rocscience

Slide2

Slope Stability

Verification Manual

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Introduction

This document contains a series of verification slope stability problems that have been analyzed using **Slide** version 7.0. These verification tests come from:

- A set of 5 basic slope stability problems, together with 5 variants, was distributed in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Association for Computer Aided Design), in 1988. The **Slide** verification problems #1 to #10 are based on these ACADS example problems (Giam & Donald (1989)).
- Published examples found in reference material such as journal and conference proceedings.

For all examples, a short statement of the problem is given first, followed by a presentation of the analysis results, using various limit equilibrium analysis methods. Full references cited in the verification tests are found at the end of this document.

The **Slide** slope stability verification files can be accessed by selecting File tab → Recent Folders → Example Folder → Slope Stability Verification. The file names are *slope stability #001.slim*, *slope stability #002.slim* and etc., corresponding to the verification problem numbers in this document.

All verification files run with the **Slide** Demo, so if you want details which are not presented in this document, then download the demo to view all the input parameters and results.

1. Slide Verification Problem #1

Slope, homogenous

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.

A slip center search grid of 20 x 20 intervals is used, with 11 circles per grid point, generating a total of 4851 circular slip surfaces. Grid is located at (22.8, 62.6), (22.8, 42.3), (43.7, 62.6), and (43.7, 42.3). Tolerance is 0.0001.

1.3. Geometry and Material Properties

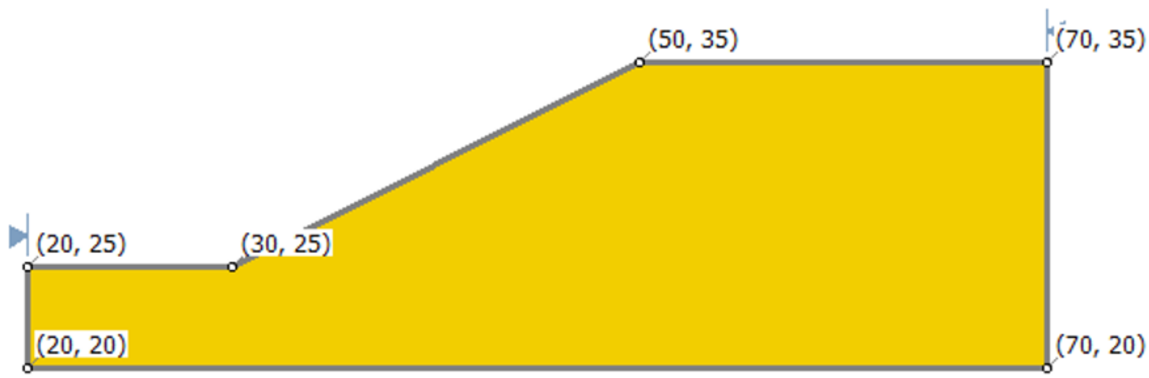


Figure 1.1: Geometry Setup in **Slide**

Table 1.1: Soil Properties

c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
3.0	19.6	20.0

1.4. Results

Table 1.2

Method	Factor of Safety
Bishop	0.987
Spencer	0.986
GLE	0.986
Janbu Corrected	0.990

Note: Reference factor of safety = 1.00 [Giam]

Mean Bishop FOS (18 samples) = 0.993

Mean FOS (33 samples) = 0.991

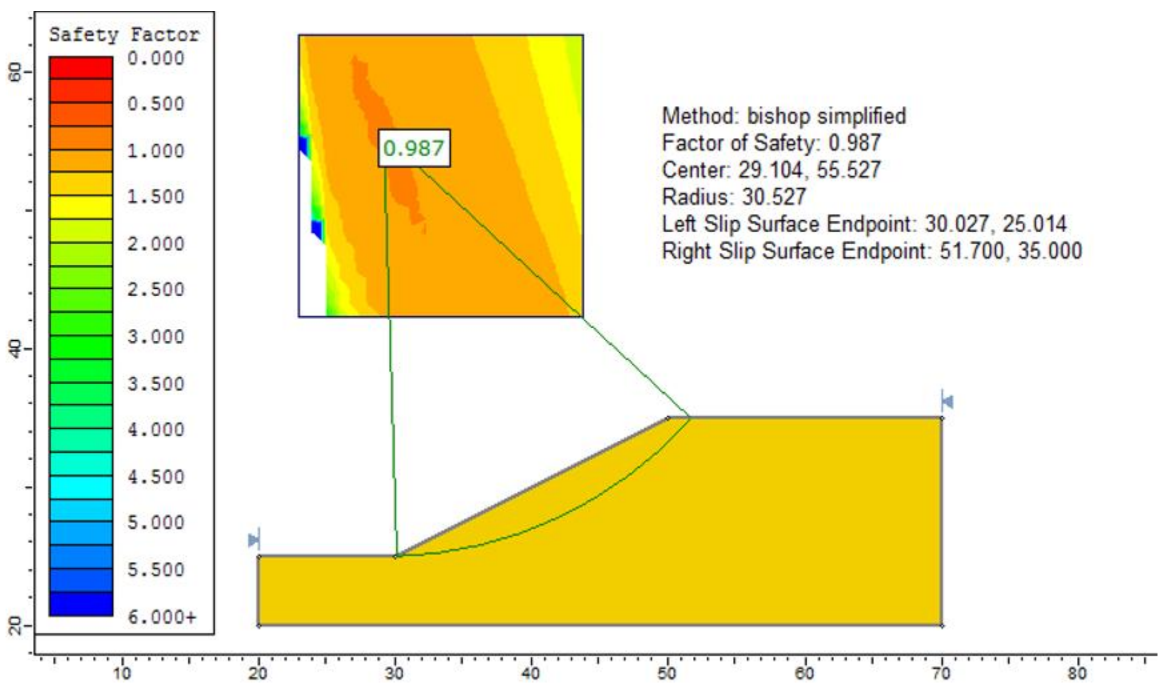


Figure 1.2: Solution, using the Bishop simplified method

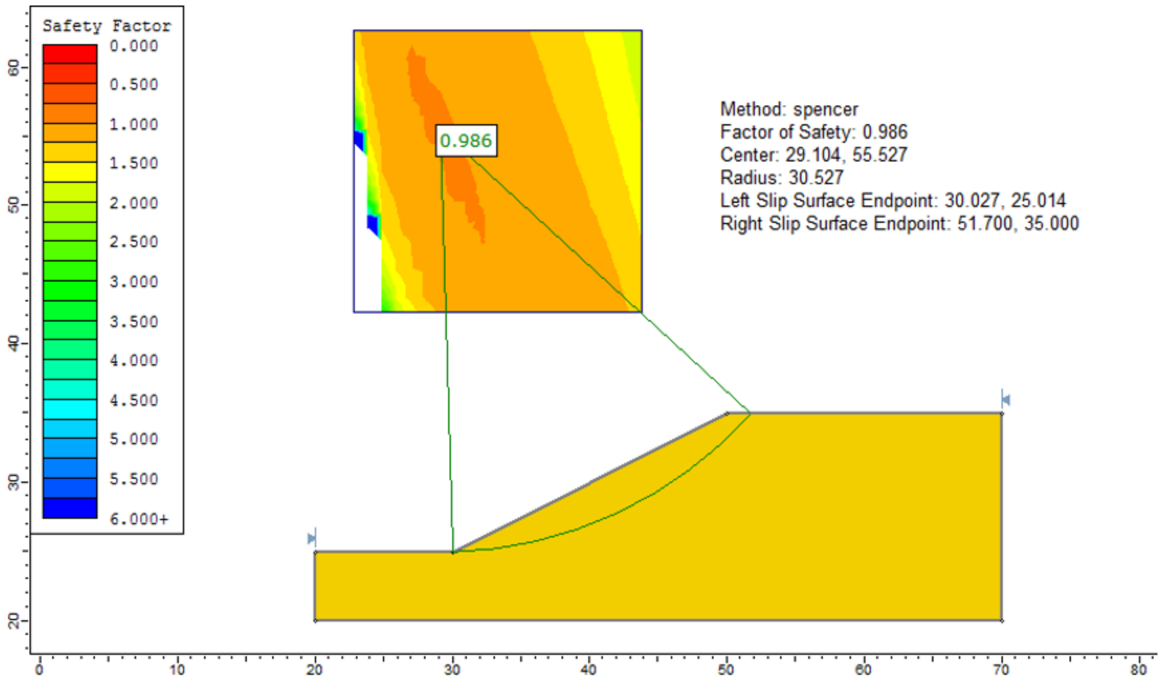


Figure 1.3: Solution, using the Spencer method

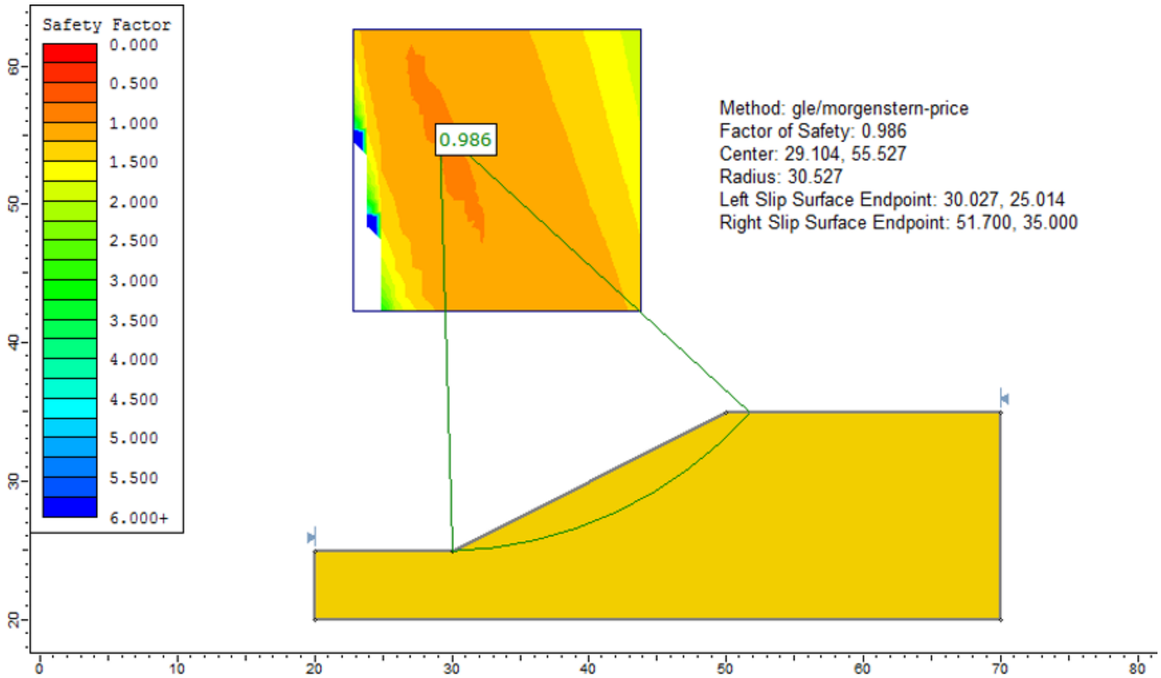


Figure 1.4: Solution, using the GLE method

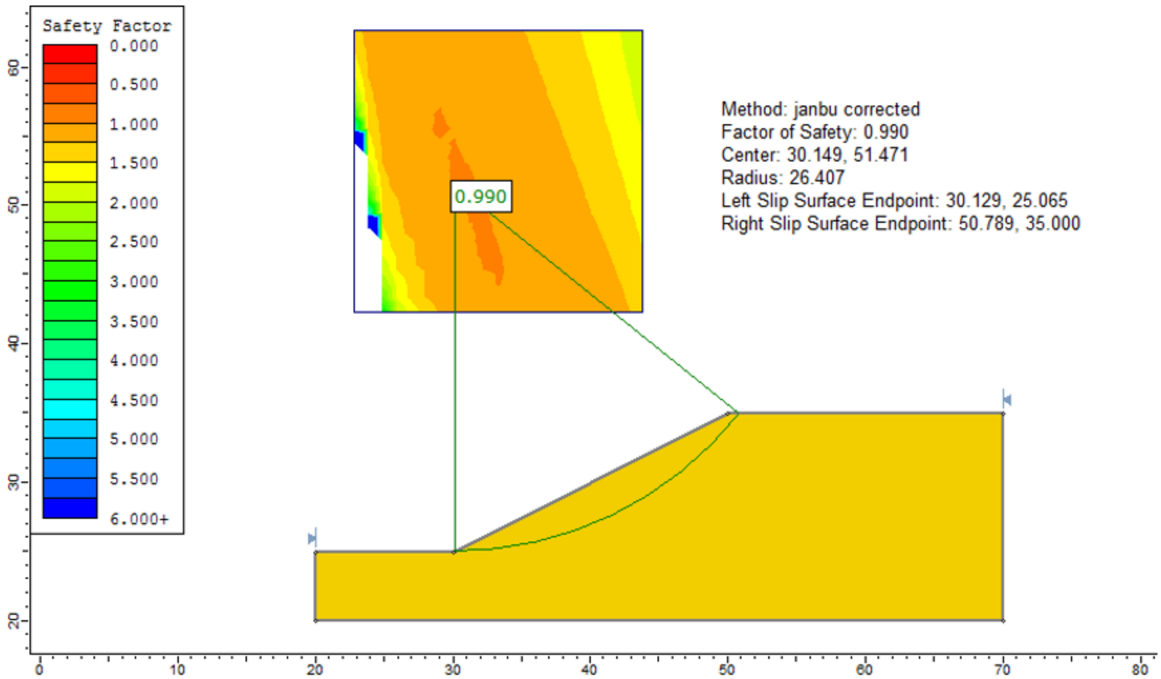


Figure 1.5: Solution, using the Janbu corrected method

2. Slide Verification Problem #2

Slope, homogenous, 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)].

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

In order to locate the critical slip surfaces, a slip center search grid of 20 x 20 intervals was used, with 11 circles per grid point, generating a total of 4851 slip surfaces. Grid located at (31, 49), (47, 49), (31, 34), and (47, 34). Tolerance is 0.0001.

2.3. Geometry and Material Properties

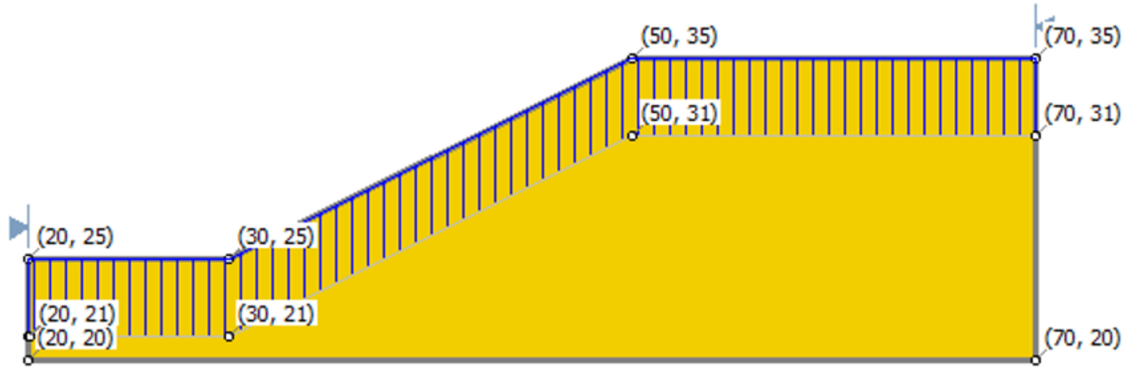


Figure 2.1: Geometry Setup in **Slide**

Table 2.1: Soil Properties

c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
32.0	10.0	20.0

2.4. Results

Table 2.2

Method	Factor of Safety
Bishop	1.596
Spencer	1.592
GLE	1.592
Janbu Corrected	1.489

Note: Reference factor of safety = 1.65 [Giam]

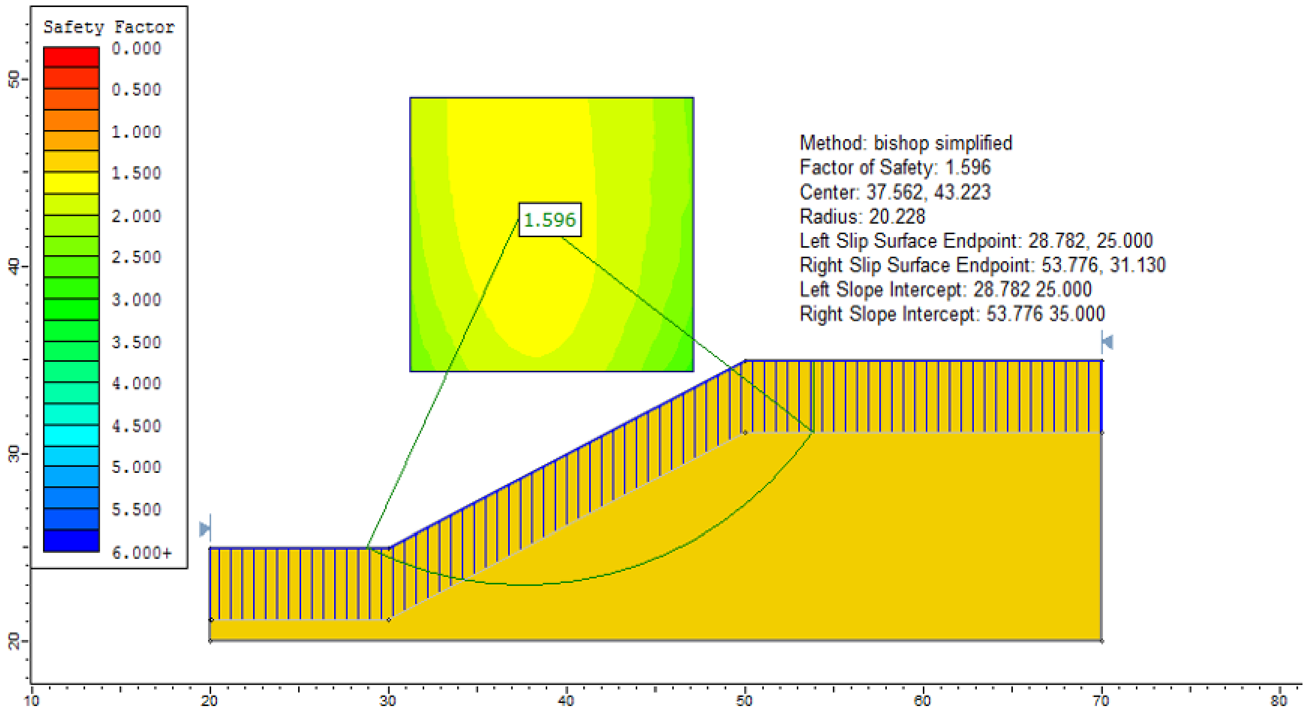


Figure 2.2: Solution, using the Bishop simplified method

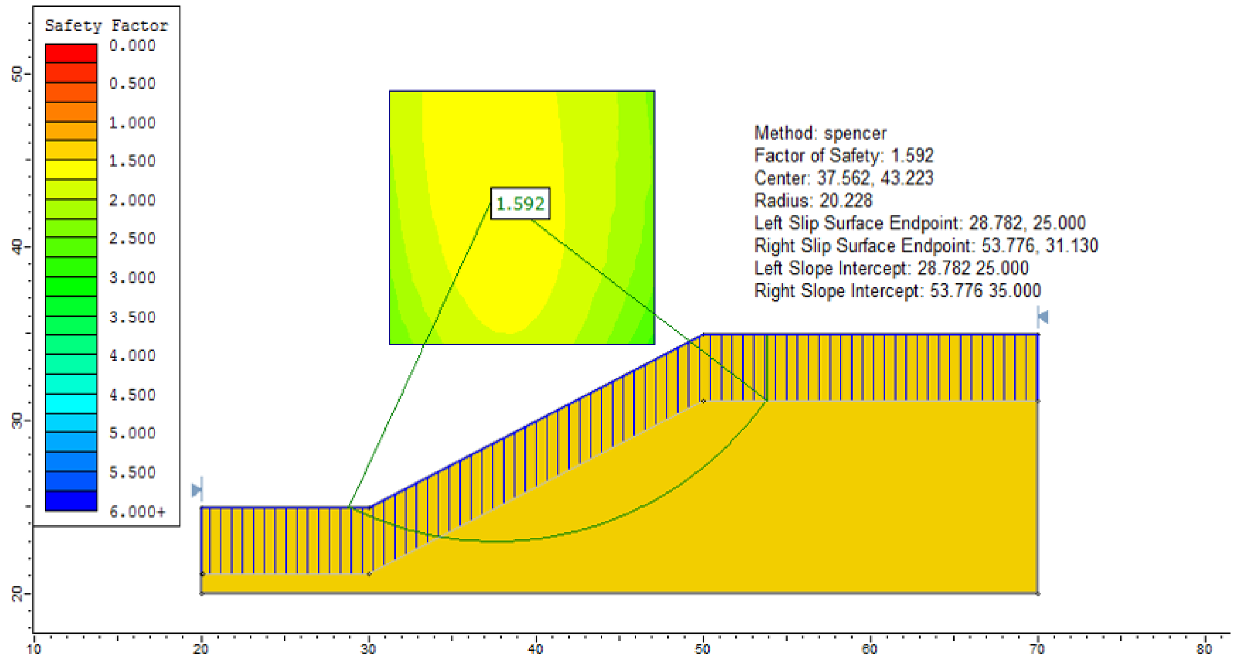


Figure 2.3: Solution, using the Spencer method

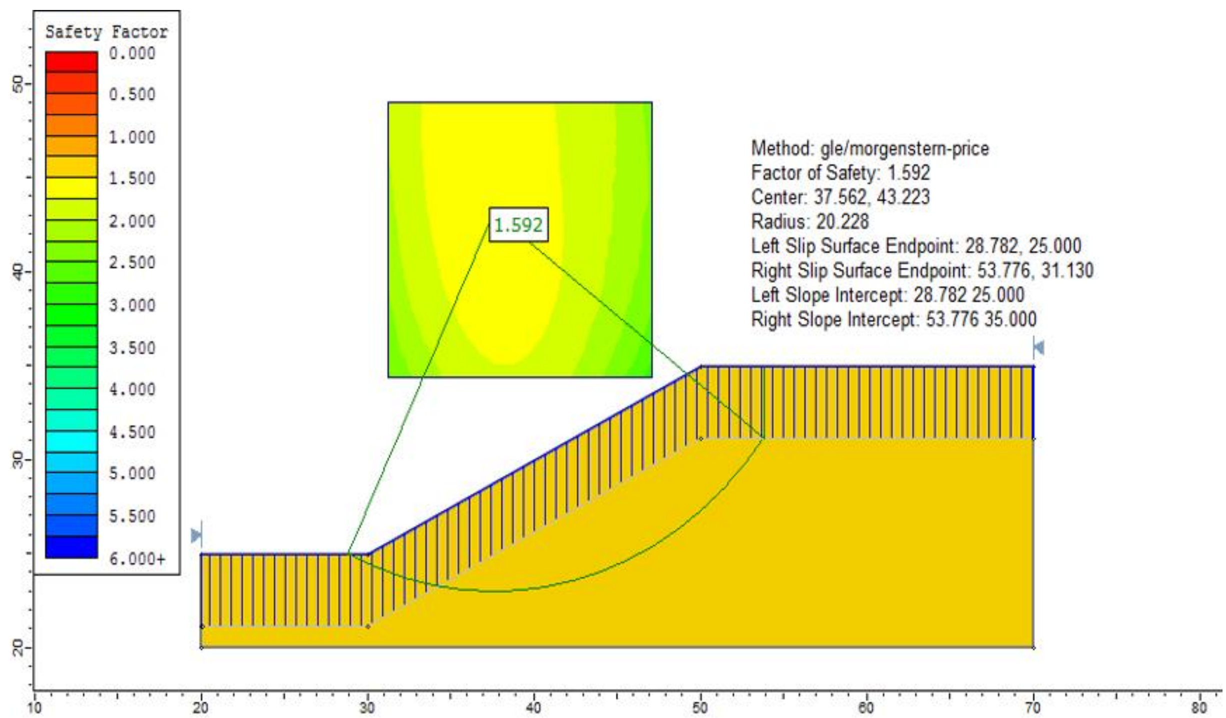


Figure 2.4: Solution, using the GLE method

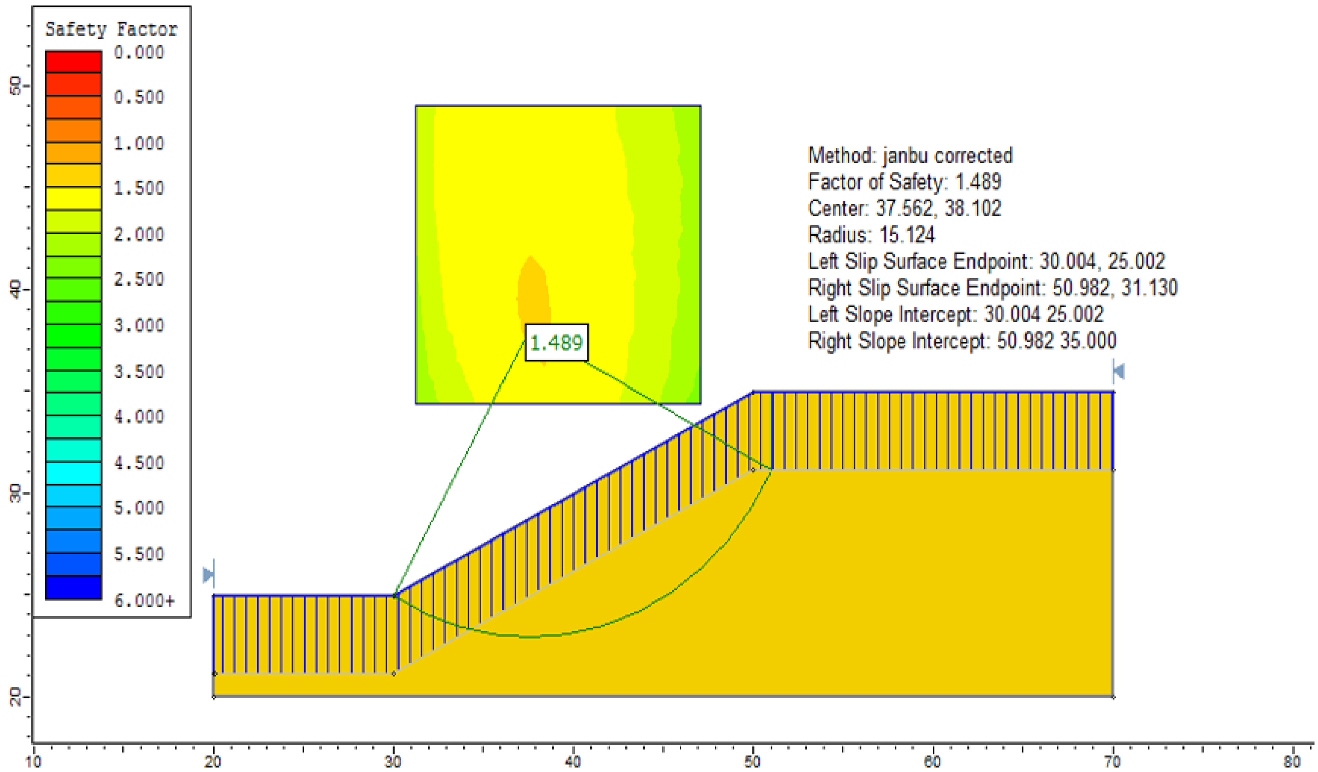


Figure 2.5: Solution, using the Janbu corrected method

3. Slide 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.

A slip center search grid of 20 x 20 intervals was used, with 11 circles per grid point, generating a total of 4851 slip surfaces.

