: Piezometric Line Approximation)

71.4 Results

Case 1

Figure 71.2 – Comparison of Results (Case 1: Finite Element Seepage Analysis)

Program	Method	Factor of Safety (non-circular)
Slide2	Spencer	1.13
	GLE	1.11
RS2	SSR	1.11

Note: Referee Factor of Safety = 1.138 [Duncan and Wright]

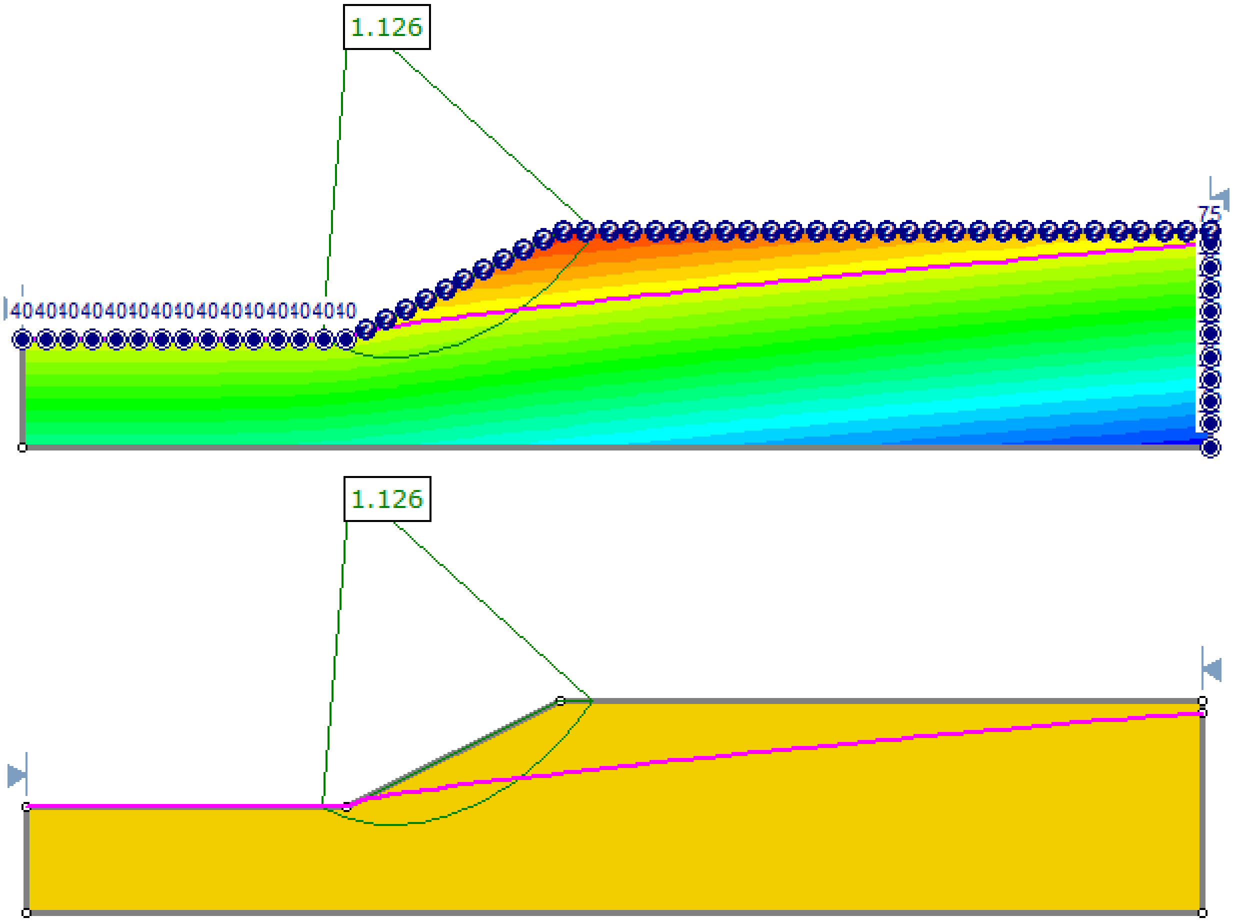


Figure 71.5 – *Slide2* Failure Surface (Non-Circular; Spencer Method) (Case 1: Finite Element Seepage Analysis)

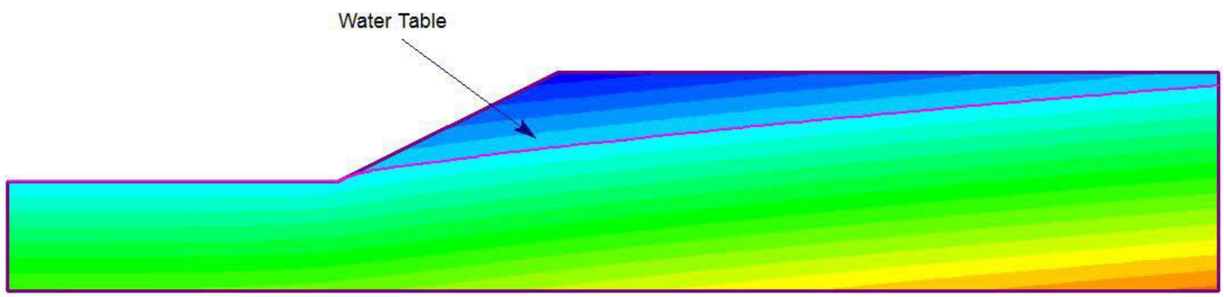


Figure 71.6 – *RS2* Pore Water Pressure Plot (Case 1: Finite Element Seepage Analysis)

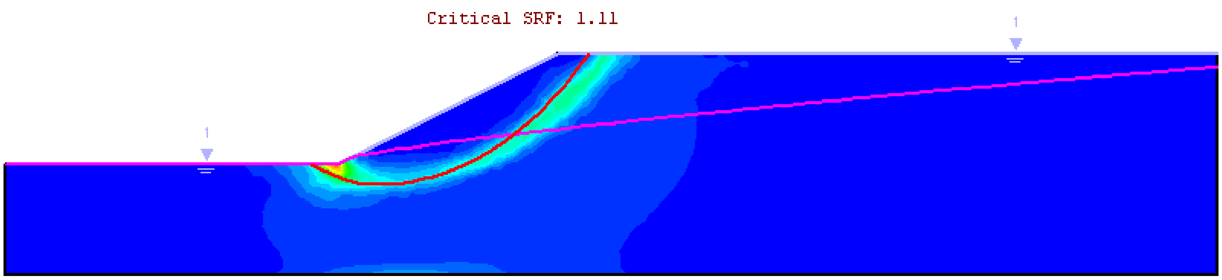


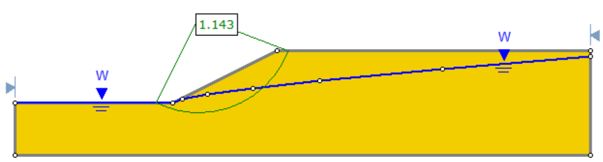
Figure 71.7 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 1: Finite Element Seepage Analysis)

Case 2

Table 71.3 – Comparison of Results (Case 2: Piezometric Line Approximation)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.14	1.15
	GLE	1.14	1.15
RS2	SSR	1.12	

Note: Reference factor of safety = 1.141 [Duncan and Wright]



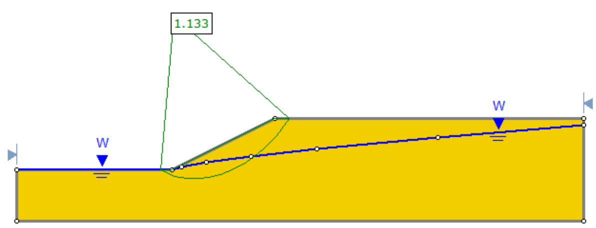


Figure 71.8– *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 2: Piezometric Line Approximation)

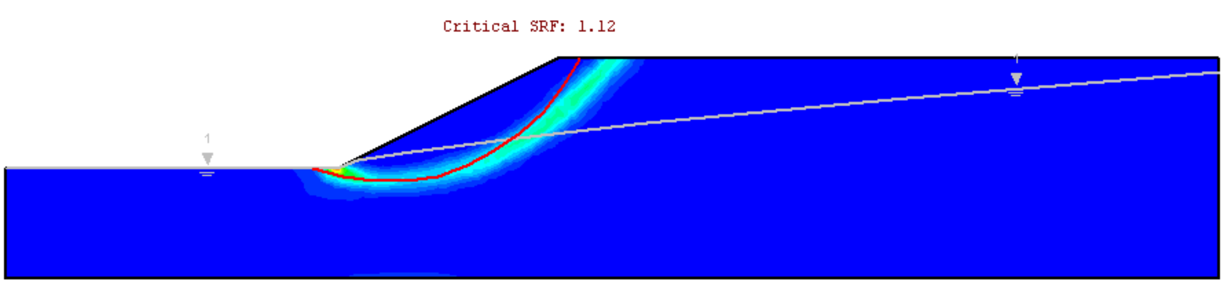


Figure 71.9 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 2: Piezometric Line Approximation)

Verification Problem #72

Embankment dam, (4) materials, finite element groundwater seepage analysis, ponded water

72.1 Introduction

This problem is taken from Figure 6.39 on page 101 of Duncan and Wright (2005).

72.2 Problem Description

Verification problem #72 for *Slide2*–a symmetric earth embankment dam resting on a layered soil foundation with ponded water at an elevation of 302 feet on the left side is shown in Figure 72.1 though Figure 72.4. The left face and right face of the dam are constructed using shell material. Two cases are studied in this verification. The global critical slip surface is of interest in case 1 and the critical slip surface tangent to elevation 197 feet (through foundation clay and sand material boundary) is of interest in case 2. Case 2 is simulated by introducing a Block Search Line or Focus Search Line in *Slide2* and SSR Exclusion Area in *RS2* as required. In each case, the pore water pressure is modelled using (a) finite element seepage analysis and (b) a piezometric line approximation. The location of the approximated piezometric line is shown in Figure 72.1b, 72.2b, 72.3b and 72.4b. The material strength properties and permeability values are given in Table 72.1. The factor of safety (Table 72.2 and Table 72.3) and its corresponding slip surface (Figure 72.5 to Figure 72.8) are required.

72.3 Geometry and Material Properties

Table 72.1 – Material Properties

	k (ft/s)	c' (psf)	ϕ' (^{0})	γ (pcf)
Outer Shell	1.67×10^{-4}	0	34	125
Clay Core	1.67×10^{-8}	100	26	122
Foundation Clay	1.67×10^{-7}	0	24	123
Foundation Sand	1.67×10^{-5}	0	32	127

Case 1

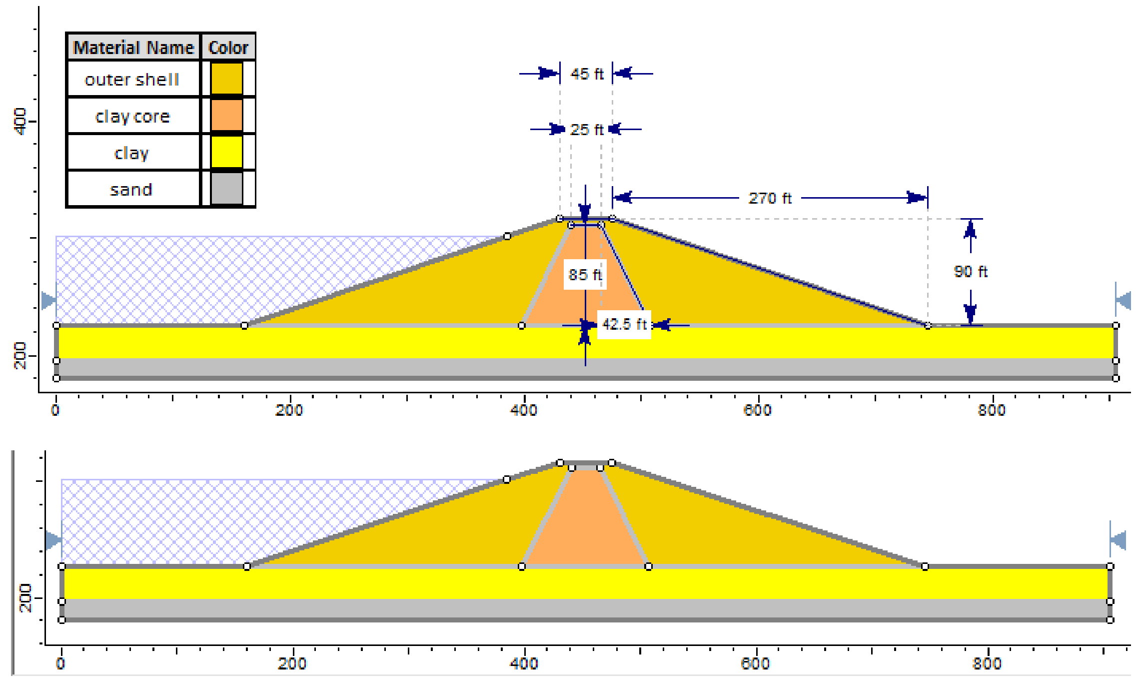


Figure 72.1a – *Slide2* Geometry (Case 1a: Global Critical Slip Surface, Finite Element Seepage Analysis)

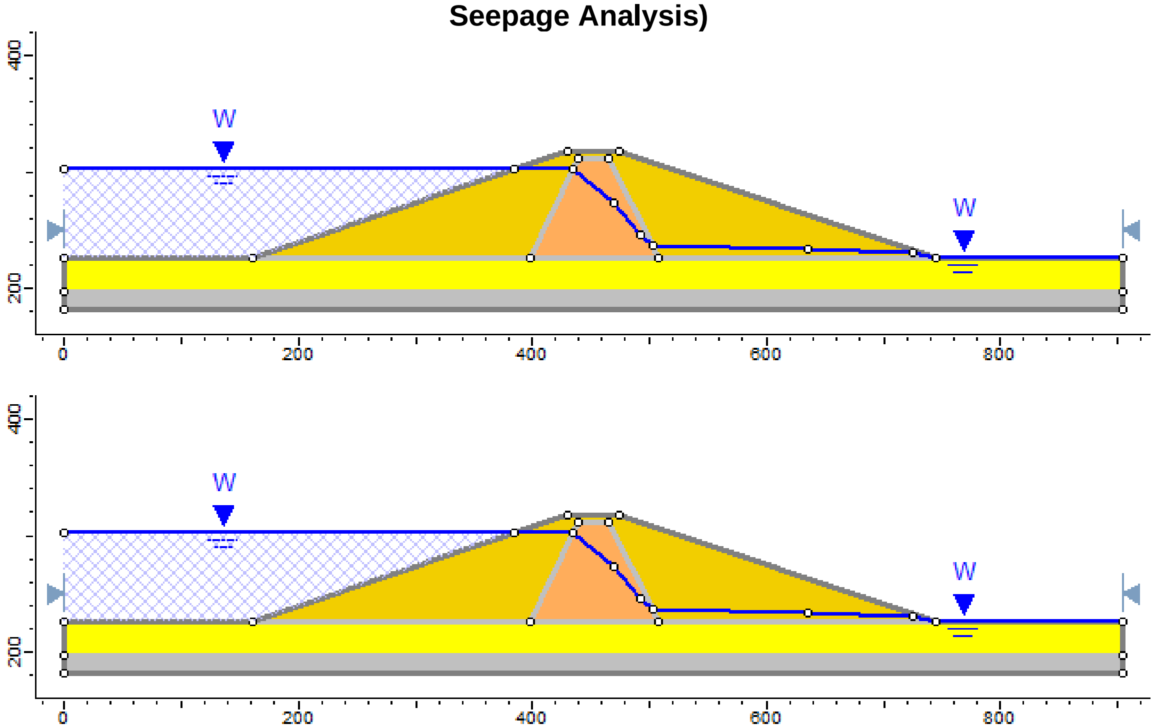


Figure 72.1b – *Slide2* Geometry (Case 1b: Global Critical Slip Surface, Piezometric Line Approximation)

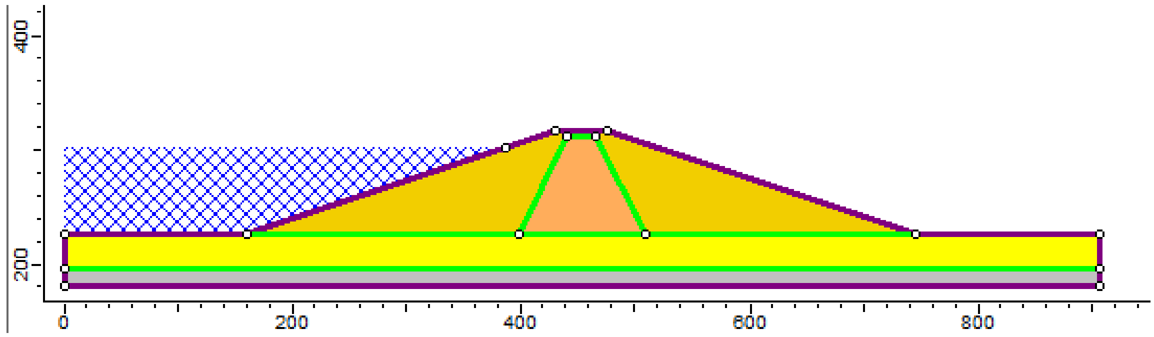


Figure 72.2a – *RS2* Geometry (Case 1a: Global Critical Slip Surface, Finite Element Seepage Analysis)

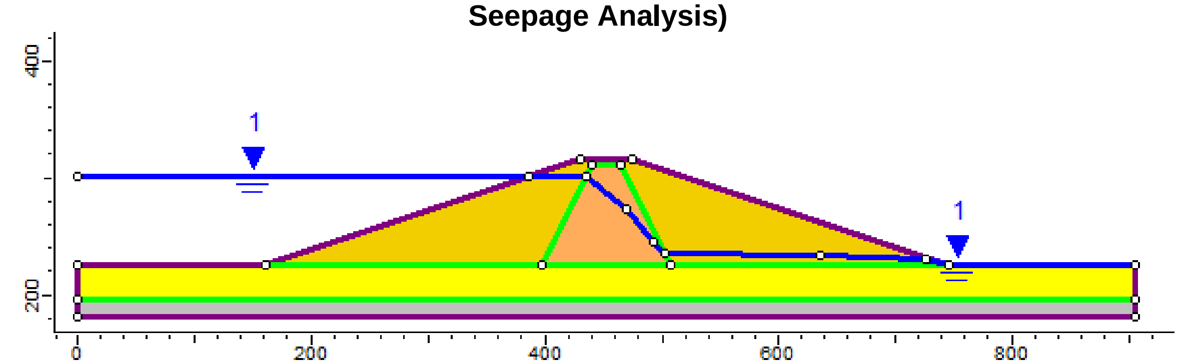


Figure 72.2b – *RS2* Geometry (Case 1b: Global Critical Slip Surface, Piezometric Line Approximation)

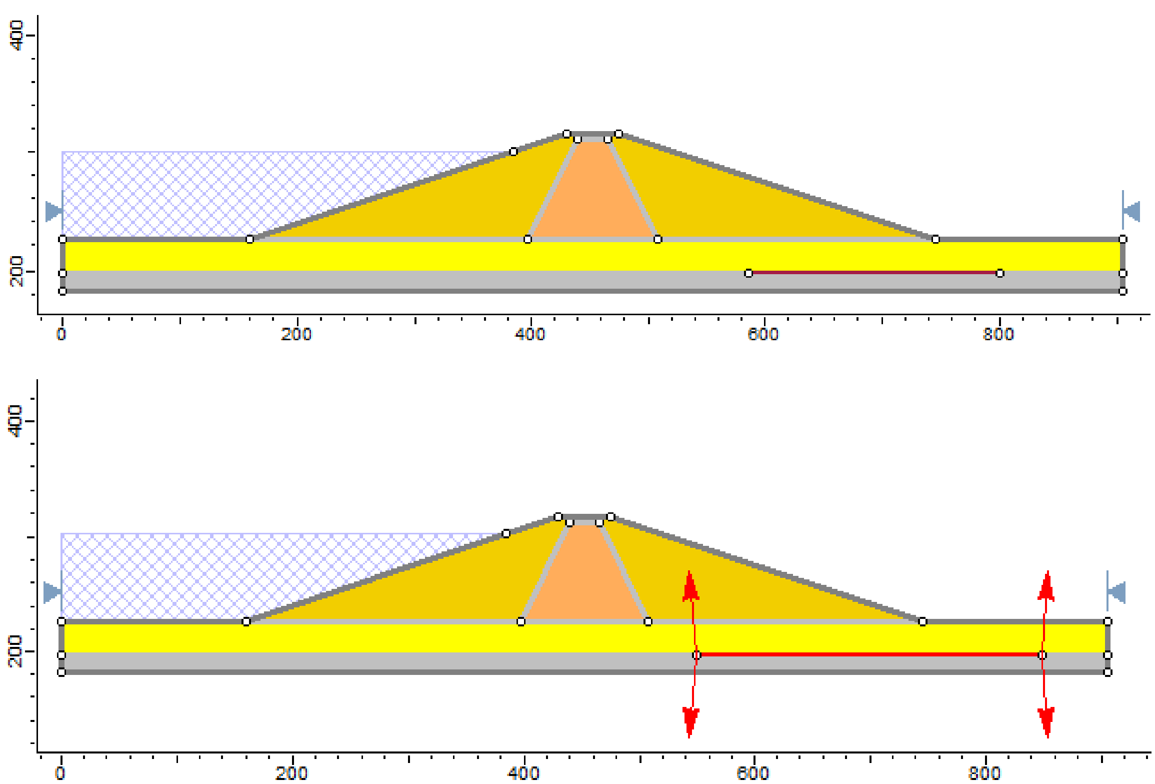
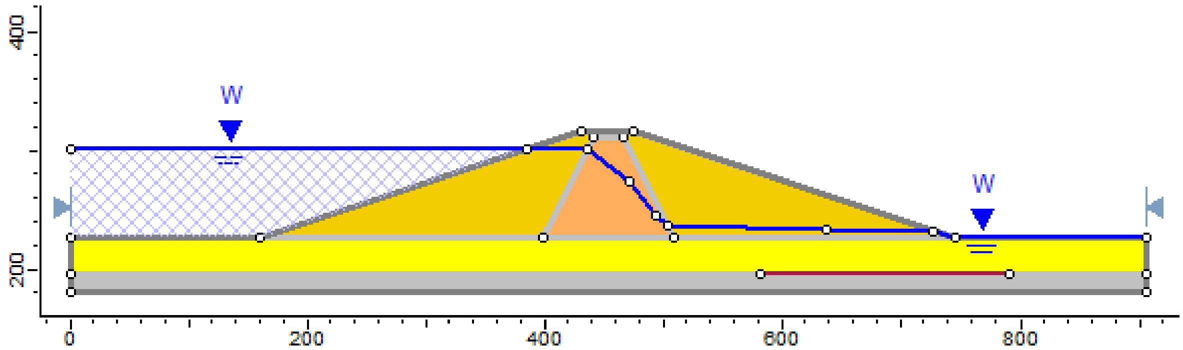


Figure 72.3a – *Slide2* Geometry (Case 2a: Failure Surface Through Foundation Clay & Sand Material Boundary, Finite Element Seepage Analysis)



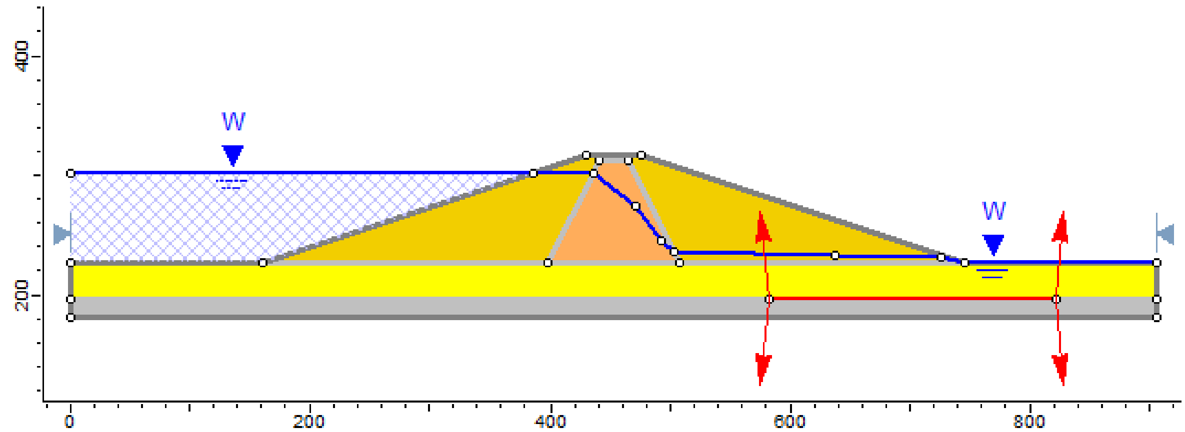


Figure 72.3b – *Slide2* Geometry (Case 2b: Failure Surface Through Foundation Clay & Sand Material Boundary, Piezometric Line Approximation)

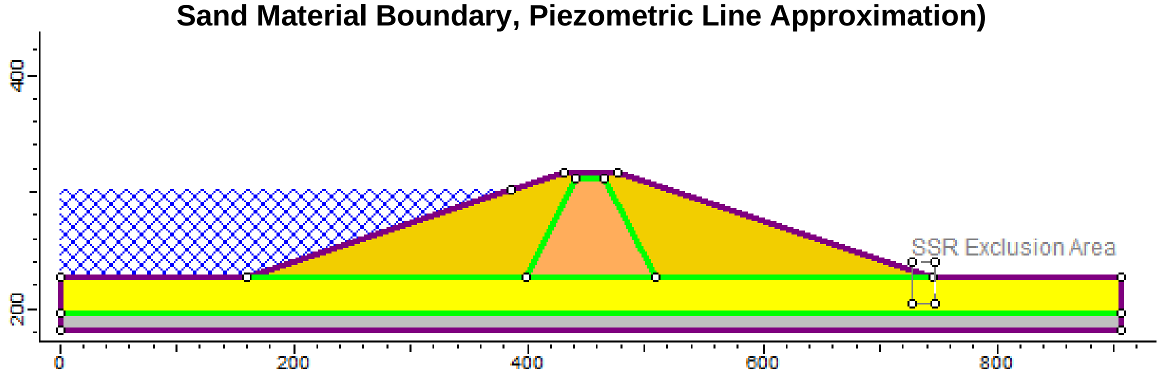


Figure 72.4a – *RS2* Geometry (Case 2a: Failure Surface Through Foundation Clay & Sand Material Boundary, Finite Element Seepage Analysis)

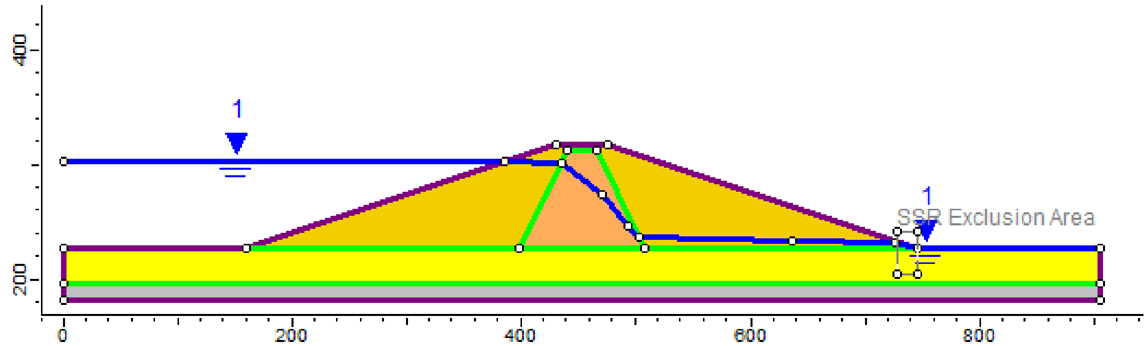


Figure 72.4b – *RS2* Geometry (Case 2b: Failure Surface Through Foundation Clay & Sand Material Boundary, Piezometric Line Approximation)

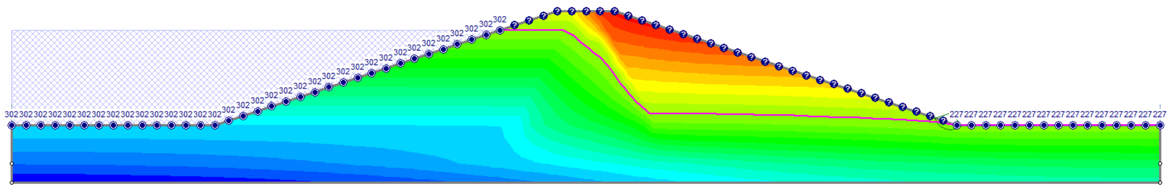
72.4 Results

Case 1

Table 72.2 – Comparison of Results (Case 1: Global Critical Slip Surface)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
(a) Finite Element Seepage Analysis			
Slide2	Spencer	1.16	1.09
	GLE	1.16	1.10
RS2	SSR	1.00	
(b) Piezometric Line Approximation			
Slide2	Spencer	1.30	1.24
	GLE	1.30	1.23
RS2	SSR	1.27	

Note: Referee Factor of Safety = 1.11 [Duncan and Wright] for Case 1a. Referee Factor of Safety = 1.30 [Duncan and Wright] for Case 1b.