3.3. Geometry and Material Properties

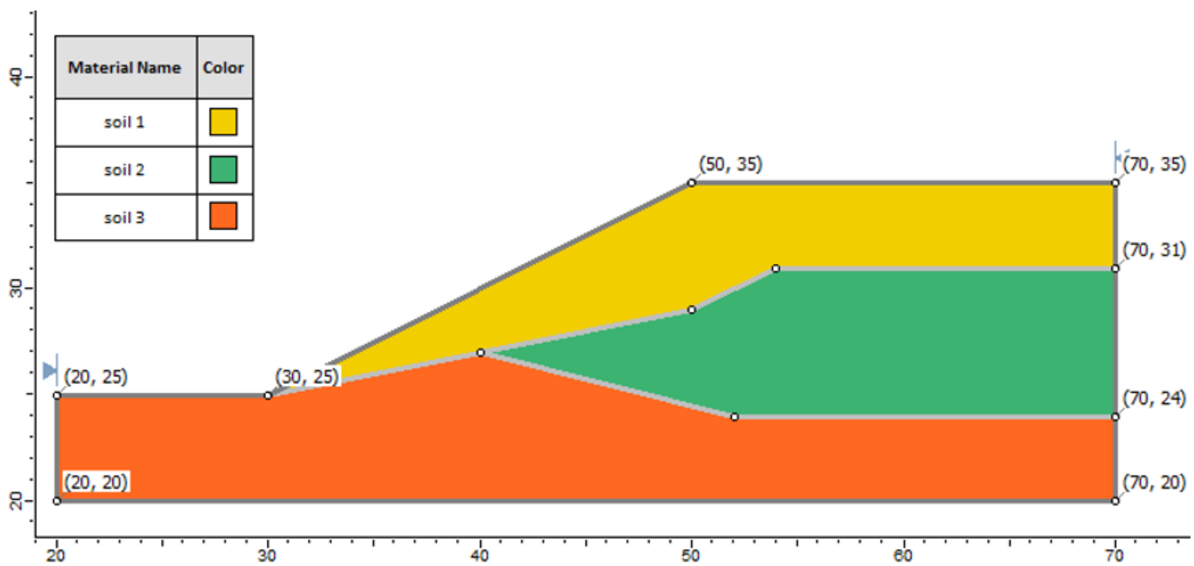


Figure 3.1: Geometry Setup in **Slide**

Table 3.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Soil #1	0.0	38.0	19.5
Soil #2	5.3	23.0	19.5
Soil #3	7.2	20.0	19.5

3.4. Results

Table 3.2

Method	Factor of Safety
Bishop	1.405
Spencer	1.375
GLE	1.374
Janbu Corrected	1.357

Note: Reference factor of safety = 1.65 [Giam]

Mean Bishop FOS (16 samples) = 1.406

Mean FOS (31 samples) = 1.381

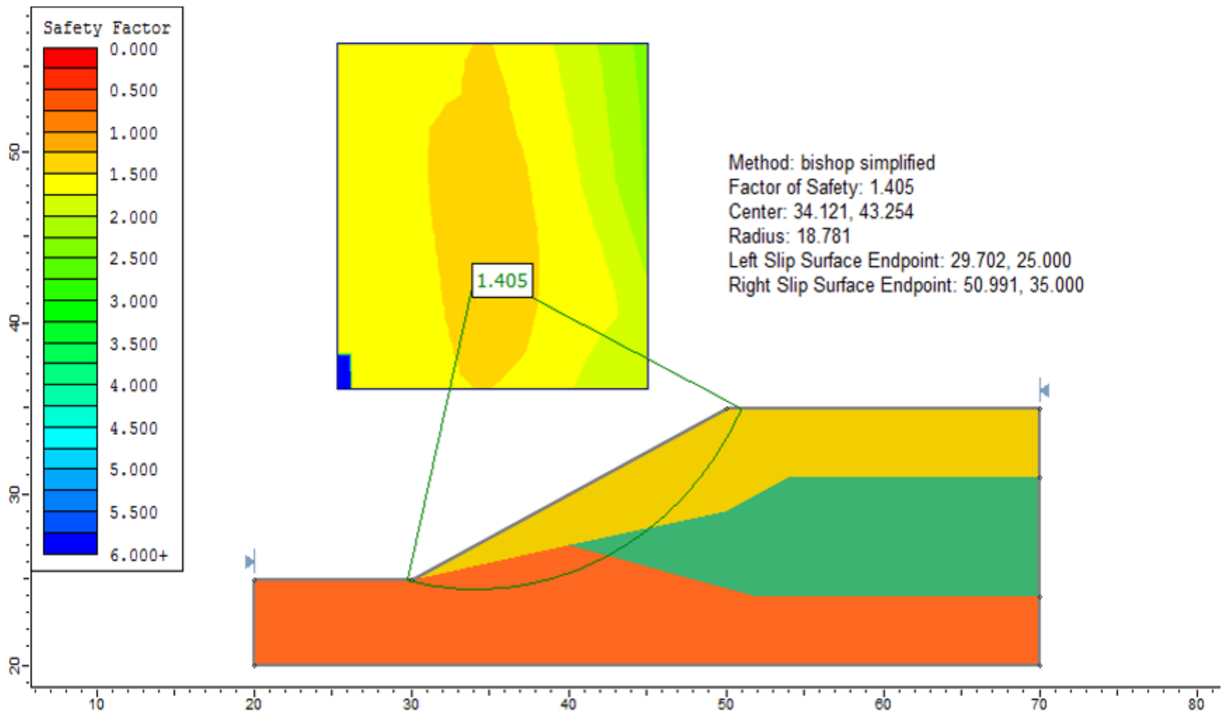


Figure 3.2: Solution, using the Bishop simplified method

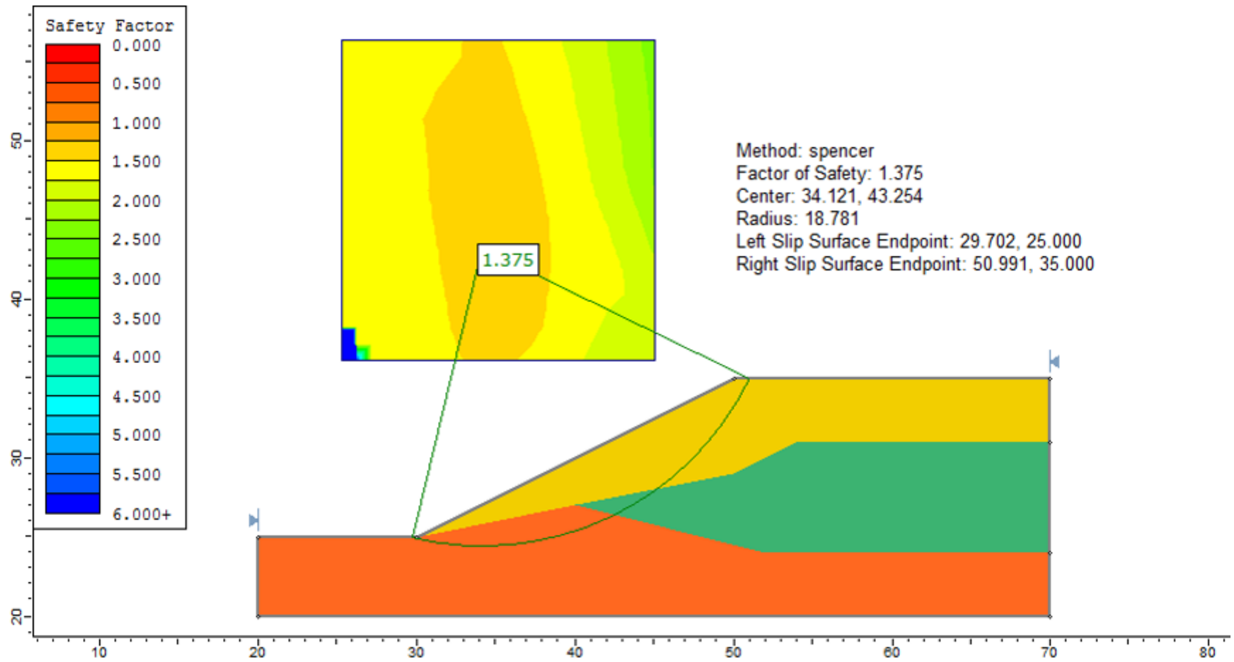


Figure 3.3: Solution, using the Spencer method

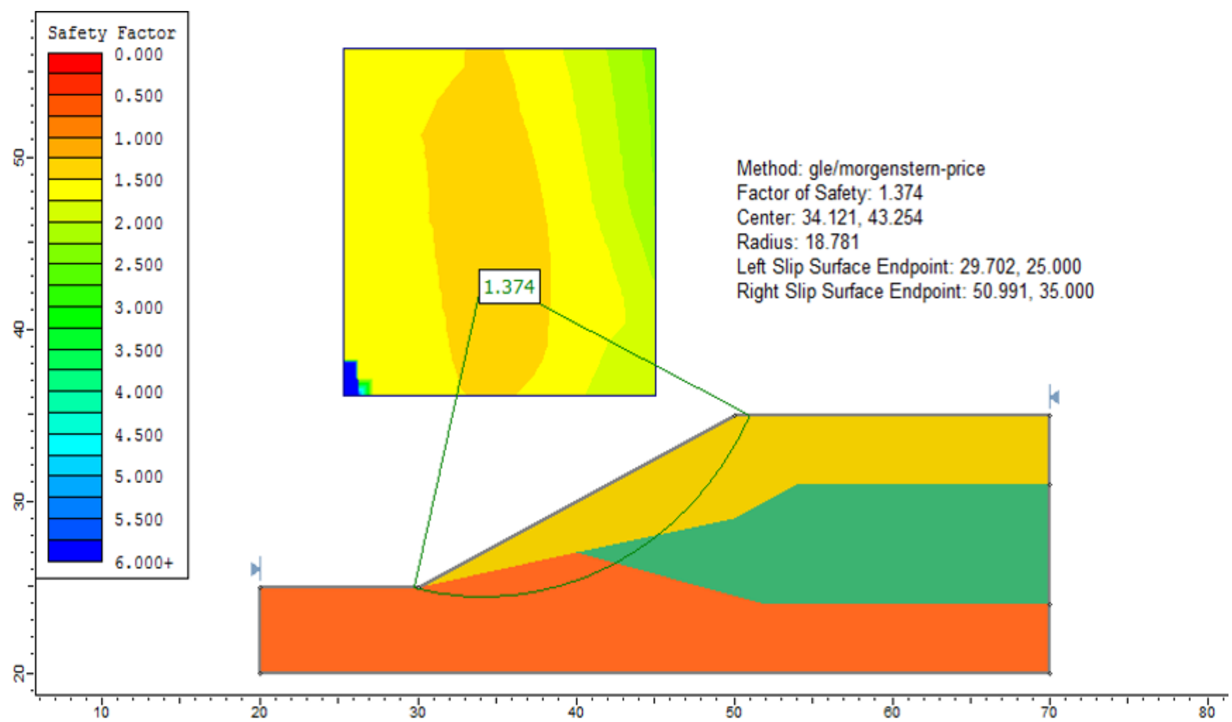


Figure 3.4: Solution, using the GLE method

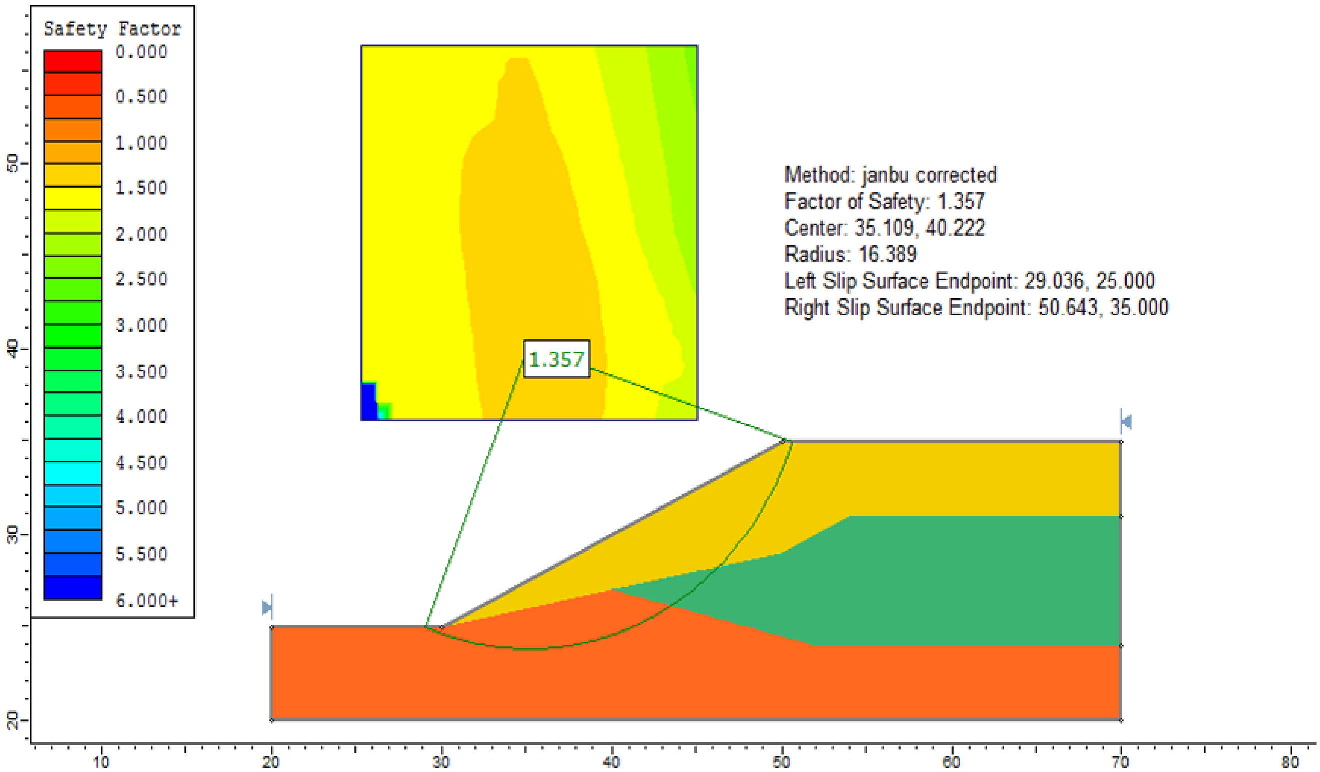


Figure 3.5: Solution, using the Janbu corrected method

4. Slide 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

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

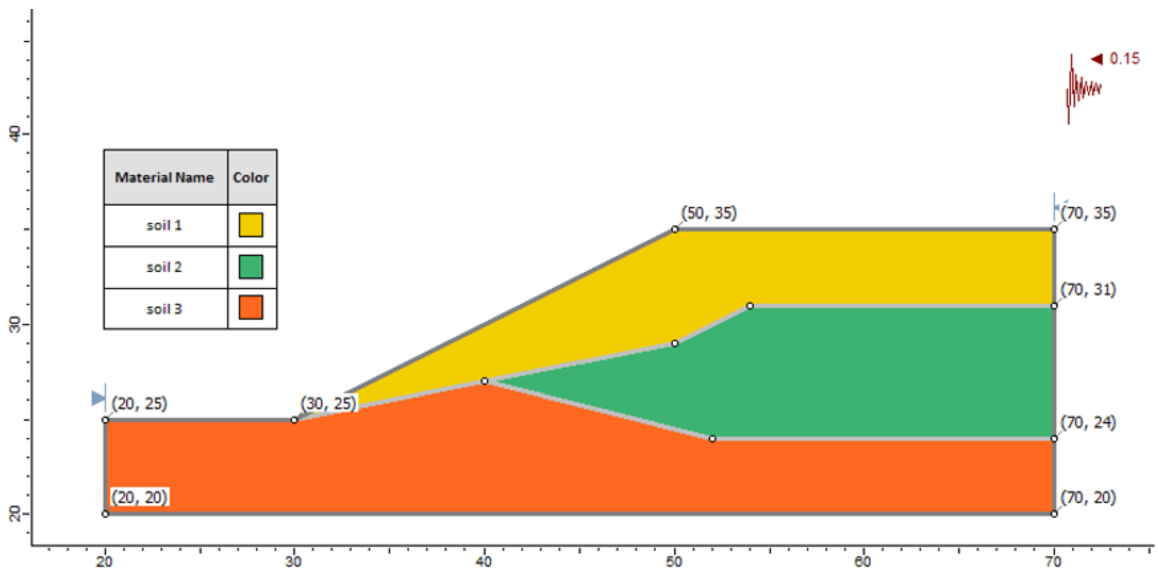


Figure 4.1: Geometry Setup in **Slide**

Table 4.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Soil #1	0.0	38.0	19.5
Soil #2	5.3	23.0	19.5
Soil #3	7.2	20.0	19.5

4.4. Results

Table 4.2

Method	Factor of Safety
Bishop	1.016
Spencer	0.991
GLE	0.989
Janbu Corrected	0.965

Note: Reference factor of safety = 1.00 [Giam]

Mean FOS (15 samples) = 0.973

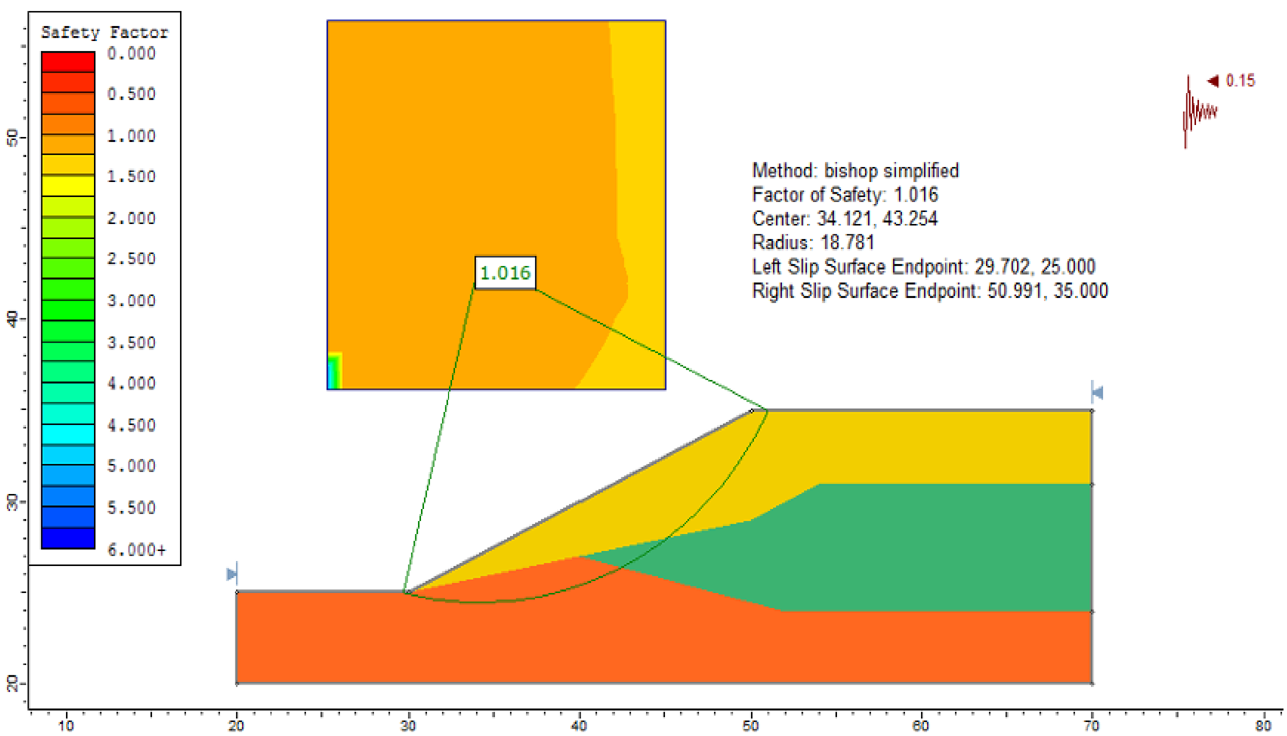


Figure 4.2: Solution, using the Bishop simplified method

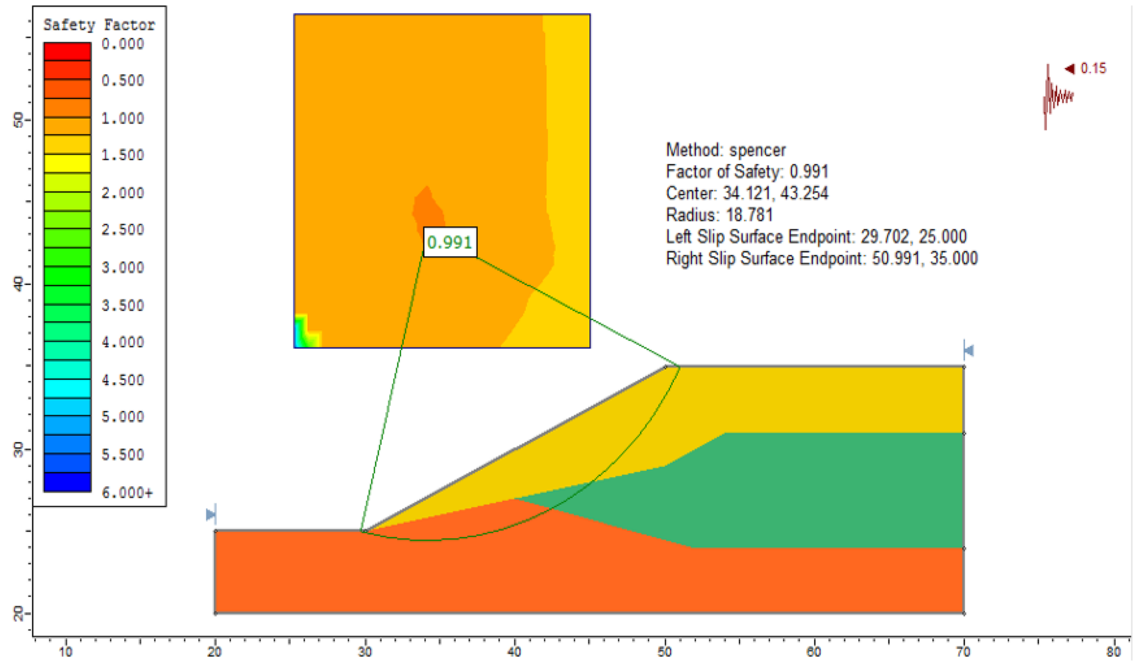


Figure 4.3: Solution, using the Spencer method

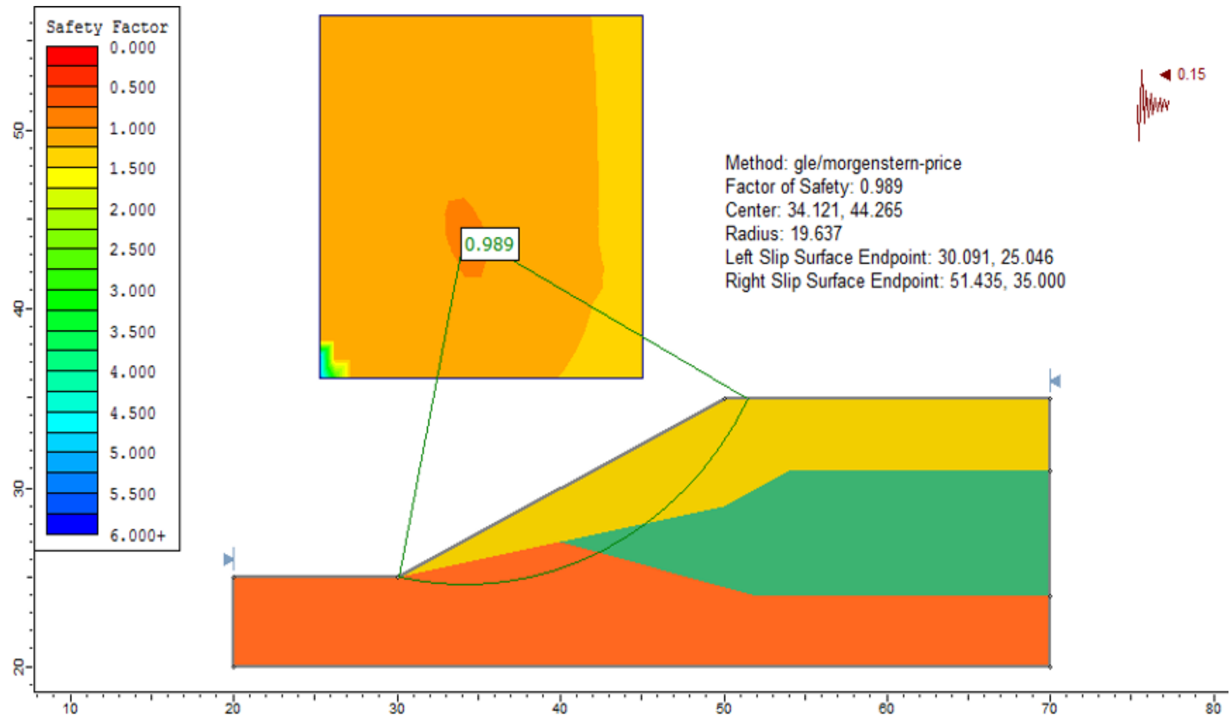


Figure 4.4: Solution, using the GLE method

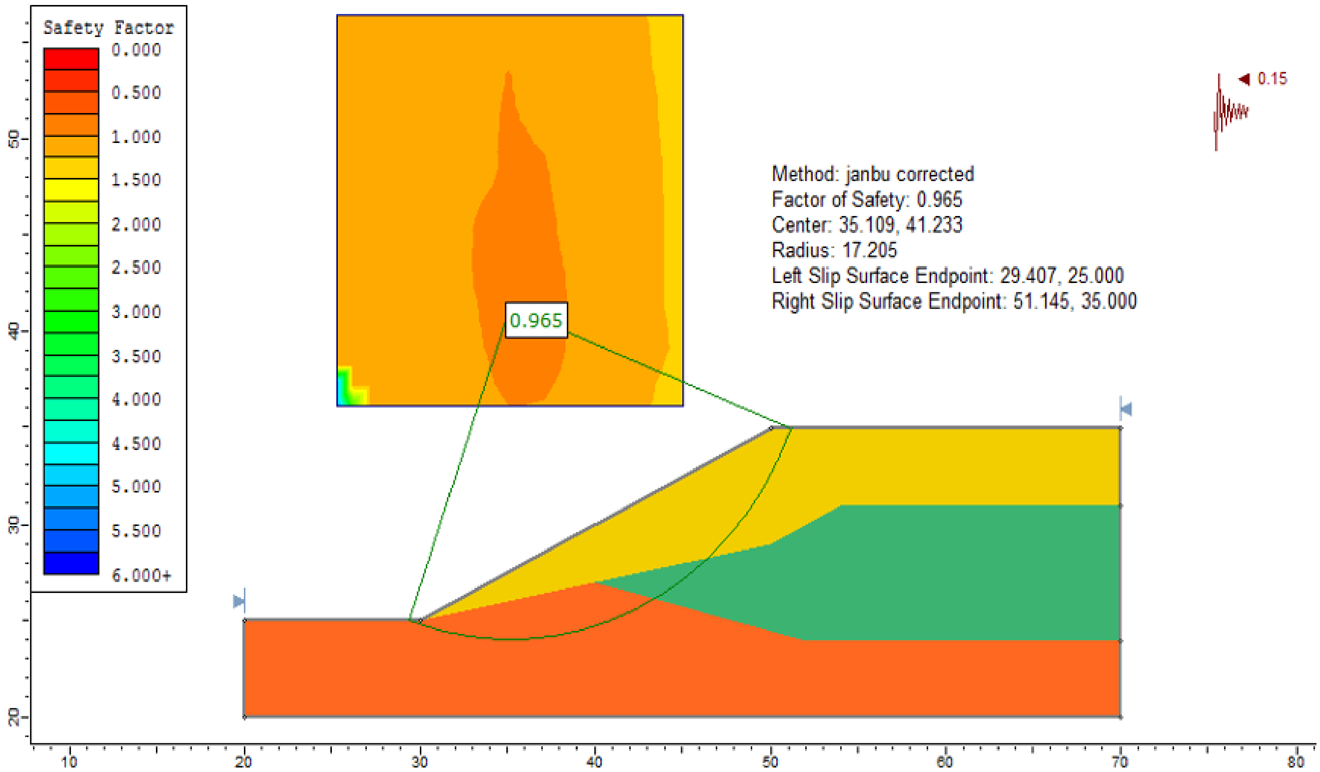


Figure 4.5: Solution, using the Janbu corrected method

5. Slide 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

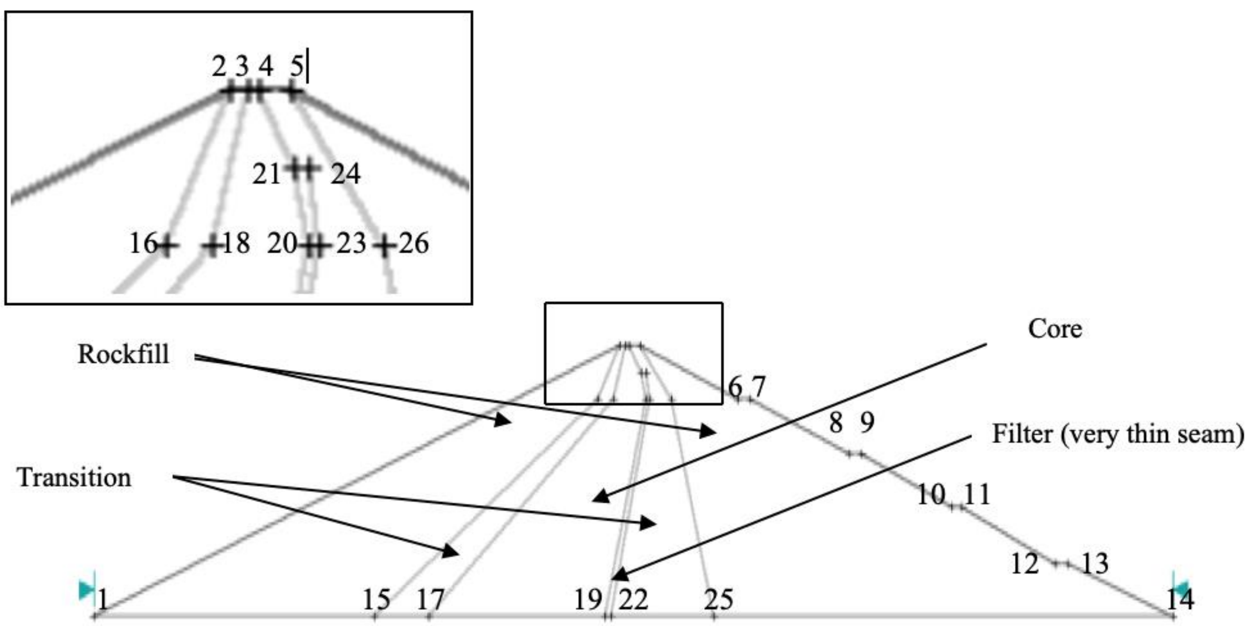


Figure 5.1: Point Identification

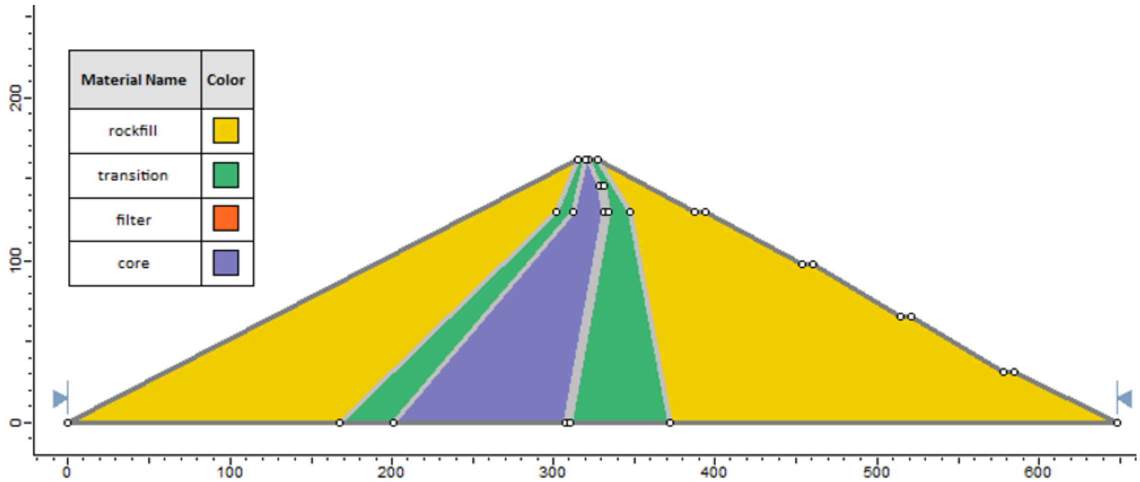


Figure 5.2: Geometry Setup in **Slide**

Table 5.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
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	--	--	--

5.4. Results

Table 5.3

Method	Factor of Safety
Bishop	1.948
Spencer	1.948
GLE	1.948
Janbu Corrected	1.949

Note: Reference factor of safety = 1.95 [Giam]

Mean FOS (24 samples) = 2.0

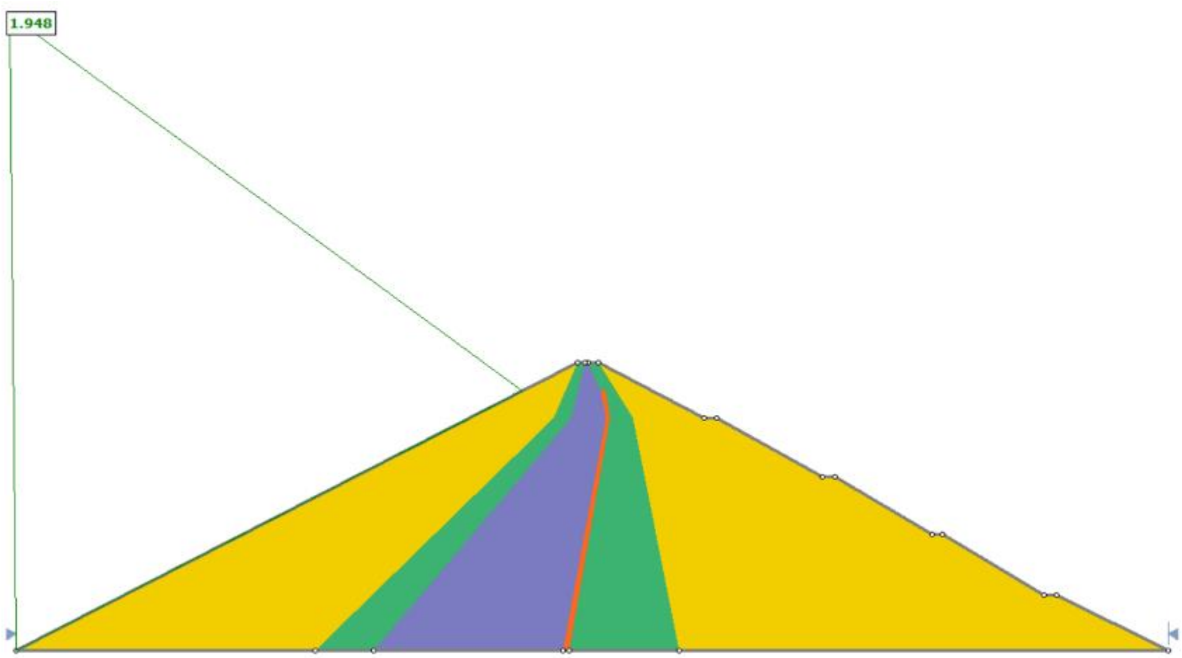


Figure 5.3: Solution, using the Bishop simplified method

Note: the minimum safety factor surfaces in this case, correspond to shallow, translational slides parallel to the slope surface.

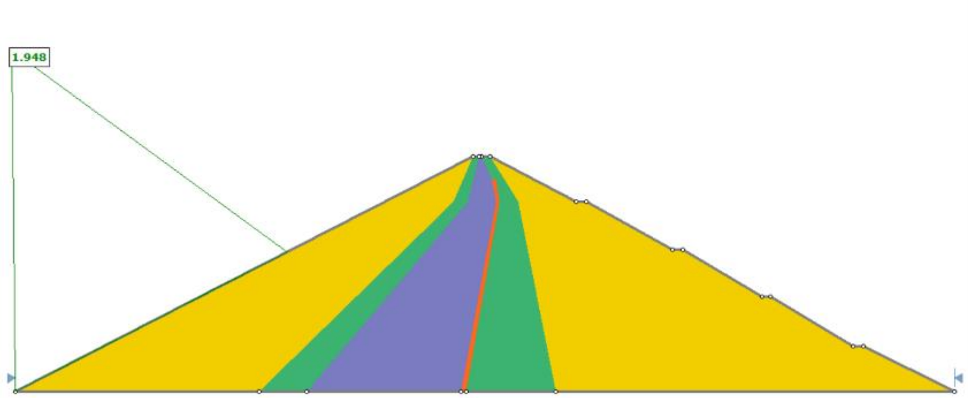


Figure 5.4: Solution, using the Spencer method

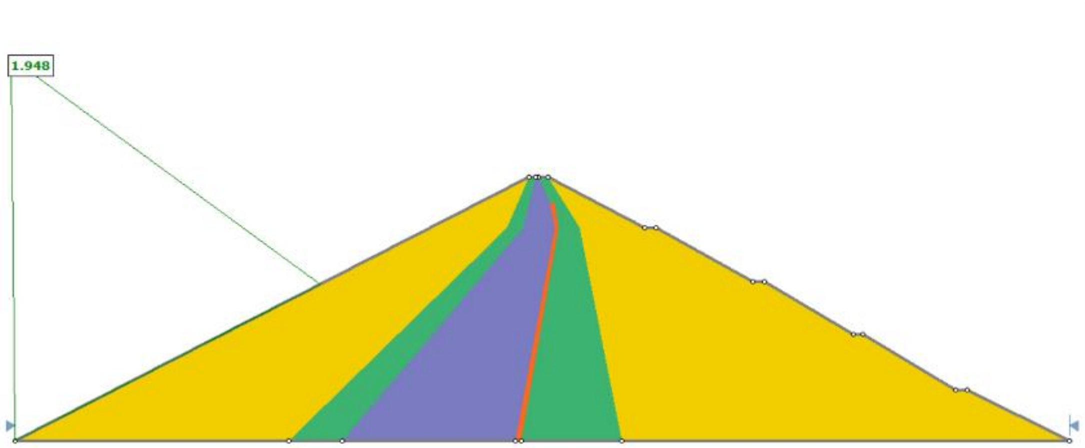


Figure 5.5: Solution, using the GLE method

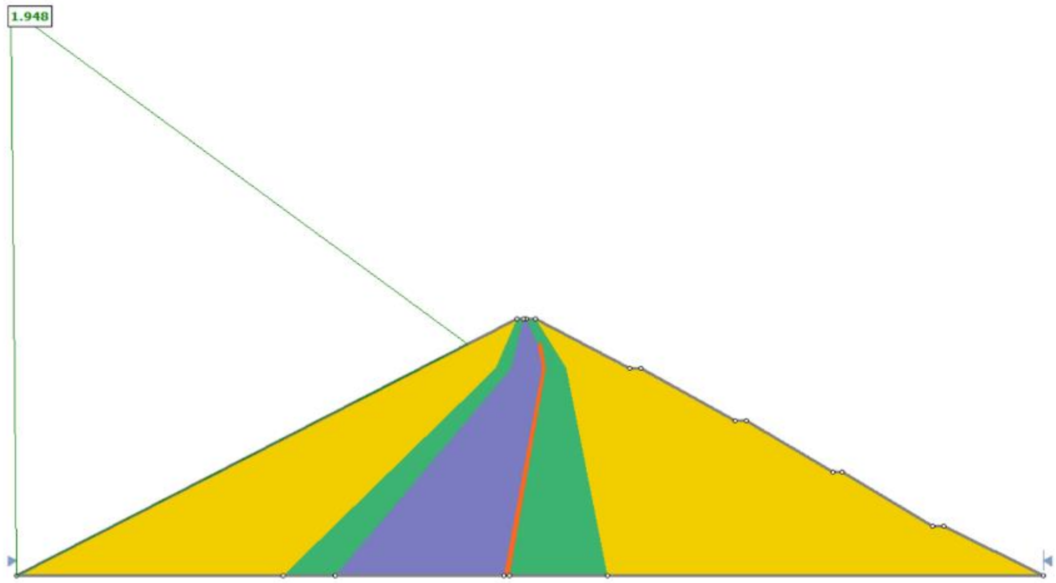


Figure 5.6: Solution, using the Janbu corrected method

6. Slide 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

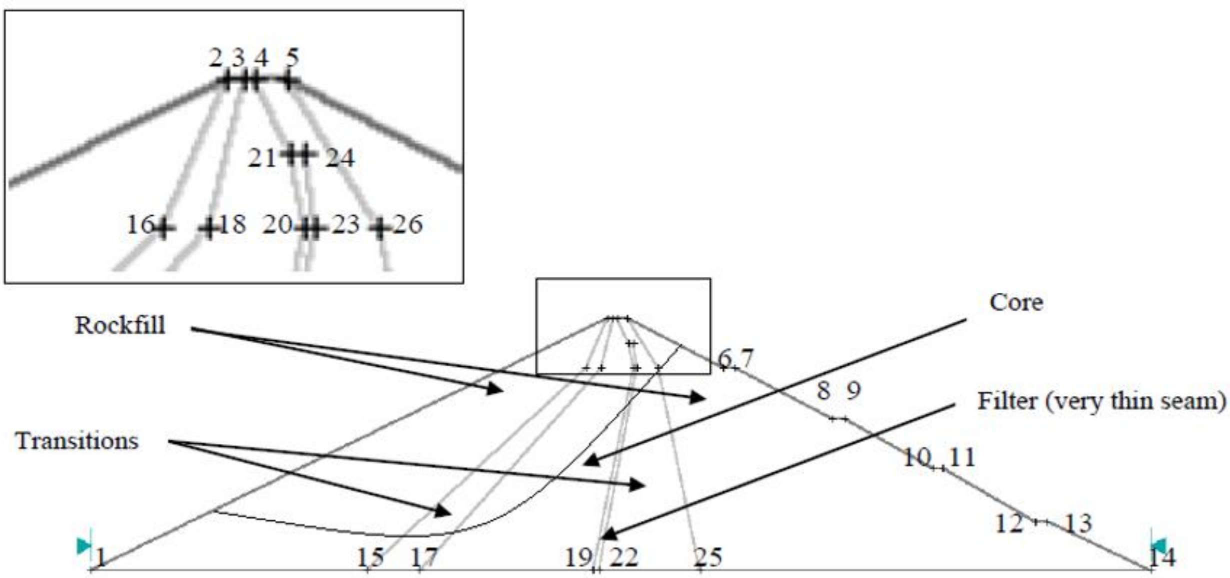


Figure 6.1: Point Identification

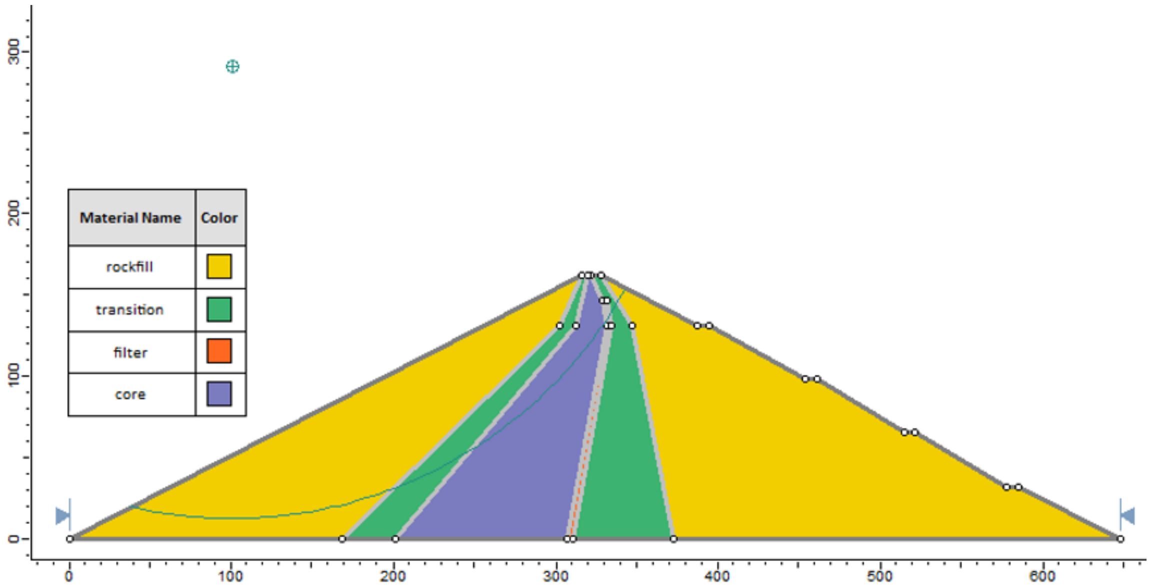


Figure 6.2: Geometry Setup in **Slide**

Table 6.1: Data for slip circle

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

Note: Soil properties in Problem #6 are the same as Problem #5

6.4. Results

Table 6.2

Method	Factor of Safety
Bishop	2.208
Spencer	2.292
GLE	2.301
Janbu Corrected	2.073

Note: Reference factor of safety = 2.29 [Giam]

Mean Bishop FOS (11 samples) = 2.204

Mean FOS (24 samples) = 2.239

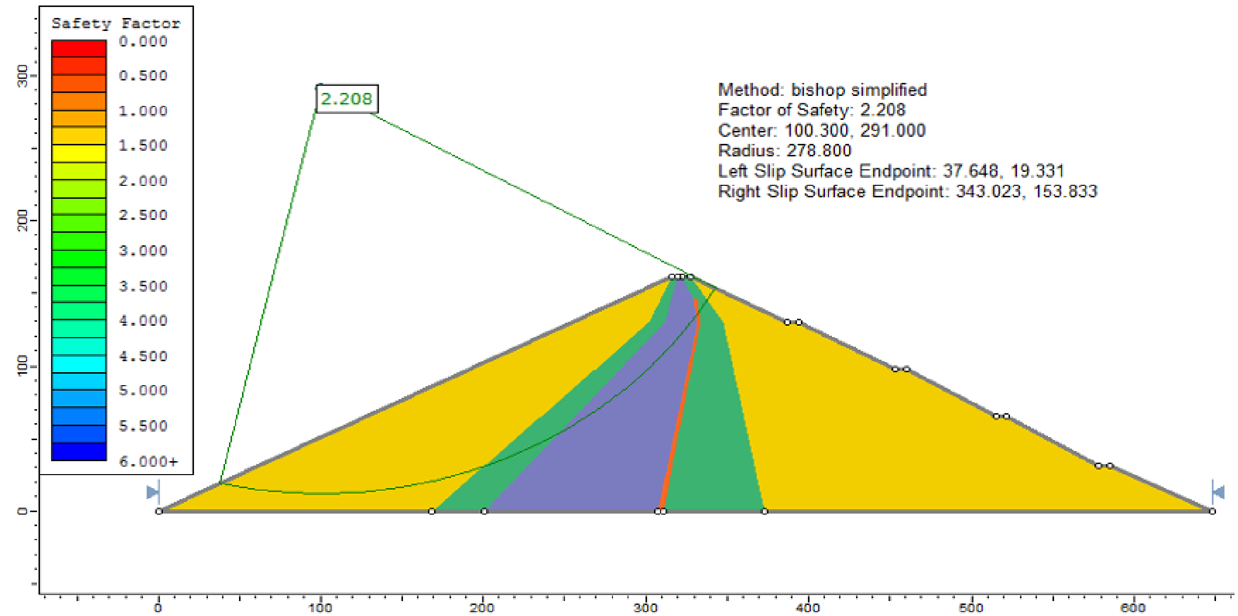


Figure 6.3: Solution, using the Bishop simplified method

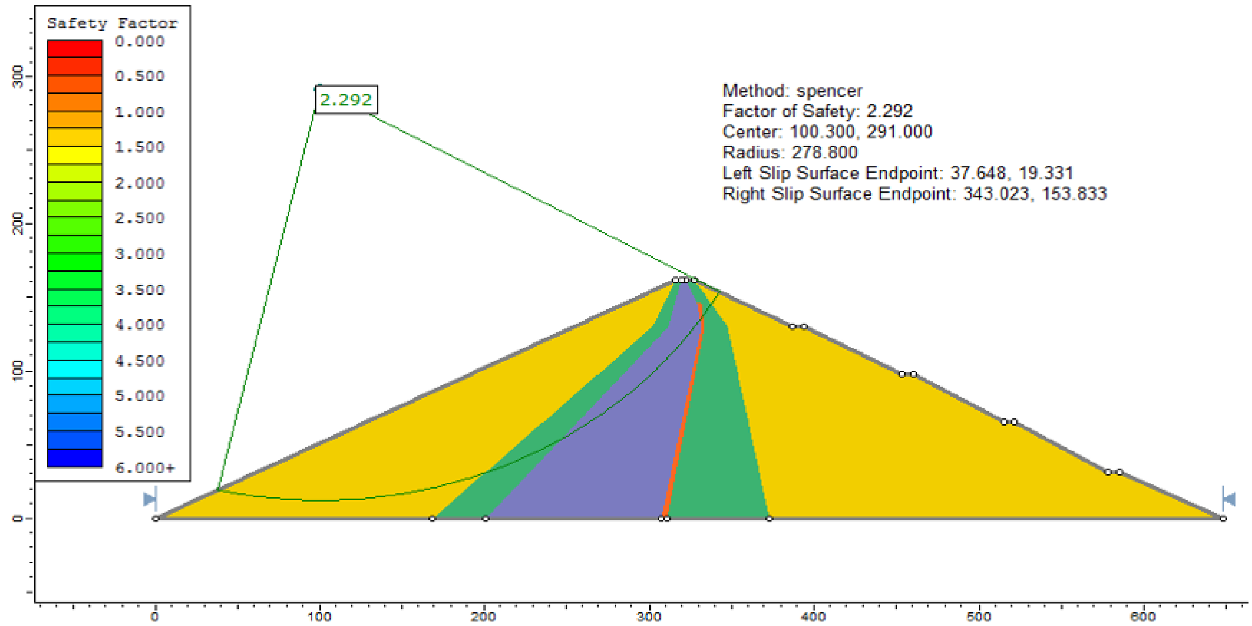


Figure 6.4: Solution, using the Spencer method

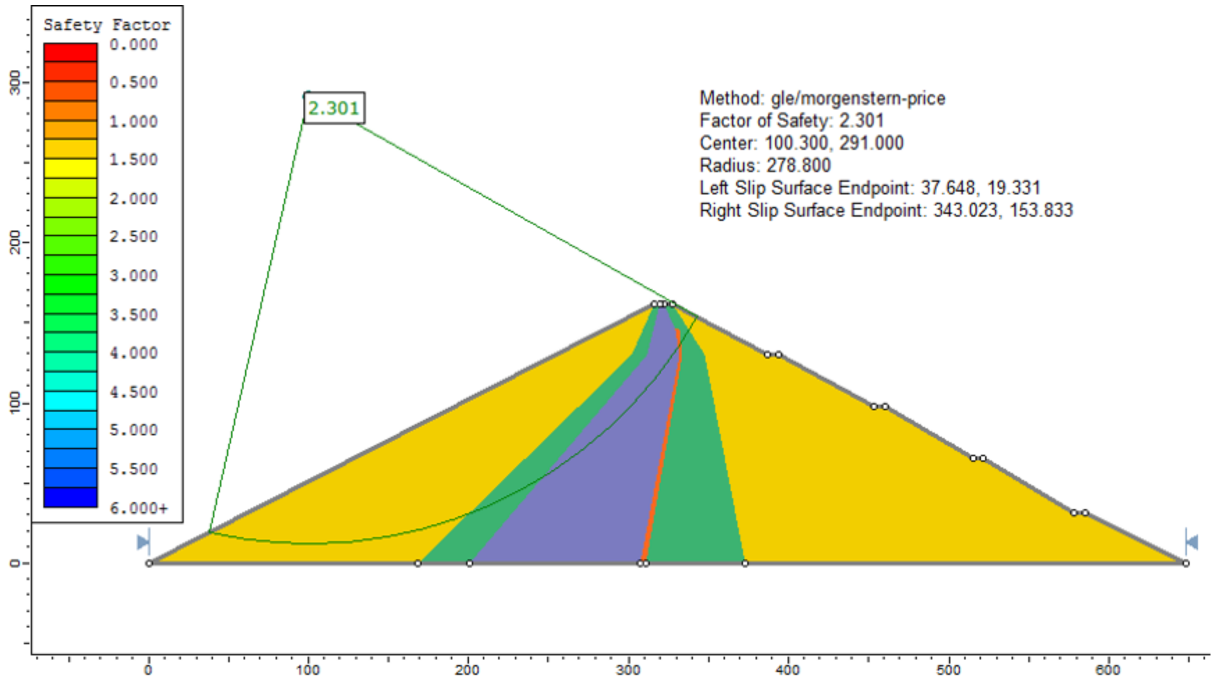


Figure 6.5: Solution, using the GLE method

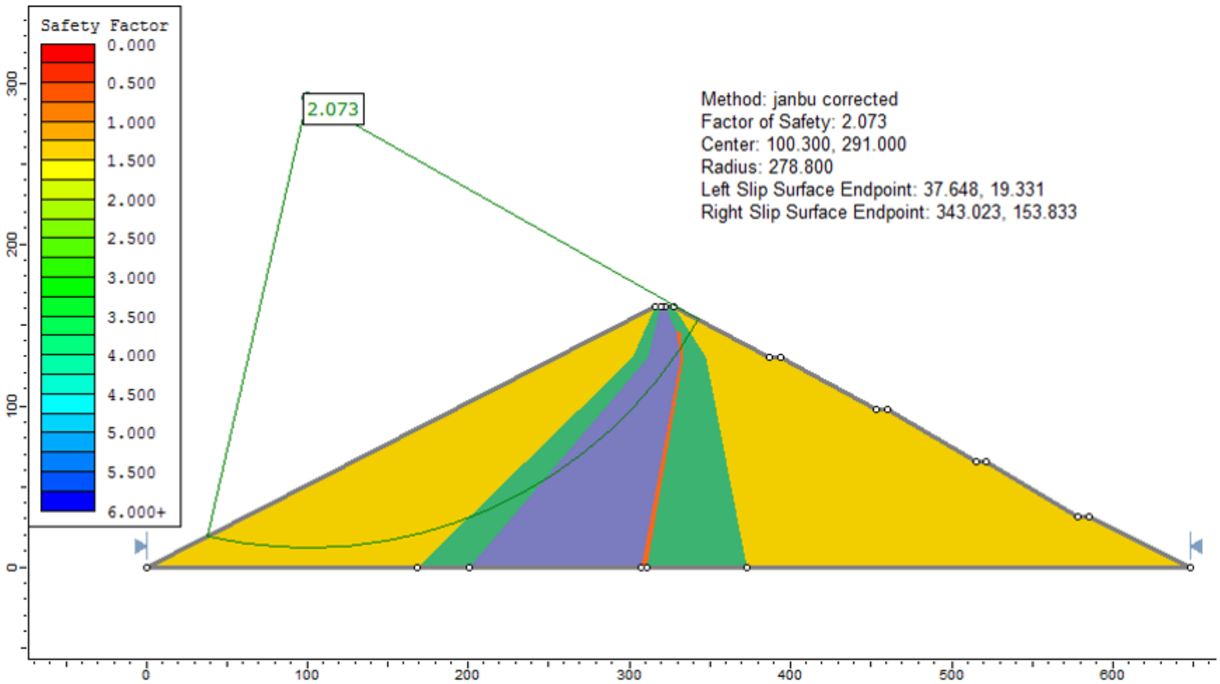


Figure 6.6: Solution, using the Janbu corrected method

7. Slide 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

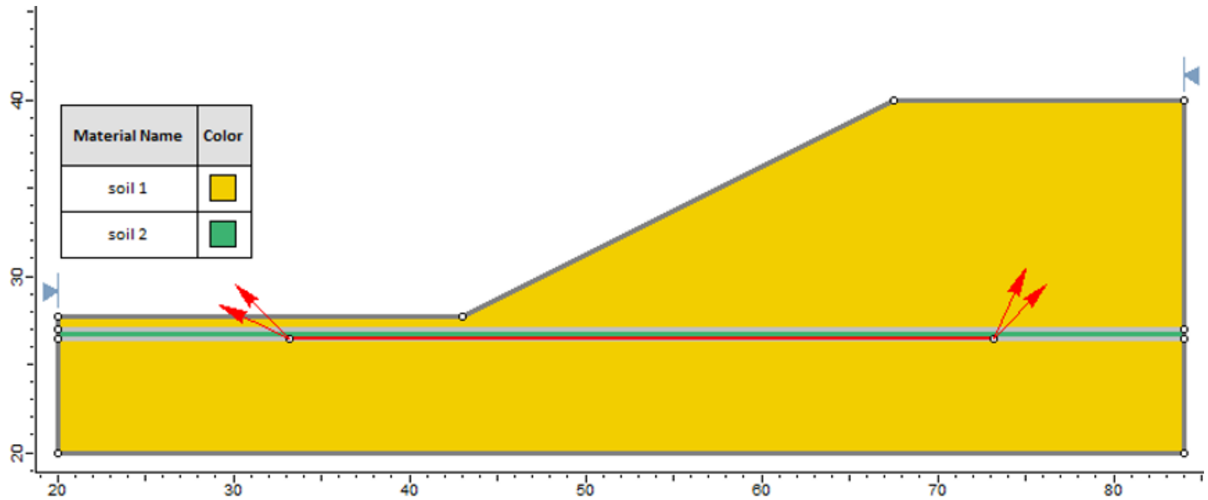


Figure 7.1: Geometry Setup in **Slide**

Table 7.1: Soil Properties

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

7.4. Results

Table 7.2

Method	Factor of Safety
Bishop	1.258
Spencer	1.246
GLE	1.275
Janbu Corrected	1.258