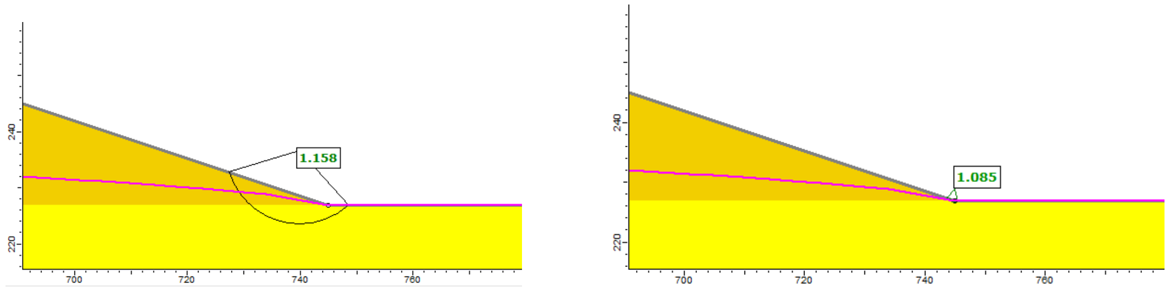


Figure 72.5a – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 1a: Global Critical Slip Surface, Finite Element Seepage Analysis)

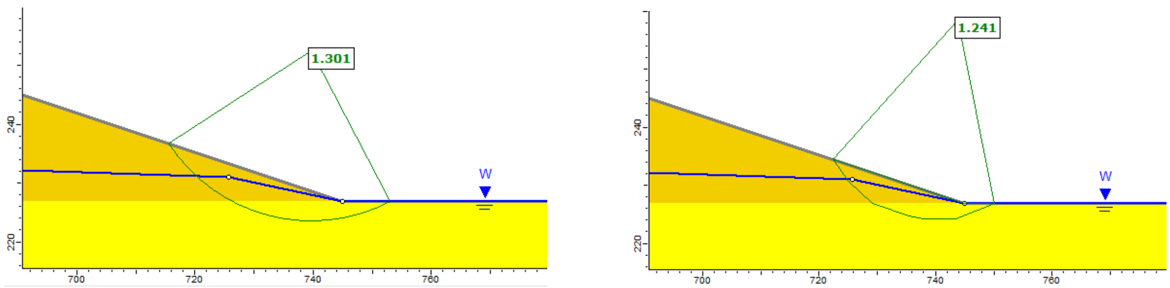


Figure 72.5b – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 1b: Global Critical Slip Surface, Piezometric Line Approximation)

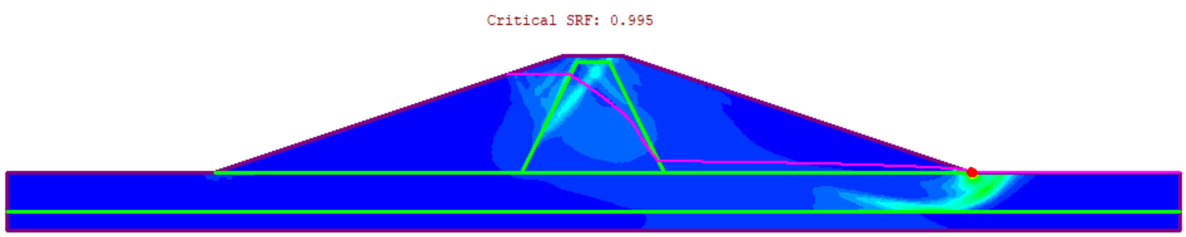


Figure 72.6a – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 1a: Global Critical Slip Surface, Finite Element Seepage Analysis)

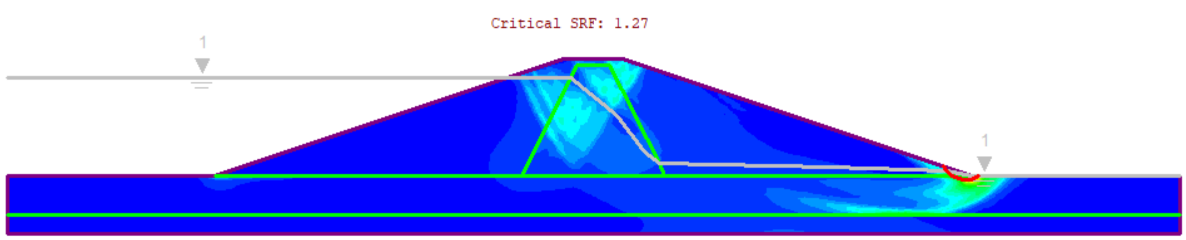


Figure 72.6b – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 1b: Global Critical Slip Surface, Piezometric Line Approximation)

Case 2

Table 72.3 – Comparison of Results (Case 2: Failure Surface Through Foundation Clay & Foundation Sand Material Boundary)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
(a) Finite Element Seepage Analysis			
Slide2	Spencer	1.31	1.38
	GLE	1.32	1.40
RS2	SSR	1.25	
(b) Piezometric Line Approximation			
Slide2	Spencer	1.56	1.63
	GLE	1.56	1.63
RS2	SSR	1.49	

Note: Referee Factor of Safety = 1.37 [Duncan and Wright] for Case 2a. Referee Factor of Safety = 1.57 [Duncan and Wright] for Case 2b.

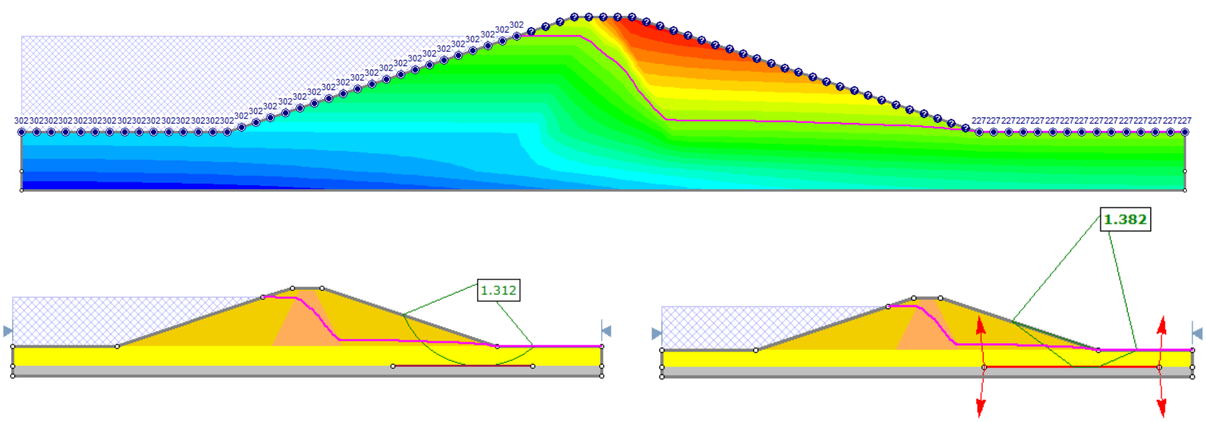


Figure 72.7a – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 2a: Failure Surface Through Foundation Clay & Foundation Sand Material Boundary, Finite Element Seepage Analysis)

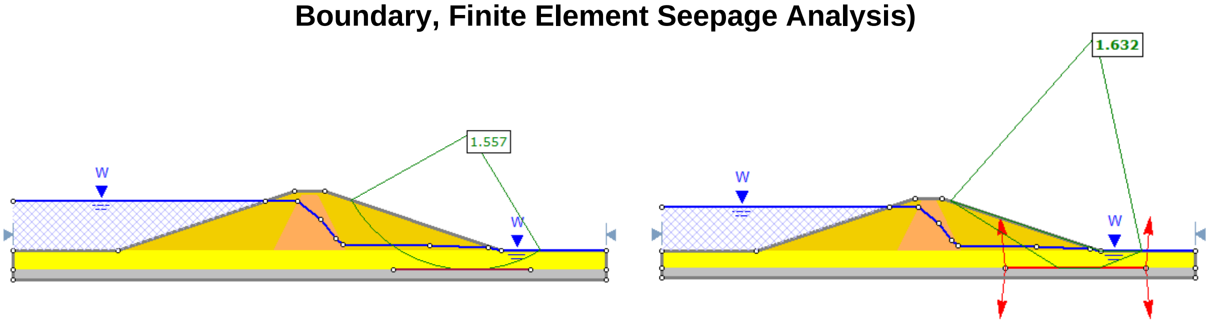


Figure 72.7b – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 2b: Failure Surface Through Foundation Clay & Foundation Sand Material Boundary, Piezometric Line Approximation)

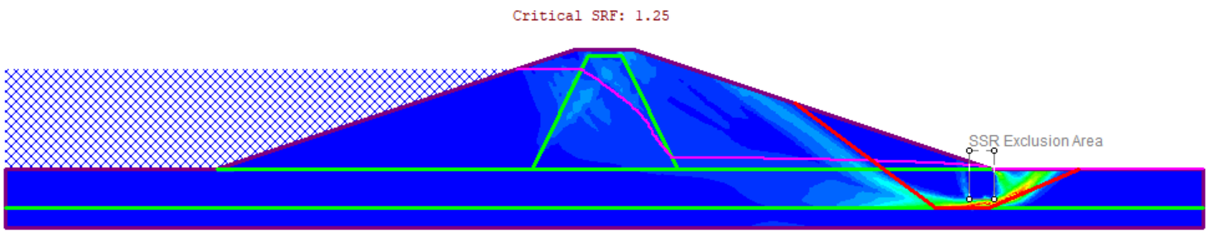


Figure 72.8a – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 2a: Failure Surface Through Foundation Clay & Foundation Sand Material Boundary, Finite Element Seepage Analysis)

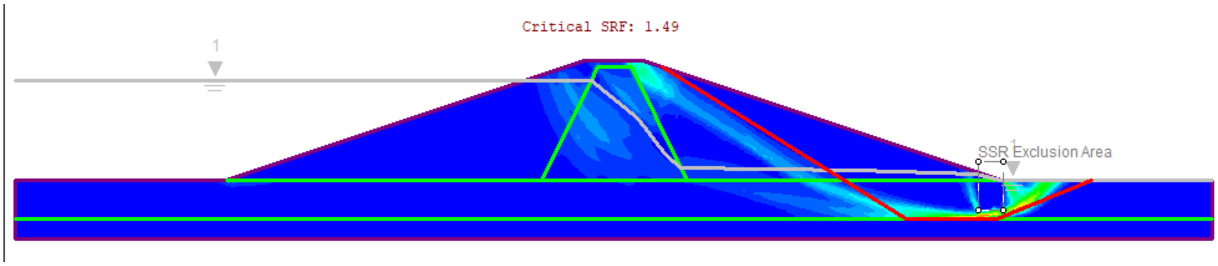


Figure 72.8b – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 2b: Failure Surface Through Foundation Clay & Foundation Sand Material Boundary, Piezometric Line Approximation)

To force *RS2* to iterate for SRF associated with a deeper failure surface, a SSR Exclusion Area Polygon was used to exclude the shallow area at the bottom of the slope (Figure 72.8a and 72.8b).

Verification Problem #74

Embankment, (2) materials

74.1 Introduction

This problem is taken from Figure 7.12 on page 120 of Duncan and Wright (2005).

74.2 Problem Description

Verification problem #74 for *Slide2*–an embankment of cohesionless material resting on a saturated clay foundation–is shown in Figure 74.1 and 74.2. The material properties are given in Table 74.1. The factor of safety (Table 74.2) and its corresponding slip surface (Figure 74.4) are required.

74.3 Geometry and Material Properties

Table 74.1 – Material Properties

Material	c' (psf)	ϕ' (°)	γ (pcf)
Embankment (Sand)	0	40	140
Foundation (Saturated Clay)	2500	0	140

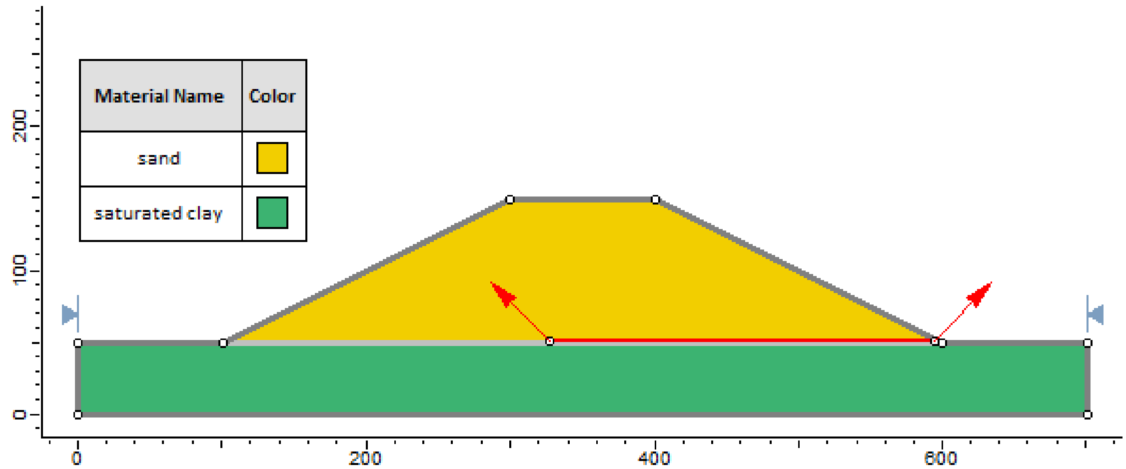


Figure 74.1 – *Slide2* Geometry

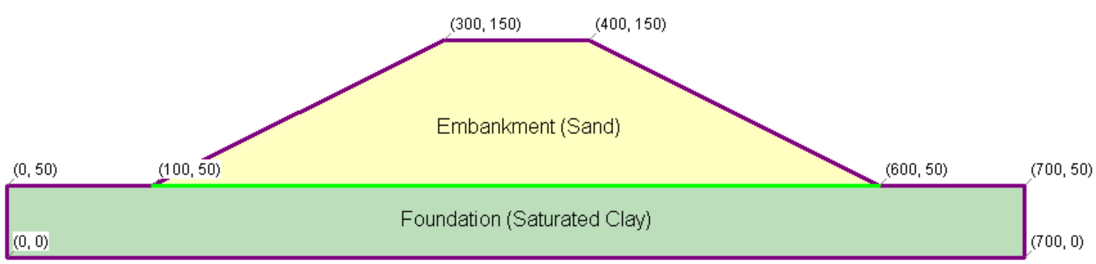


Figure 74.2 – *RS2* Geometry

74.4 Results

Table 74.2 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.20	1.17
	GLE	1.21	1.18
RS2	SSR	1.17	

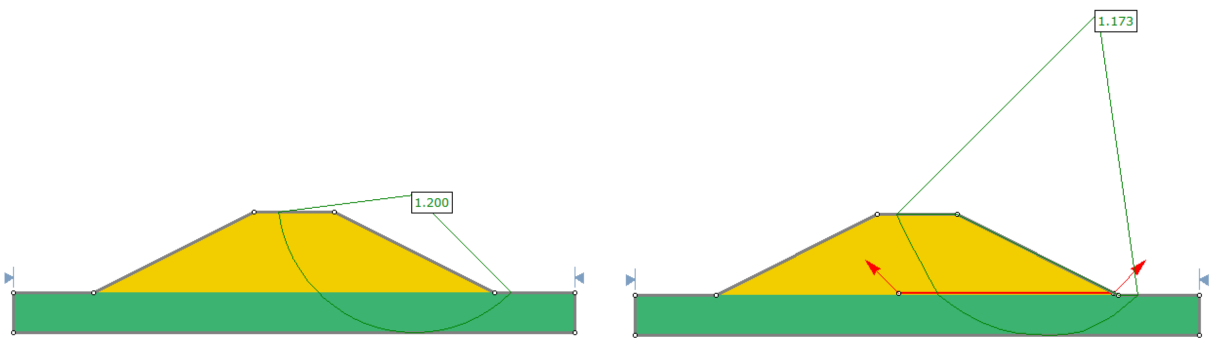


Figure 74.3 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method)

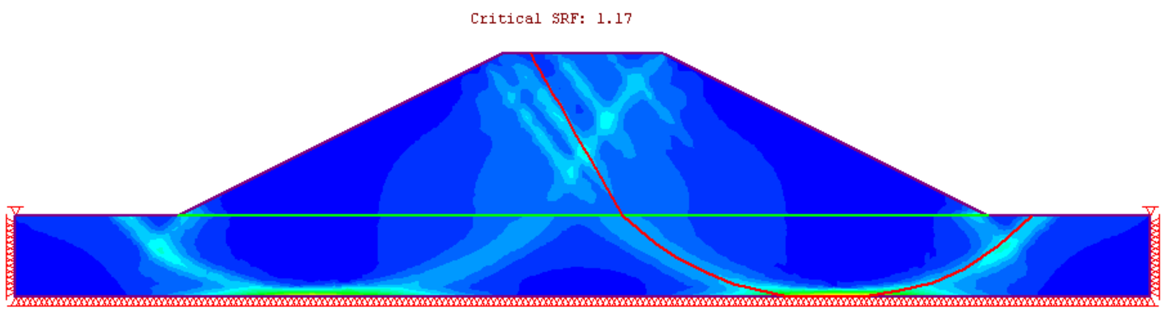


Figure 74.4 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #75

Dyke, (4) materials

75.1 Introduction

This problem is an analysis of one of the planned James Bay dykes. The model is taken from Figure 7.16 on page 124 of Duncan and Wright (2005).

75.2 Problem Description

Verification problem #75 for ***Slide2***–a stepped slope of horizontally layered materials–is shown in Figure 75.1 and 75.2. A Block Search Line was implemented in ***Slide2*** for a non-circular failure surface. The material properties are given in Table 75.1. The factor of safety (Table 75.2) and its corresponding slip surface (Figure 75.4) are required.

75.3 Geometry and Material Properties

Table 75.1 – Material Properties

Material	c (psf)	ϕ (°)	γ (pcf)
Fill	0	30	20
Clay “crust”	41	0	20
Marine Clay	34.5	0	18.8
Lacustrine Clay	31.2	0	20.3

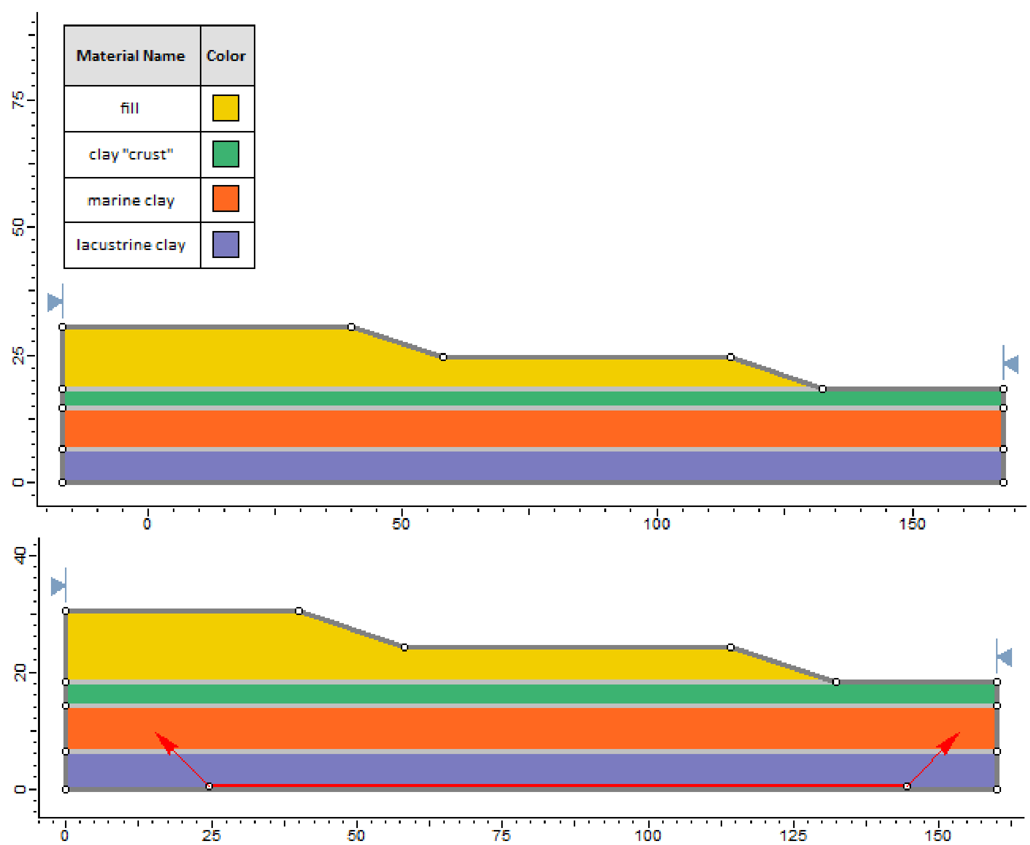


Figure 74.1 – *Slide2* Geometry

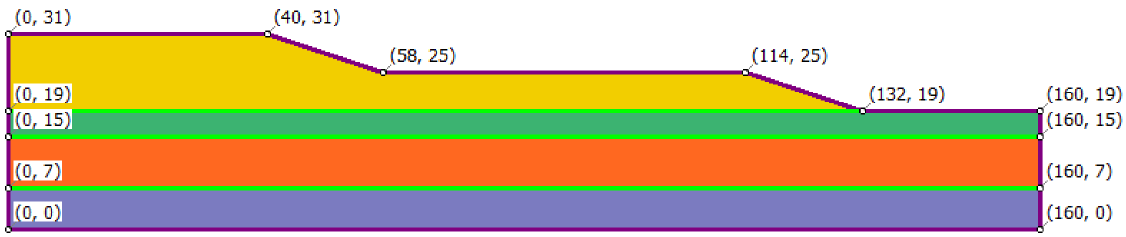


Figure 74.2 – *RS2* Geometry

75.4 Results

Table 75.2 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.47	1.16
	GLE	1.47	1.14
RS2	SSR	1.19	

Note: Reference factor of safety for a circular critical slip surface = 1.45; Reference factor of safety for a non-circular critical slip surface = 1.17 [Duncan and Wright].