Note: Reference factor of safety = 1.24 – 1.27 [Giam]

Mean Non-circular FOS (19 samples) = 1.293

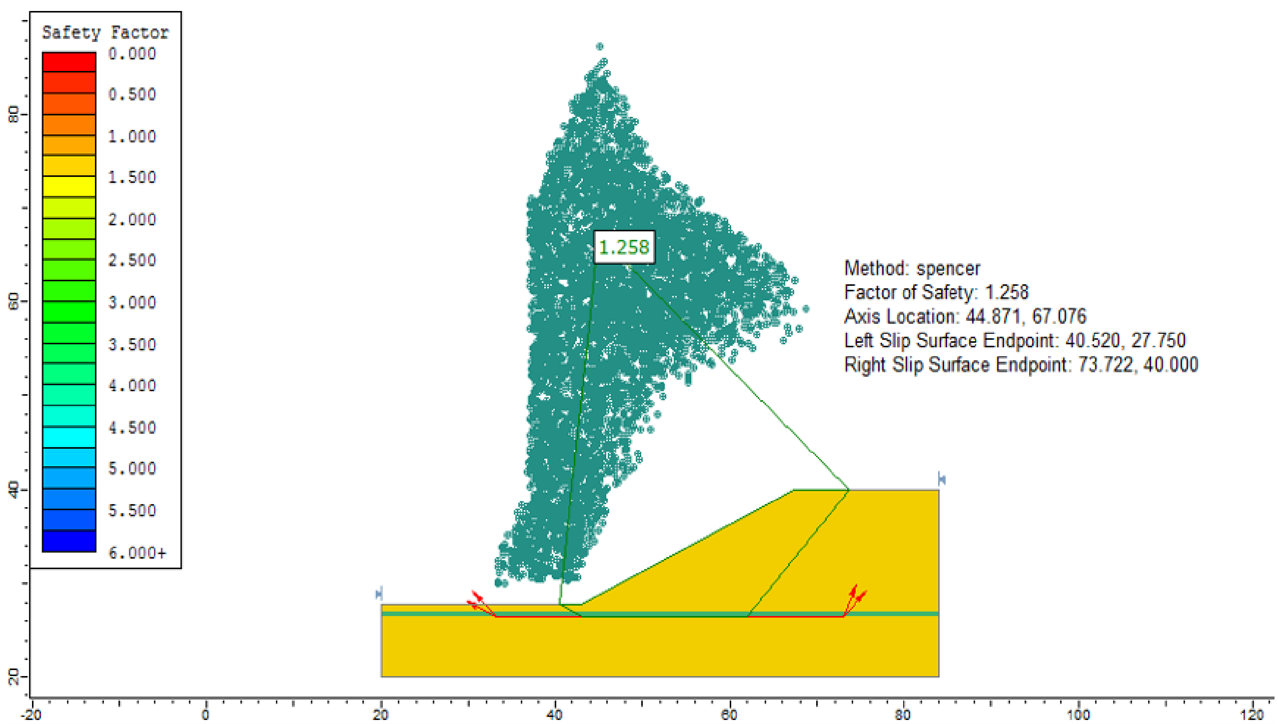


Figure 7.2: Solution, using the Spencer method

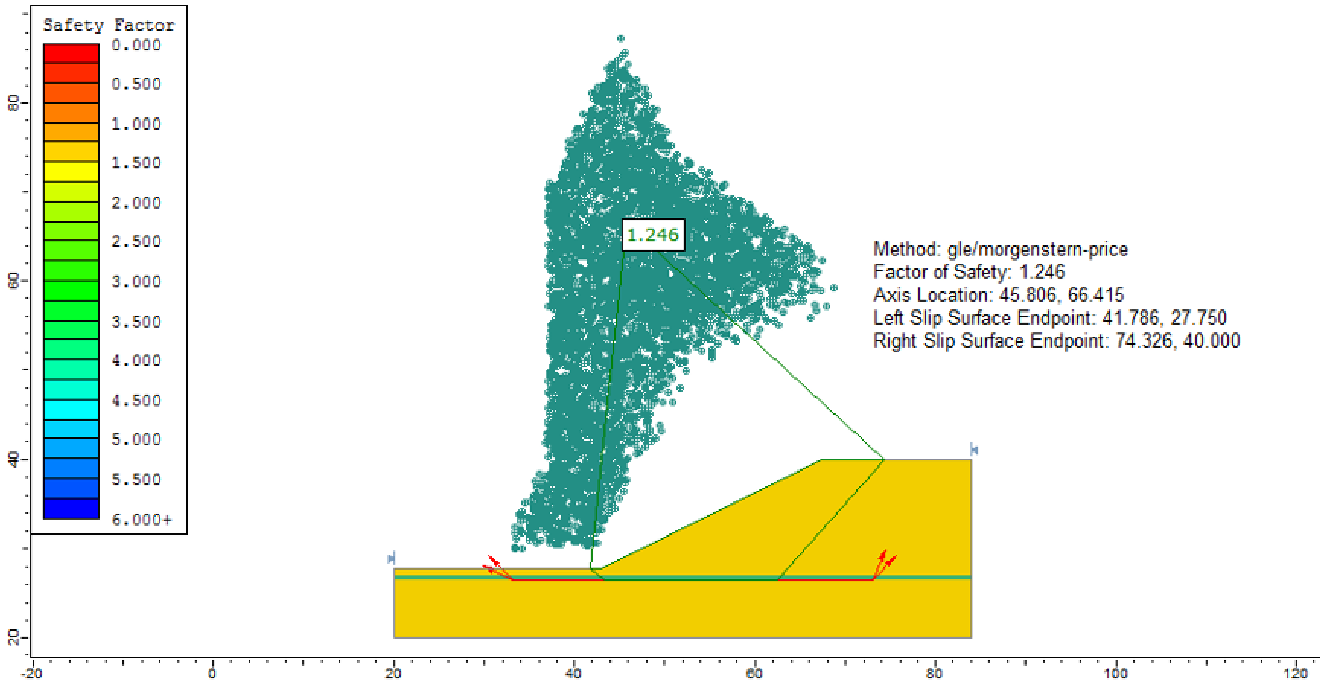


Figure 7.3: Solution, using the GLE method

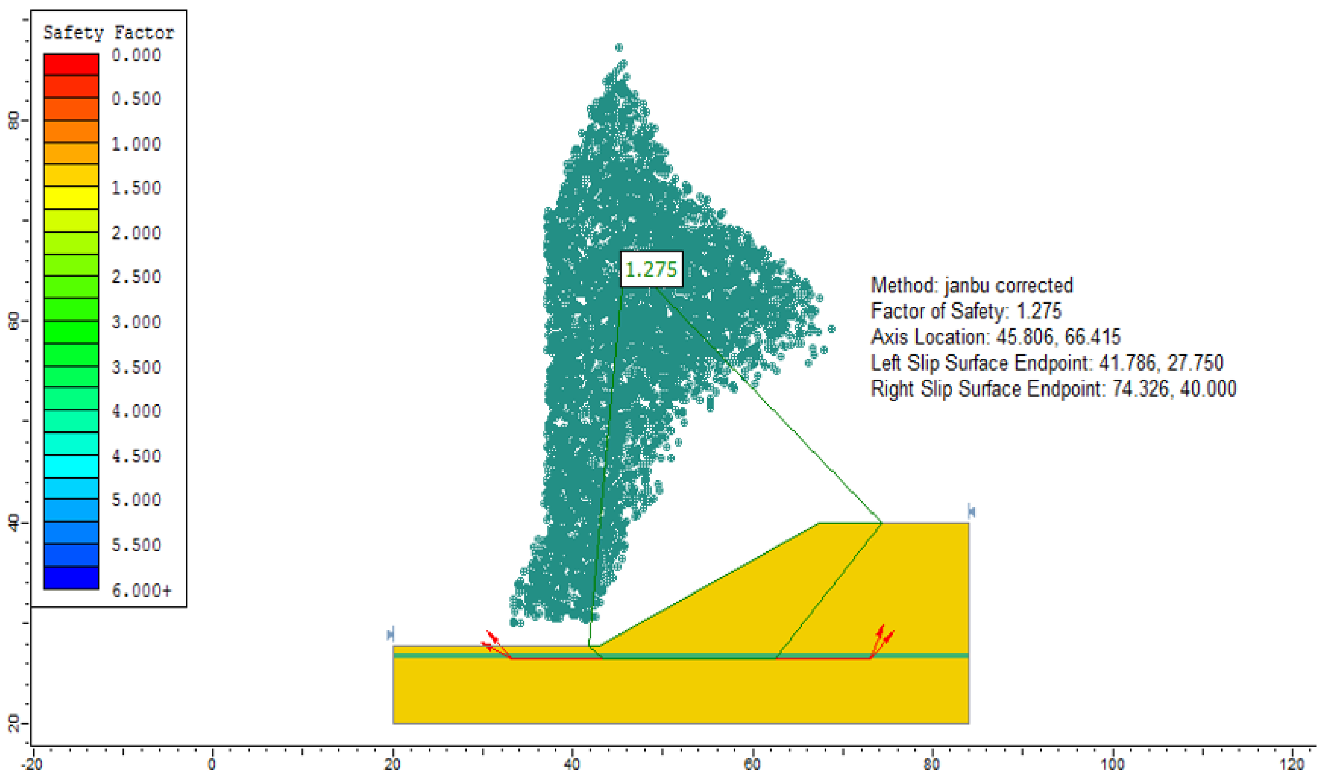


Figure 7.4: Solution, using the Janbu corrected method

8. Slide Verification Problem #8

Slope, (2) materials, weak layer, predefined slip surface

8.1. 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(b) problem.

8.2. Problem Description

Problem #8 is identical to verification problem #7, except that a single non-circular slip surface of known coordinates is analyzed.

8.3. Geometry and Material Properties

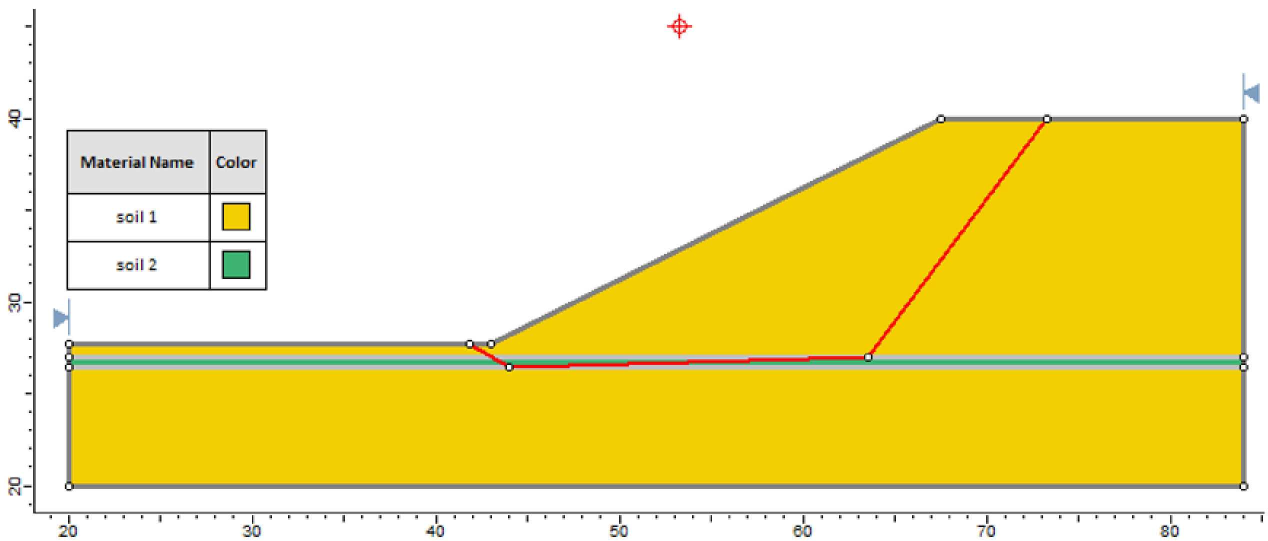


Figure 8.1: Geometry Setup in **Slide**

Table 8.1: Material Properties

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

Table 8.2: Failure Surface Coordinates

X (m)	Y (m)
41.85	27.75
44.00	26.50
63.50	27.00
73.31	40.00

8.4. Results

Table 8.3

Method	Factor of Safety
Spencer	1.277
GLE	1.262
Janbu Corrected	1.294

Note: Reference factor of safety = 1.34 [Giam]

Mean FOS (30 samples) = 1.29

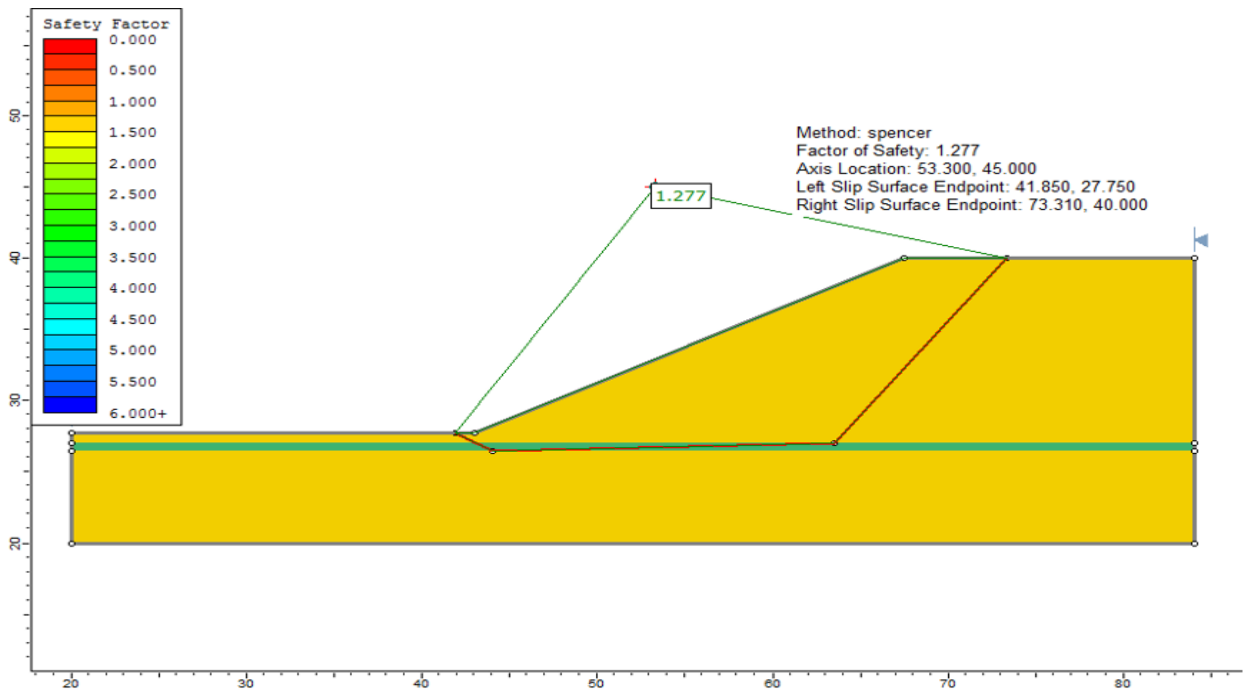


Figure 8.2: Solution, using the Spencer method

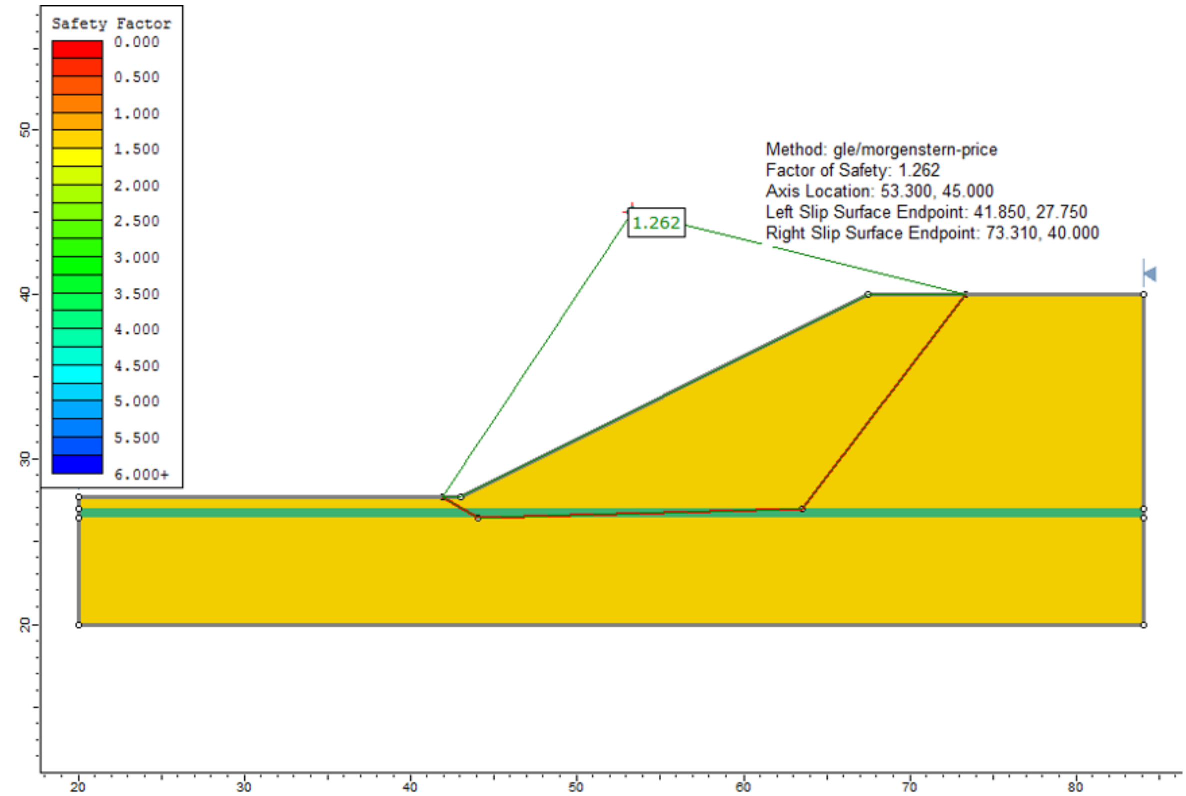


Figure 8.3: Solution, using the GLE method

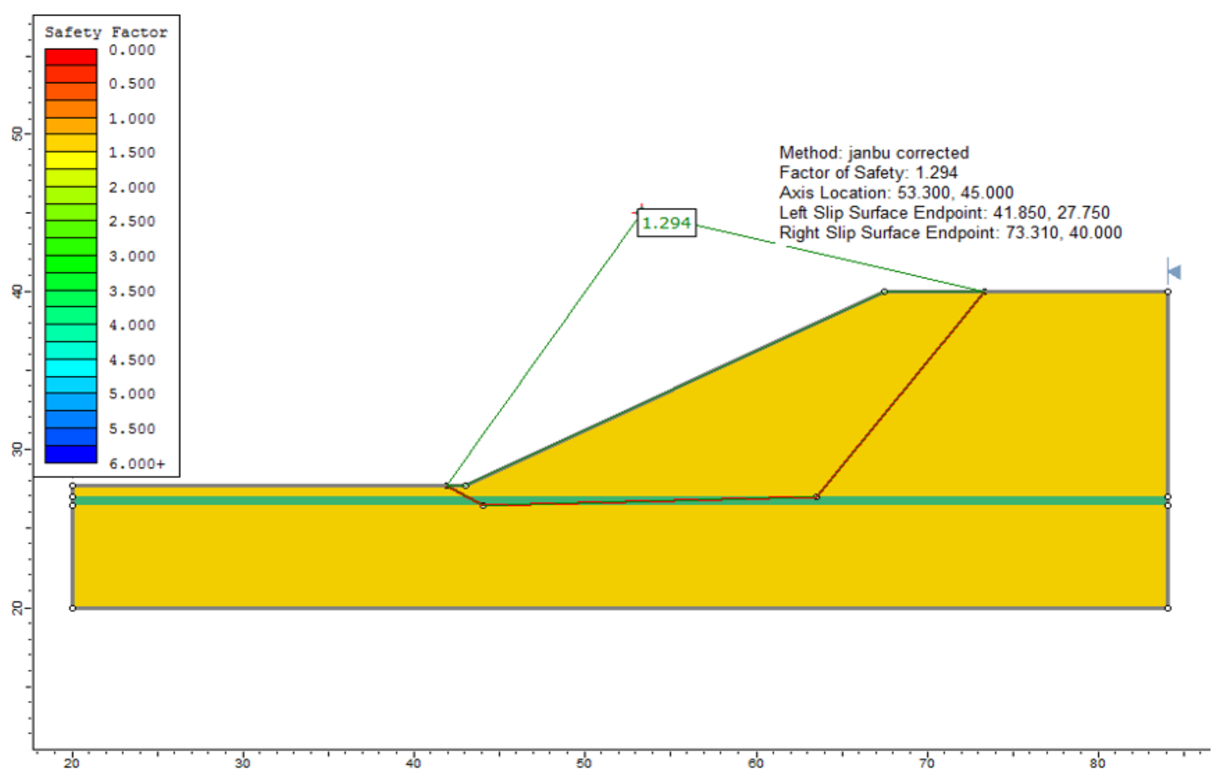


Figure 8.4: Solution, using the Janbu corrected method

9. Slide 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. A total of 5000 random surfaces were generated by the search. The results are compared with optimization results.