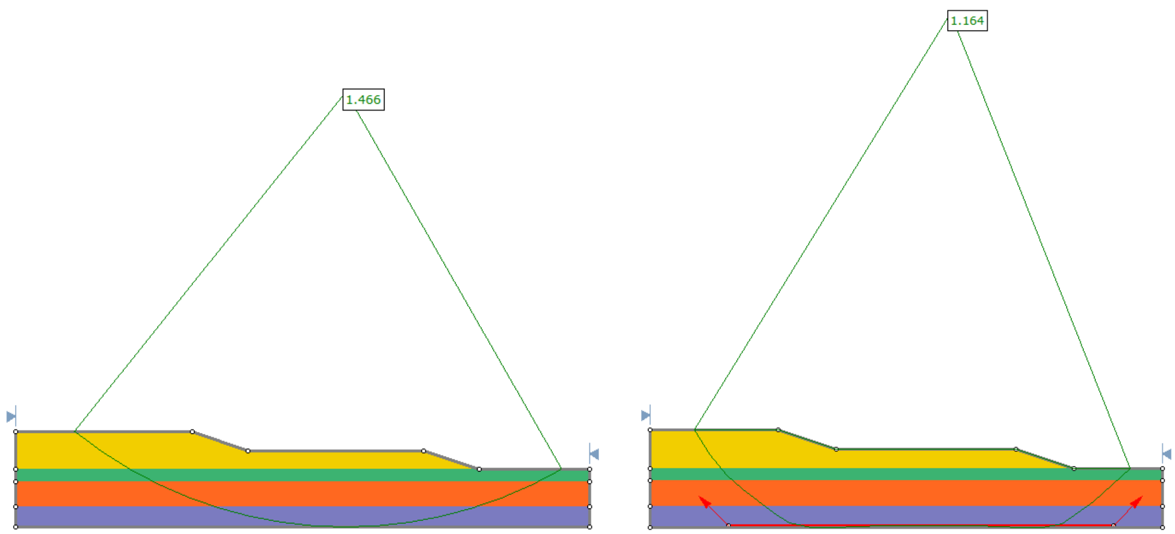


Figure 75.3 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method)

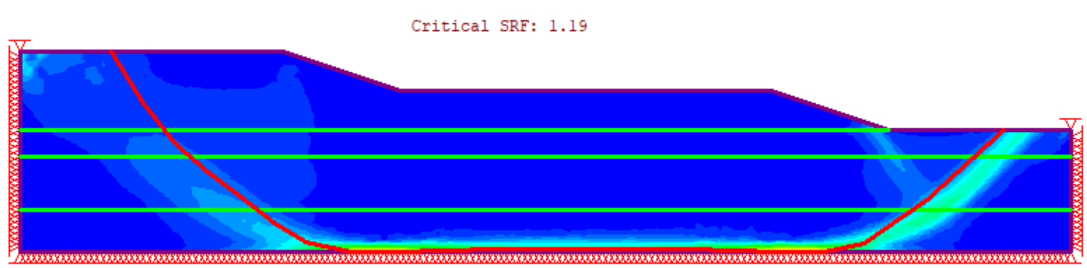


Figure 75.4 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #76

Embankment dam, homogeneous, finite element groundwater seepage analysis, ponded water

76.1 Introduction

This problem is taken from Figure 7.19 on page 128 of Duncan and Wright (2005).

76.2 Problem Description

Verification problem #76 for *Slide2*–a symmetric homogeneous earth embankment resting on an impermeable foundation with a ponded water of elevation 40 feet on its left side–is shown in Figure 76.1 through Figure 76.4. The material properties and permeability values are given in Table 76.1. Seepage analysis was carried out using two different methods in this verification problem. The first method was using Finite Element seepage analysis (Case 1) and the second method was using piezometric line approximation (Case 2). The location of the approximated piezometric line is shown in Figure 76.3 and 76.4. The factor of safety (Table 76.2 and Table 76.3) and its corresponding slip surface (Figure 76.6 and Figure 76.9) are required.

76.3 Geometry and Material Properties

Table 76.1 – Material Properties

c′ (psf)	ϕ′ (0)	γ (pcf)	k_{sat} (ft/s)
100	30	100	1.67×10^{-7}

Case 1

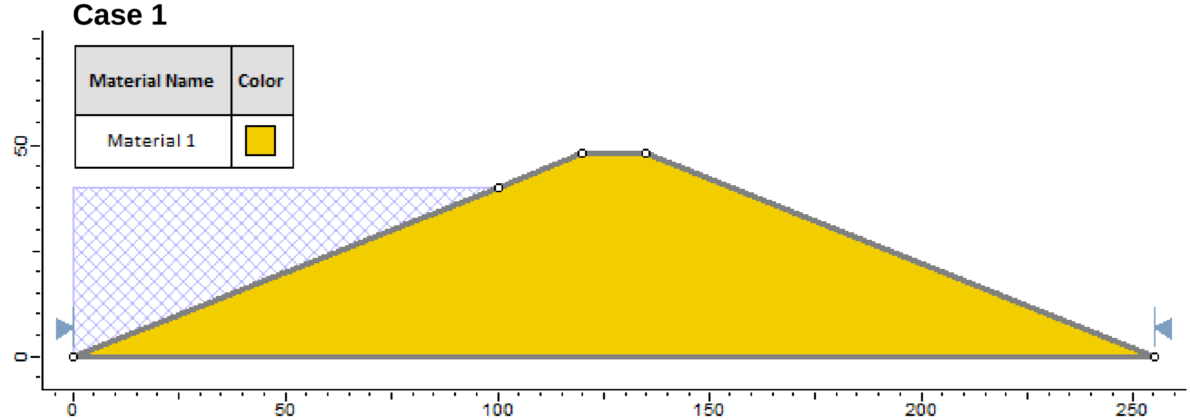


Figure 76.1 – *Slide2* Geometry (Case 1: Finite Element Seepage Analysis)

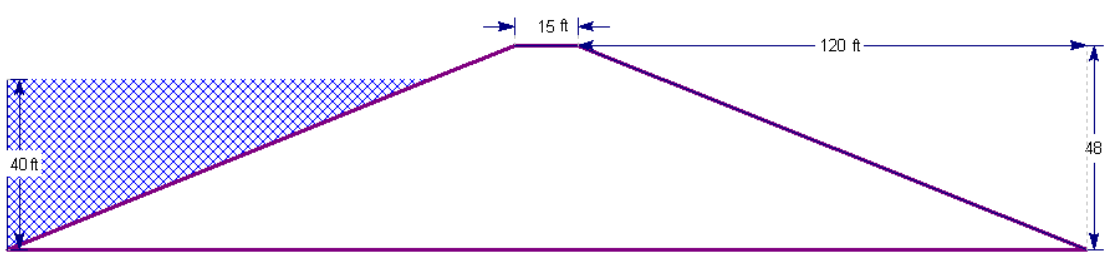


Figure 76.2 – *RS2* Geometry (Case 1: Finite Element Seepage Analysis)

Case 2

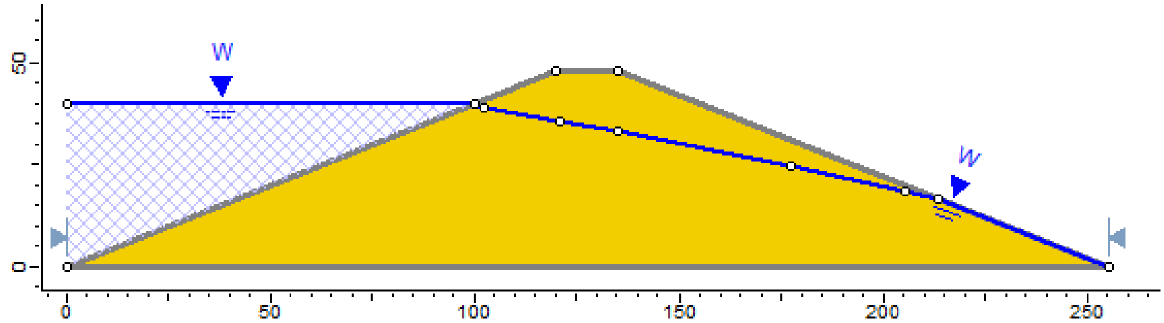


Figure 76.3 – *Slide2* Geometry (Case 2: Piezometric Line Approximation)

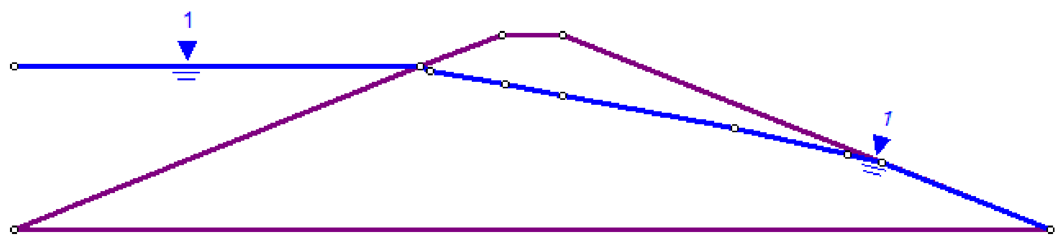


Figure 76.4 – *RS2* Geometry (Case 2: Piezometric Line Approximation)

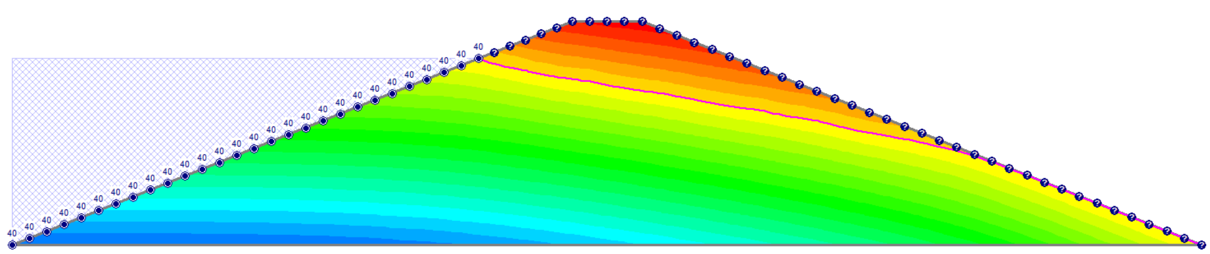
76.4 Results

Case 1

Table 76.2 – Comparison of Results (Case 1: Finite Element Seepage Analysis)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.08	1.05
	GLE	1.08	1.06
RS2	SSR	0.97	

Note: Reference factor of safety = 1.19 & 1.08 (from chart) [Duncan and Wright]



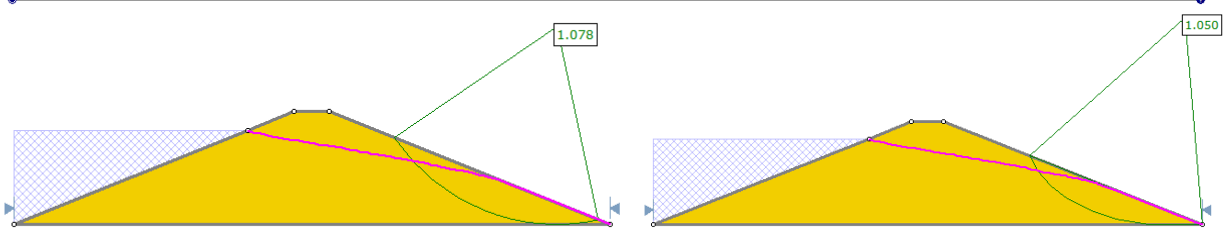


Figure 76.5 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 1: Finite Element Seepage Analysis)

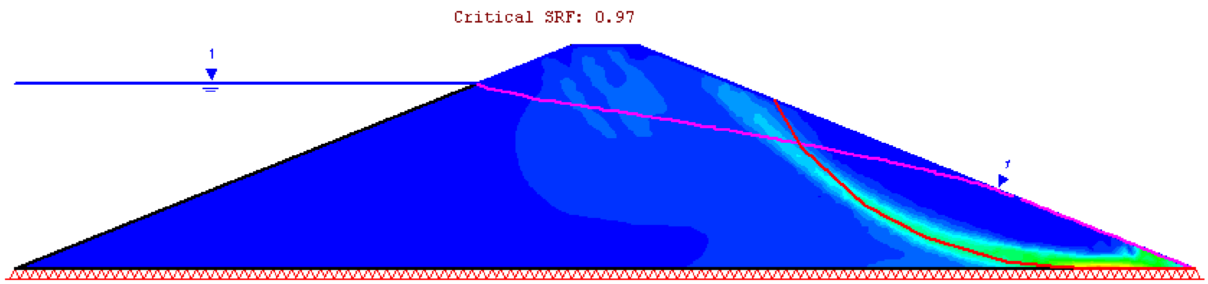


Figure 76.6 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 1: Finite Element Seepage Analysis)

Case 2

Table 76.3 – Comparison of Results (Case 2: Piezometric Line)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.10	1.07
	GLE	1.10	1.07
RS2	SSR	0.98	

Note: Reference factor of safety = 1.16 [Duncan and Wright]

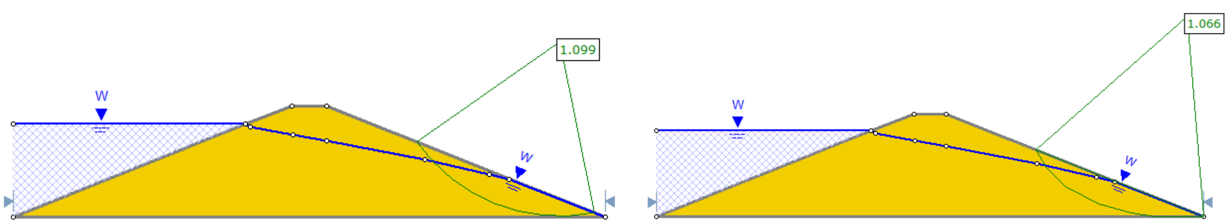


Figure 76.7 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 2: Piezometric Line Approximation)

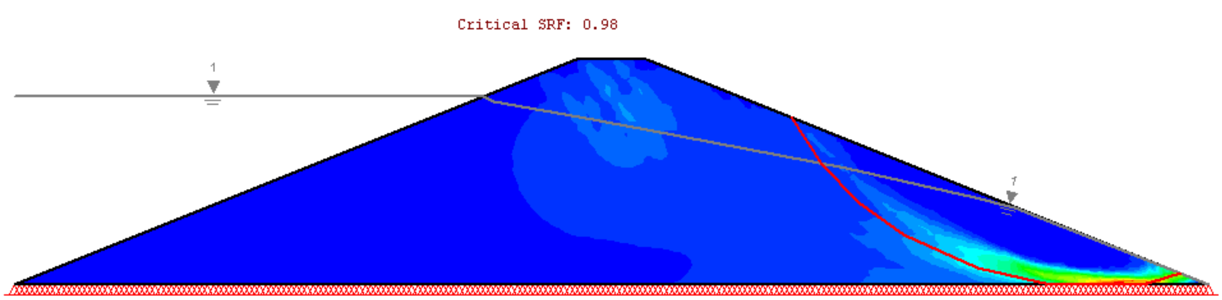


Figure 76.8 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 2: Piezometric Line Approximation)

Verification Problem #78

Slope, homogeneous

78.1 Introduction

This problem is taken from Figure 14.3 on page 216 of Duncan and Wright (2005)

78.2 Problem Description

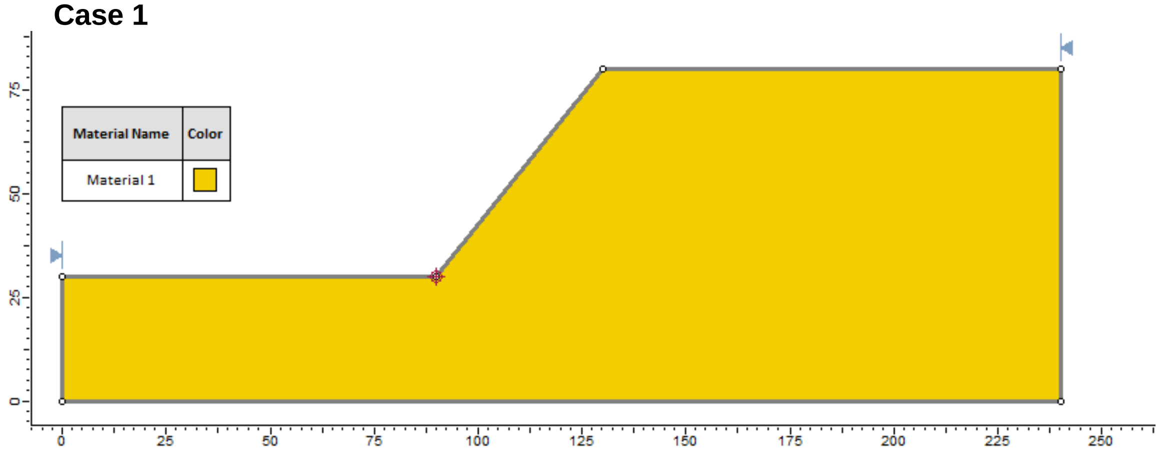
Verification problem #78 for *Slide2*–a simple, pure cohesive slope–is shown in Figure 78.1 through Figure 78.6. Three different foundation thicknesses–30 feet-thick (Case 1), 46.5 feet-thick (Case 2) and 60 feet-thick (Case 3)–are tested. Two subcases are simulated for (a) failure surface through the toe of the embankment and (b) failure surface tangent to the bottom of the embankment. The cases are simulated in *Slide2* by implementing a Focus Search Point or focused slope limits at the toe or a Focus Search Line or Block Search Polyline at the bottom of the embankment. A SSR Exclusion Area was used in *RS2* to analyze the failure surface through the toe. The material properties are given in Table 78.1. The factor of safety (Table 78.2 through Table 78.4) and its corresponding slip surface (Figure 78.8, Figure 78.10, and Figure 78.12) are required.

78.3 Geometry and Material Properties

Table 78.1 – Material Properties

c' (psf)	ϕ' (^{0})	γ (pcf)
1000	0	100

Case 1



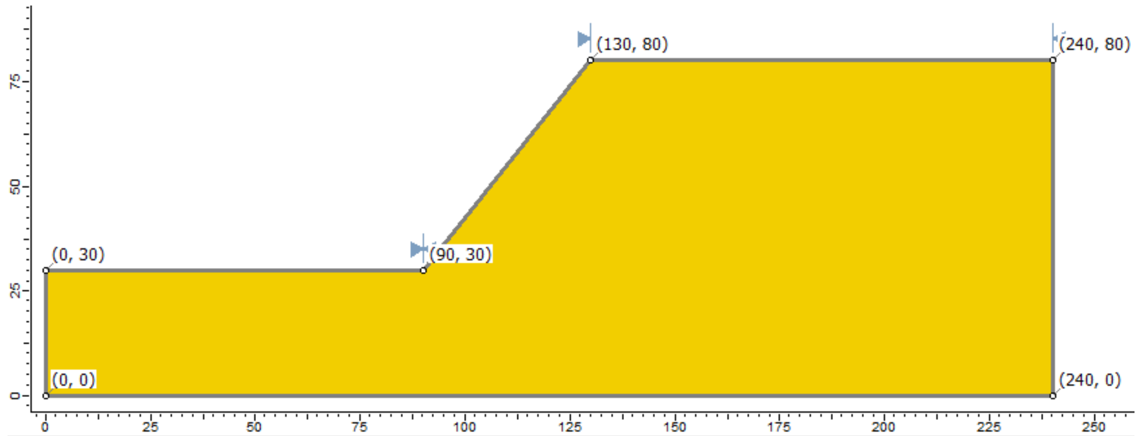
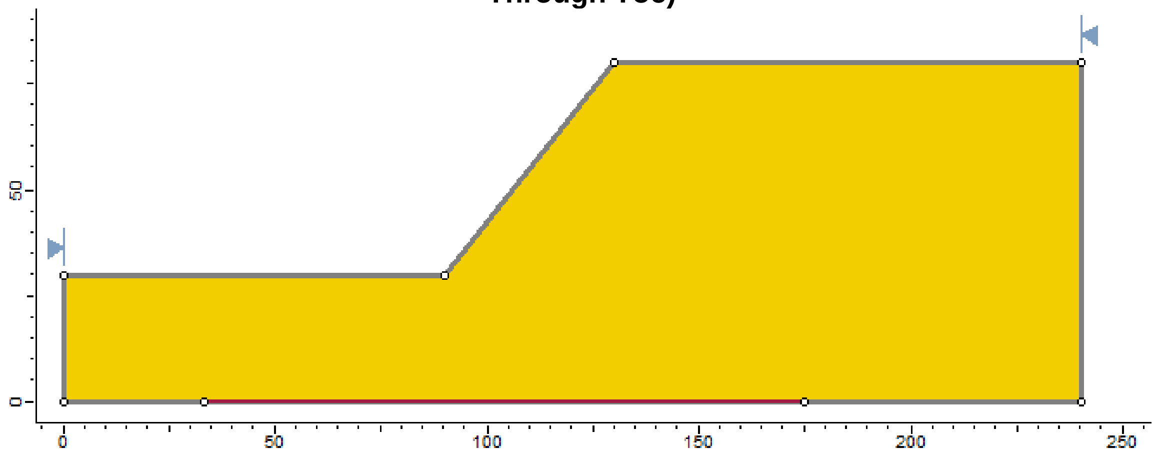


Figure 78.1a – *Slide2* Geometry (Case 1a: 30ft Thick Foundation, Slip Surface Passes Through Toe)



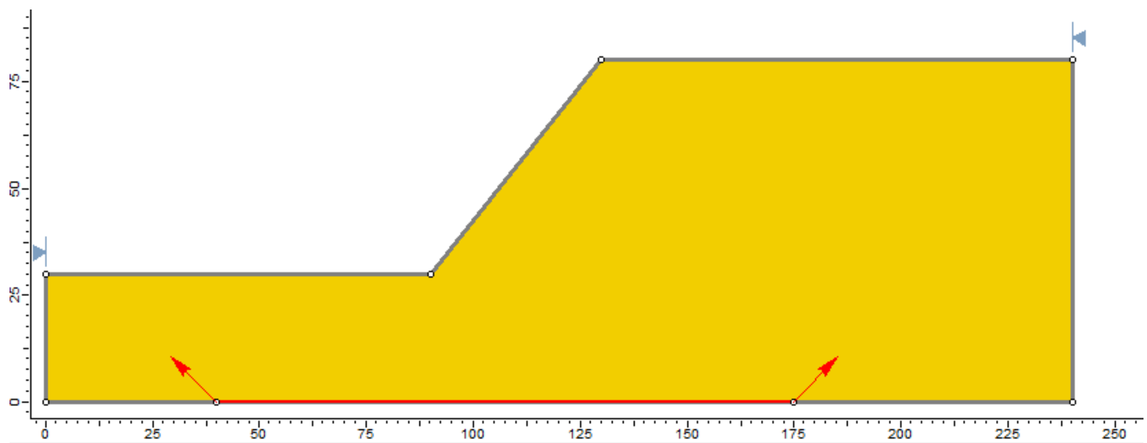


Figure 78.1b – *Slide2* Geometry (Case 1b: 30ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

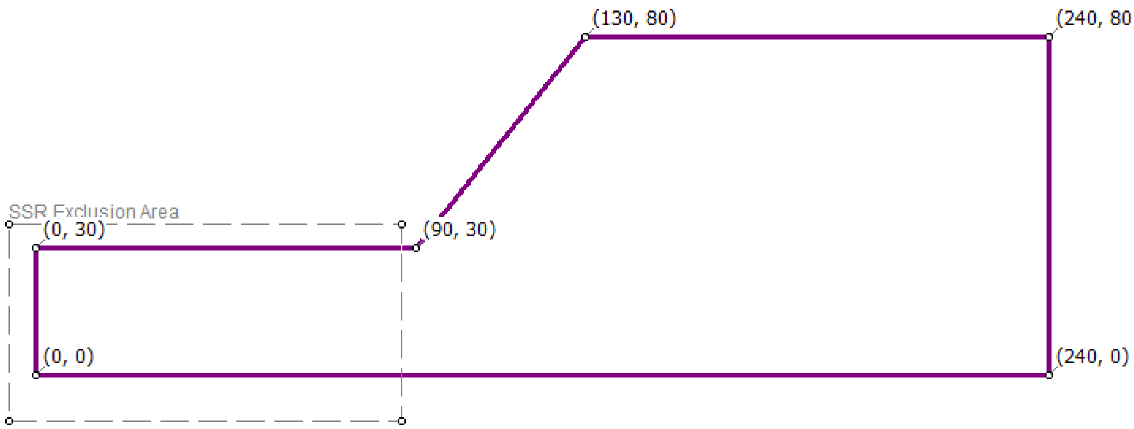


Figure 78.2a – *RS2* Geometry (Case 1a: 30ft Thick Foundation, Slip Surface Passes Through Toe)

To force *RS2* to iterate for SRF associated with a failure surface passing through the toe of the slope, a SSR Exclusion Area was used to limit the failure surface to the slope (Figure 78.2a).