9.3. Geometry and Material Properties

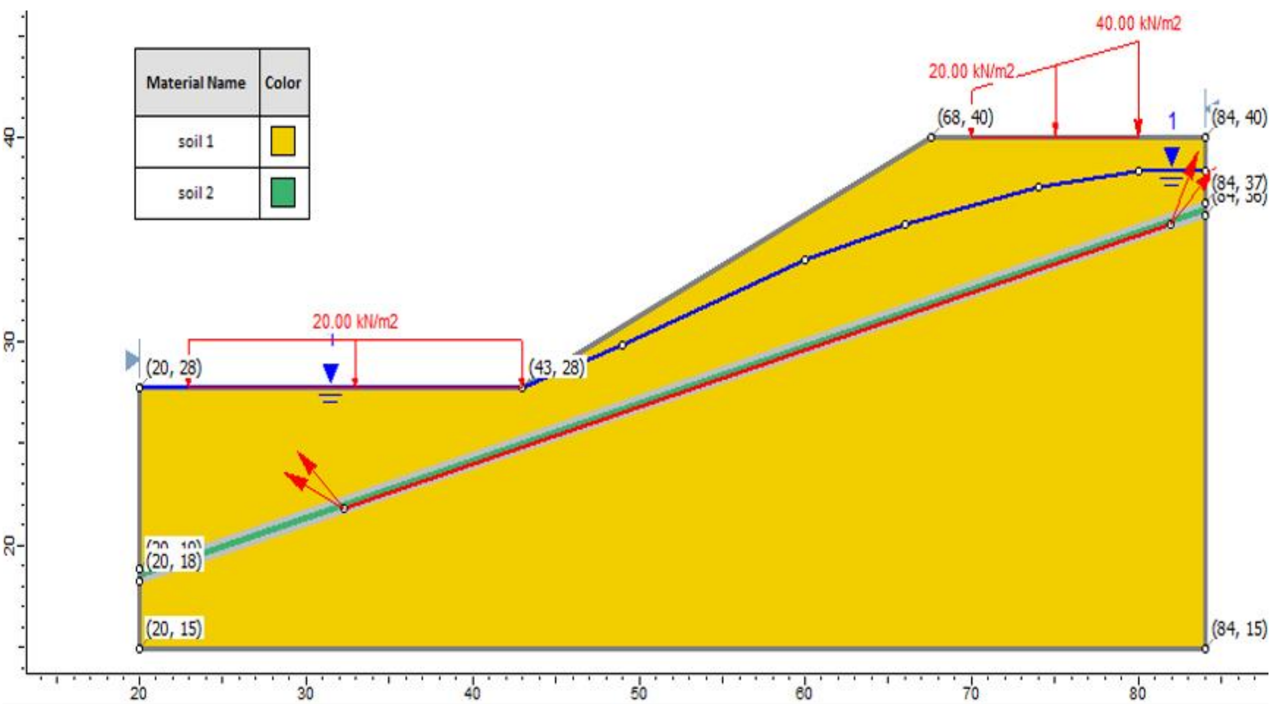


Figure 9.1: Geometry Setup in **Slide**

Table 9.1: Soil Properties

	c´ (kN/m^2)	**ϕ´ (deg.)**	**γ (kN/m^3)**
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/m^2)**
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

9.4. Results

No optimization

Table 9.4

Method	Factor of Safety
Spencer	0.760
GLE	0.720
Janbu Corrected	0.734

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]

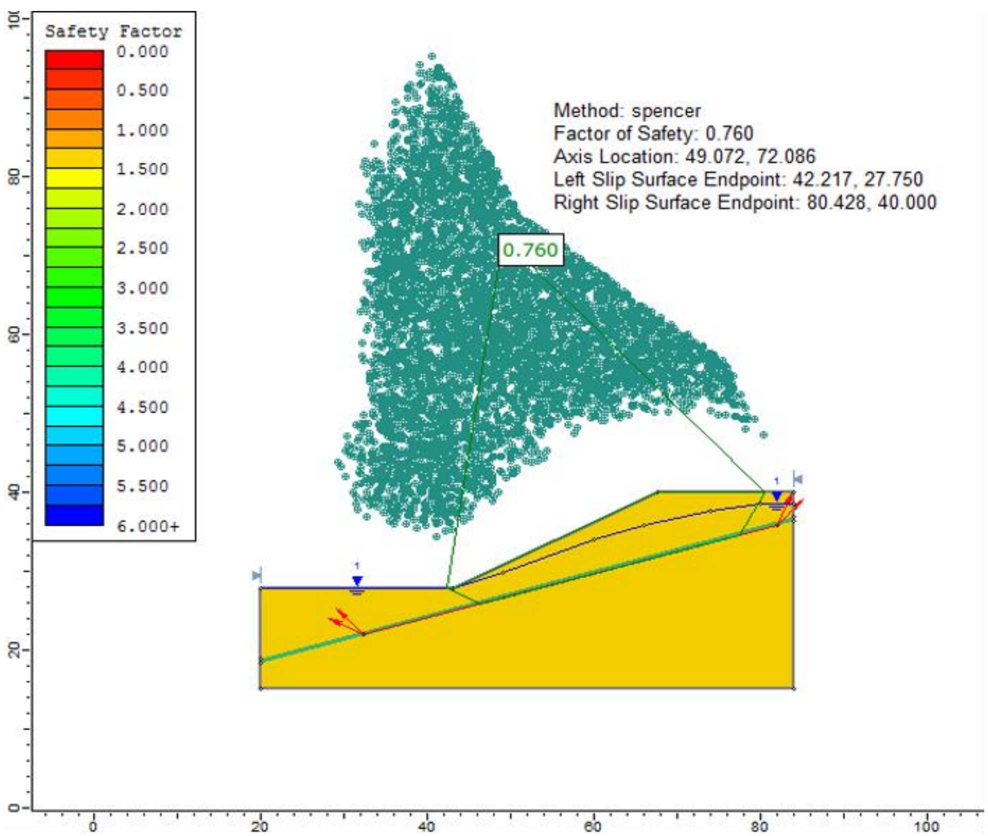


Figure 9.2: Solution, using the Spencer method

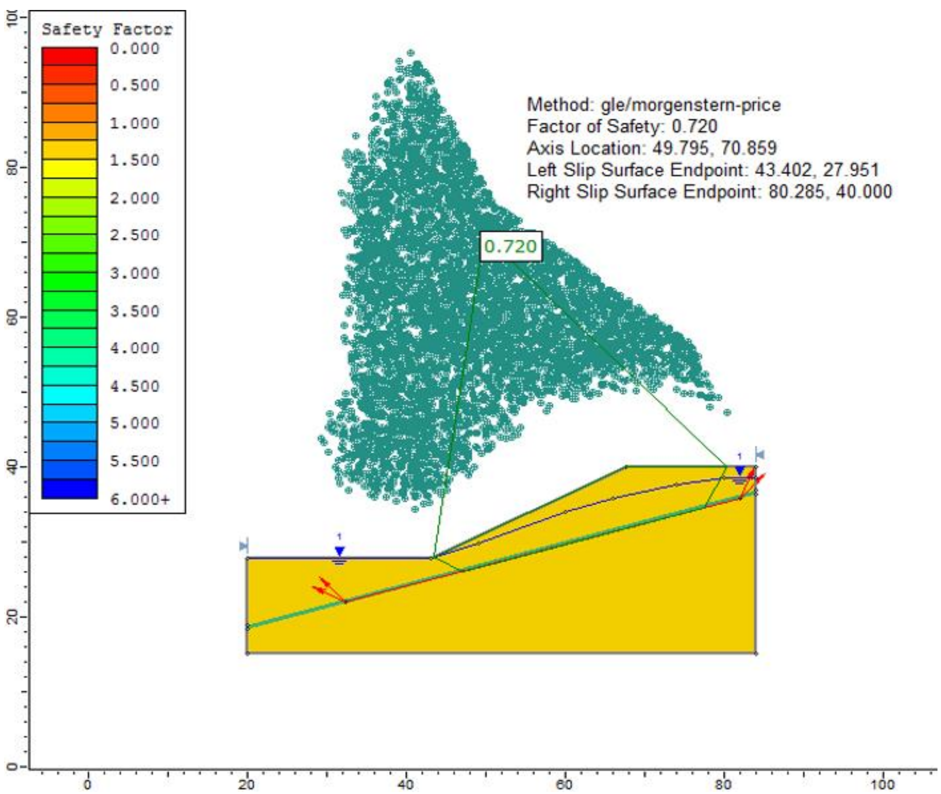


Figure 9.3: Solution, using the GLE method

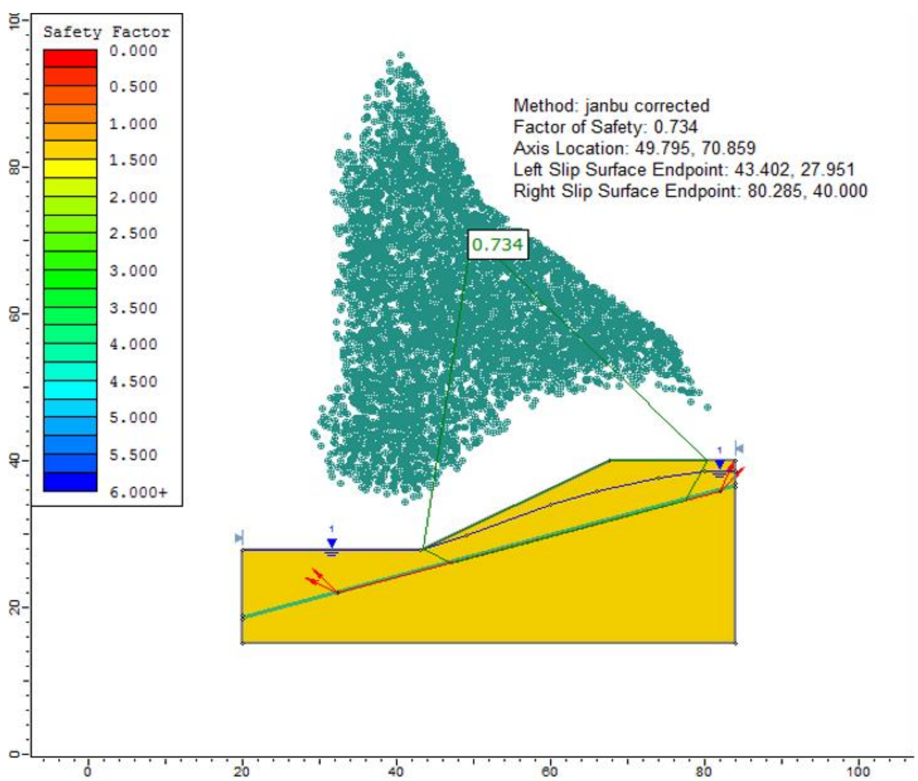


Figure 9.4: Solution, using the Janbu correction method

Table 9.5: Block search with optimization

Method	Factor of Safety
Spencer	0.707
GLE	0.683
Janbu Corrected	0.699

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]

10. Slide Verification Problem #10

Slope, homogenous, 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

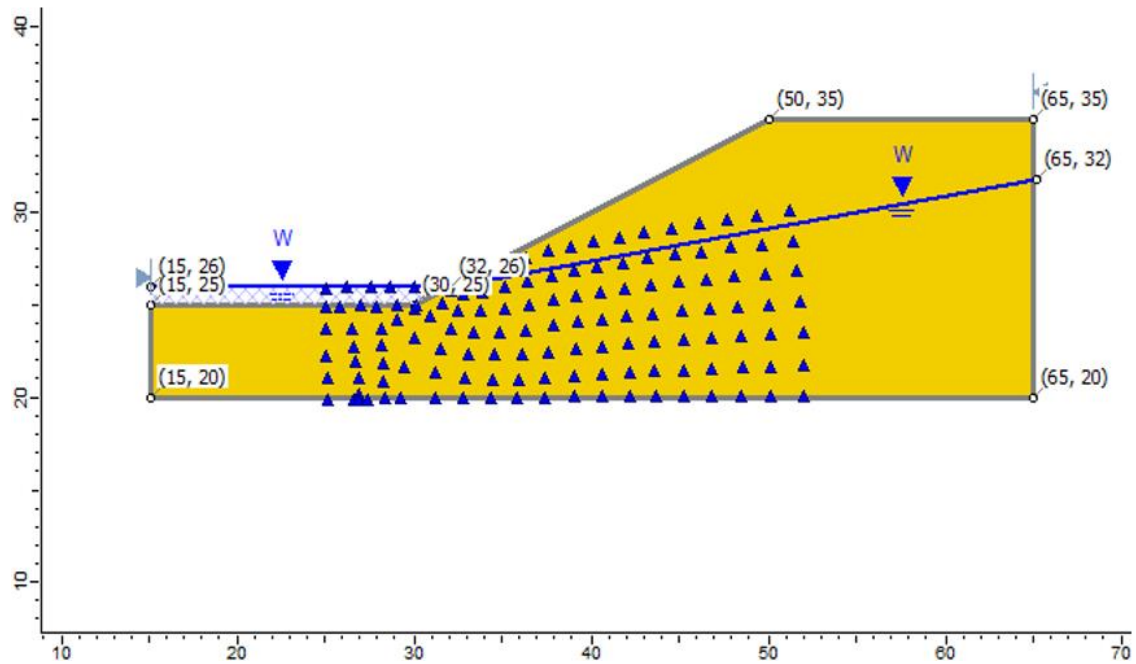


Figure 10.1: Geometry Setup in **Slide**

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

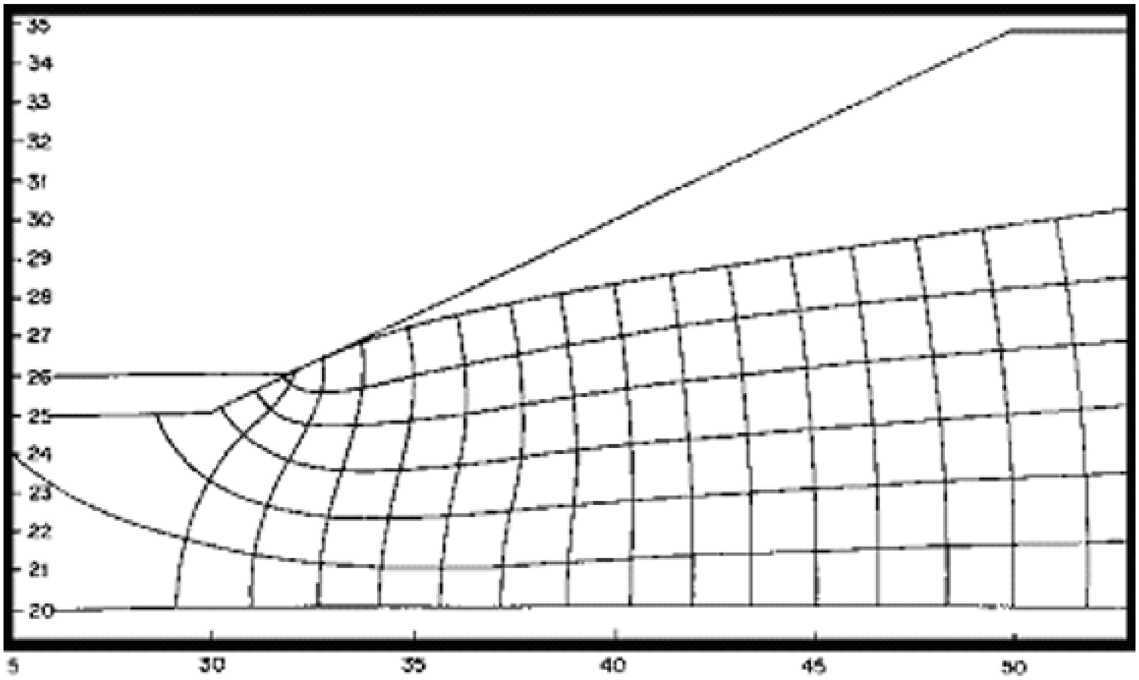


Figure 10.2: Approximate Flow Net

Table 10.1: Soil Properties

c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
11.0	28.0	20.00

10.4. Results

Table 10.2

Method	Factor of Safety
Bishop	1.498
Spencer	1.500
GLE	1.500
Janbu Corrected	1.457

Note: Reference factor of safety = 1.53 [Giam]

Mean FOS (23 samples) = 1.464

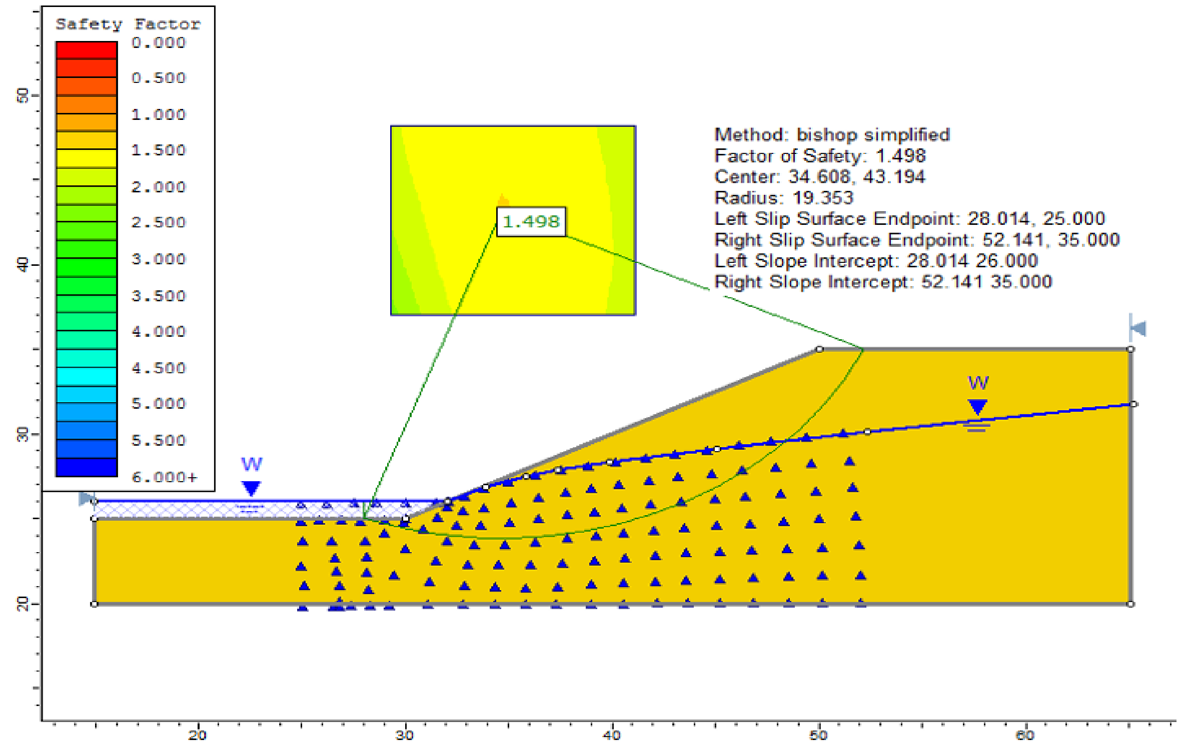


Figure 10.3: Solution, using the Bishop simplified method

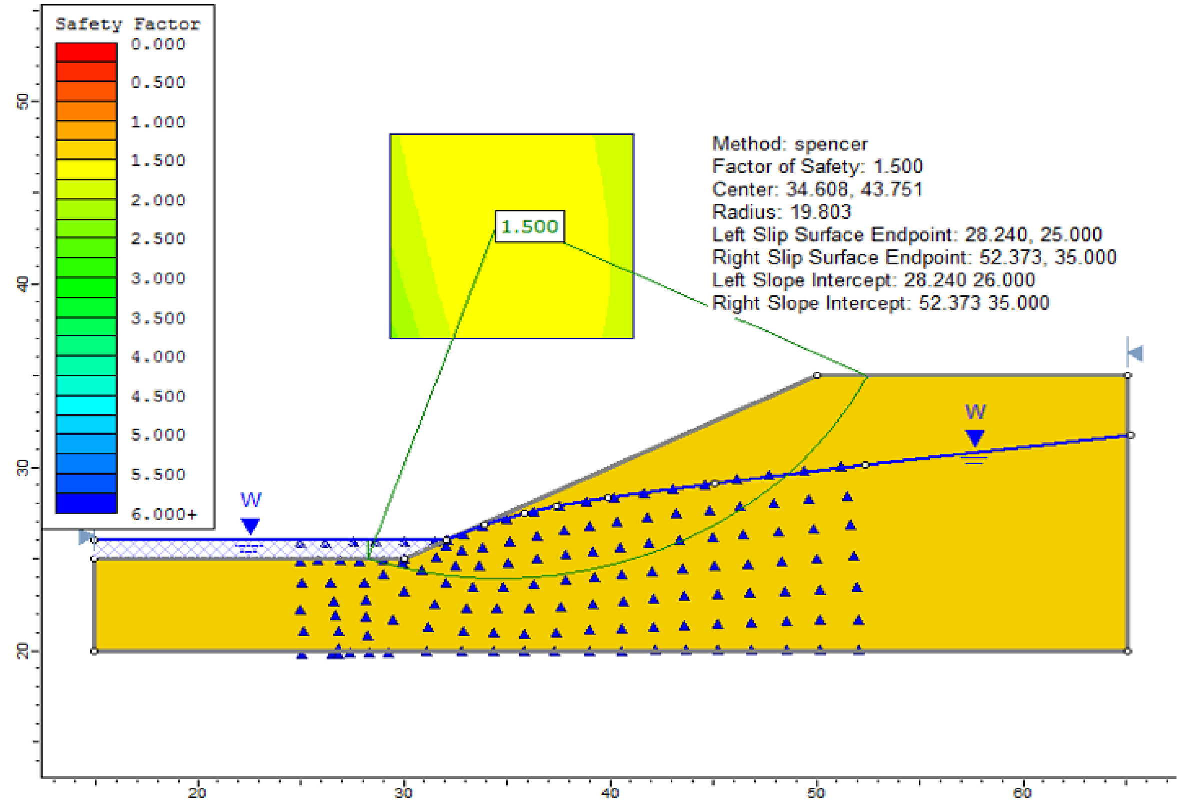


Figure 10.4: Solution, using the Spencer method

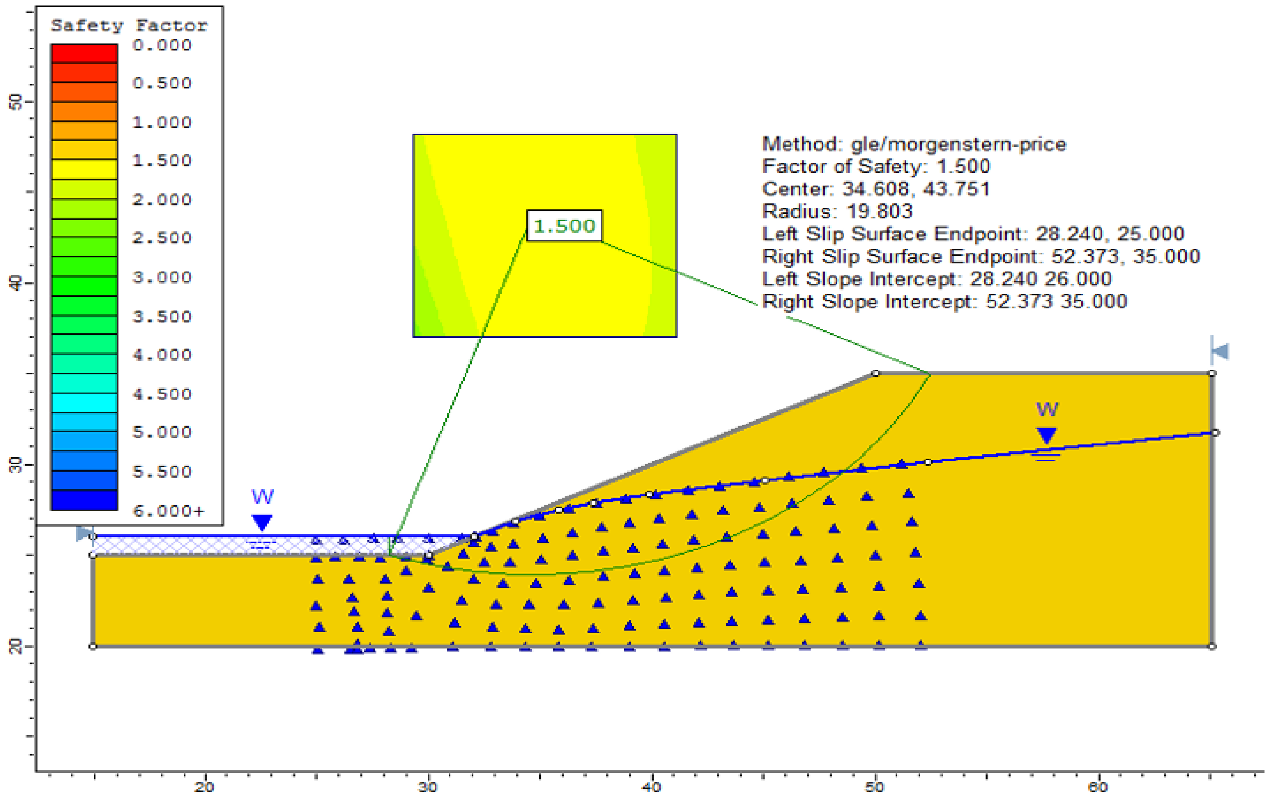


Figure 10.5: Solution, using the GLE method

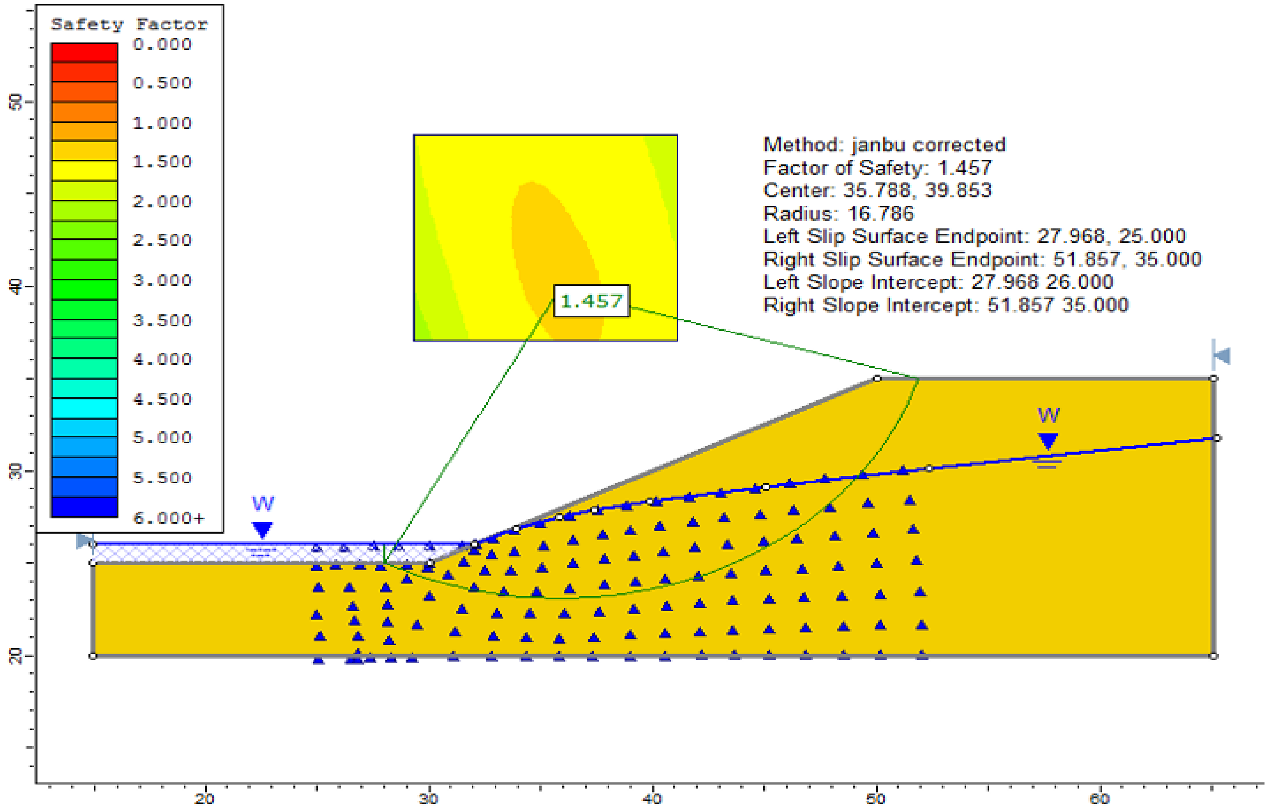


Figure 10.6: Solution, using the Janbu corrected method

11. Slide Verification Problem #11

Embankment, (2) materials, pore pressure grid

11.1. Introduction

This problem is an analysis of the Saint-Alban embankment (in Quebec) which was built and induced to failure for testing and research purposes in 1972 (Pilot et.al, 1982).

11.2. Problem Description

Problem #11 is shown in Figure 11.1. The material properties are given in Table 11.1. The position of the critical slip surface and the corresponding factor of safety are required. Pore water pressures were derived from the given equal pore pressure lines on Figure 11.1., using the Thin-Plate Spline interpolation method.