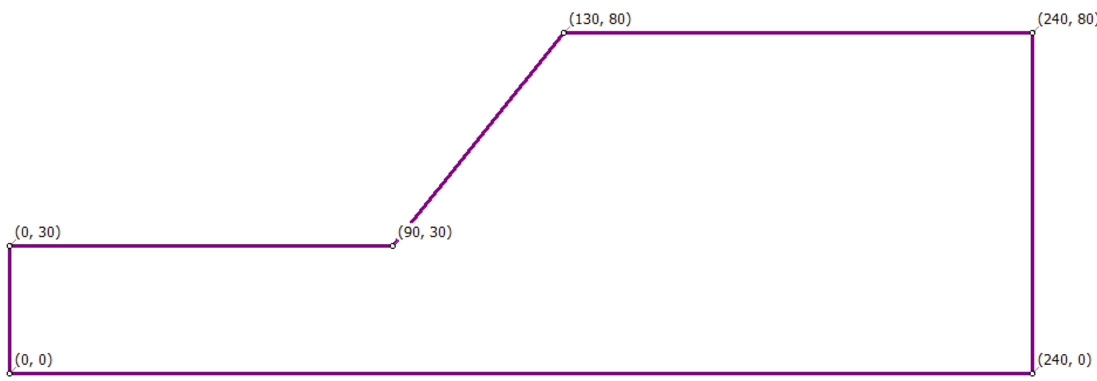


Figure 78.2b – *RS2* Geometry (Case 1b: 30ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

Case 2

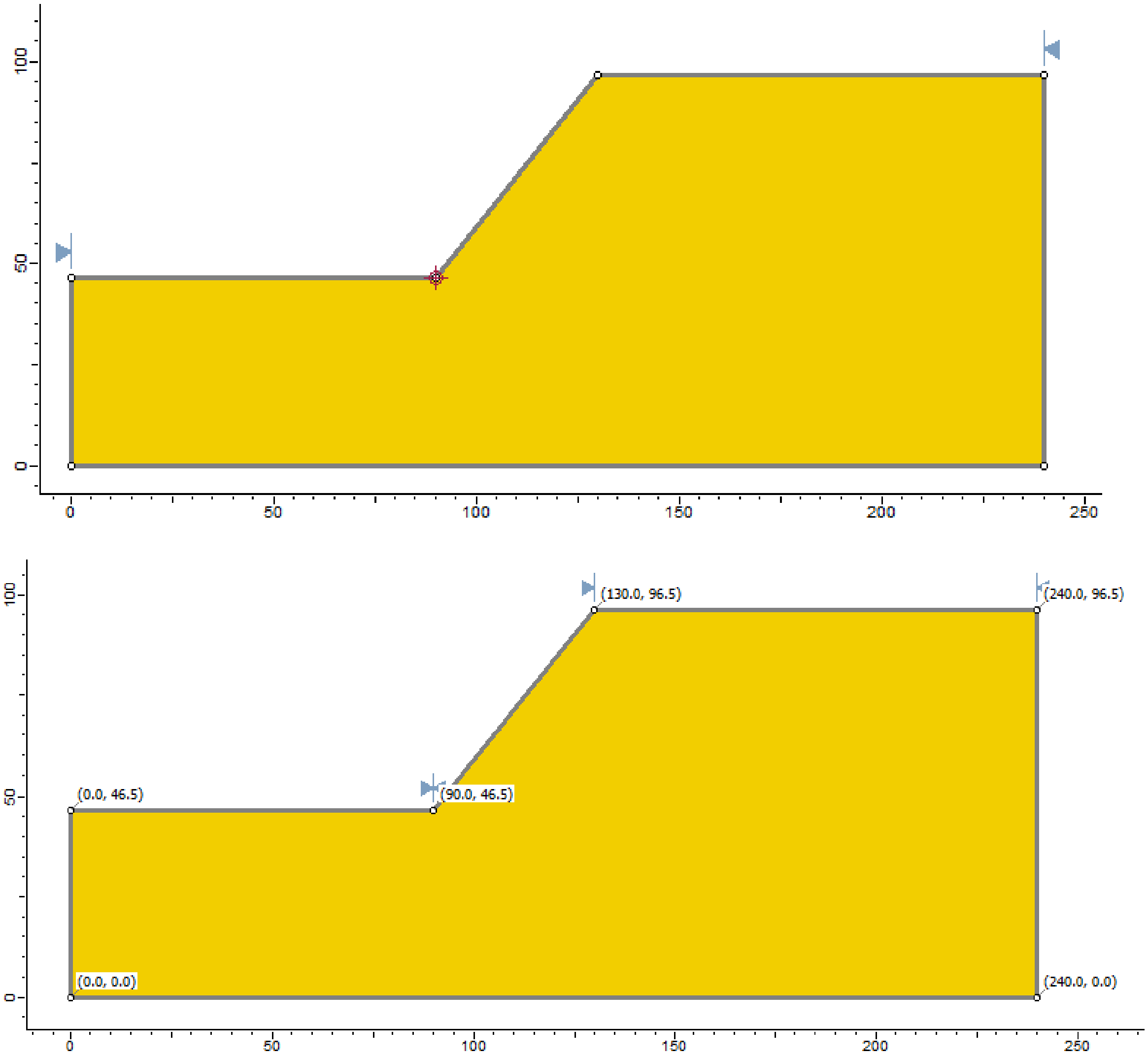
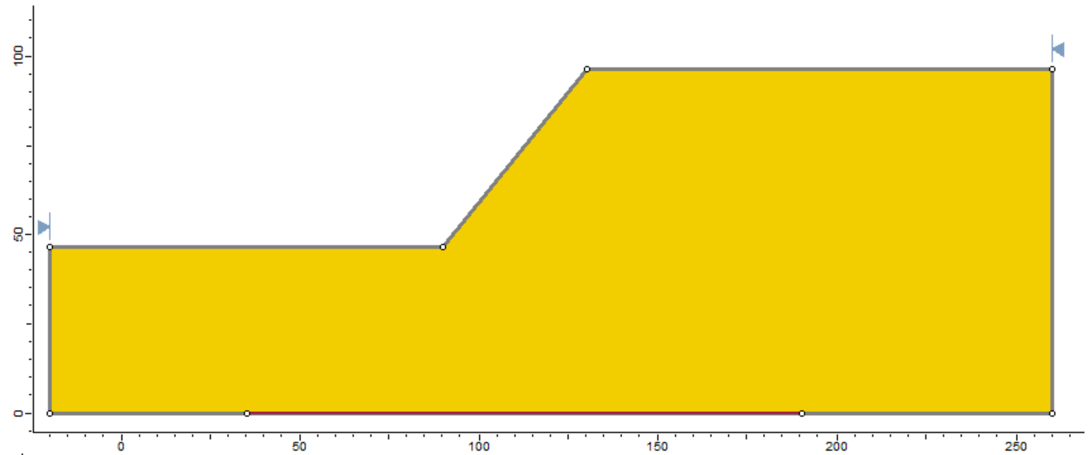


Figure 78.3a – *Slide2* Geometry (Case 2a: 46.5ft Thick Foundation, Slip Surface Passes Through Toe)



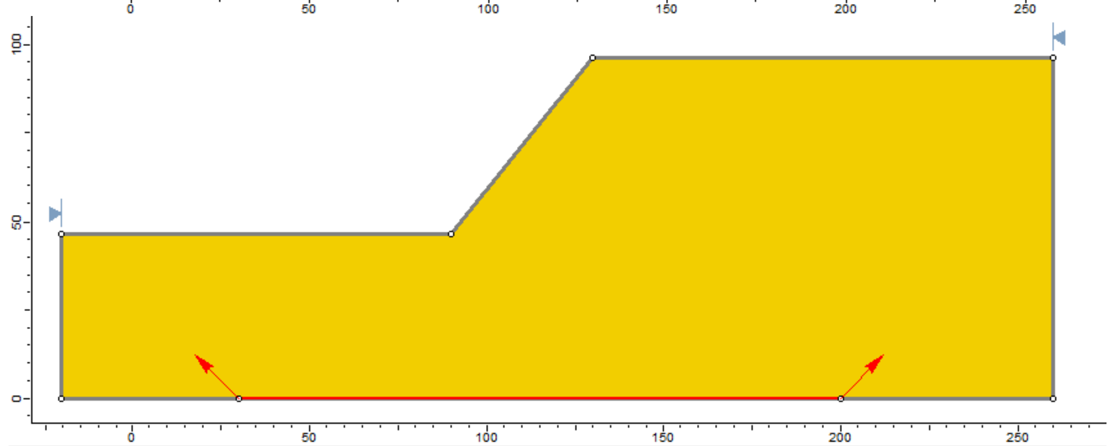


Figure 78.3b – *Slide2* Geometry (Case 2b: 46.5ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

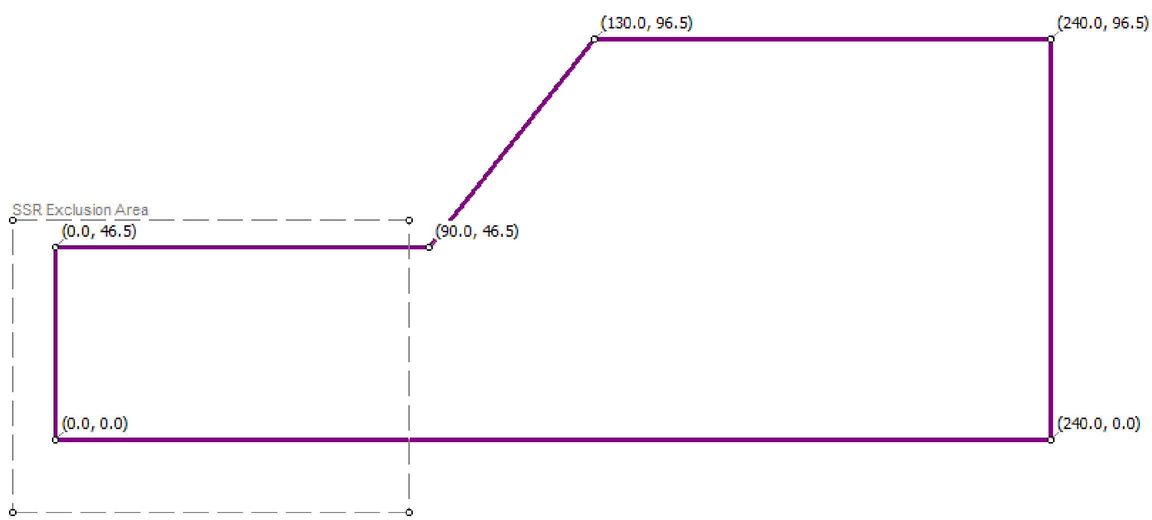


Figure 78.4a – *RS2* Geometry (Case 2: 46a.5ft Thick Foundation, Slip Surface Passes Through Toe)

To force *RS2* to iterate for SRF associated with a failure surface passing through the toe of the slope, a SSR Exclusion Area was used to limit the failure surface to the slope (Figure 78.4a).

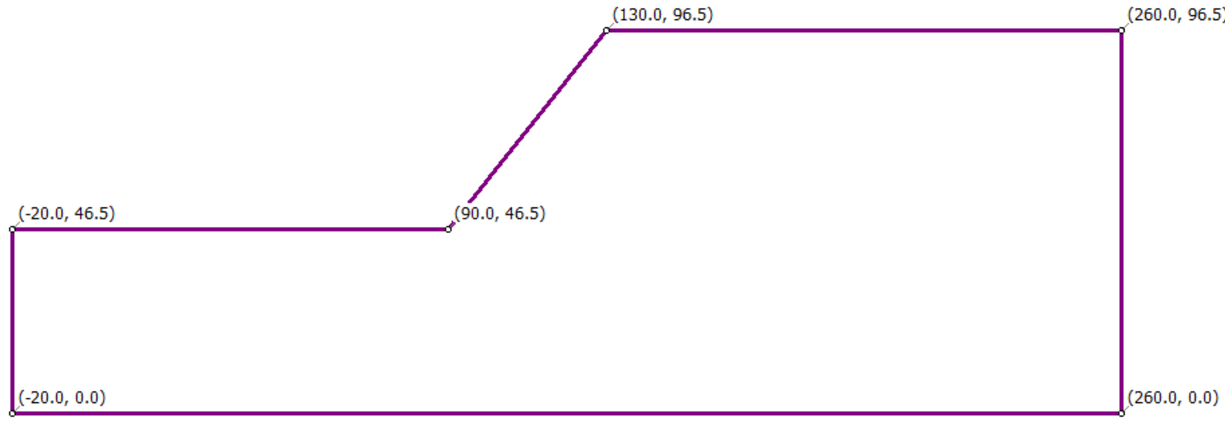
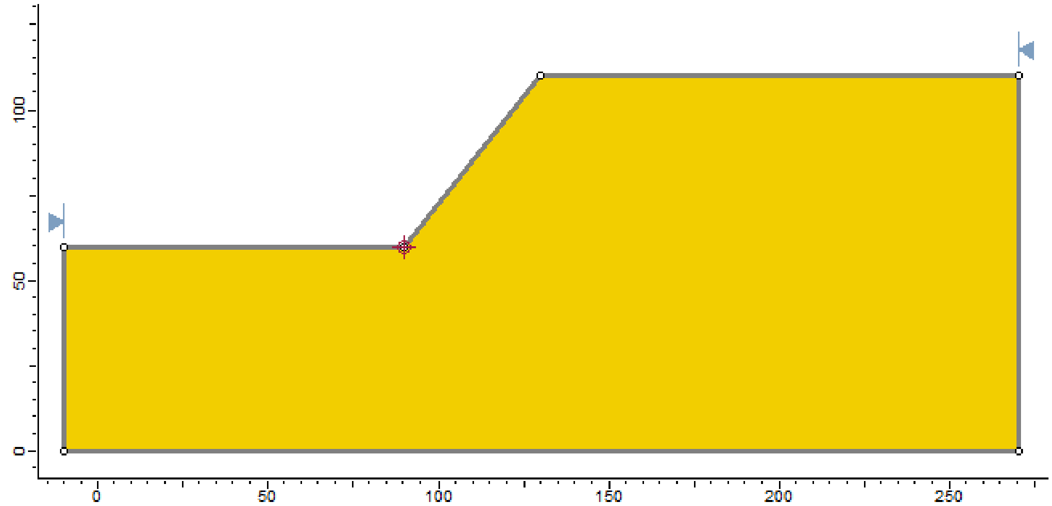


Figure 78.4b – *RS2* Geometry (Case 2b: 46.5ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

Case 3



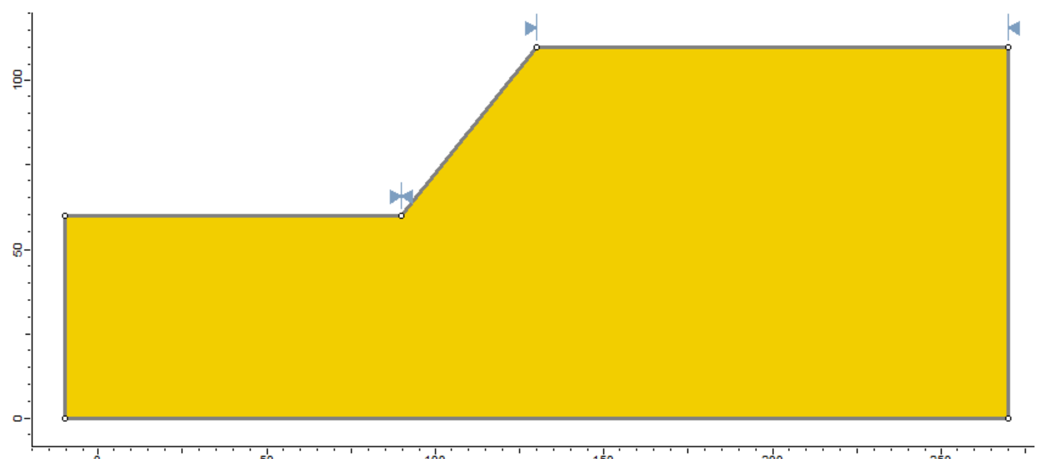
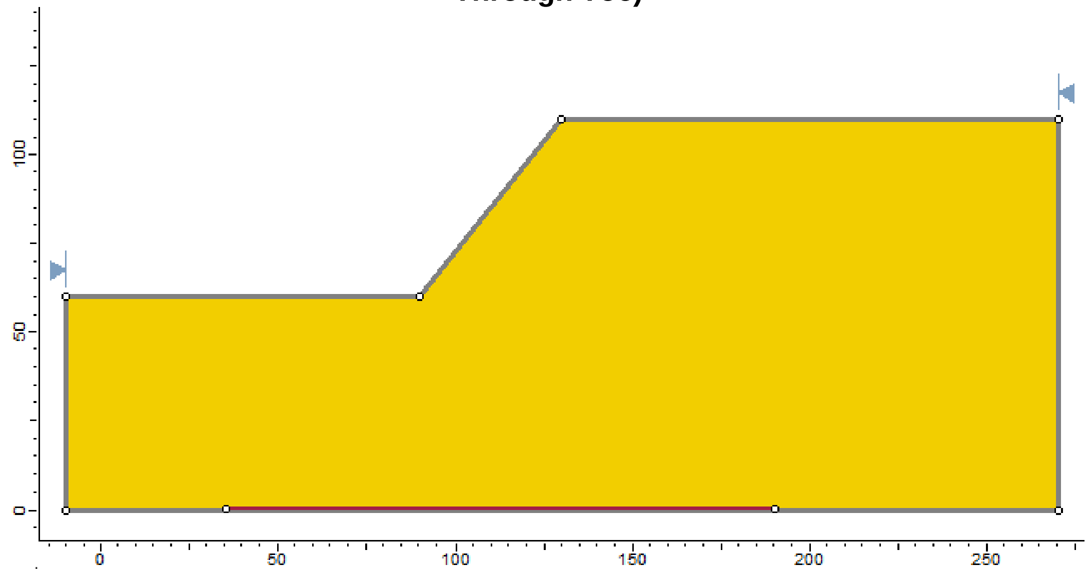


Figure 78.5a – *Slide2* Geometry (Case 3a: 60ft Thick Foundation, Slip Surface Passes Through Toe)



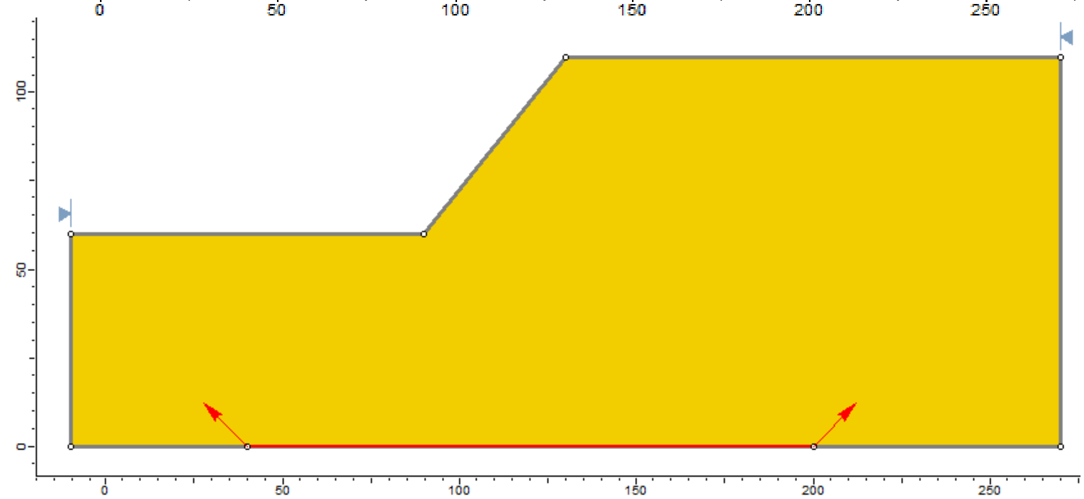


Figure 78.5b – *Slide2* Geometry (Case 3a: 60ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

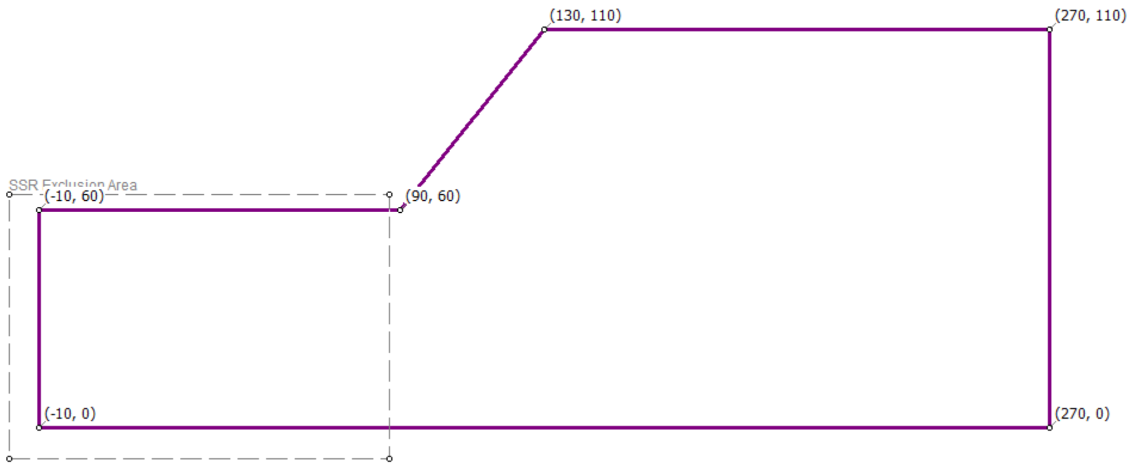


Figure 78.6a – *RS2* Geometry (Case 3a: 60ft Thick Foundation, Slip Surface Passes Through Toe)

To force *RS2* to iterate for SRF associated with a failure surface passing through the toe of the slope, a SSR Exclusion Area was used to limit the failure surface to the slope (Figure 78.6a).

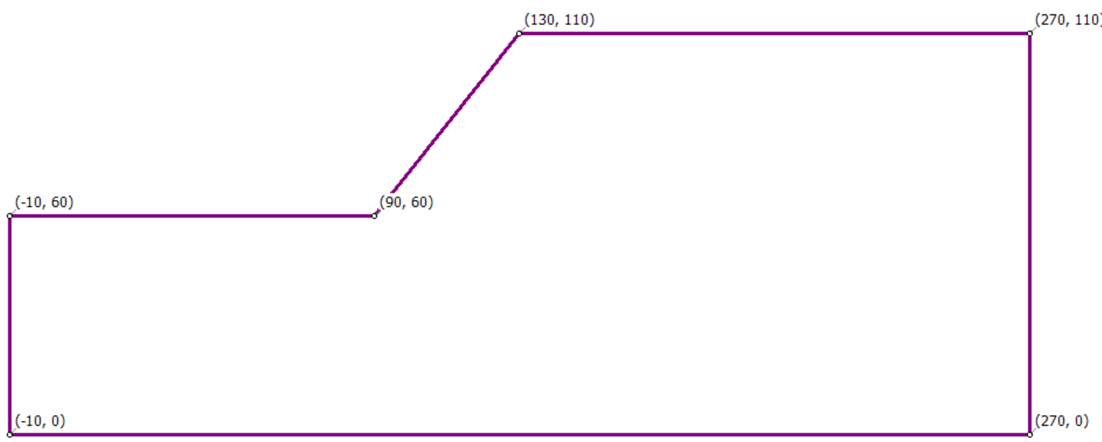


Figure 78.6b – *RS2* Geometry (Case 3b: 60ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

78.4 Results

Case 1

Table 78.2 – Comparison of Results (Case 1: 30ft Thick Foundation)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Failure Through Toe			
Slide2	Spencer	1.20	0.88
	GLE	1.19	0.91
RS2	SSR	1.06	
Failure Tangent to Bottom of Foundation			
Slide2	Spencer	1.14	0.88
	GLE	1.14	0.89
RS2	SSR	1.04	

Note: Reference factor of safety = 1.124 [Duncan and Wright].

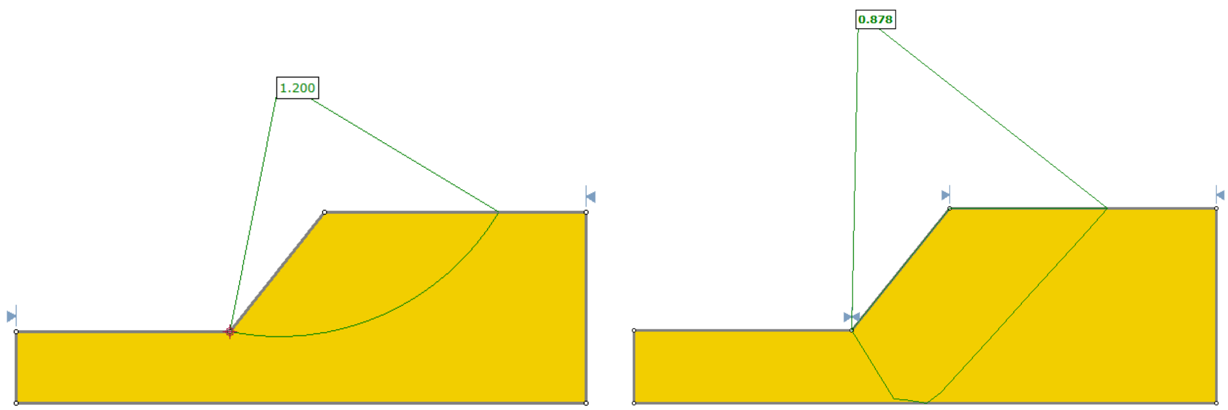


Figure 78.7a – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 1a: 30ft Thick Foundation, Slip Surface Passes Through Toe)

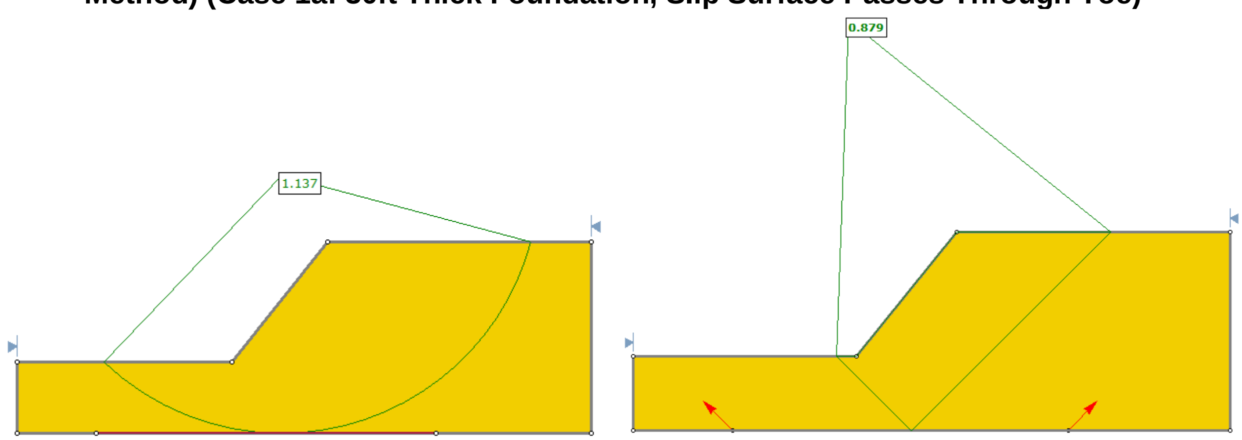


Figure 78.7b – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 1b: 30ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

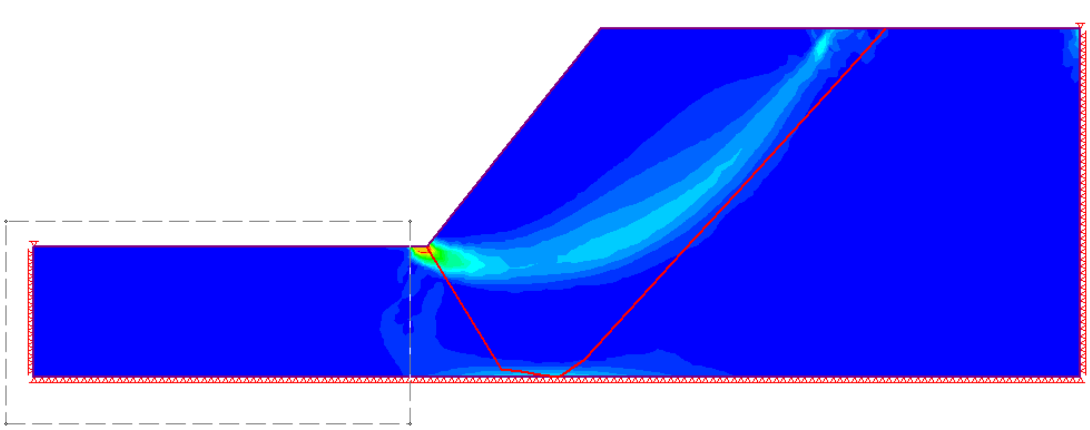


Figure 78.8a – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 1a: 30ft Thick Foundation, Slip Surface Passes Through Toe with Focus Search Point)

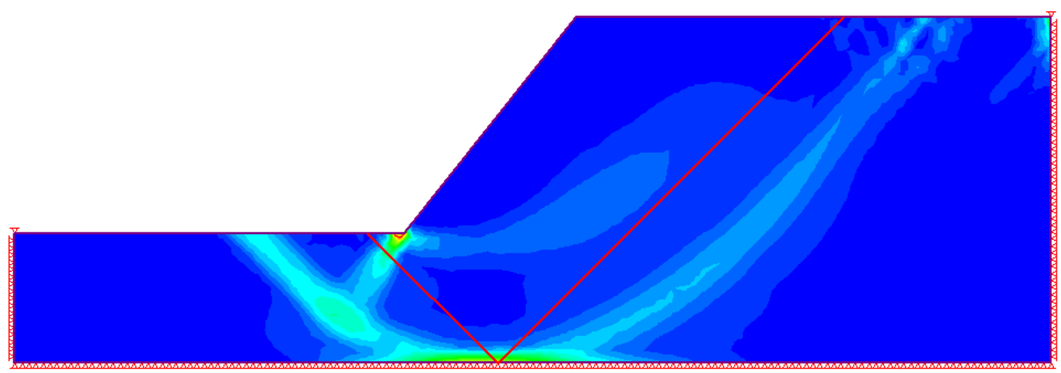


Figure 78.8b – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 1b: 30ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

Case 2

Table 78.3 – Comparison of Results (Case 2: 46.5ft Thick Foundation)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Failure Through Toe			
Slide2	Spencer	1.20	0.88
	GLE	1.19	0.91
RS2	SSR	1.06	
Failure Tangent to Bottom of Foundation			
Slide2	Spencer	1.13	0.89
	GLE	1.13	0.89
RS2	SSR	1.04	

Note: Reference factor of safety = 1.124 [Duncan and Wright].