11.3. Geometry and Material Properties

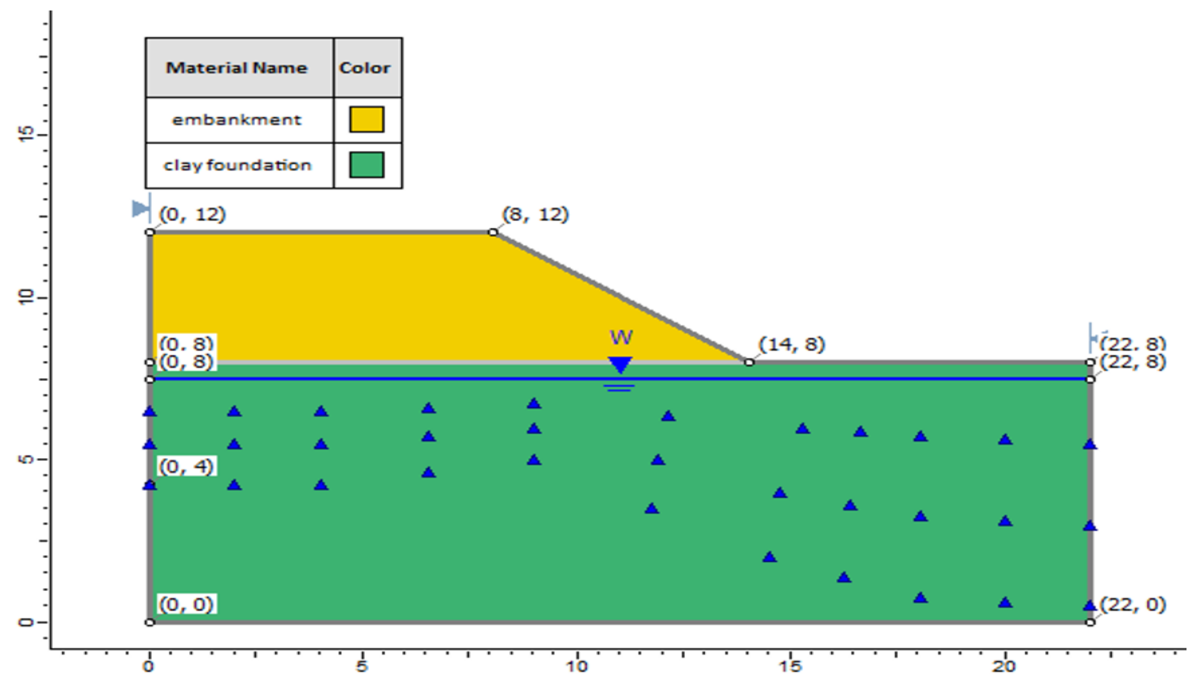


Figure 11.1: Geometry Setup in **Slide**

Table 11.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Embankment	0	44.0	18.8
Clay Foundation	2	28.0	16.68

11.4. Results

Table 11.2

Method	Factor of Safety
Bishop	1.037
Spencer	1.065
GLE	1.059
Janbu Corrected	1.077

Note: Reference factor of safety = 1.04 [Pilot]

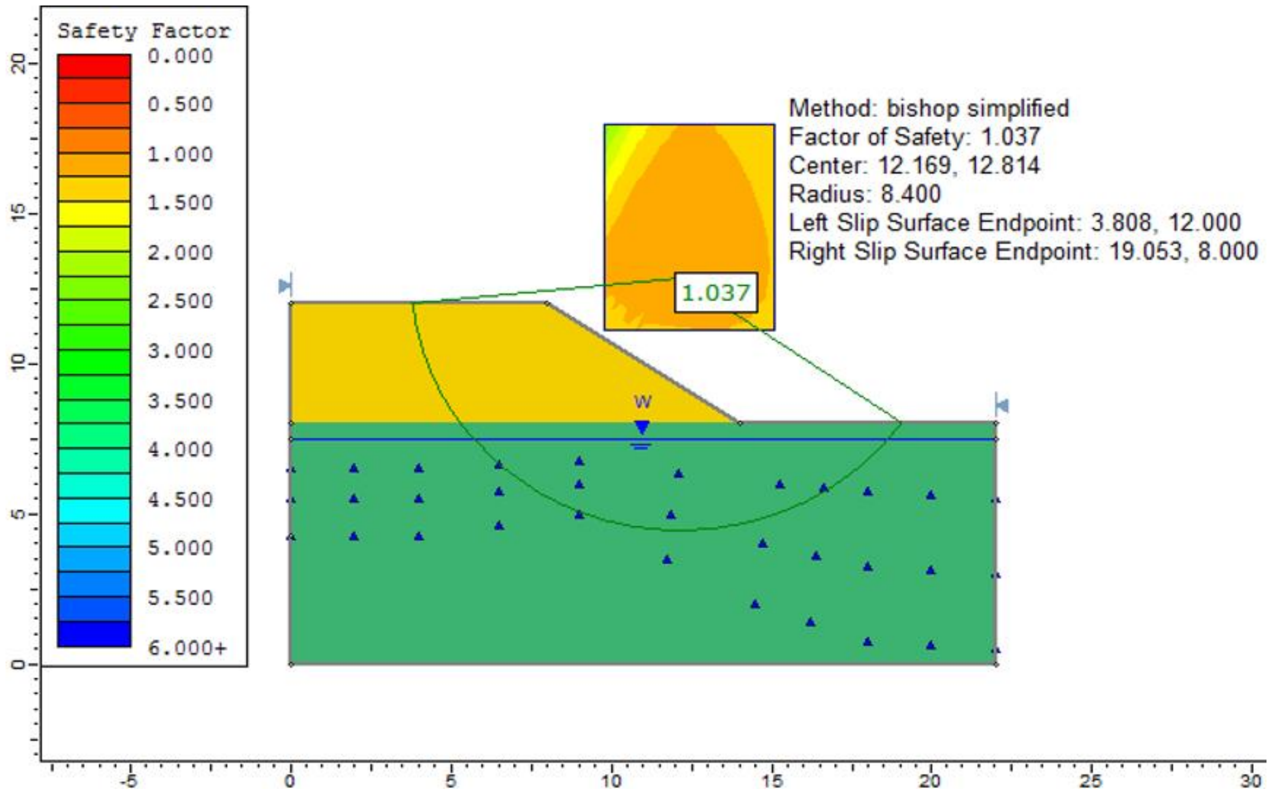


Figure 11.2: Solution, using the Bishop simplified method

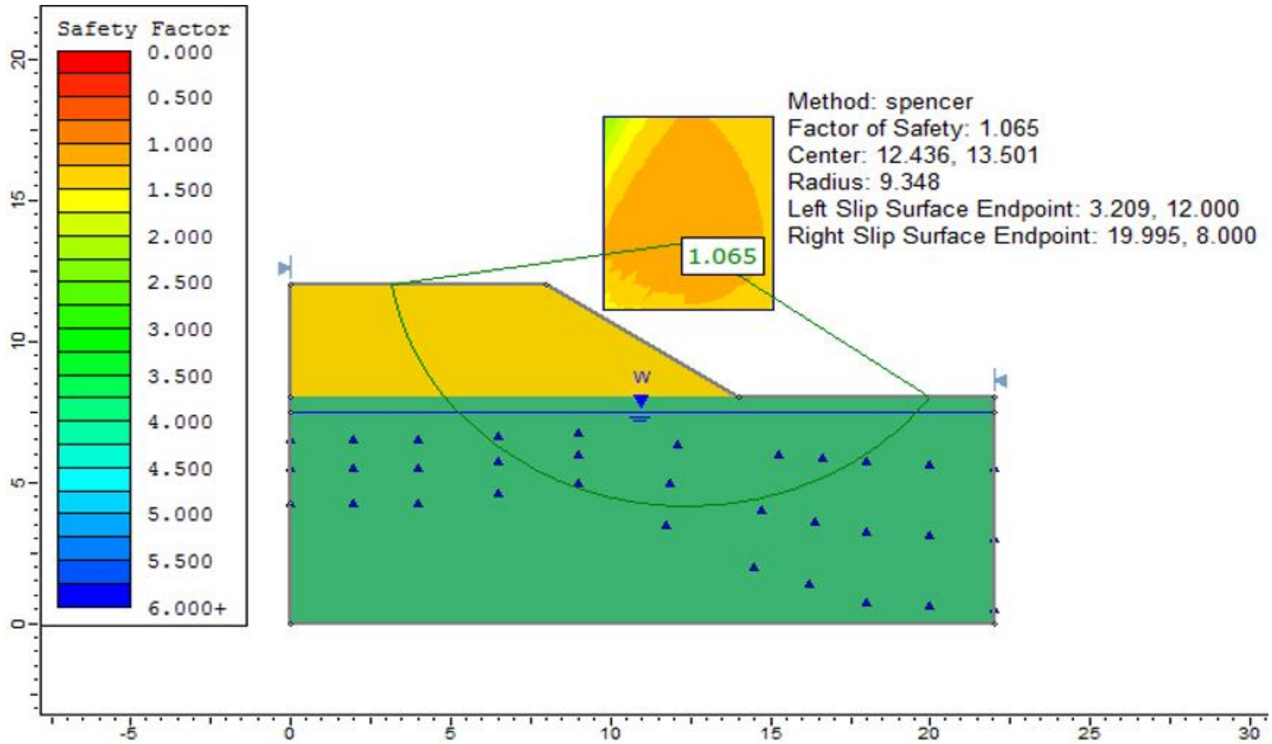


Figure 11.3: Solution, using the Spencer method

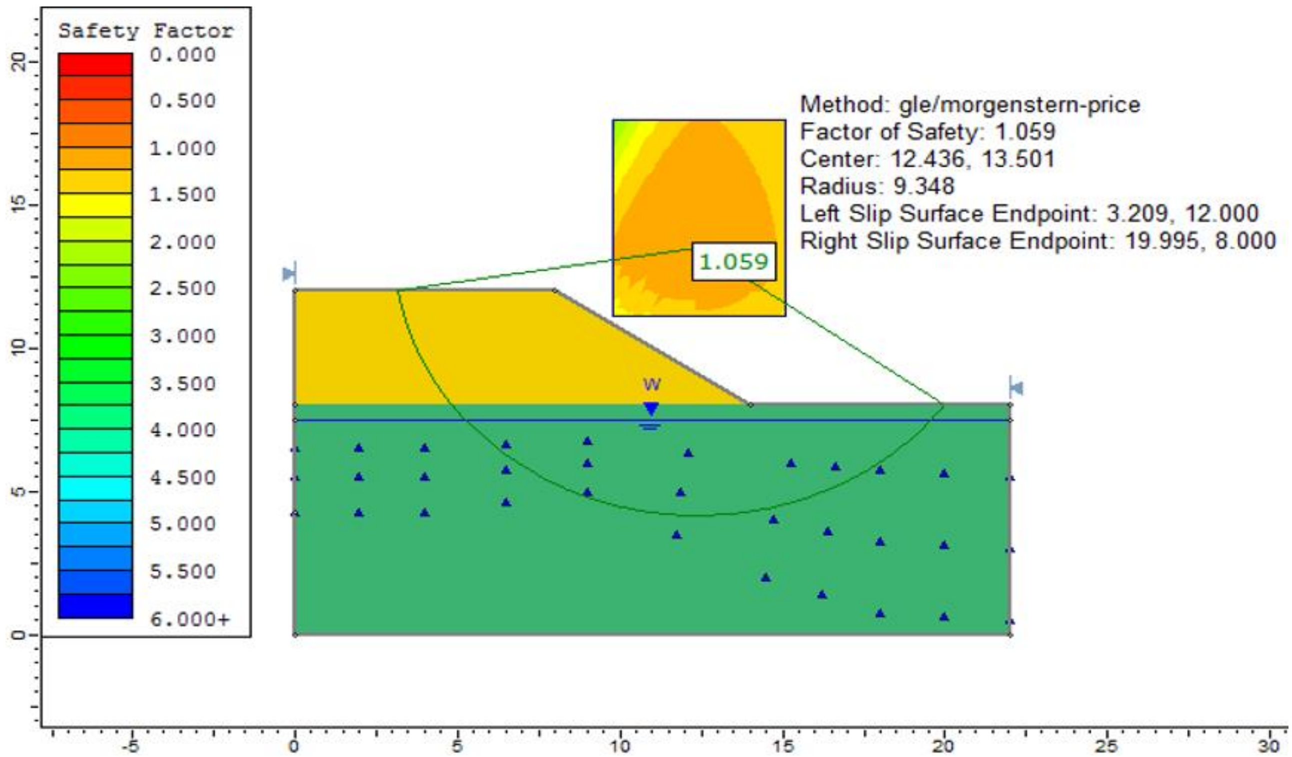


Figure 11.4: Solution, using the GLE method

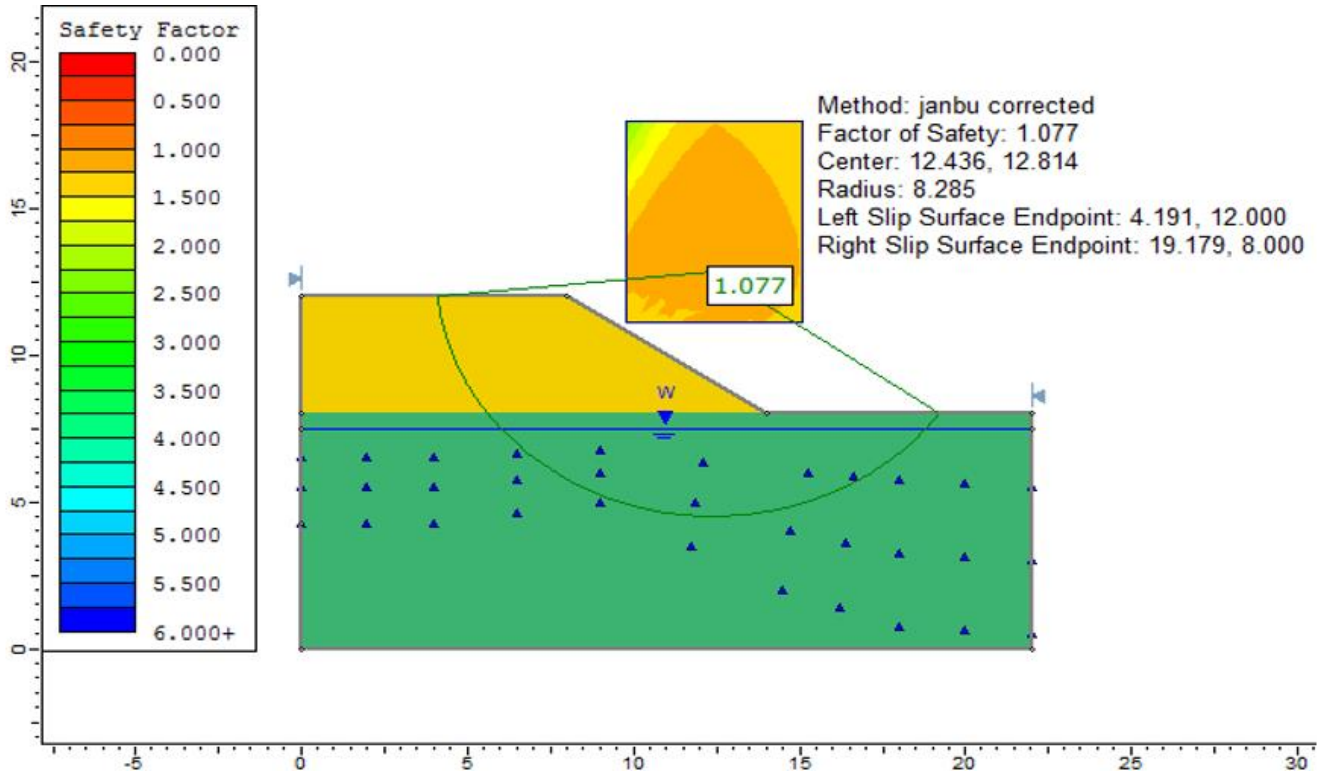


Figure 11.5: Solution, using the Janbu corrected method

12. Slide Verification Problem #12

Embankment, (4) materials, tension crack, pore pressure grid

12.1. Introduction

This problem is an analysis of the Lanester embankment (in France) which was built and induced to failure for testing and research purposes in 1969 (Pilot et.al, 1982).

12.2. Problem Description

Problem #12 is shown in Figure 12.1. The material properties are given in Table 12.1. The entire embankment is assumed to represent a dry tension crack zone. The position of the critical slip surface and the corresponding factor of safety is calculated. Pore water pressures were derived from the data in Table 12.2 using the Thin-Plate Spline interpolation method.

Note: 30 slices used.

12.3. Geometry and Material Properties

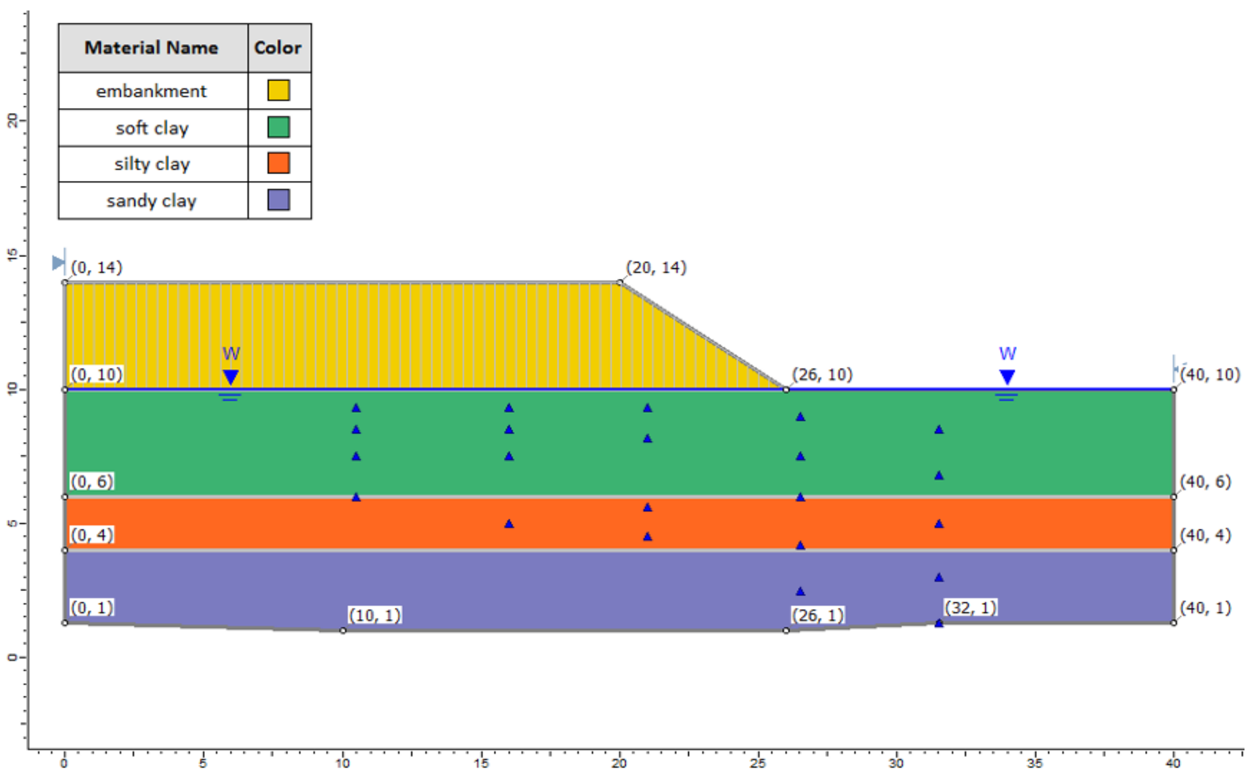


Figure 12.1: Geometry Setup in **Slide**

Note: Tension crack depth (hatched region in the diagram) is 4 m

Table 12.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Embankment	30	31	18.2
Soft Clay	4	37	14
Silty Clay	7.5	33	13.2
Sandy Clay	8.5	35	13.7

Table 12.2: Water Pressure Points

Pt.#	Xc (m)	Yc (m)	u (kPa)	Pt.#	Xc (m)	Yc (m)	u (kPa)	Pt.#	Xc (m)	Yc (m)	u (kPa)
1	26.5	9	20	9	16	8.5	60	17	31.5	3	80
2	31.5	8.5	20	10	21	8.2	60	18	10.5	6	100
3	10.5	9.3	40	11	26.5	6	60	19	16	5	100
4	16	9.3	40	12	31.5	5	60	20	21	4.5	100
5	21	9.3	40	13	10.5	7.5	80	21	26	2.5	100
6	26.5	7.5	40	14	16	7.5	80	22	31.5	1.3	100
7	31.5	6.8	40	15	21	5.6	80	23	--	--	--
8	10.5	8.5	60	16	26	4.2	80	24	--	--	--

12.4. Results

Table 12.3

Method	Factor of Safety
Bishop	1.069
Spencer	1.079
GLE	1.077
Janbu Corrected	1.138

Note: Author’s factor of safety (by Bishop method) = 1.13 [Pilot]

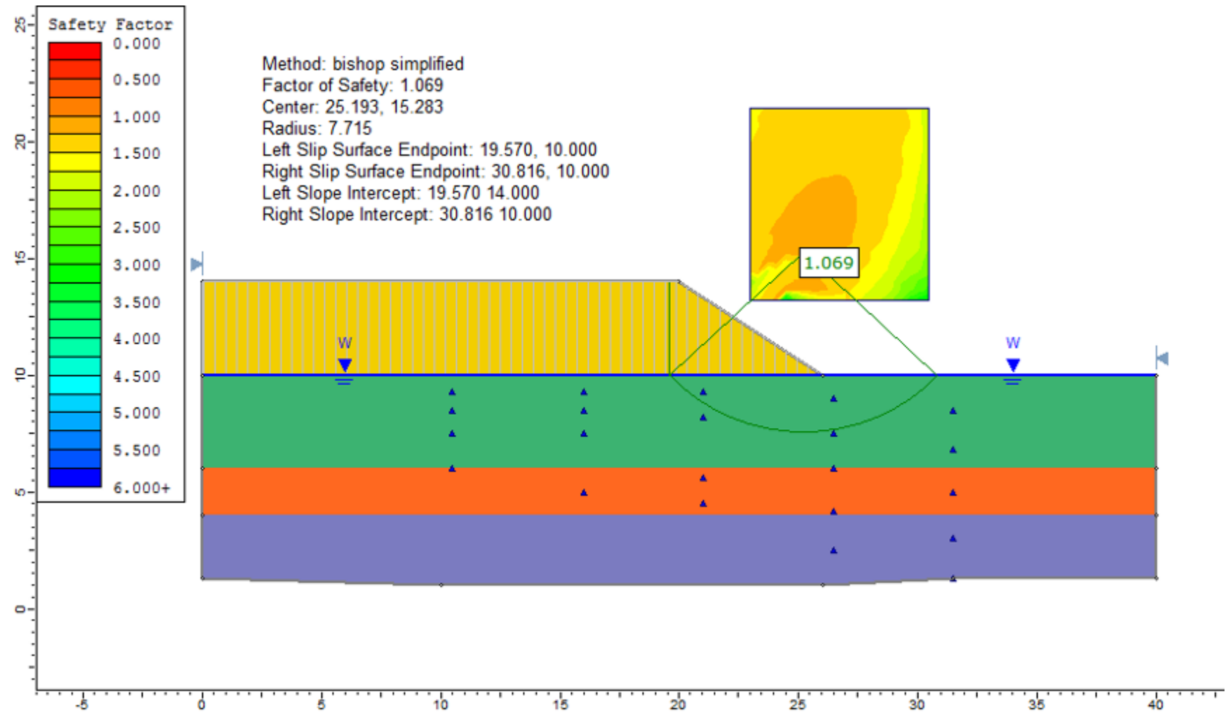


Figure 12.2: Solution, using the Bishop simplified method

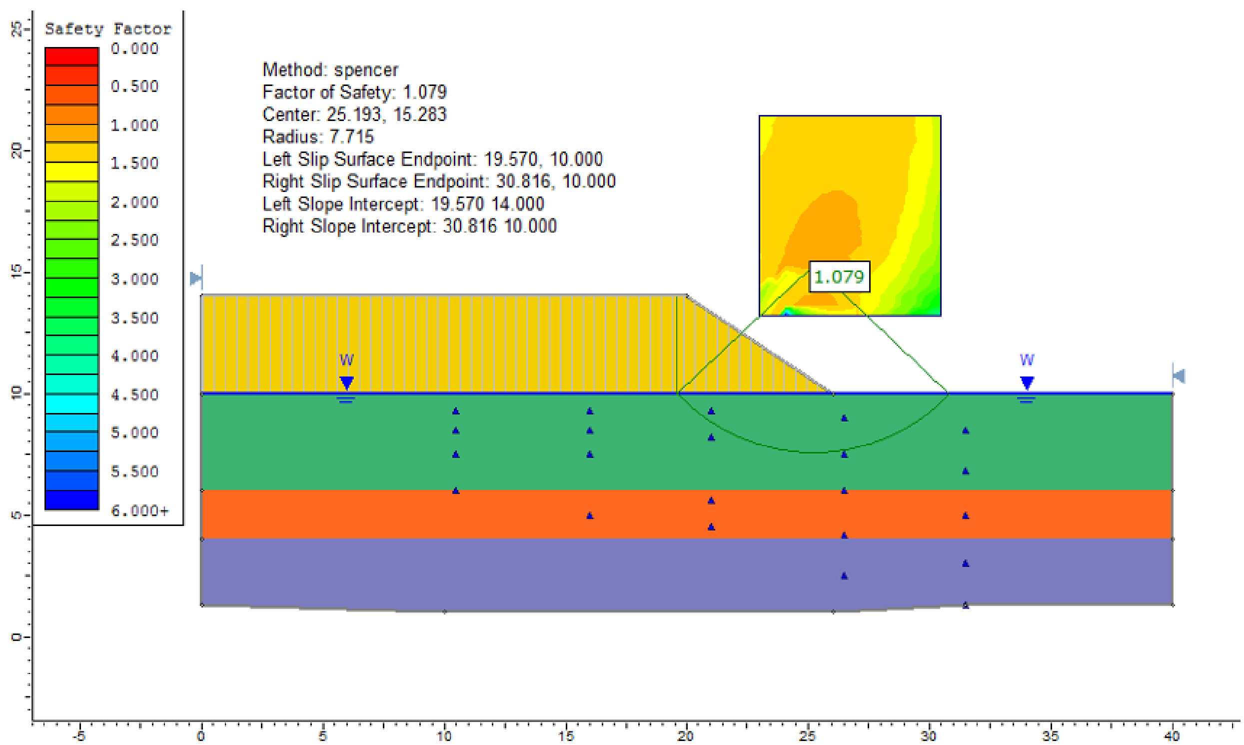


Figure 12.3: Solution, using the Spencer method

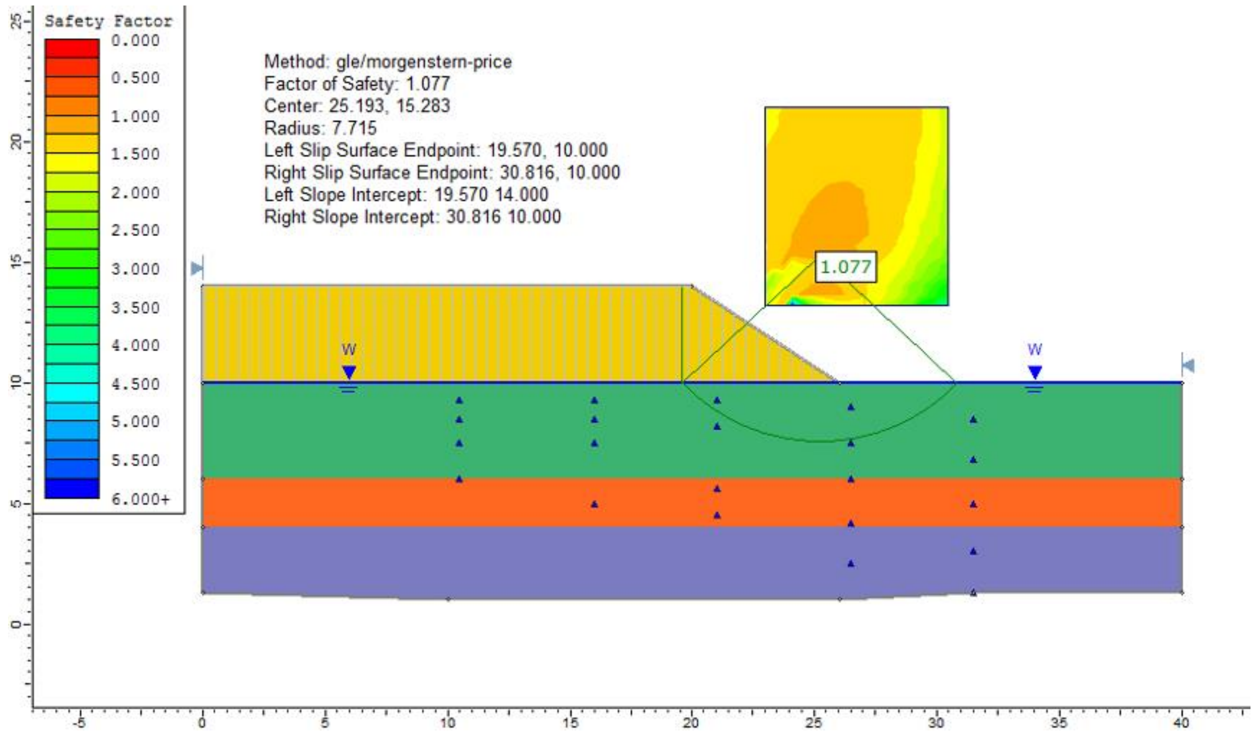


Figure 12.4: Solution, using the GLE method

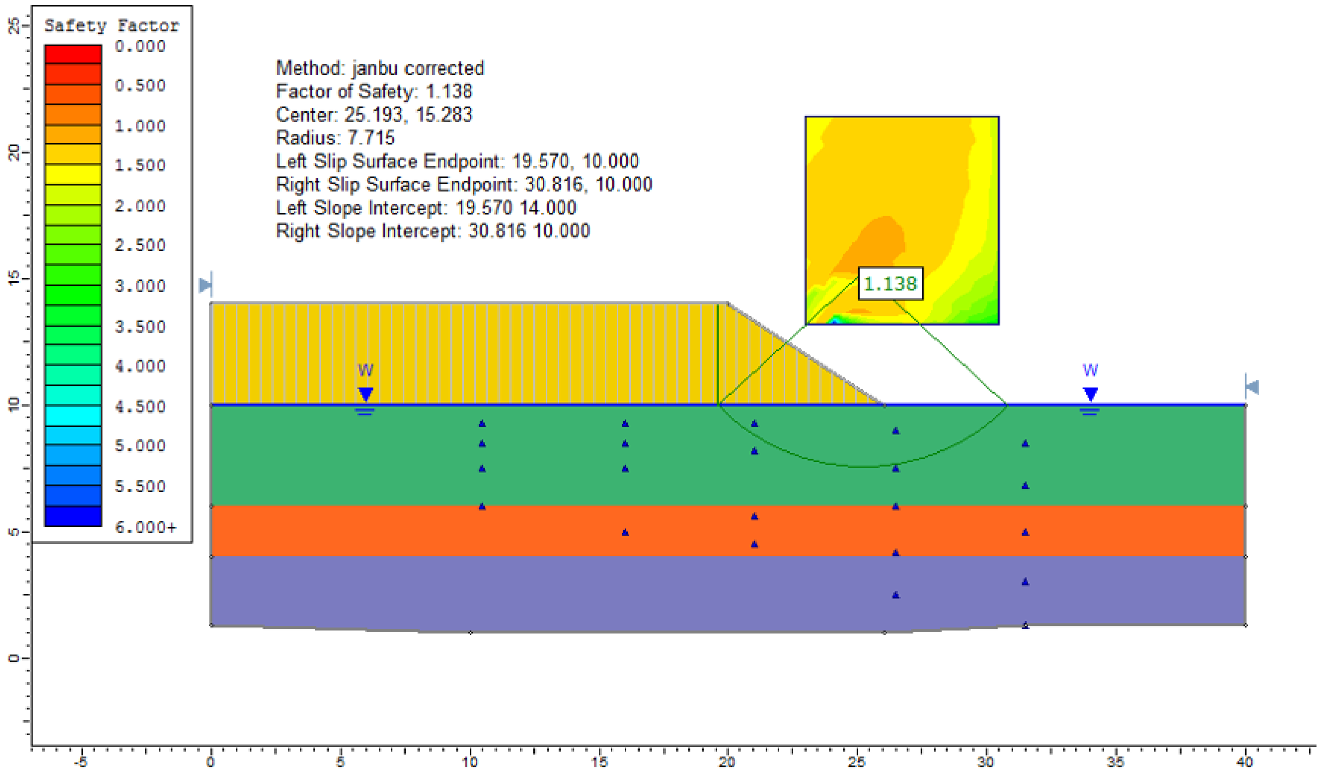


Figure 12.5: Solution, using the Janbu corrected method

13. Slide Verification Problem #13

Embankment, (3) materials, pore pressure grid

13.1. Introduction

This problem is an analysis of the Cubzac-les-Ponts embankment (in France) which was built and induced to failure for testing and research purposes in 1974 (Pilot et.al, 1982).

13.2. Problem Description

Problem #13 is shown in Figure 13.1. The material properties are given in Table 13.1. The position of the critical slip surface and the corresponding factor of safety is required. Pore water pressures were derived from the data in Table 13.2 using the Thin Plate Spline interpolation method.

13.3. Geometry and Material Properties

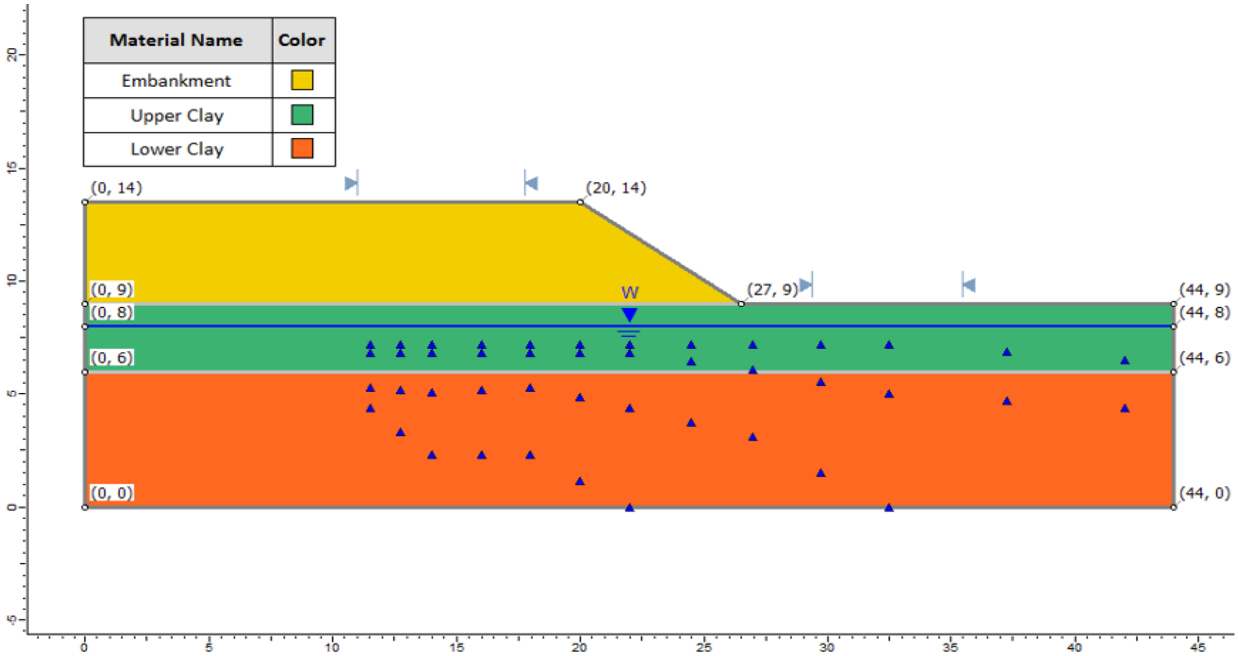


Figure 13.1: Geometry Setup in **Slide**

Table 13.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Embankment	0	35	21.2
Upper Clay	10	24	15.5
Lower Clay	10	28.4	15.5

Table 13.2: Water Pressure Points

Pt.#	Xc (m)	Yc (m)	u (kPa)	Pt.#	Xc (m)	Yc (m)	u (kPa)	Pt.#	Xc (m)	Yc (m)	u (kPa)
1	11.5	4.5	125	16	16	7.2	25	31	24.5	7.2	25
2	11.5	5.3	100	17	18	2.3	125	32	27	3.1	100
3	11.5	6.8	50	18	18	5.3	100	33	27	6.1	50
4	11.5	7.2	25	19	18	6.8	50	34	27	7.2	25
5	12.75	3.35	125	20	18	7.2	25	35	29.75	1.55	100
6	12.75	5.2	100	21	20	1.15	125	36	29.75	5.55	50
7	12.75	6.8	50	22	20	4.85	100	37	29.75	7.2	25
8	12.75	7.2	25	23	20	6.8	50	38	32.5	0	100
9	14	2.3	125	24	20	7.2	25	39	32.5	5	50
10	14	5.1	100	25	22	0	125	40	32.5	7.2	25
11	14	6.8	50	26	22	4.4	100	41	37.25	4.7	50
12	14	7.2	25	27	22	6.8	50	42	37.25	6.85	25
13	16	2.3	125	28	22	7.2	25	43	42	4.4	50
14	16	5.2	100	29	24.5	3.75	100	44	42	6.5	25
15	16	6.8	50	30	24.5	6.45	50	45	--	--	--

13.4. Results

Table 13.3

Method	Factor of Safety
Bishop	1.314
Spencer	1.334
GLE	1.336
Janbu Corrected	1.306

Note: Author’s factor of safety (by Bishop method) = 1.24 [Pilot]

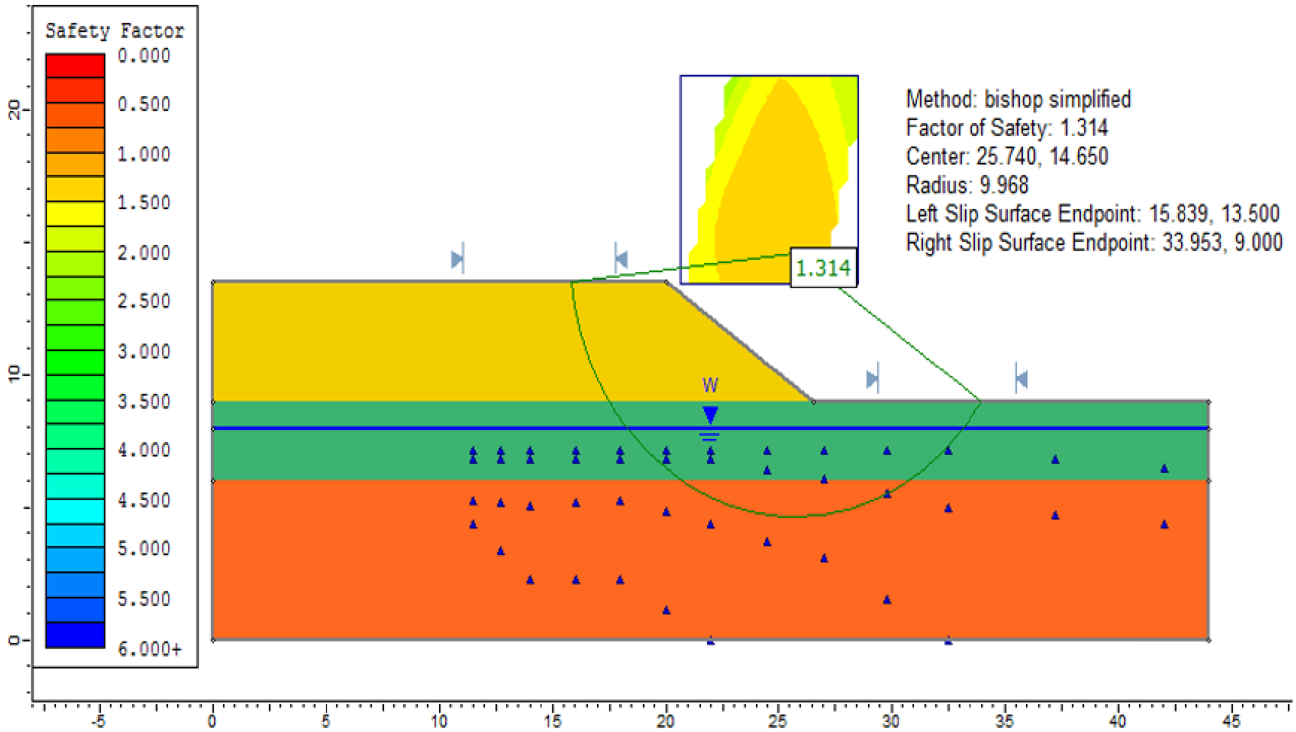


Figure 13.2: Solution, using the Bishop simplified method

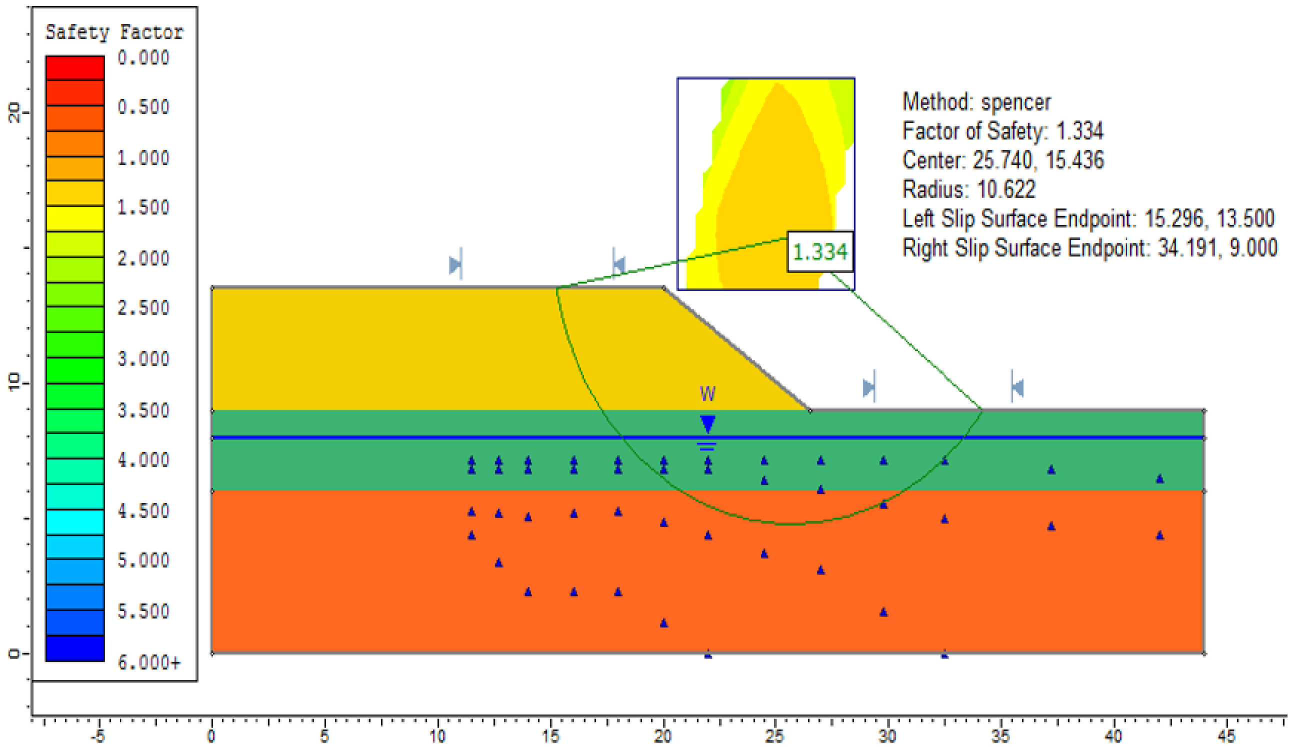


Figure 13.3: Solution, using the Spencer method

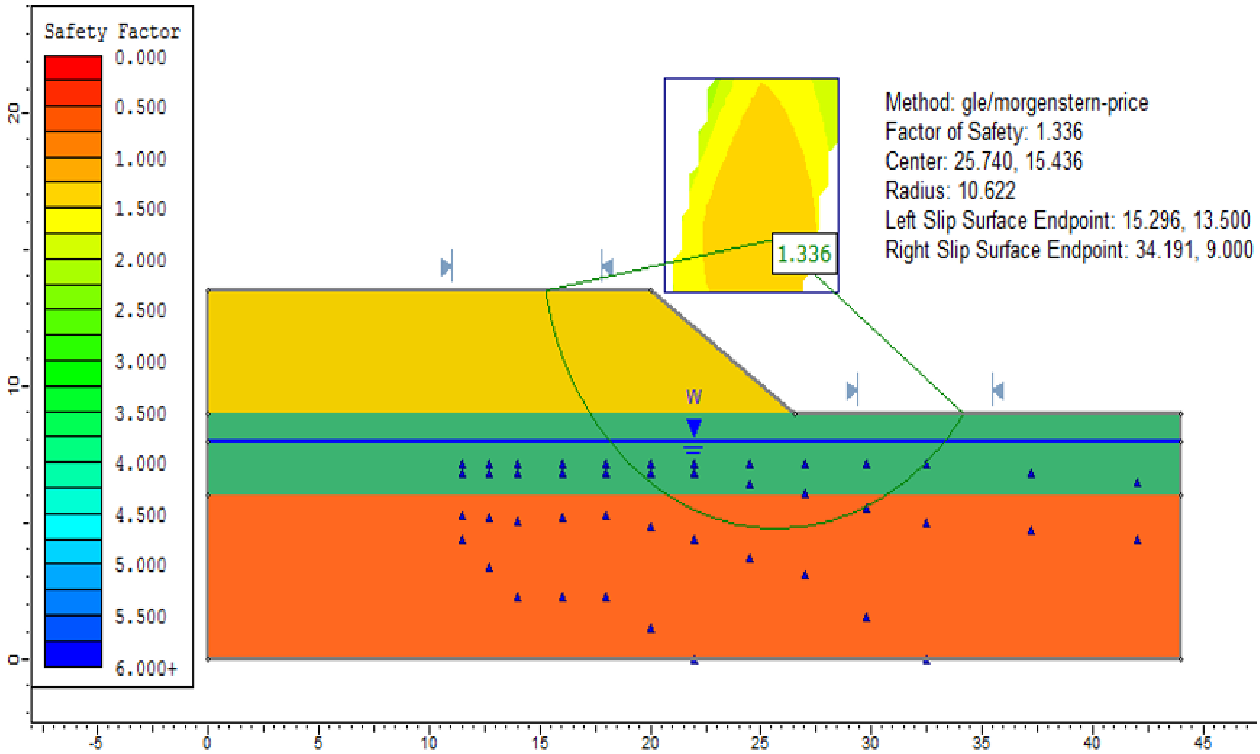


Figure 13.4: Solution, using the GLE method

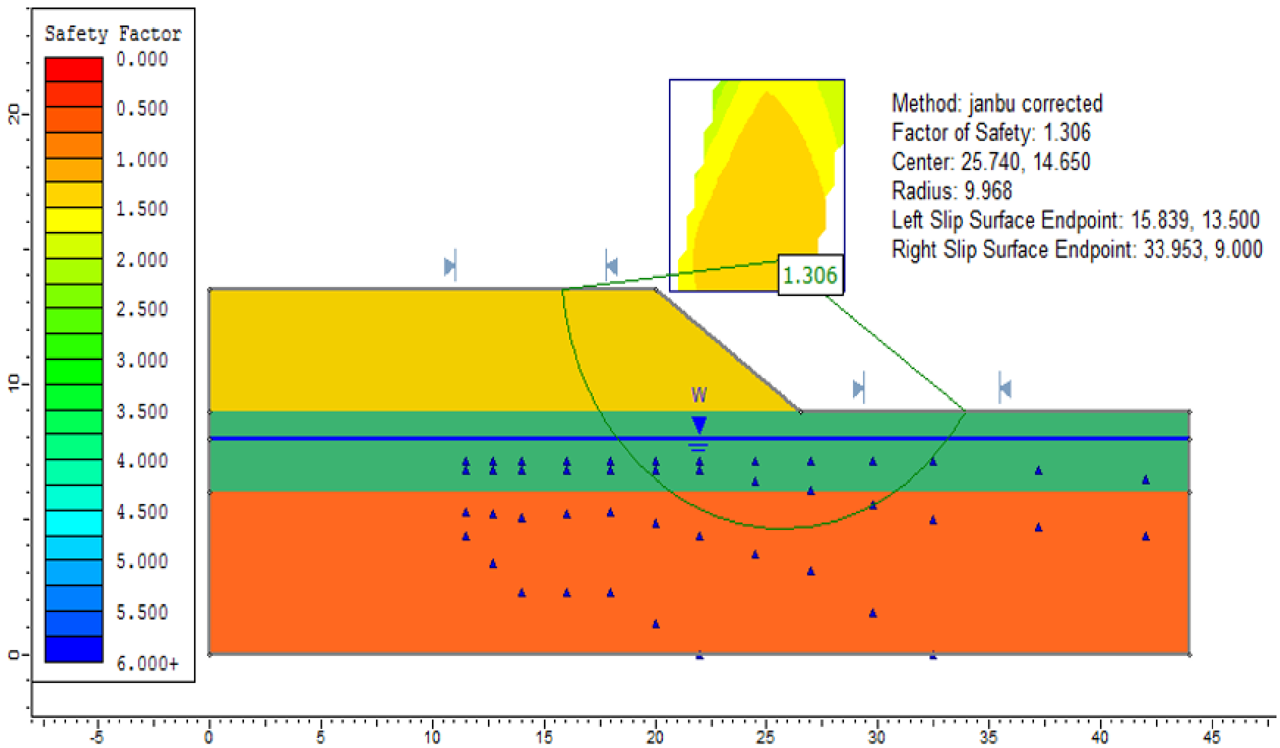


Figure 13.5: Solution, using the Janbu corrected method

14. Slide 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

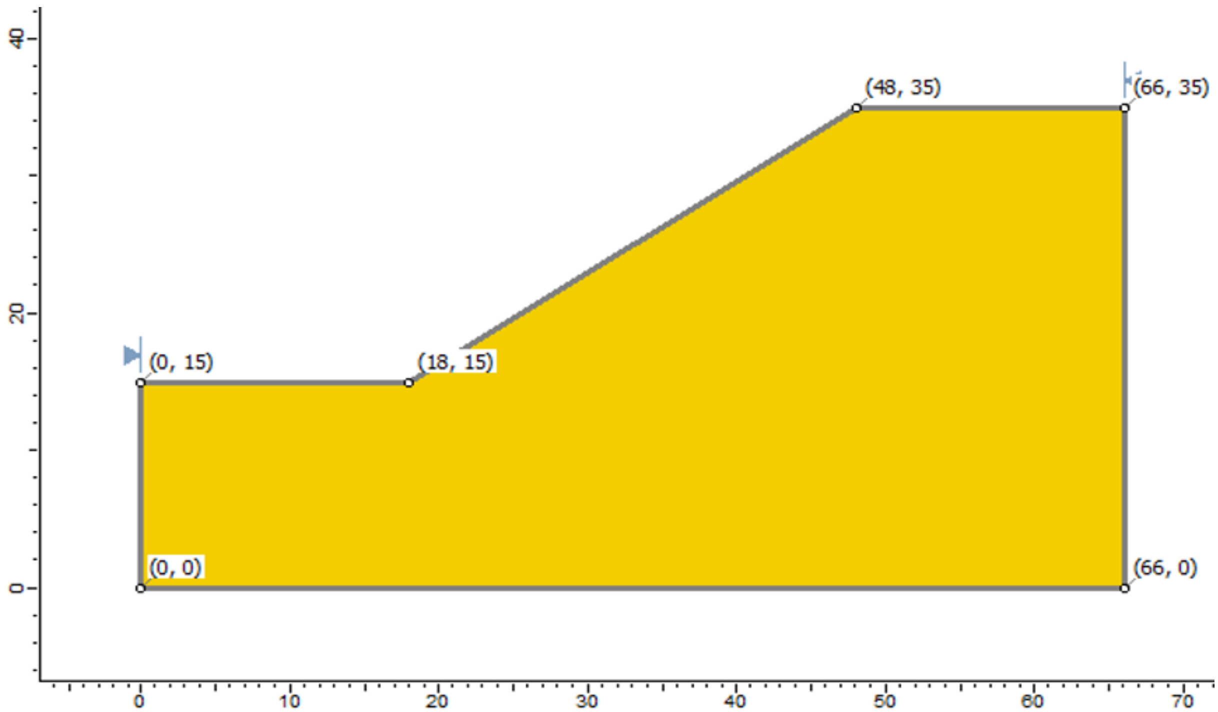


Figure 14.1: Geometry Setup in **Slide**

Table 14.1: Soil Properties

	c´ (kN/m²)	ϕ´ (deg.)	γ (kN/m³)
Soil	41.65	15	18.82

14.4. Results

Table 14.2: Circular – using auto-refine search

Method	Factor of Safety
Bishop	1.409
Spencer	1.319
GLE	1.414
Janbu Corrected	1.407

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

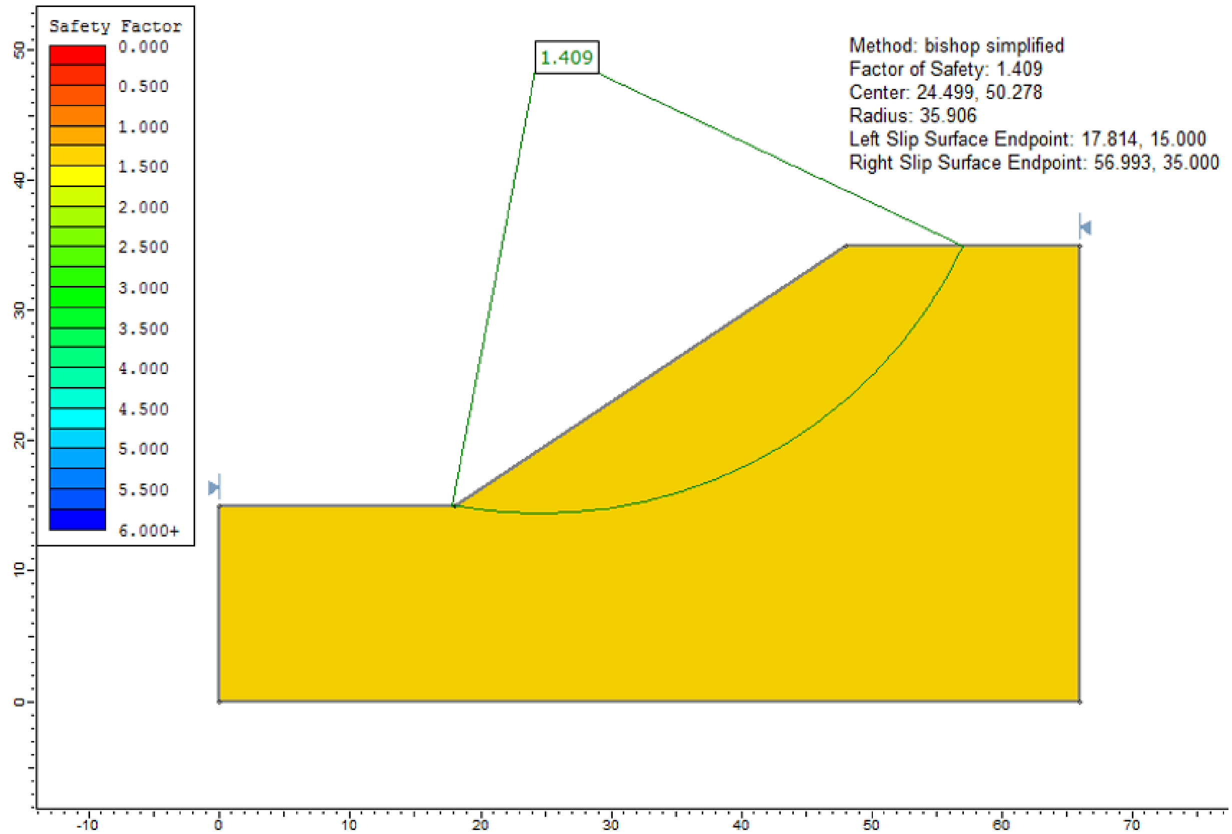


Figure 14.2: Solution, using the Bishop simplified method

Table 14.3: Noncircular – using Path search with Optimization

Method	Factor of Safety
Janbu Simplified	1.253
Janbu Corrected	1.346
Spencer	1.386