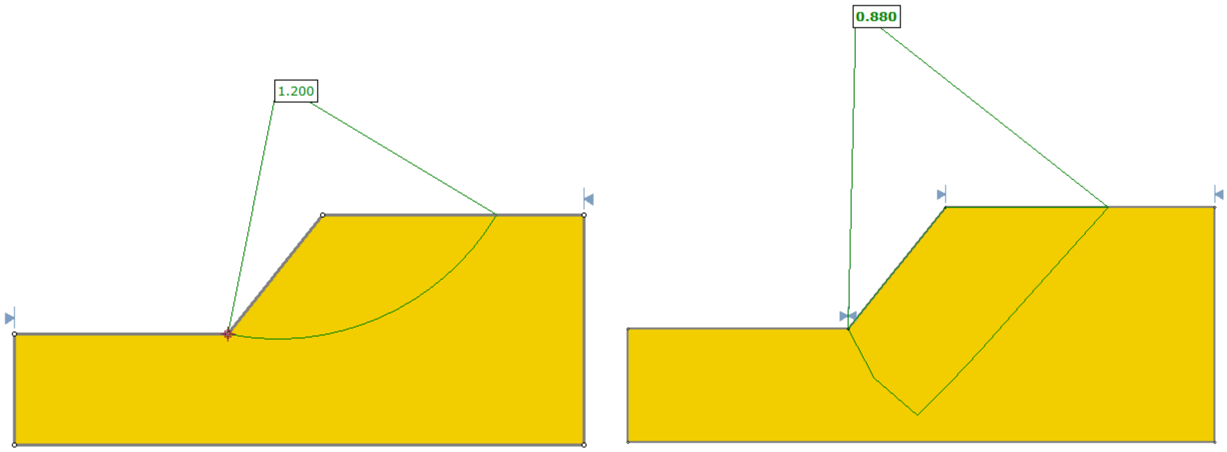


Figure 78.9a – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 2a: 46.5ft Thick Foundation, Slip Surface Passes Through Toe)

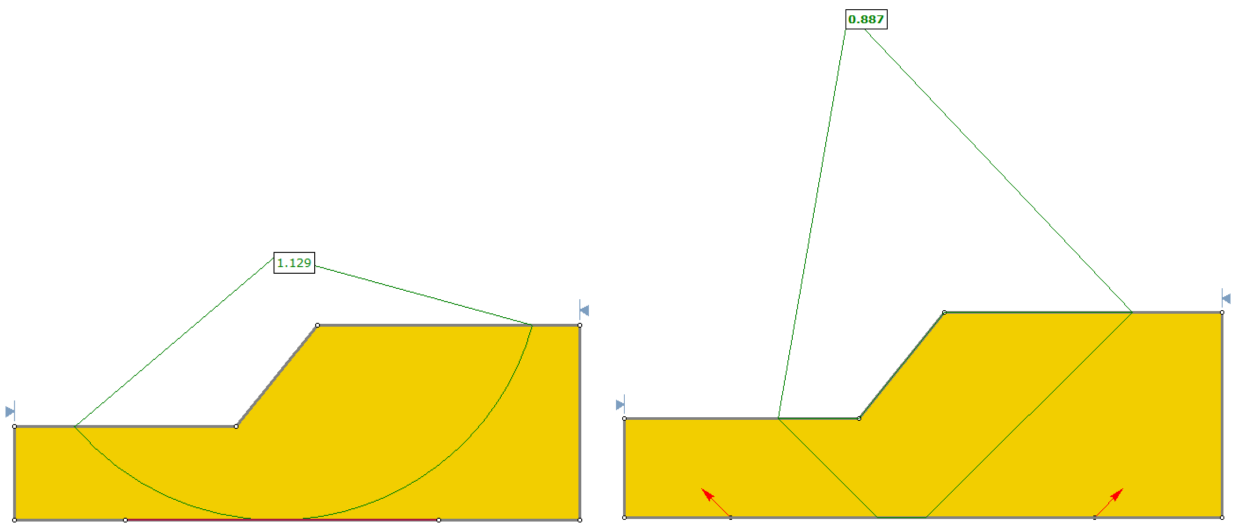


Figure 78.9b – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 2b: 46.5ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

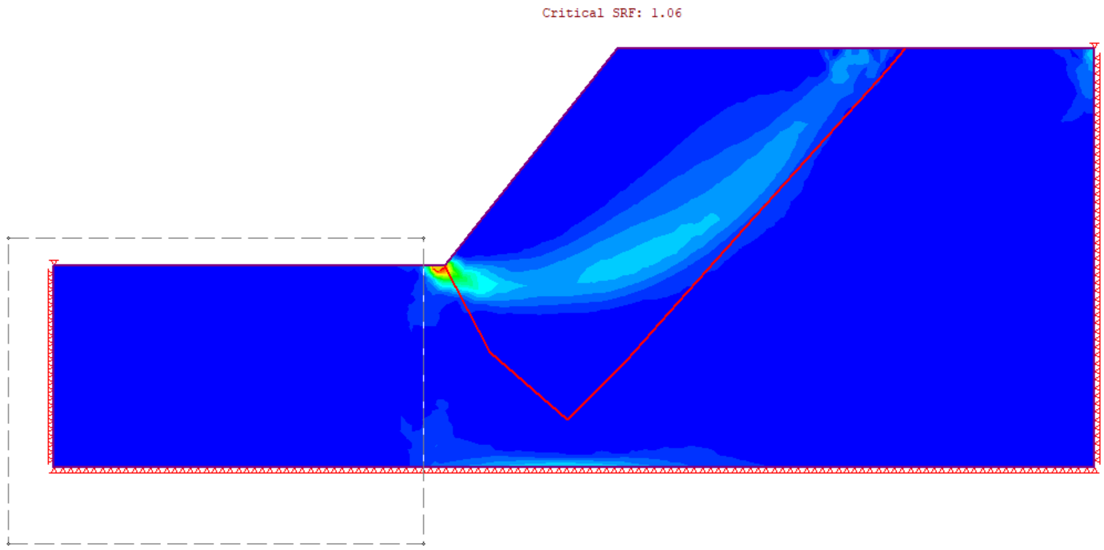


Figure 78.10a – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 2a: 46.5ft Thick Foundation, Slip Surface Passes Through Toe)

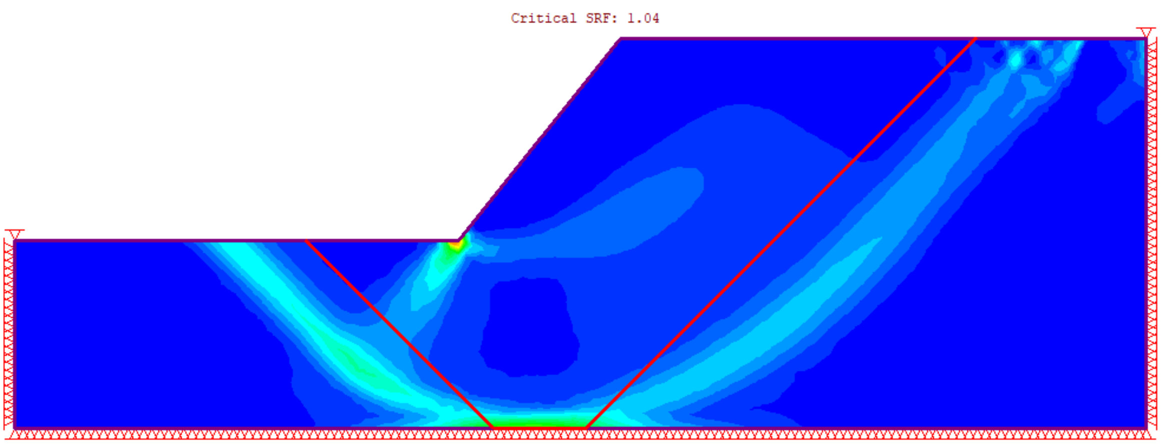


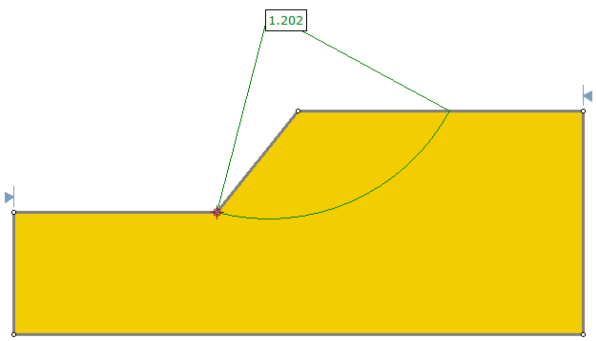
Figure 78.10b – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 2b: 46.5ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

Case 3

Table 78.4 – Comparison of Results (Case 3: 60ft Thick Foundation)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Failure Through Toe			
Slide2	Spencer	1.20	0.88
	GLE	1.19	0.91
RS2	SSR	1.07	
Failure Tangent to Bottom of Foundation			
Slide2	Spencer	1.12	0.83
	GLE	1.13	0.84
RS2	SSR	1.04	

Note: Reference factor of safety = 1.119 [Duncan and Wright].



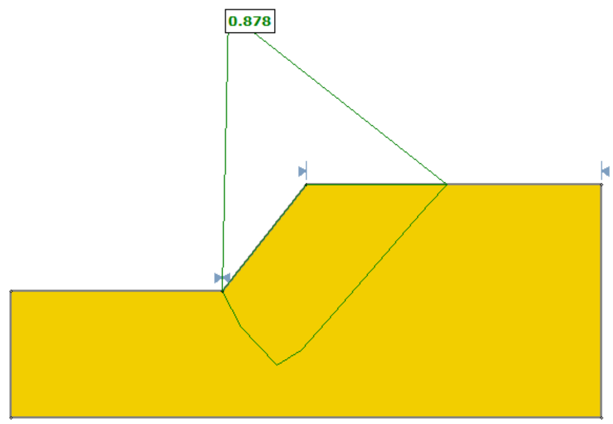


Figure 78.11a – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 3b: 60ft Thick Foundation, Slip Surface Passes Through Toe)

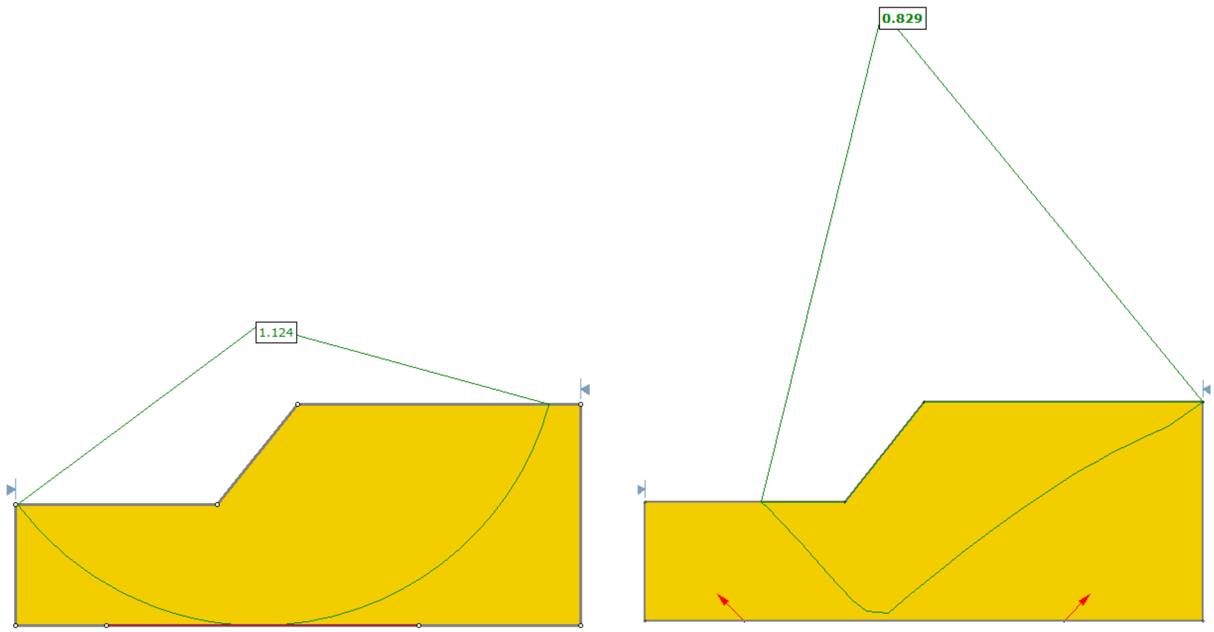


Figure 78.11b – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 3b: 60ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

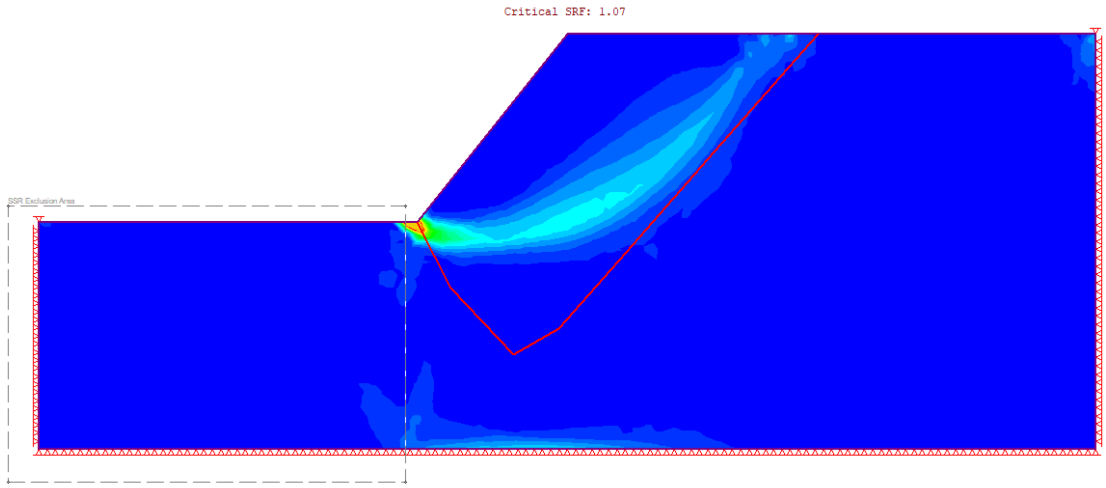


Figure 78.12a – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 3a: 60ft Thick Foundation, Slip Surface Passes Through Toe with Focus Search Point)

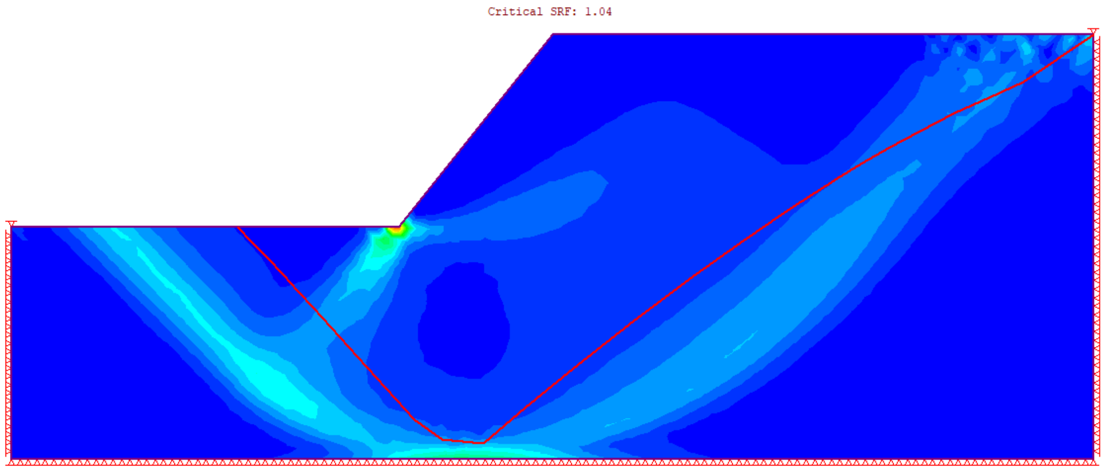


Figure 78.12b – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 3b: 60ft Thick Foundation, Slip Surface is Tangent to the Bottom of the Foundation)

Verification Problem #79

Slope, (2) materials, infinite slope failure

79.1 Introduction

This problem is taken from Figure 14.4 on page 217 of Duncan and Wright (2005).

79.2 Problem Description

Verification problem #79 for ***Slide2***–an earth embankment–is shown in Figure 79.1 through Figure 79.4. Two slip surfaces are of interest in this verification problem. The first is a deep slip surface that is tangent to the bottom of the foundation, for which an elastic material is assumed for the Foundation (Case 1). The second is a very shallow slip surface (infinite slope mechanism) (Case 2). The material properties are given in Table 79.1. The factor of safety (Table 79.2 and Table 79.3) and its corresponding slip surface (Figure 79.6 and Figure 79.9) are required.

79.3 Geometry and Material Properties

Table 79.1 – Material Properties

Zone	c′ (psf)	ϕ′ (⁰)	γ (pcf)
Embankment	0	30	120
Foundation	450	0	120

Case 1

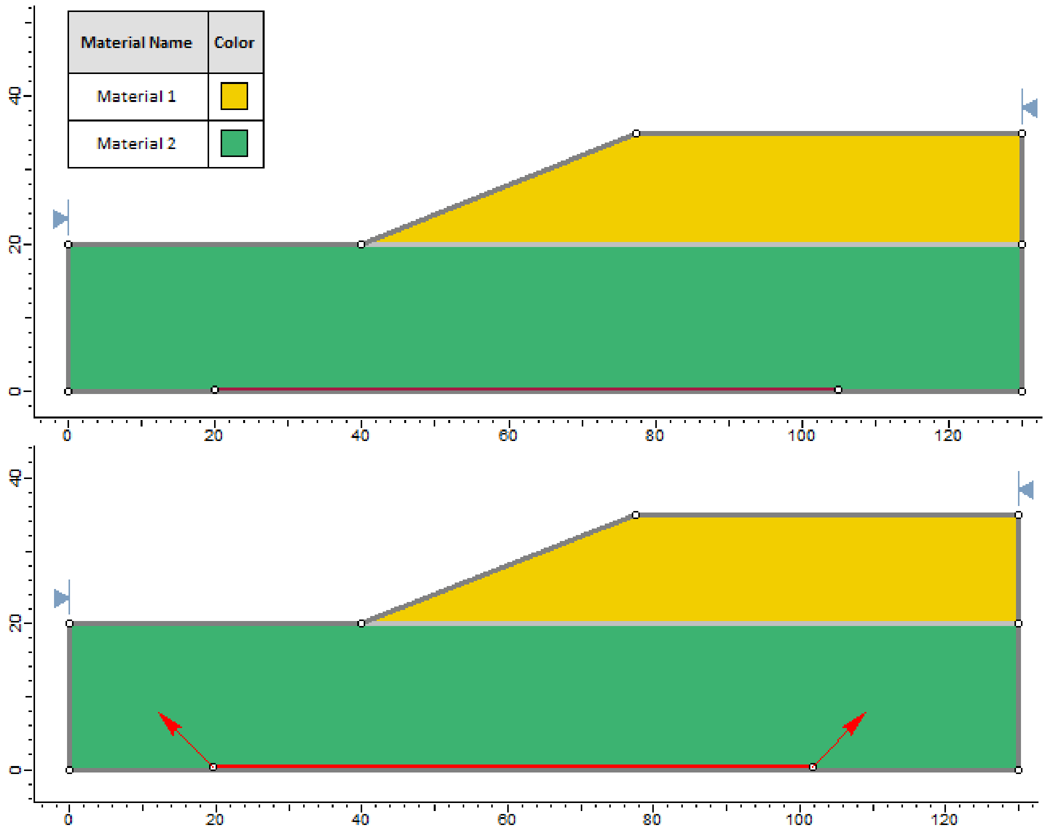


Figure 79.1 – *Slide2* Geometry (Case 1: Deep Slip Surface)

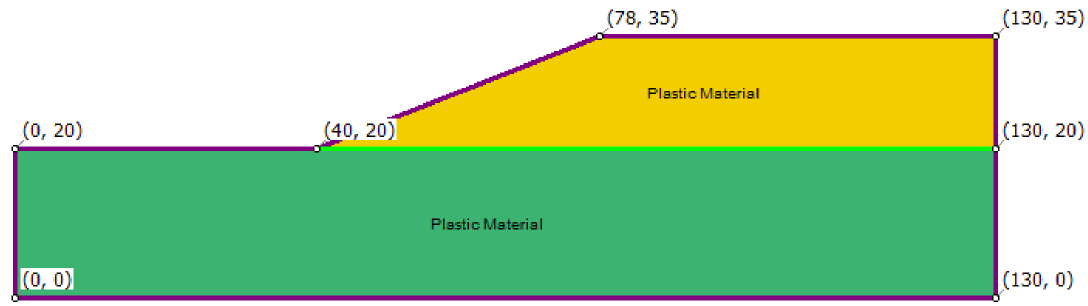


Figure 79.2 – *RS2* Geometry (Case 1: Deep Slip Surface)

Case 2

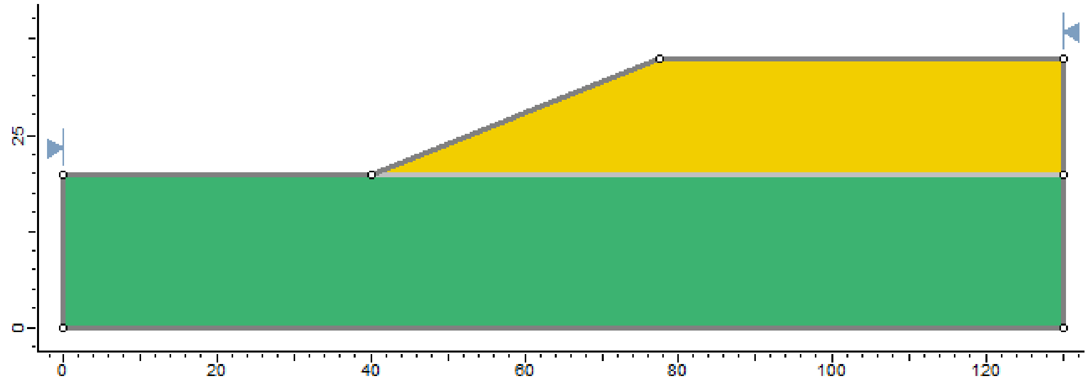


Figure 79.3 – *Slide2* Geometry (Case 2: Very Shallow Slip Surface, Infinite Slope)

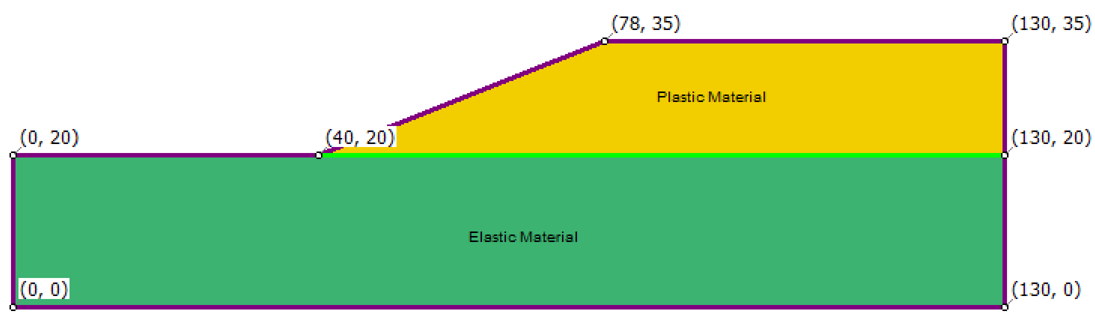


Figure 79.4 – *RS2* Geometry (Case 2: Very Shallow Slip Surface, Infinite Slope)

The bottom layer is modelled as an elastic material (Figure 79.4).

79.4 Results

Case 1

Table 79.2 – Comparison of Results (Case 1: Deep Slip Surface)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.40	1.35
	GLE	1.41	1.37
RS2	SSR	1.41	

Note: Reference factor of safety = 1.40 [Duncan and Wright].

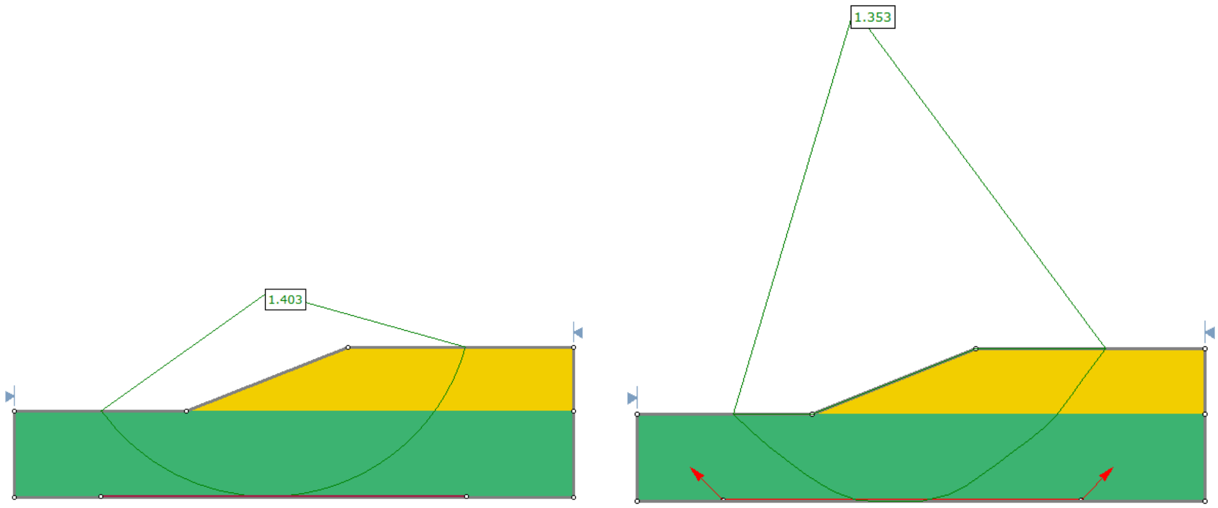


Figure 79.5 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 1: Deep Slip Surface)

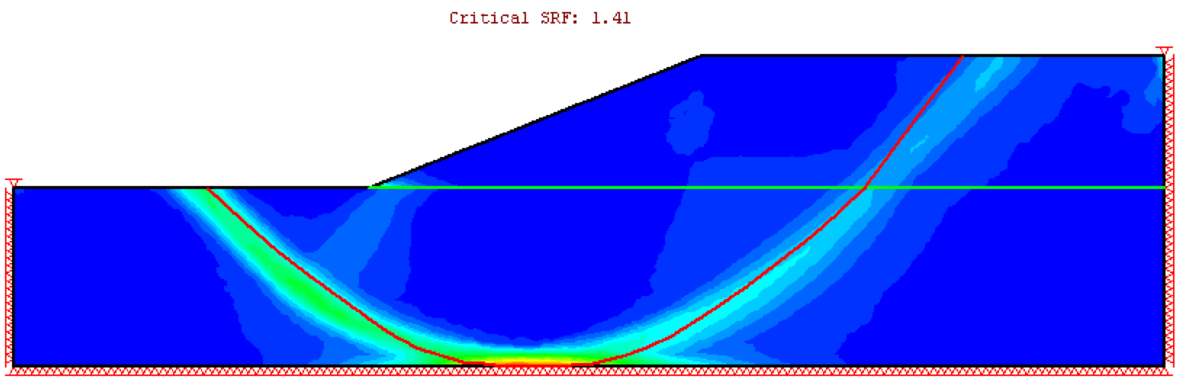


Figure 79.6 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 1: Deep Slip Surface)

Case 2

Table 79.3 – Comparison of Results (Case 2: Very Shallow Slip Surface, Infinite Slope)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.44	1.44
	GLE	1.44	1.44
RS2	SSR	1.45	

Note: Reference factor of safety = 1.44 [Duncan and Wright].

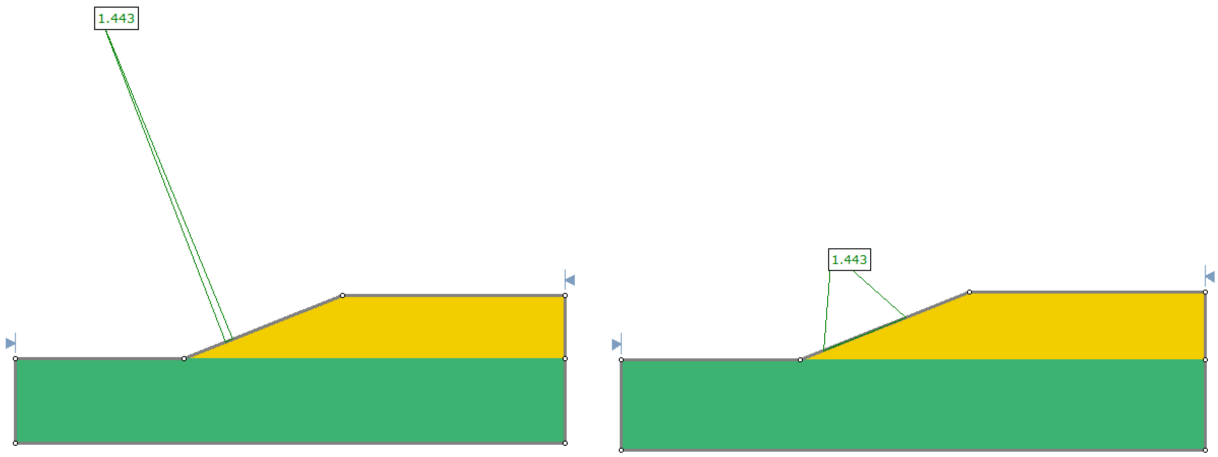


Figure 79.7 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 1: Case 2: Very Shallow Slip Surface, Infinite Slope)

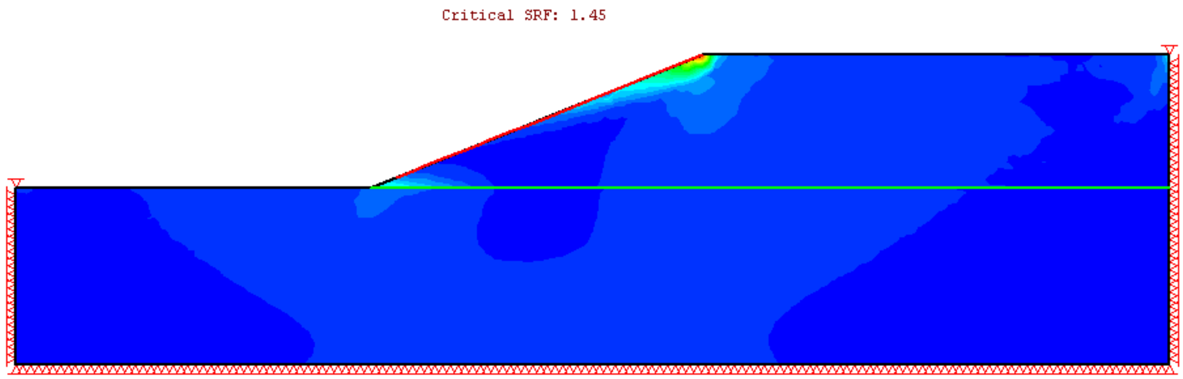


Figure 79.8 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 2: Very Shallow Slip Surface, Infinite Slope)

Note: Next SRF iteration shown for clarity.

Verification Problem #81

Embankment, (2) materials, infinite slope failure

81.1 Introduction

This problem is taken from Figure 14.7 on page 220 of Duncan and Wright (2005)

81.2 Problem Description

Verification problem #81 for *Slide2*–an earth embankment–is shown in Figure 81.1 through Figure 81.4. Two slip surfaces are of interest in this verification problem. The first is a deep slip surface (Case 1) and the second is very shallow slip surface (infinite slope mechanism) (Case 2). To simulate a deep failure surface, a Focus Search Line or Block Search Line is implemented in *Slide2*. In order to get the first slip surface, it was assumed that the slip surface would not go through the boundary between the embankment and its foundation. To prevent the slip surface from crossing that boundary, the foundation was considered as elastic material in the analysis. The material properties are given in Table 81.1. The factor of safety (Table 81.2 and Table 81.3) and its corresponding slip surface (Figure 81.6 and Figure 81.9) are required.

81.3 Geometry and Material Properties

Table 81.1 – Material Properties

Zone	c′ (psf)	ϕ′ (°)	γ (pcf)
Embankment	0	30	124
Foundation	500	0	98

Case 1

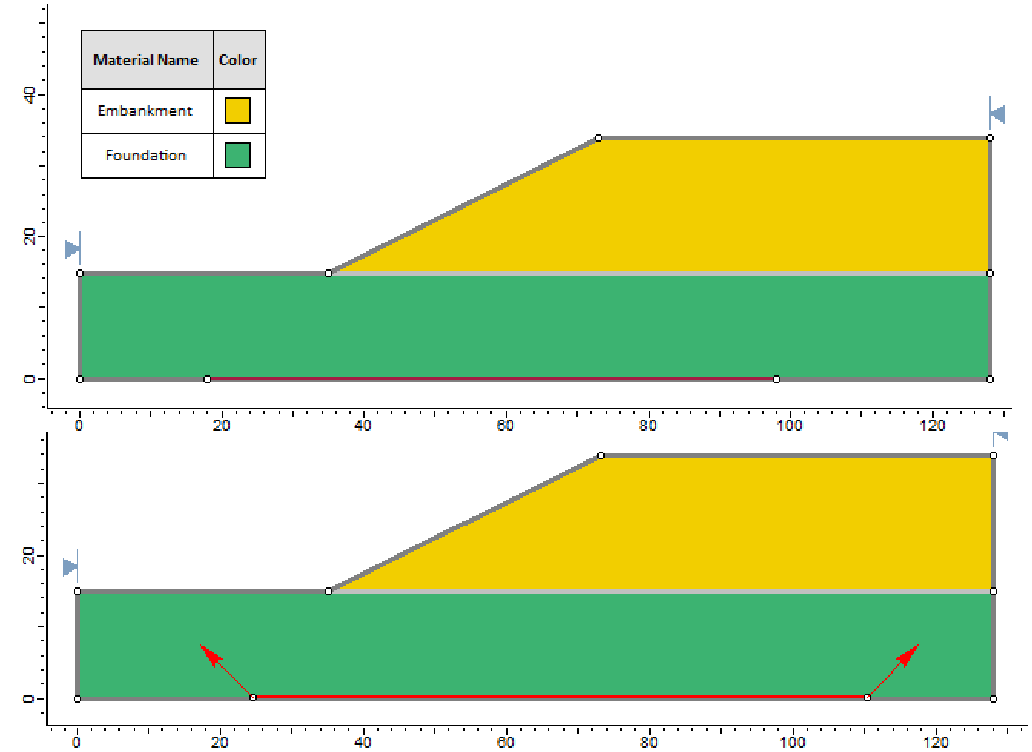


Figure 81.1 – *Slide2* Geometry (Case 1: Deep Slip Surface)

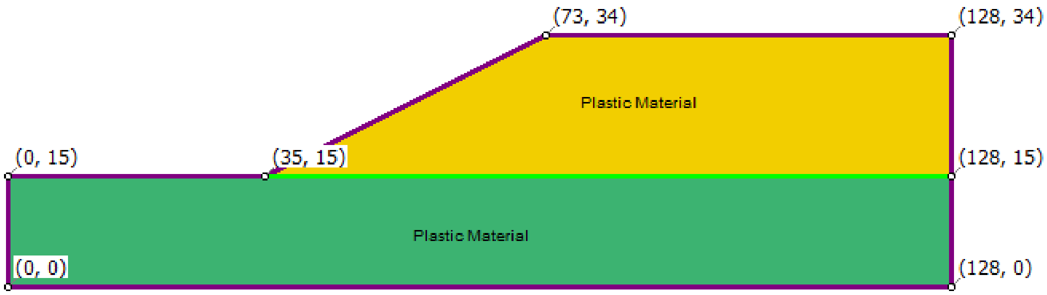


Figure 81.2 – *RS2* Geometry (Case 1: Deep Slip Surface)

Case 2

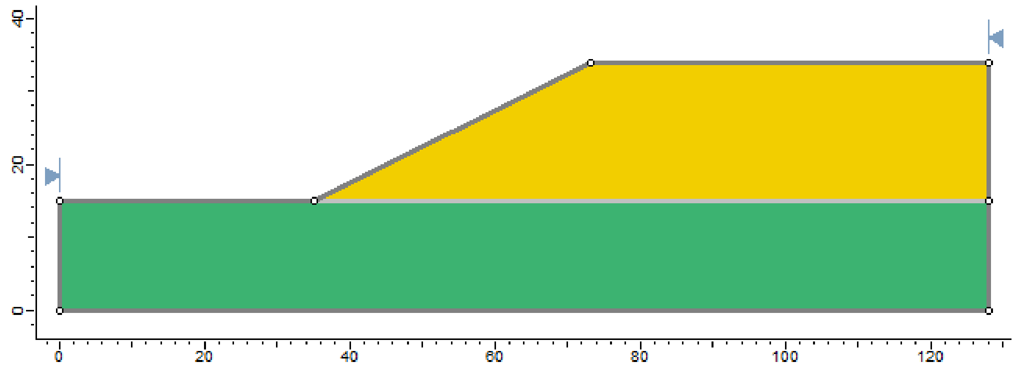


Figure 81.3 – *Slide2* Geometry (Case 2: Very Shallow Slip Surface, Infinite Slope Mechanism)

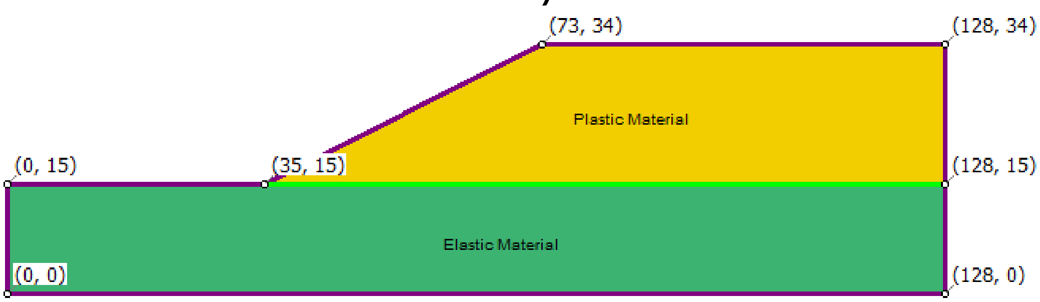


Figure 81.4 – *RS2* Geometry (Case 2: Very Shallow Slip Surface, Infinite Slope Mechanism)

81.4 Results

Case 1

Table 81.2 – Comparison of Results (Case 1: Deep Slip Surface)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.21	1.19
	GLE	1.22	1.19
RS2	SSR	1.23	

Note: Reference factor of safety = 1.21 [Duncan and Wright].

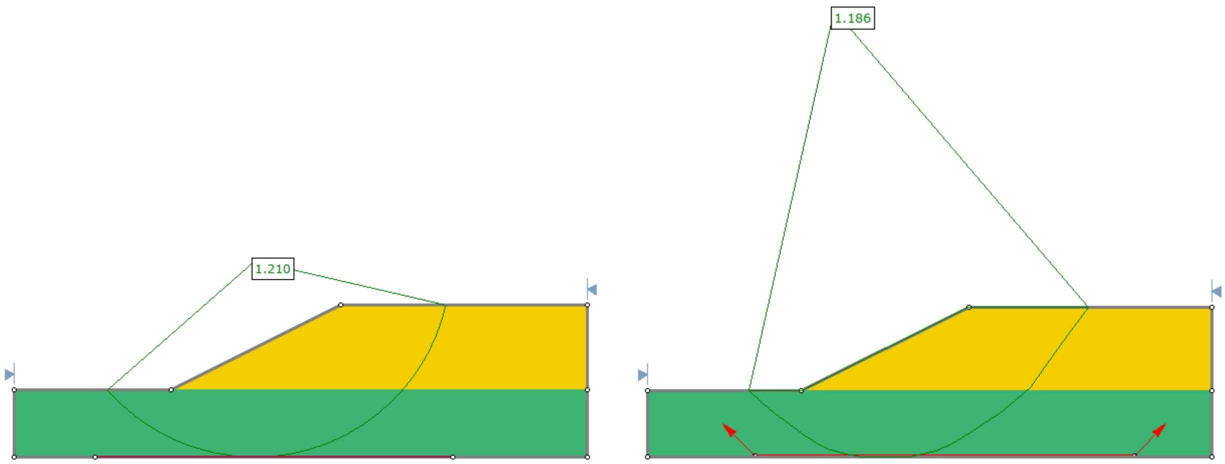


Figure 81.5 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 1: Deep Slip Surface)

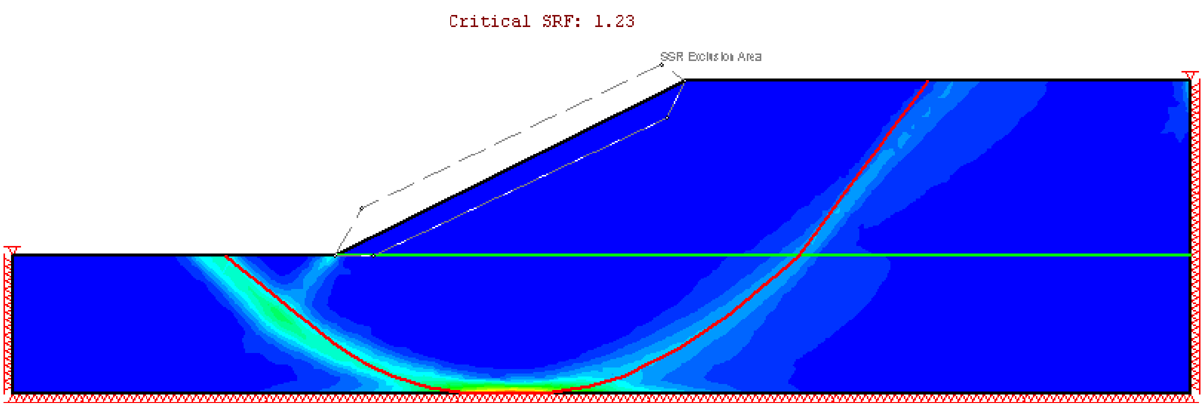


Figure 81.6 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 1: Deep Slip Surface)

Case 2

Table 81.3 – Comparison of Results (Case 2: Very Shallow Slip Surface, Infinite Slope Mechanism)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.16	1.16
	GLE	1.16	1.16
RS2	SSR	1.15	

Note: Reference factor of safety = 1.15 [Duncan and Wright].

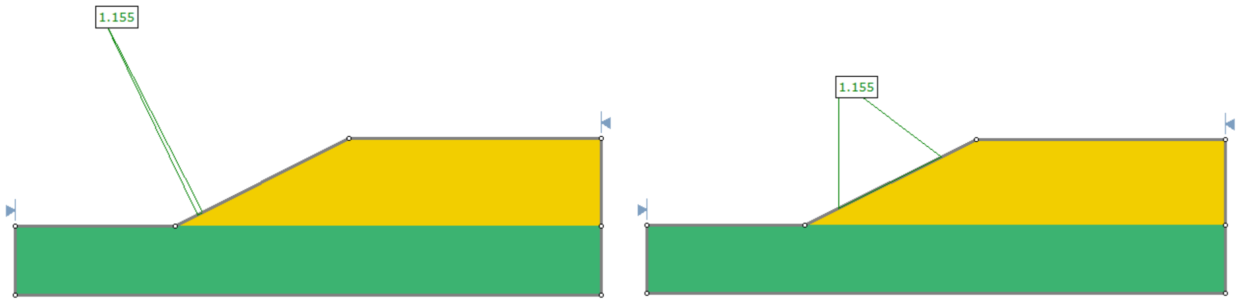


Figure 81.7 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Case 2: Very Shallow Slip Surface, Infinite Slope Mechanism)

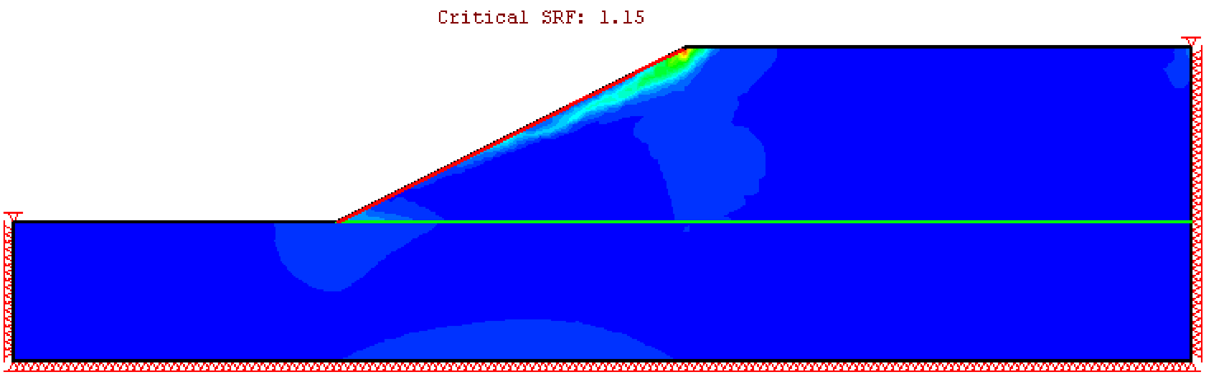


Figure 81.8 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 2: Very Shallow Slip Surface, Infinite Slope Mechanism)

Verification Problem #82

Embankment, (2) materials, water table

82.1 Introduction

This problem is taken from Figure 14.20-a on page 230 of Duncan and Wright (2005)

82.2 Problem Description

Verification problem #82 for *Slide2*–an earth embankment–is shown in Figure 82.1 and Figure 82.2. The material properties are given in Table 82.1. The pore water pressure is modelled using piezometric line approximation. The critical slip surface is assumed to be circular and located using Auto Refine Search. The factor of safety (Table 82.2) and its corresponding slip surface (Figure 82.4) are required.

82.3 Geometry and Material Properties

Table 82.1 – Material Properties

Zone	c′ (psf)	ϕ′ (°)	γ (pcf)
Embankment	600	25	125
Foundation	0	30	132

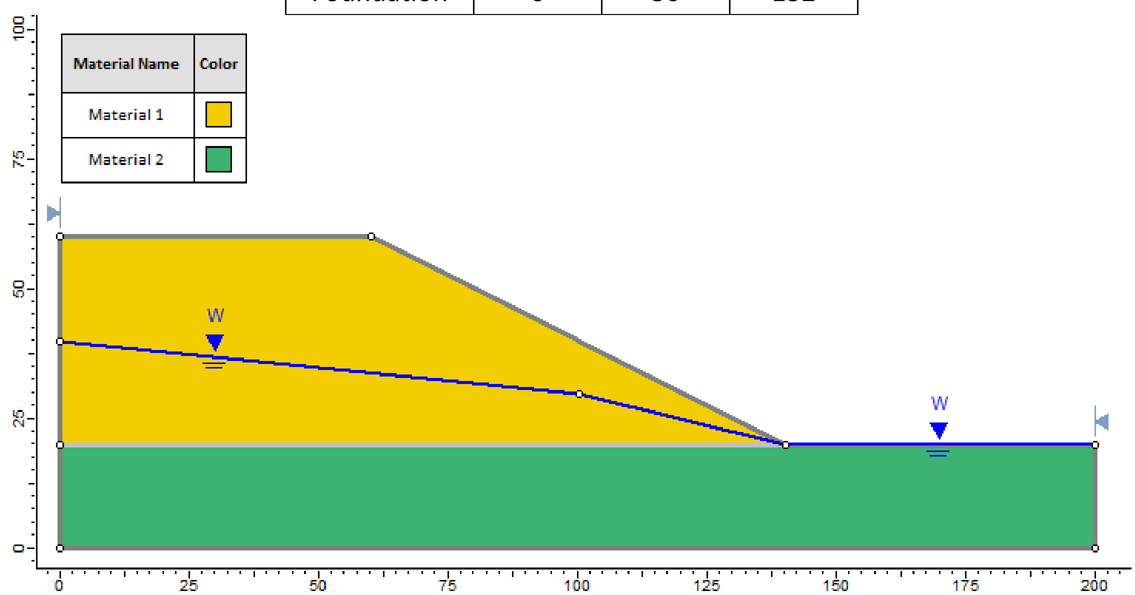


Figure 82.1 – *Slide2* Geometry

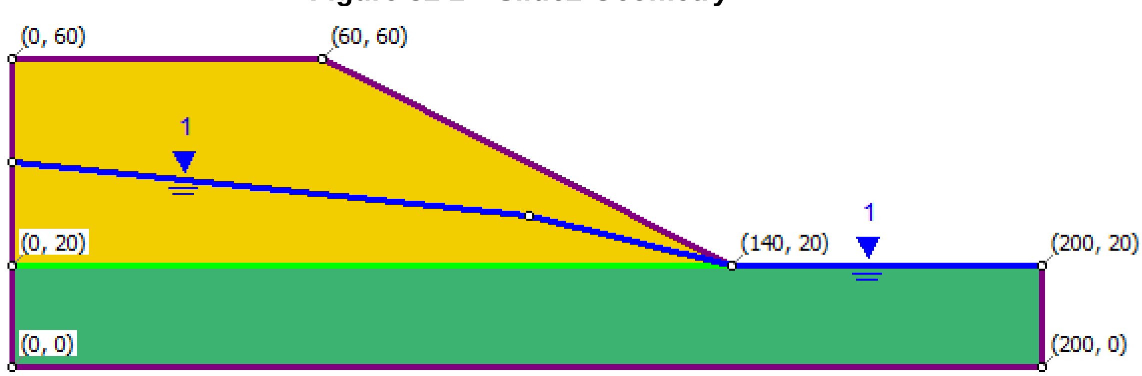


Figure 82.2 – *RS2* Geometry

82.4 Results

Table 82.2 – Comparison of Results

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.54	1.53
	GLE	1.55	1.52
RS2	SSR	1.50	

Note: Reference factor of safety values varied from 1.528 to 1.542 for different subtended angle, which defines the number of slices. Reference factor of safety used (FS average) = 1.535 [Duncan and Wright].

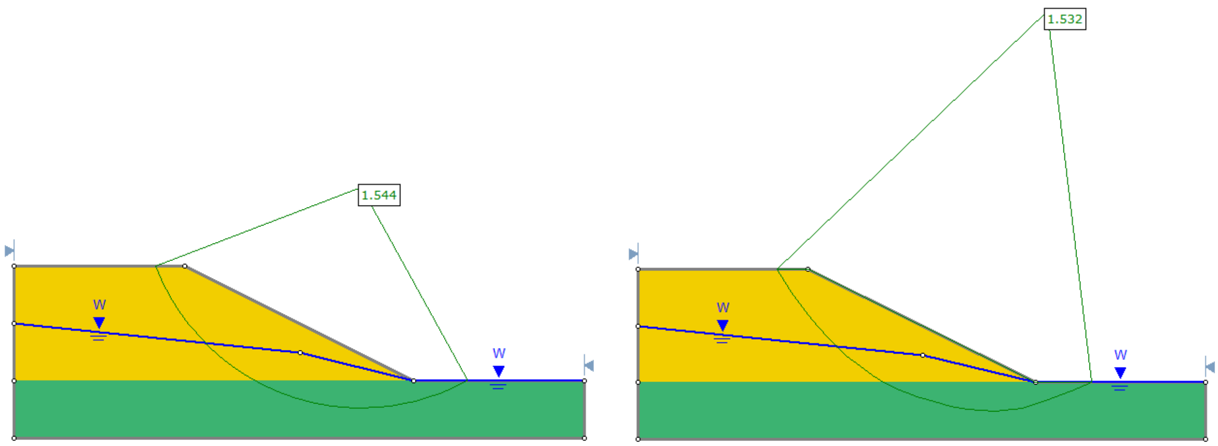


Figure 82.3 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method)

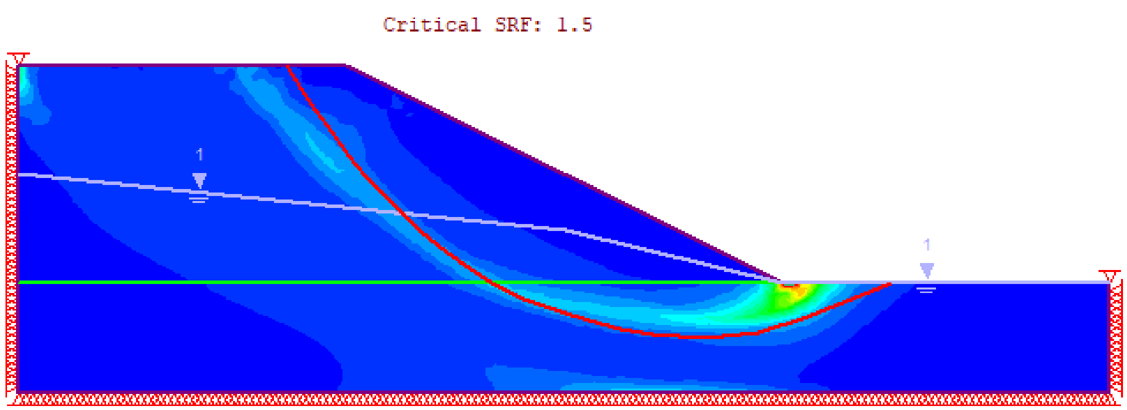


Figure 82.4 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay)

Verification Problem #83

Embankment, (2) materials

83.1 Introduction

This problem is taken from Figure 14.20-b on page 230 of Duncan and Wright (2005).

83.2 Problem Description

Verification problem #83 for *Slide2*, an embankment wall, is shown in Figure 83.2 and 83.3. Two undrained shear strength profiles for its foundation are tested. The foundation's undrained shear strength profiles are shown in Figure 83.1 and Table 83.1. The slip surface that is tangent to the bottom of the foundation is of interest for the second profile. The factor of safety (Table 83.2) and its corresponding slip surface (Figure 83.4) are presented.

83.3 Geometry and Material Properties

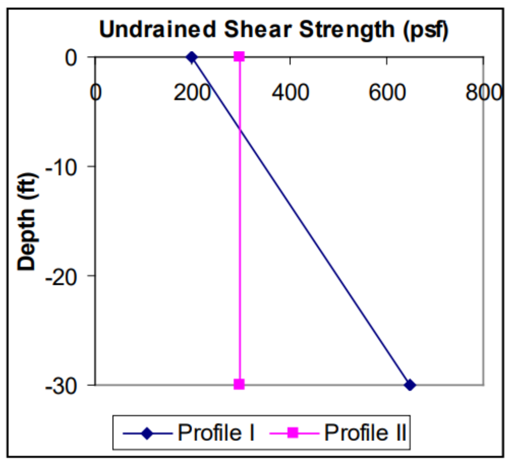


Figure 83.1 – Undrained Shear Strength Profiles from Duncan and Wright (2005)

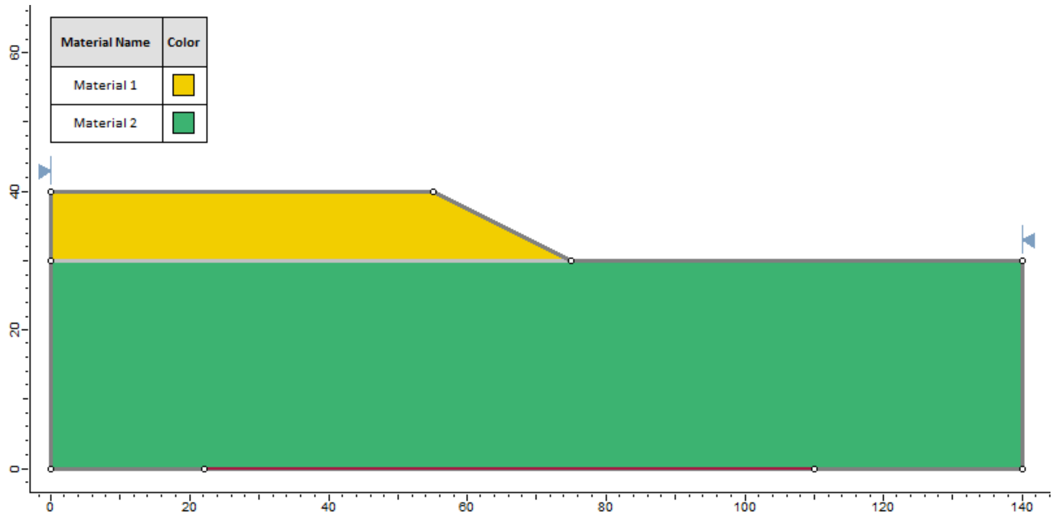


Figure 83.2 – *Slide2* Geometry

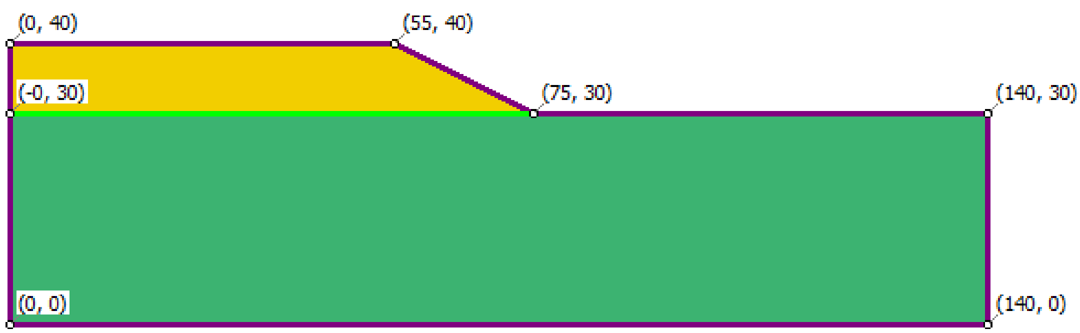


Figure 83.3 – *RS2* Geometry

Table 83.1 – Material Properties

Zone	c' (psf)		ϕ' (°)	γ (pcf)
Embankment	0		36	123
Foundation	Case 1	c' = 200 + 15 × *depth*	0	97
	Case 2	c' = 300		

83.4 Results

Case 1: Undrained shear strength profile I

Table 83.2 – Comparison of Results (Undrained Shear Strength Profile I)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.28	1.26
	GLE	1.29	1.26
RS2	SSR	1.29	

Note: Reference factor of safety values varied from 1.276 to 1.323 for different subtended angle, which defines the number of slices. Reference factor of safety used (FS average) = 1.300 [Duncan and Wright].

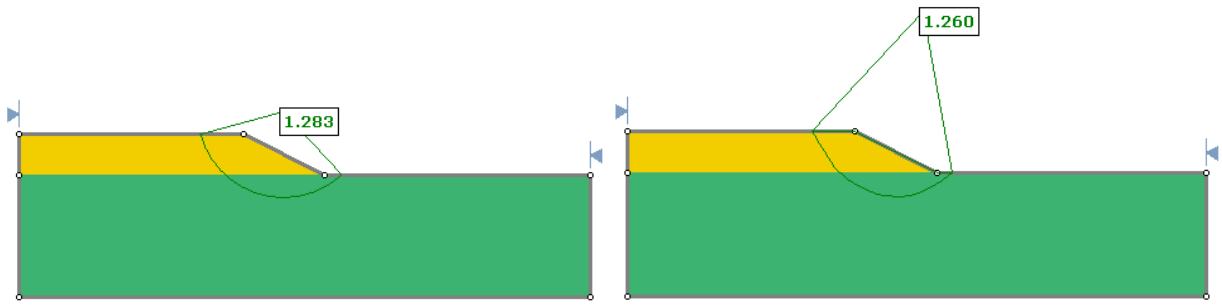


Figure 83.4 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method) (Undrained Shear Strength Profile I)

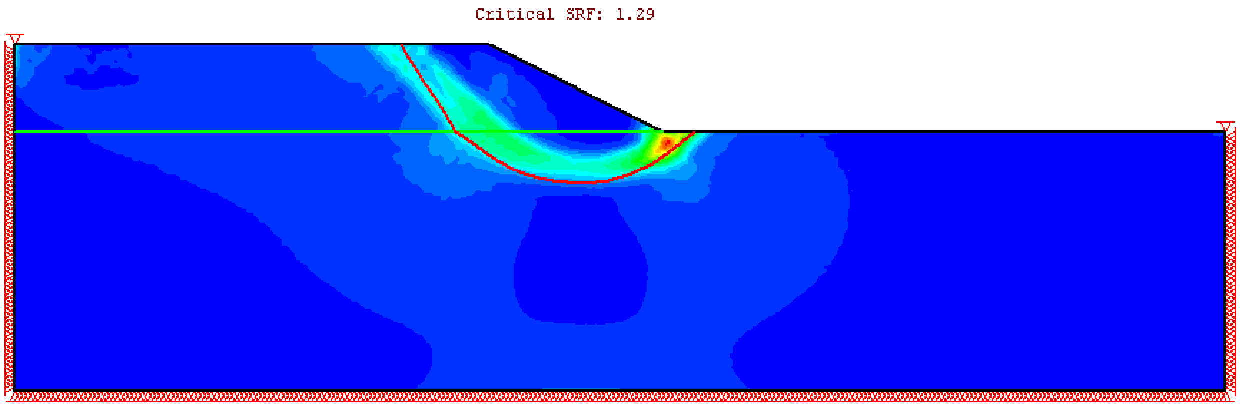


Figure 83.5 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Undrained Shear Strength Profile I)

Case 2: Undrained shear strength profile II

Table 83.2 – Comparison of Results (Undrained Shear Strength Profile II)

Program	Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Slide2	Spencer	1.33	1.17
	GLE	1.34	1.20
RS2	SSR	1.30	

Note: Reference factor of safety values varied from 1.295 to 1.328 for different subtended angle, which defines the number of slices. Reference factor of safety used (FS average) = 1.312 [Duncan and Wright].

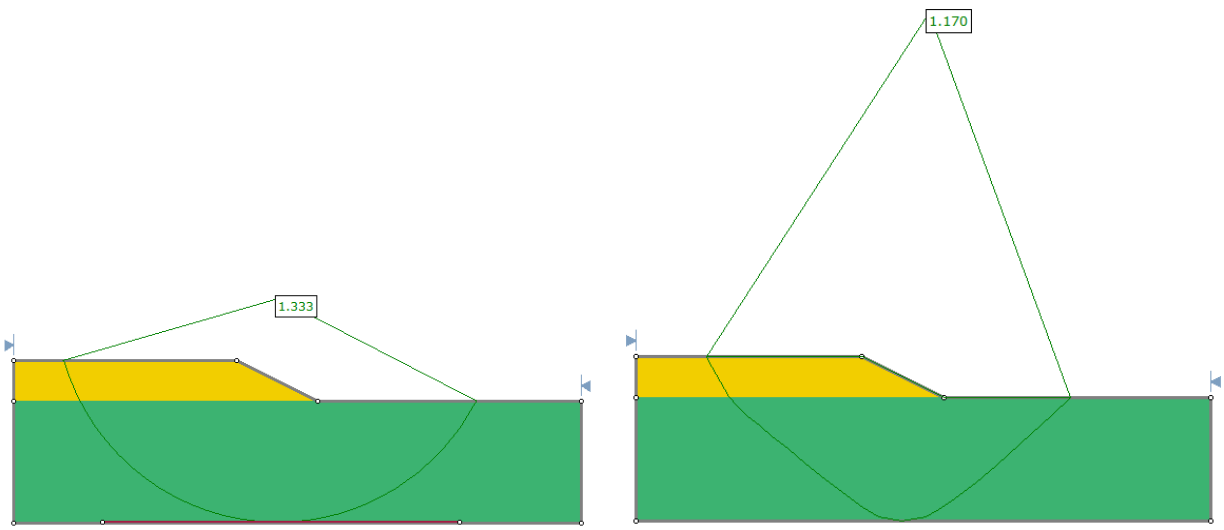


Figure 83.6 – *Slide2* Failure Surface (Circular [Left], Non-Circular [Right]; Spencer Method)
(Undrained Shear Strength Profile II)

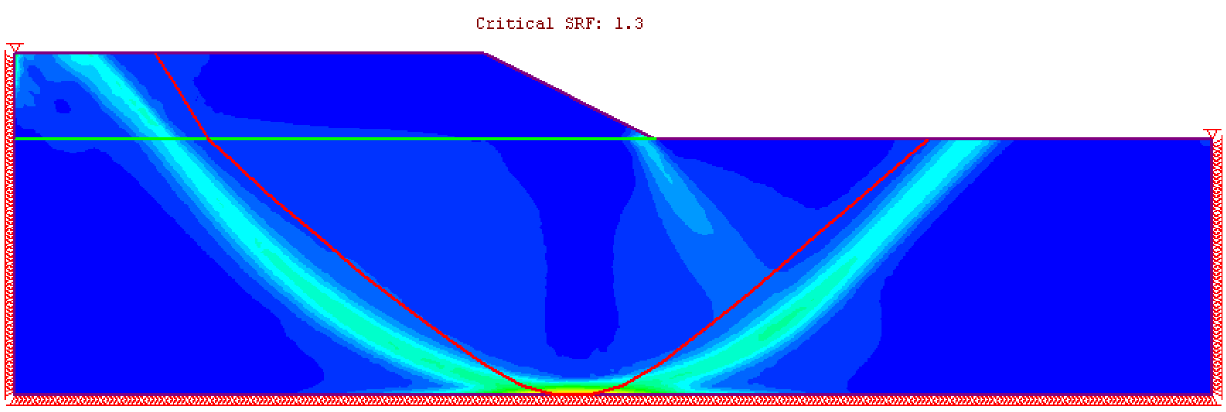


Figure 83.7 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Undrained Shear Strength Profile II)

Verification Problem #102

Embankment dam, homogeneous, rapid drawdown

102.1 Introduction

This problem investigates the stability of an earth dam subjected to rapid drawdown conditions.

102.2 Problem Description

Verification problem #102 for *Slide2*–an earth dam under dry conditions (Case 1)–is shown in Figure 83.1 and Figure 83.2. The dam material is a homogenous, isotropic soil with the soil properties outlined in Table 102.1. The factor of safety (Table 102.2) and its corresponding slip surface (Figure 102.6) are required.

Figure 102.3 and Figure 102.4 show the earth dam at initial steady state before rapid drawdown, with water level 17 feet above the left side. Transient analysis considers a basal friction angle value of and 0° (Case 2) and 37° (Case 3). *Slide2* results at different times for the two cases are summarized within Table 102.3 and Figure 102.4, along with values from Huang and Jia (2008). Figures 102.9 and Figure 102.12 show the results for both cases at various analysis times. For both Case 2 and Case 3, the critical SRF occurs at the initial stage.

102.3 Geometry and Material Properties

Table 102.1 – Material Properties

c' (kPa)	ϕ' (⁰)	γ (kN/m³)	E (kPa)	ν
13.8	37	18.2	1×10^5	0.3

Case 1

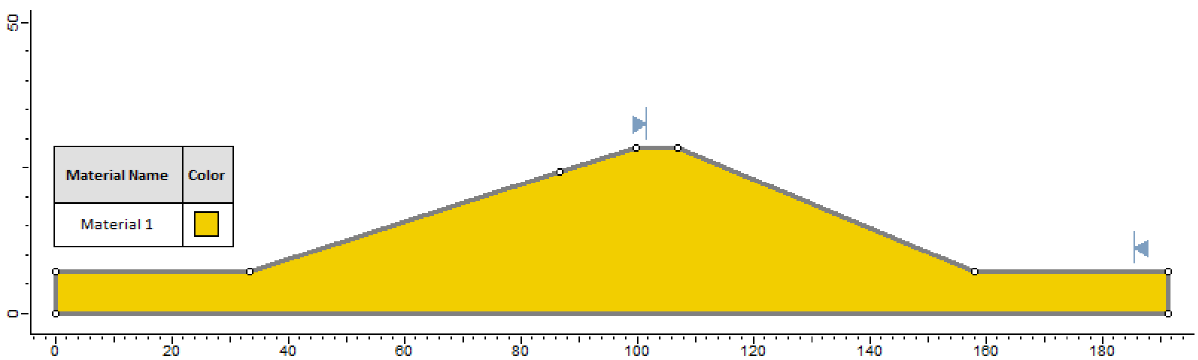


Figure 102.1 – *Slide2* Geometry (Case 1: Dam Under Dry Conditions)

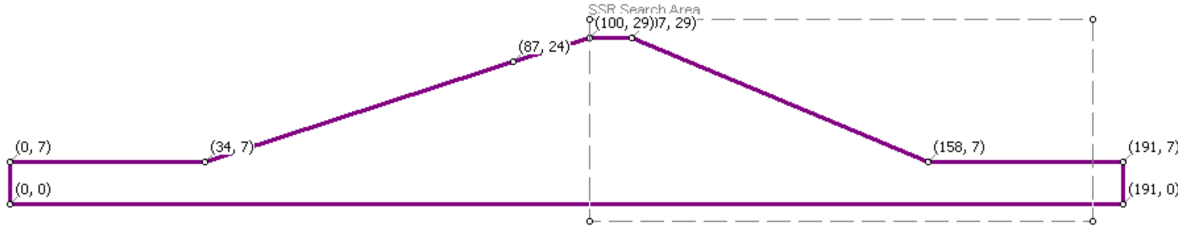


Figure 102.2 – *RS2* Geometry (Case 1: Dam Under Dry Conditions)

Case 2

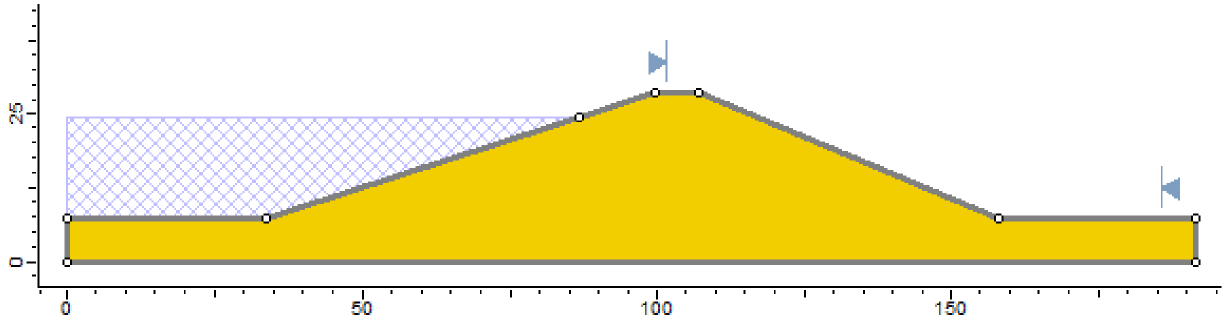


Figure 102.3 – *Slide2* Geometry (Case 2 & Case 3: Initial Steady State Before Rapid Drawdown, Transient Analysis)

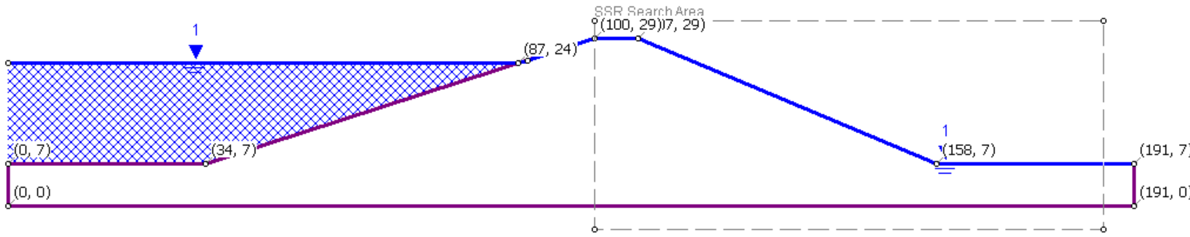


Figure 102.4 – *RS2* Geometry (Case 2 & Case 3: Initial Steady State Before Rapid Drawdown, Transient Analysis)

102.4 Results

Case 1

Table 102.2 – Comparison of Results (Case 1: Dam Under Dry Conditions)

Program	Method	Factor of Safety (circular)
Slide2	Spencer	2.46
	GLE	2.46
RS2	SSR	2.43

Note: Reference factor of safety = 2.43 [Huang and Jia].

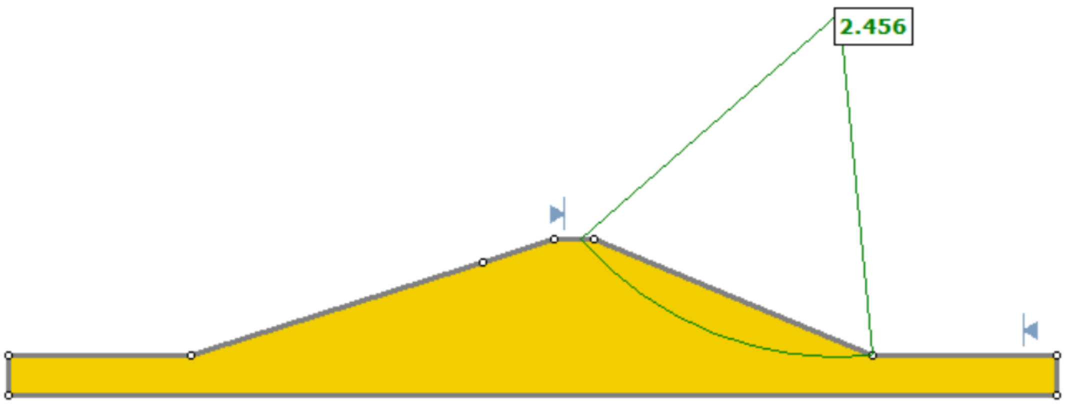


Figure 102.5 – *Slide2* Failure Surface (Circular; Spencer Method) (Case 1: Dam Under Dry Conditions)

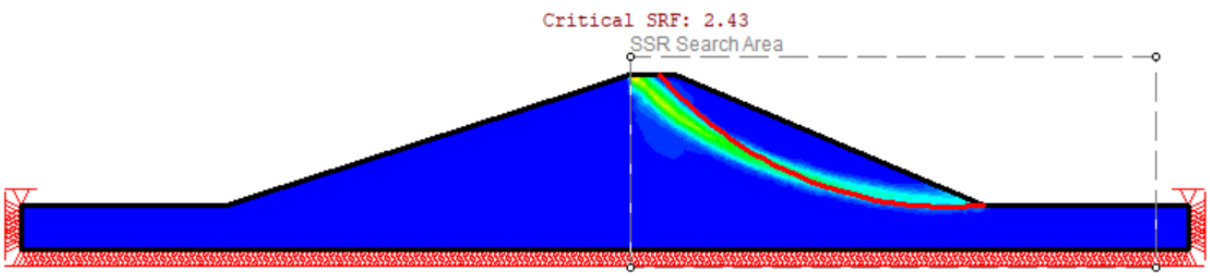


Figure 102.6 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 1: Dam Under Dry Conditions)

Case 2

Table 102.3 – Comparison of Results (Case 2: Rapid Drawdown, Transient Analysis, $\phi_b = 0°$)

Stage	Program			Reference Factor of Safety [Huang and Jia]
	Slide2		*RS2*	
	Spencer	GLE	SSR	
	Factor of Safety (circular)	Factor of Safety (circular)	SRF	
Initial (Steady State)	**1.745**	**1.745**	**1.7**	**1.683**
Stage 1: 60 hr	1.804	1.805	1.77	1.805
Stage 2: 70 hr	1.820	1.819	1.78	1.840
Stage 3: 75 hr	1.828	1.827	1.79	1.858
Stage 4: 80 hr	1.835	1.835	1.8	1.875
Stage 5: 85 hr	1.842	1.843	1.81	1.893
Stage 6: 90 hr	1.851	1.851	1.82	1.909
Stage 7: 100 hr	1.867	1.868	1.83	1.940
Stage 8: 300 hr	2.092	2.094	2.06	2.274
Stage 9: 600 hr	2.242	2.249	2.19	2.360
Stage 10: 1000 hr	2.329	2.336	2.26	2.374
Stage 11: 1500 hr	2.373	2.378	2.29	2.374

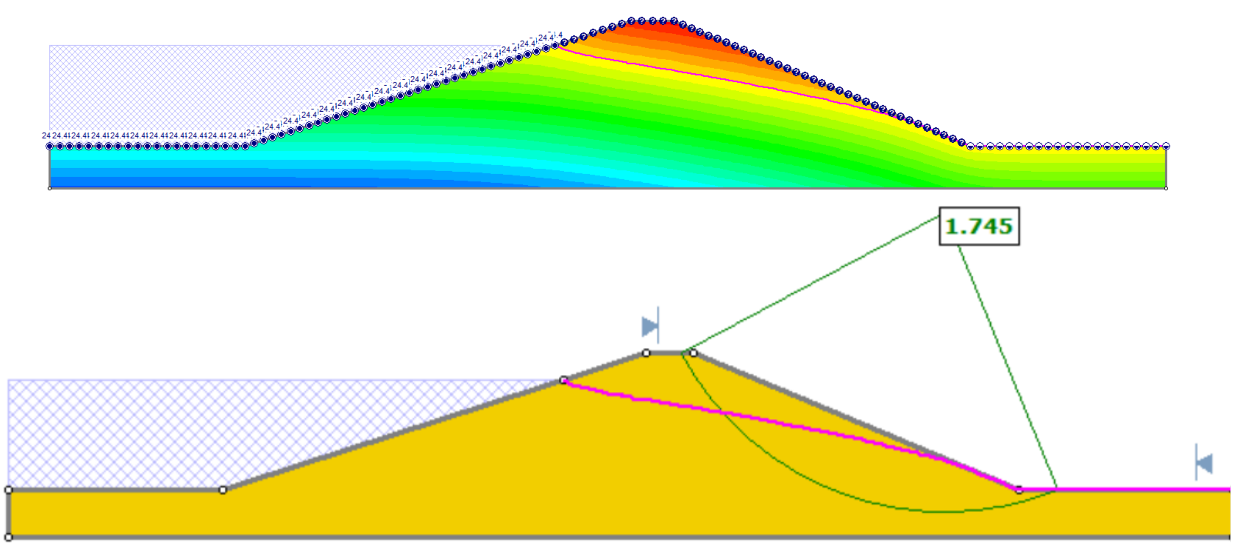
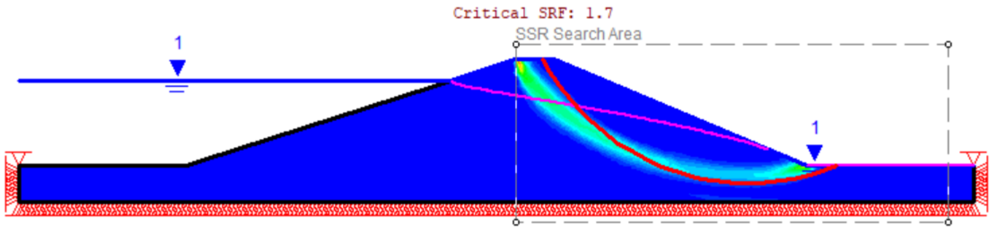
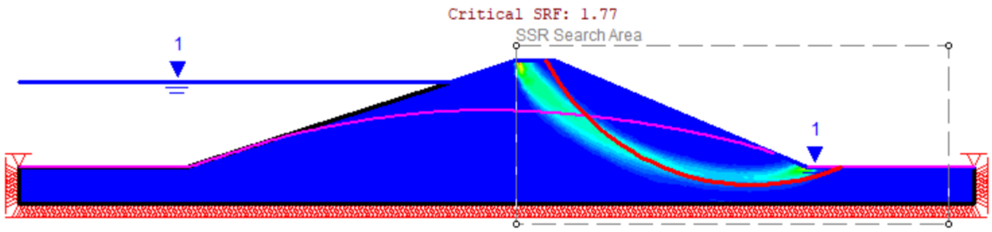


Figure 102.7 – *Slide2* Failure Surface (Circular; Spencer Method) (Case 2: Rapid Drawdown, Transient Analysis, $\phi_b = 0°$ (Initial Stage))

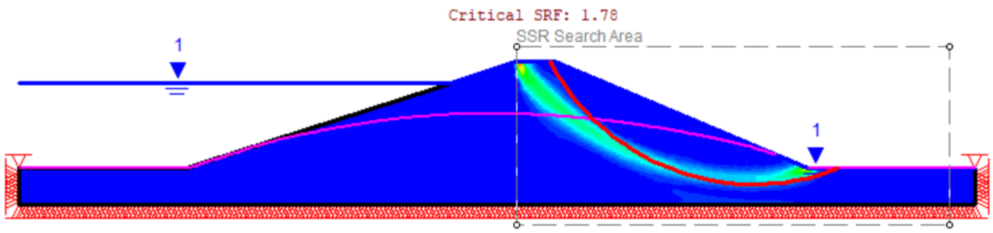
Initial
(Steady State)



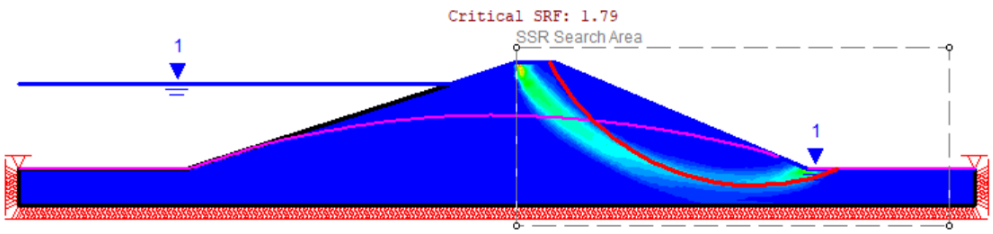
Stage 1:
60 hr



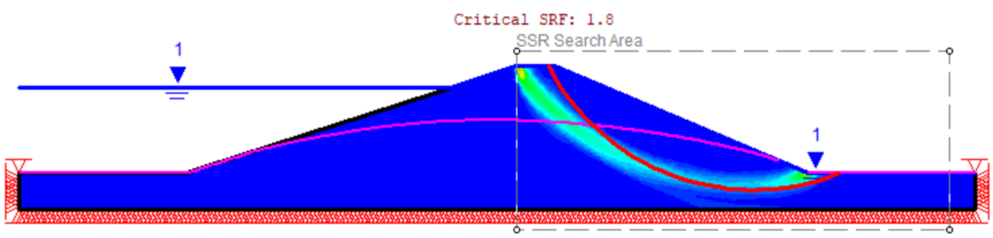
Stage 2:
70 hr



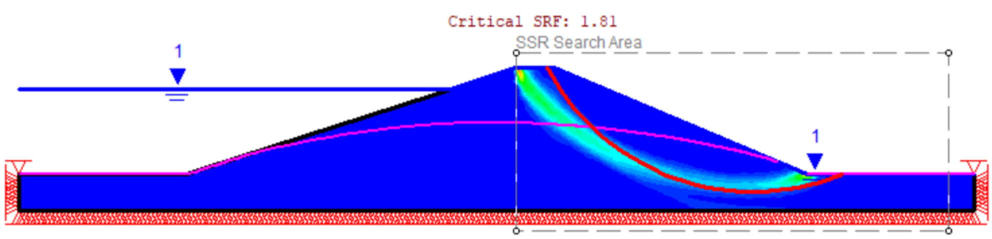
Stage 3:
75 hr



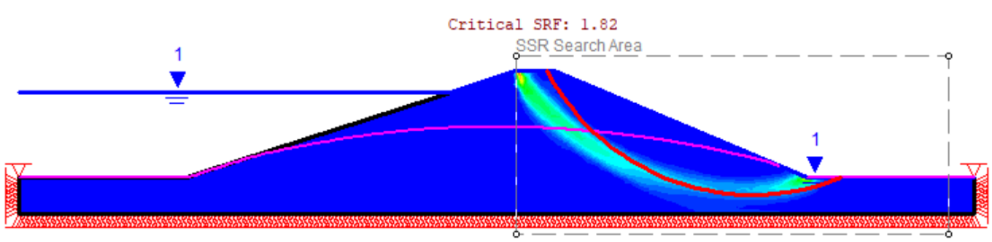
Stage 4:
80 hr



Stage 5:
85 hr



Stage 6:
90 hr



Stage 7:
100 hr

Stage 8:
300 hr

Stage 9:
600 hr

Stage 10:
1000 hr

Stage 11:
1500 hr

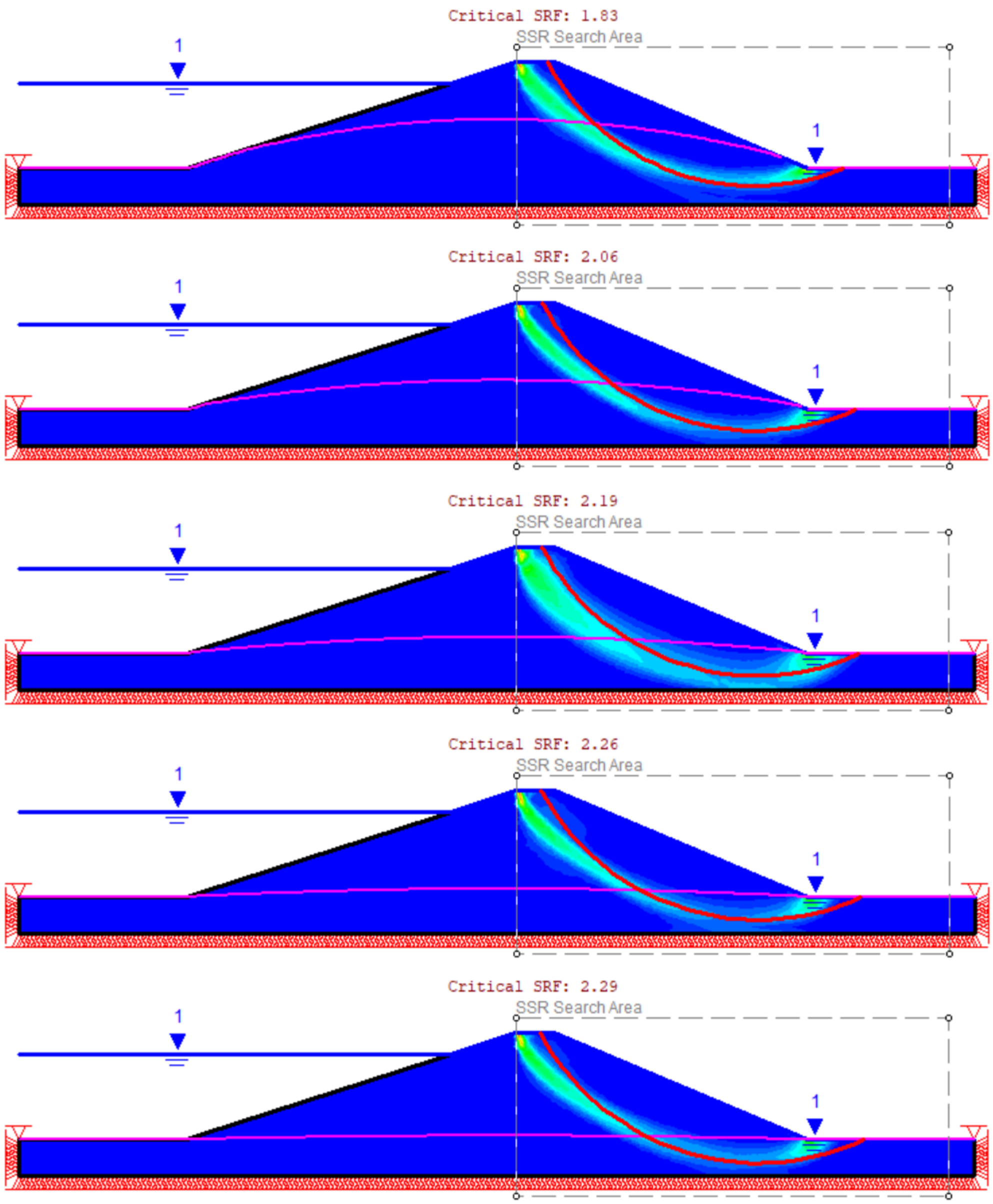


Figure 102.8 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 2: Rapid Drawdown, Transient Analysis, $\phi_b = 0°$)

Case 3

Table 102.4 – Comparison of Results (Case 3: Rapid Drawdown, Transient Analysis, $\phi_b = 37°$)

Stage	Program			Reference Factor of Safety
	Slide2		*RS2*	
	Spencer	GLE	SSR	
	Factor of Safety (circular)	Factor of Safety (circular)	SRF	[Huang and Jia]
Initial (Steady State)	1.822	1.818	1.76	1.764
Stage 1: 60 hr	1.893	1.889	1.82	1.930
Stage 2: 70 hr	1.910	1.907	1.84	1.982
Stage 3: 75 hr	1.919	1.916	1.85	2.009
Stage 4: 80 hr	1.928	1.925	1.85	2.035
Stage 5: 85 hr	1.938	1.935	1.86	2.065
Stage 6: 90 hr	1.948	1.944	1.87	2.098
Stage 7: 100 hr	1.967	1.964	1.89	2.134
Stage 8:300 hr	2.224	2.221	2.14	2.595
Stage 9: 600 hr	2.421	2.417	2.31	2.754
Stage 10: 1000 hr	2.549	2.541	2.42	2.804
Stage 11: 1500 hr	2.615	2.610	2.48	2.813

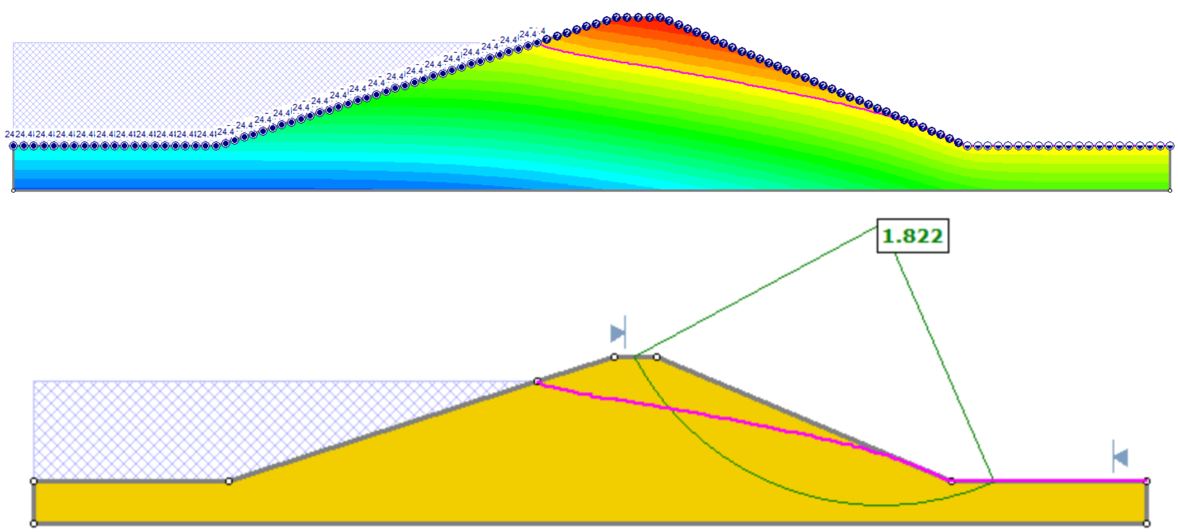
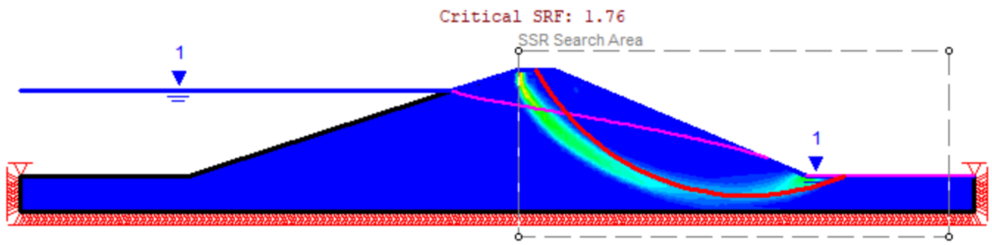
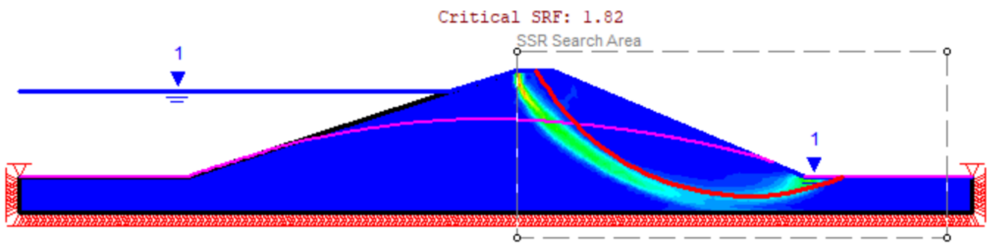


Figure 102.9 – *Slide2* Failure Surface (Circular; Spencer Method) (Case 3: Rapid Drawdown, Transient Analysis, $\phi_b = 37°$ (Initial Stage))

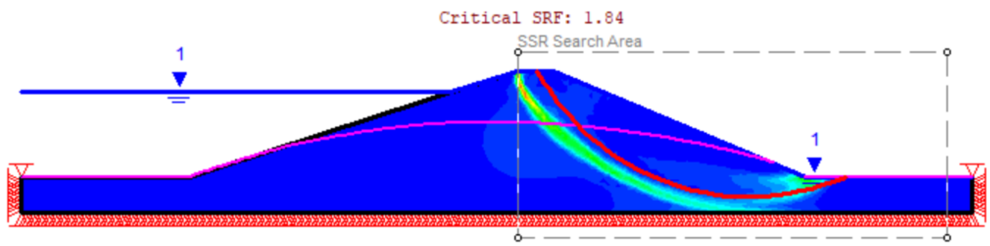
Initial (Steady State)



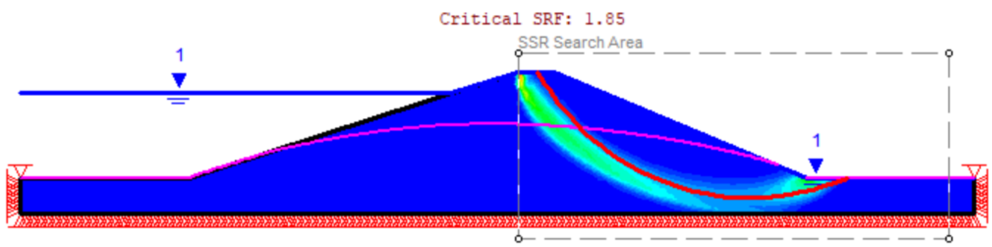
Stage 1: 60 hr



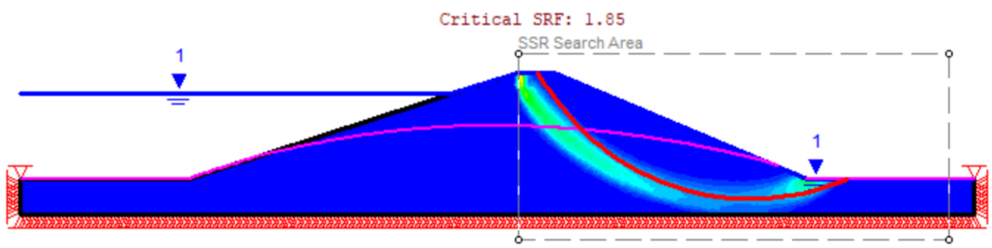
Stage 2: 70 hr



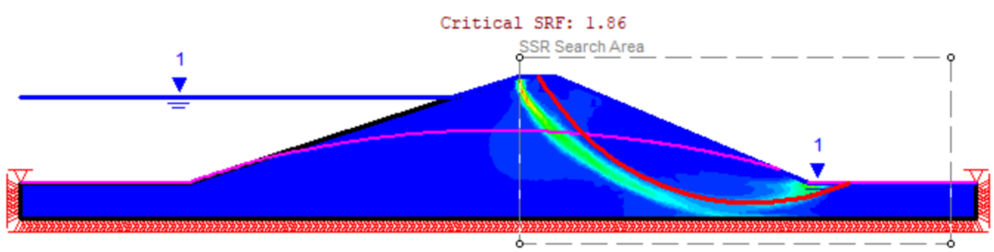
Stage 3: 75 hr



Stage 4: 80 hr



Stage 5: 85 hr



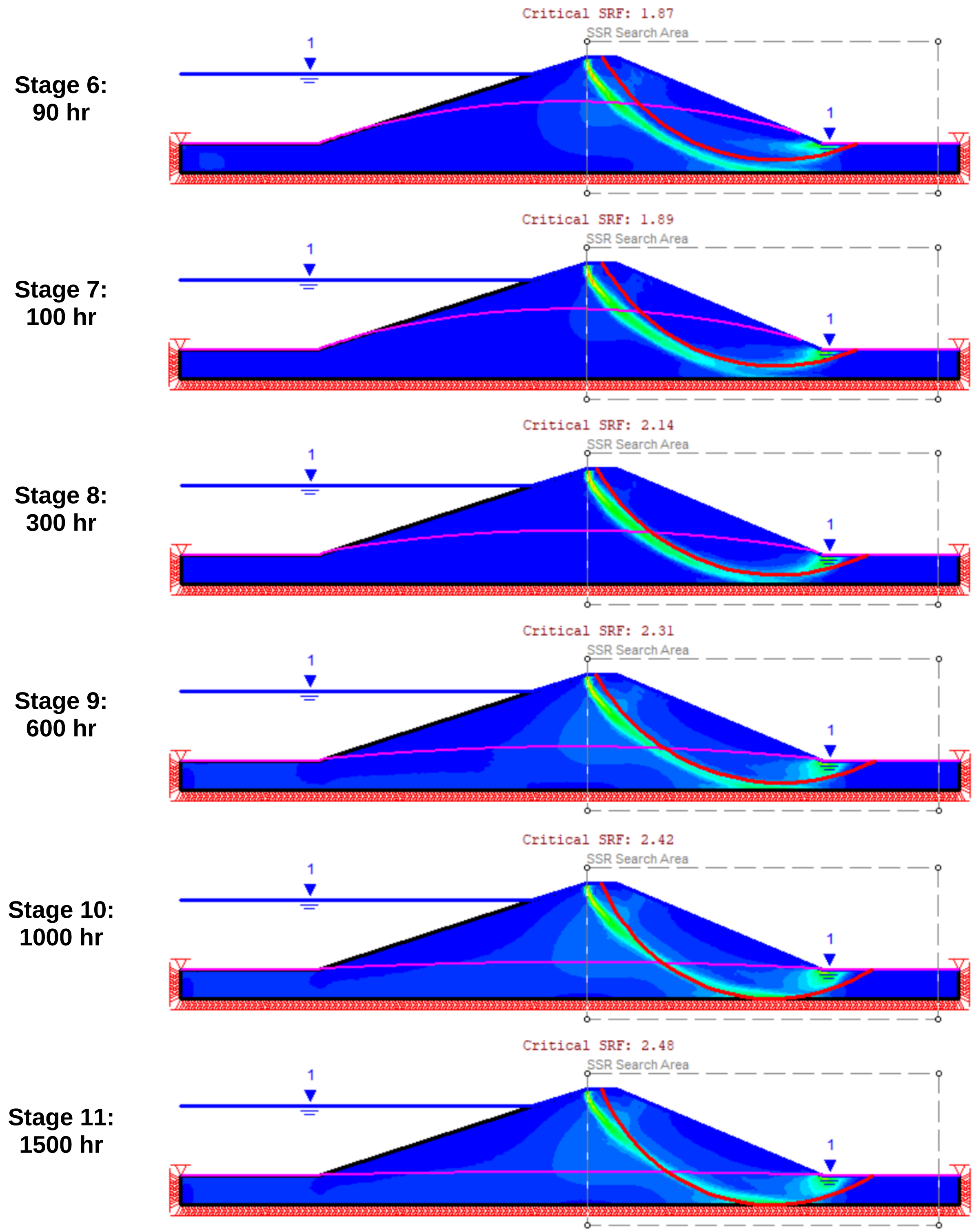


Figure 102.10 – *RS2* Maximum Shear Strain Plot (with *Slide2* Spencer Method Failure Surface Overlay) (Case 3: Rapid Drawdown, Transient Analysis, $\phi_b = 37°$)

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