Note: Arai and Tagyo (1985) Janbu Simplified Factor of Safety = 1.265

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

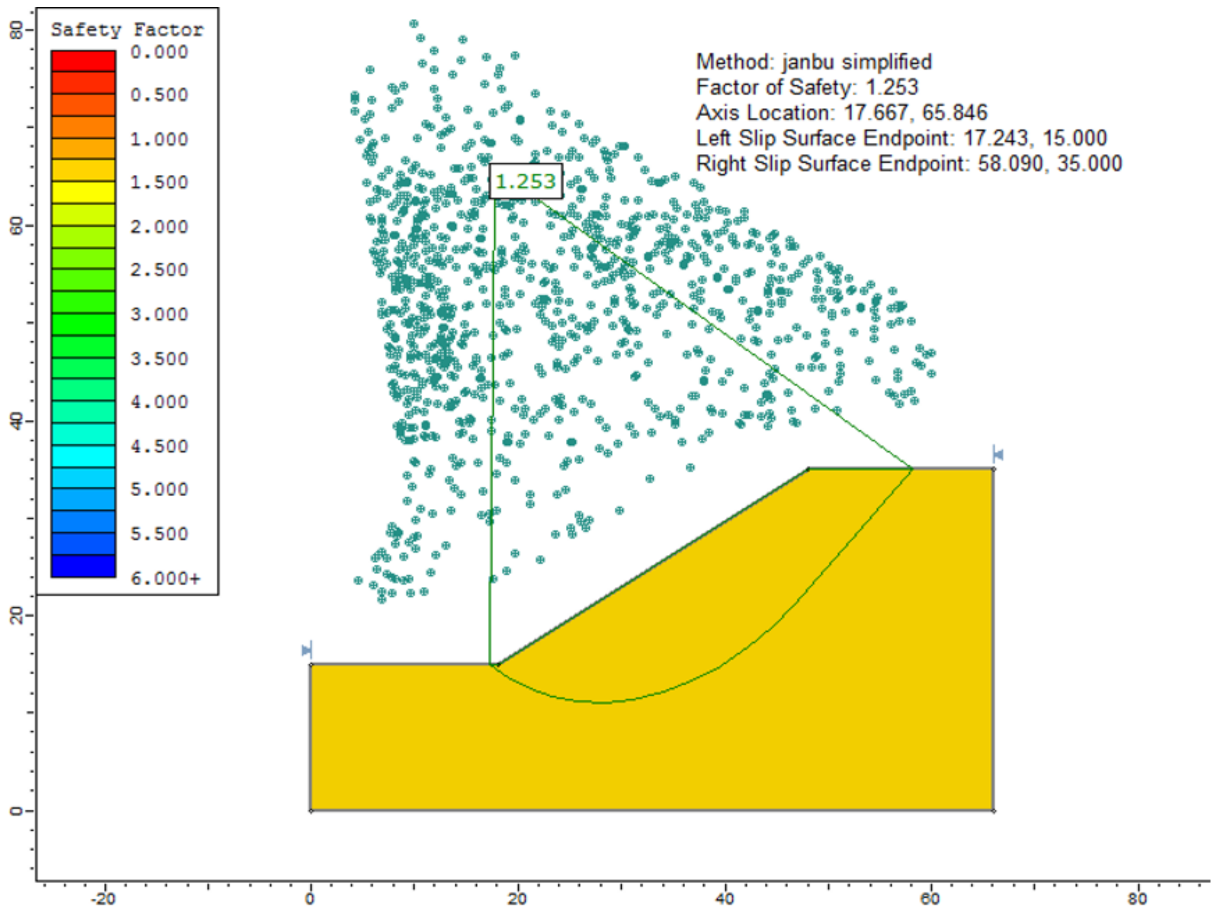


Figure 14.3: Noncircular failure surface, using the janbu simplified method

15. Slide 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

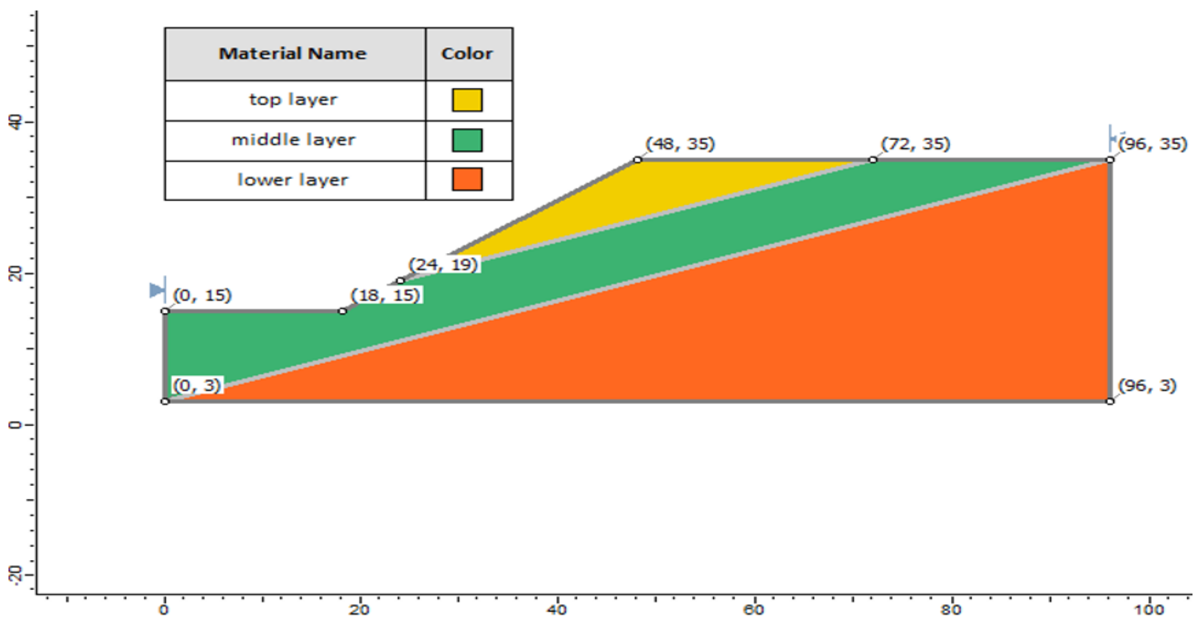


Figure 15.1: Geometry Setup in **Slide**

Table 15.1: Soil Properties

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

15.4. Results

Table 15.2: Circular – using auto refine search

Method	Factor of Safety
Bishop	0.420
Spencer	0.409
GLE	0.437
Janbu Corrected	0.423

Note: Arai and Tagyo (1985) Bishops Simplified factor of safety = 0.417

Kim et al. (2002) Bishops Simplified factor of safety = 0.43

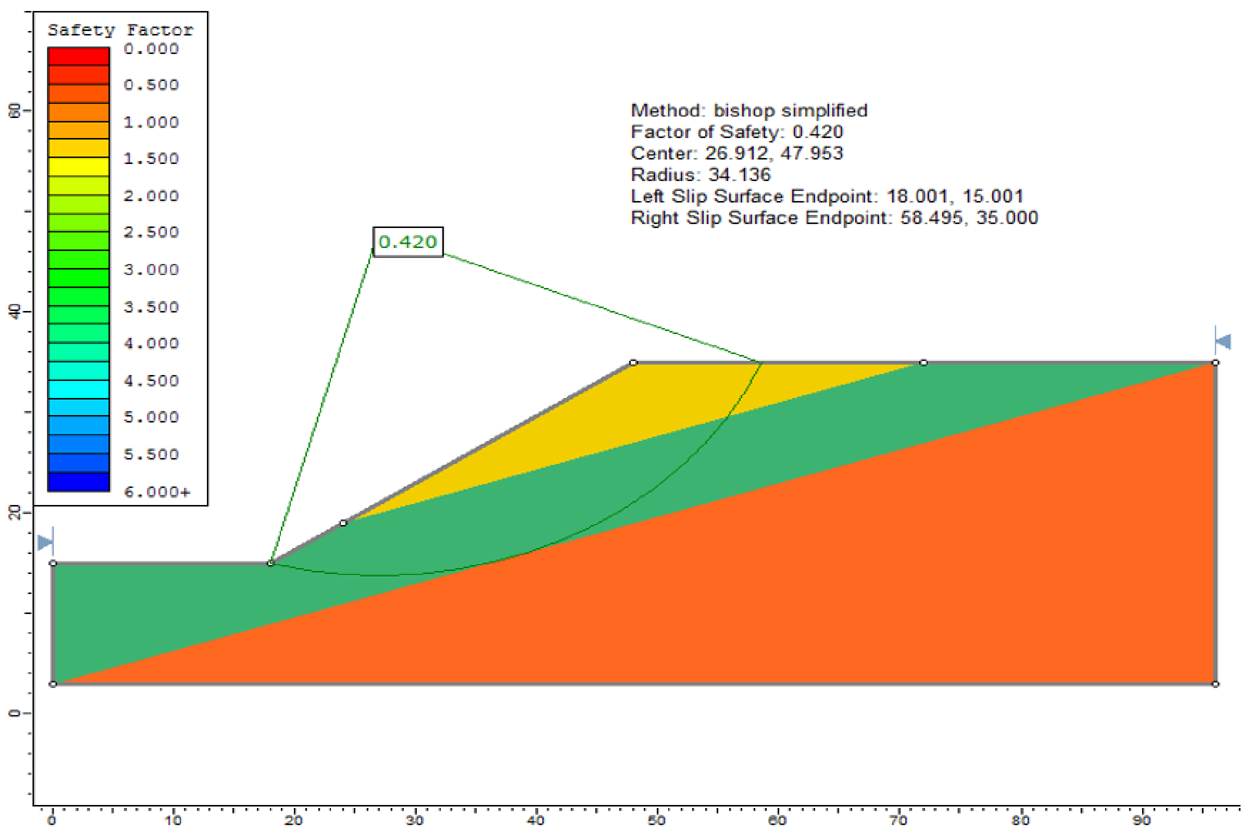


Figure 15.2: Circular failure surface, using the Bishop simplified method

Table 15.3: Noncircular – using Random search with Optimization (1000 surfaces)

Method	Factor of Safety
Janbu Simplified	0.396
Janbu Corrected	0.418
Spencer	0.414

Note: Greco (1996) Spencer method using monte carlo searching = 0.39

Kim et al. (2002) Spencer method using random search = 0.44

Kim et al. (2002) Spencersmethod using pattern search = 0.39

Arai and Tagyo (1985) Janbu Simplified Factor of Safety = 0.405

Arai and Tagyo (1985) Janbu Corrected Factor of Safety = 0.430

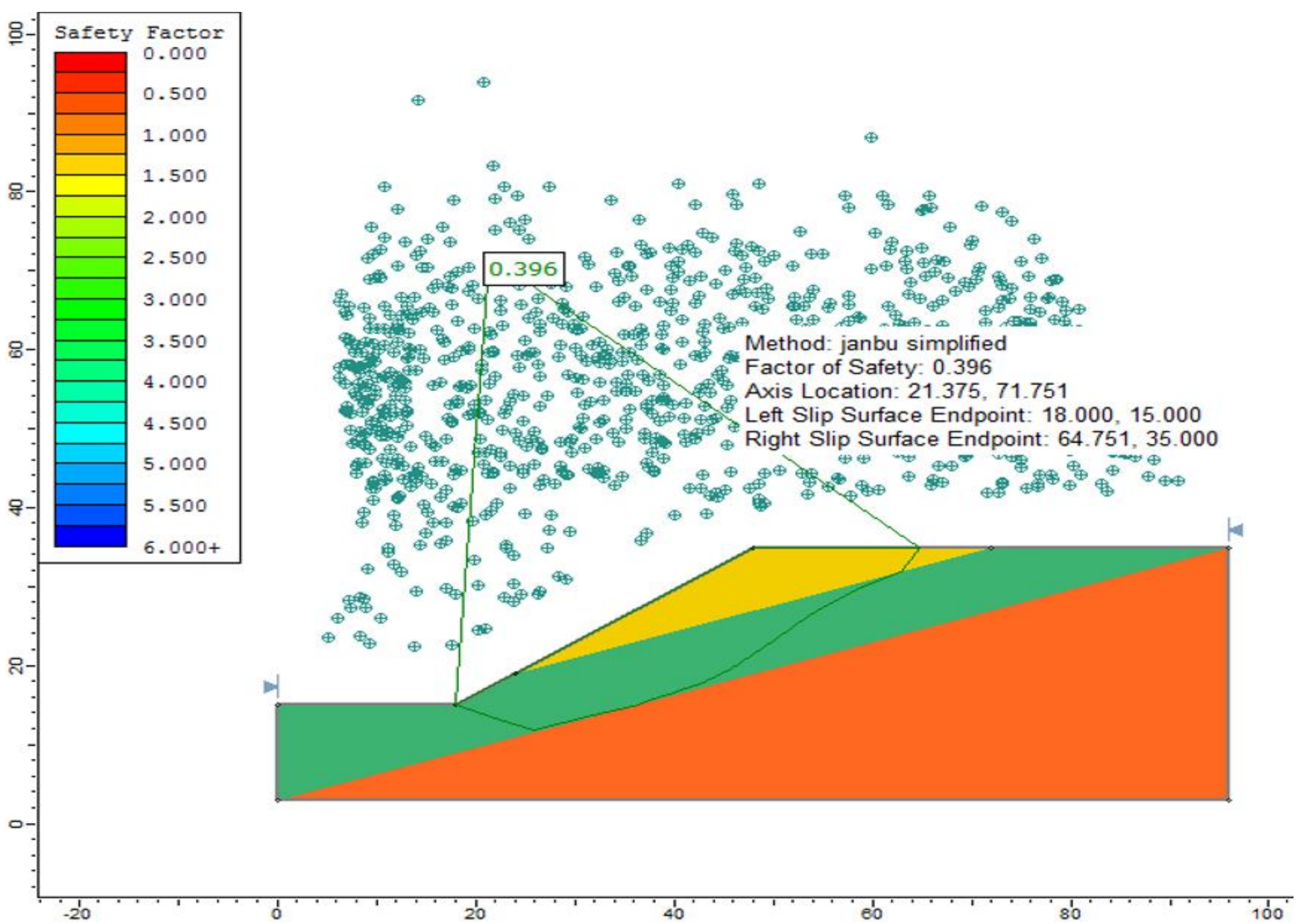


Figure 15.3: Noncircular failure surface using the Spencer method and random search

16. Slide Verification Problem #16

Slope, homogenous, 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

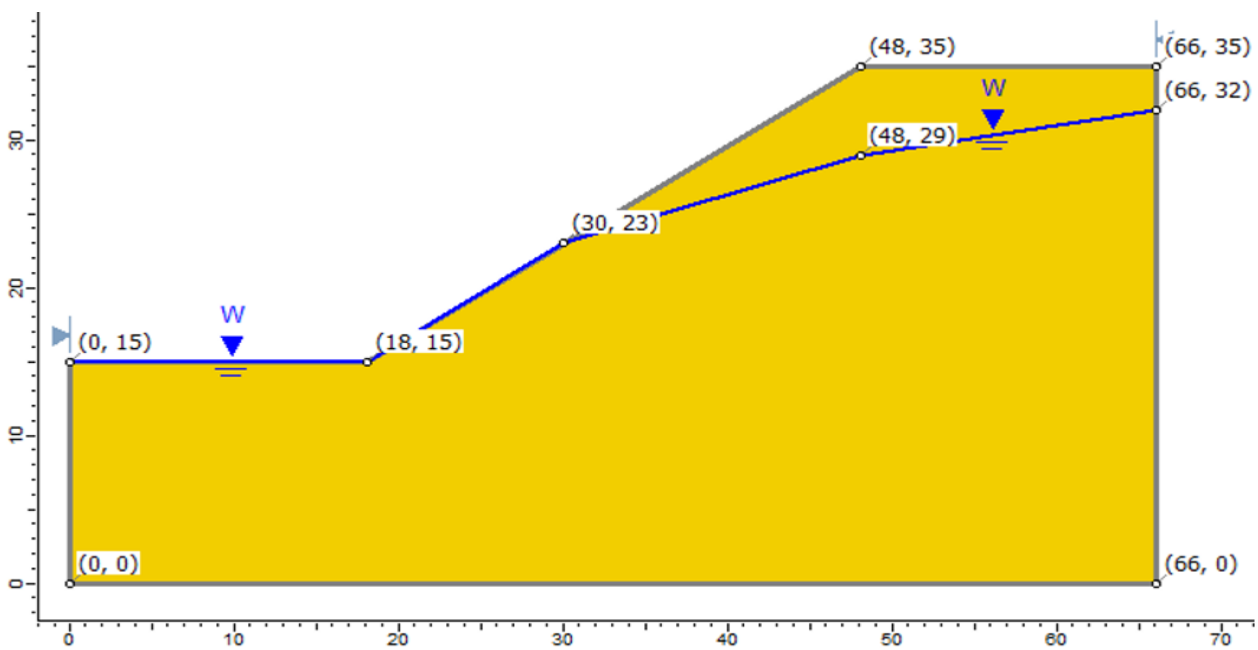


Figure 16.1: Geometry Setup in **Slide**

Table 16.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Soil	41.65	15	18.82

16.4. Results

Table 16.2: Circular – using auto refine search

Method	Factor of Safety
Bishop	1.118
Janbu Simplified	1.046
Janbu Corrected	1.131
Spencer	1.118

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

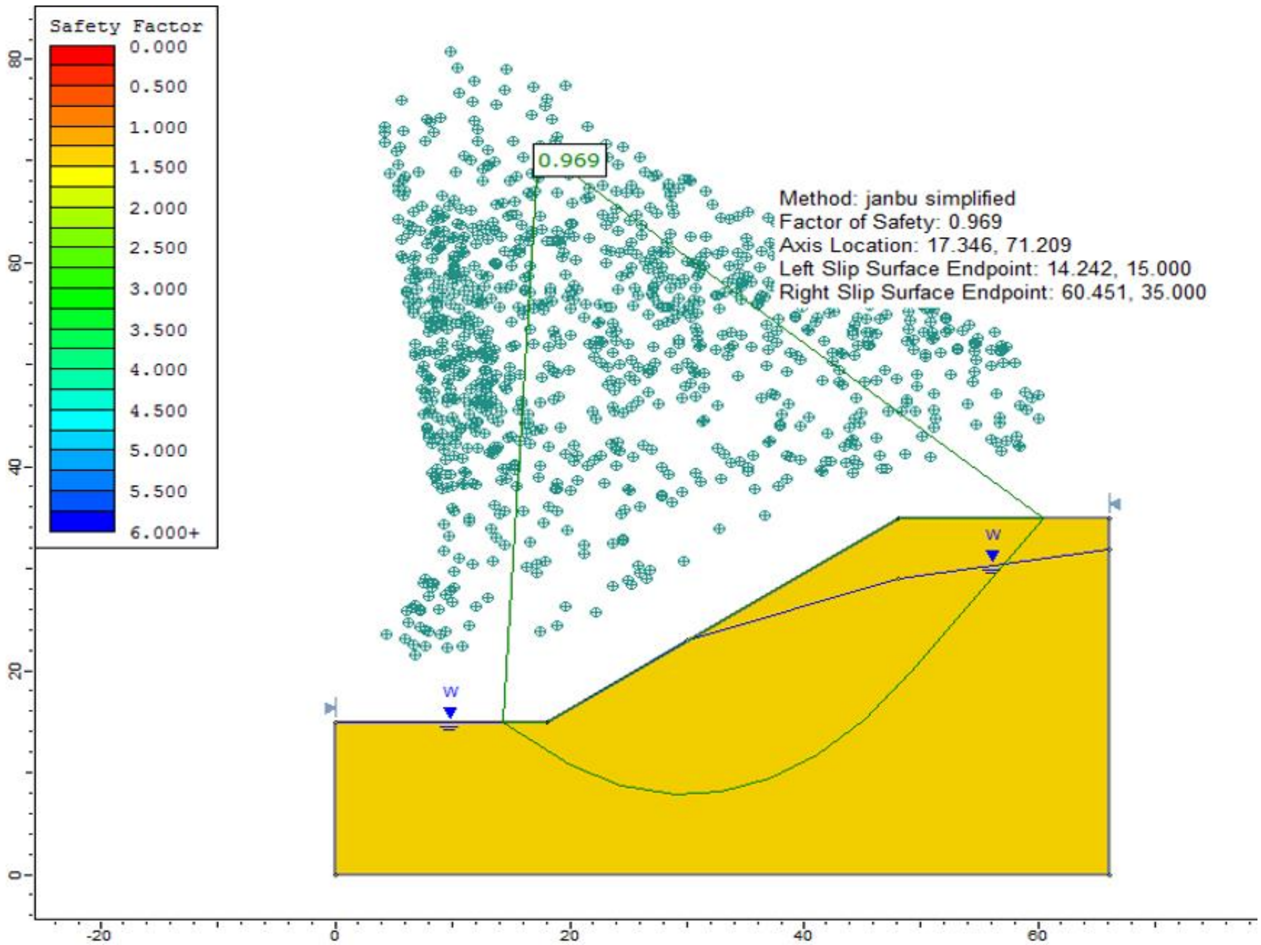


Figure 16.2: Circular failure surface using the Bishop simplified method

Table 16.3: Noncircular – using Random search with Monte-Carlo optimization

Method	Factor of Safety
Janbu Simplified	0.968
Janbu Corrected	1.050
Spencer	1.094

Note: Arai and Tagyo (1985) Janbu Simplified Factor of Safety = 0.995

Arai and Tagyo (1985) Janbu Corrected Factor of Safety = 1.071

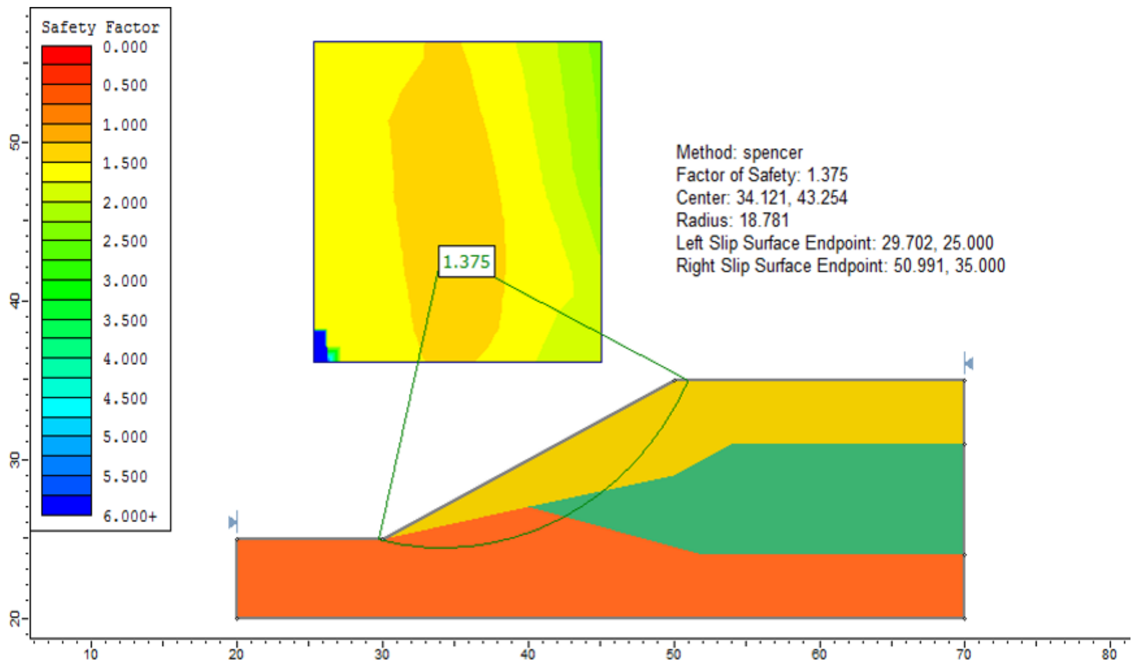


Figure 16.3: Noncircular failure surface using Janbu simplified method

17. Slide Verification Problem #17

Slope, homogenous

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

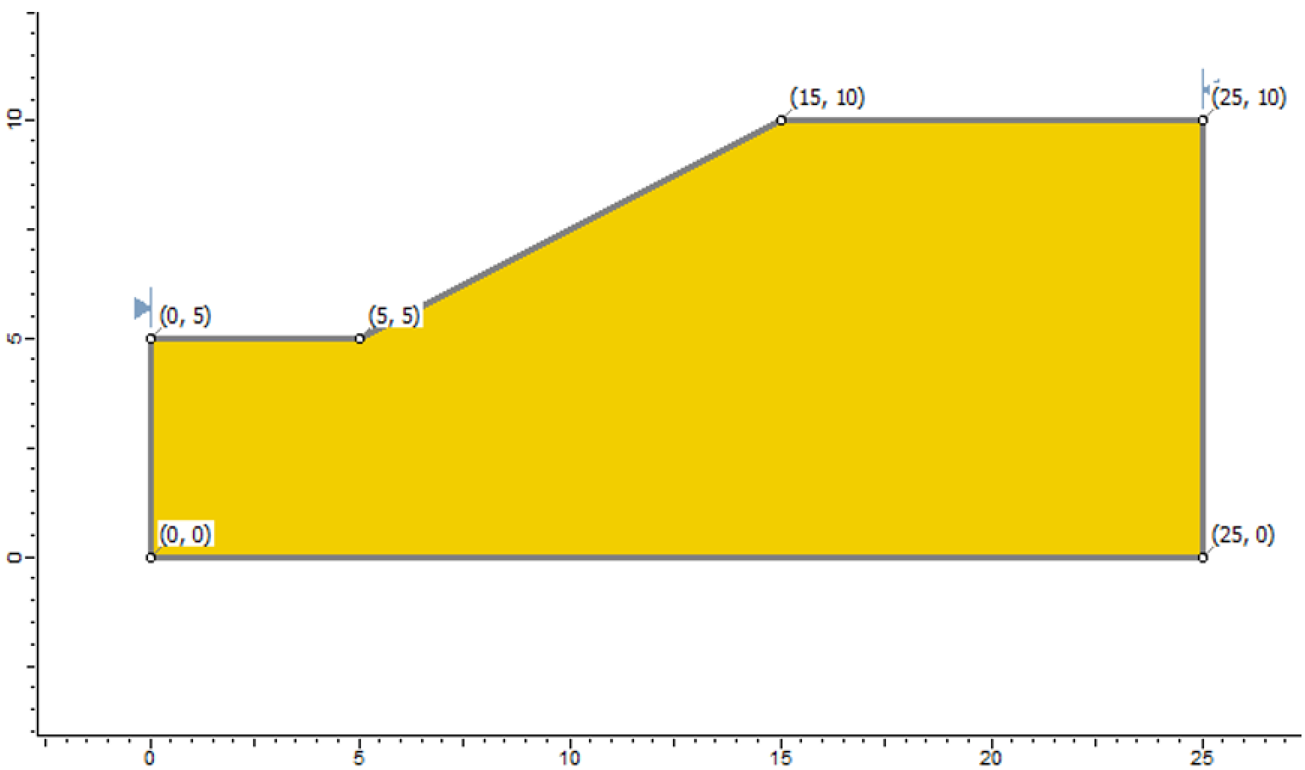


Figure 17.1: Geometry Setup in **Slide**

Table 17.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Soil	9.8	10	17.64

17.4. Results

Table 17.2: Circular – using auto refine search

Method	Factor of Safety
Bishop	1.344
Original	1.278

Note: Yamagami and Ueta (1988) Bishop Simplified factor of safety = 1.348

Yamagami and Ueta (1988) Fellenius/Ordinary factor of safety = 1.282

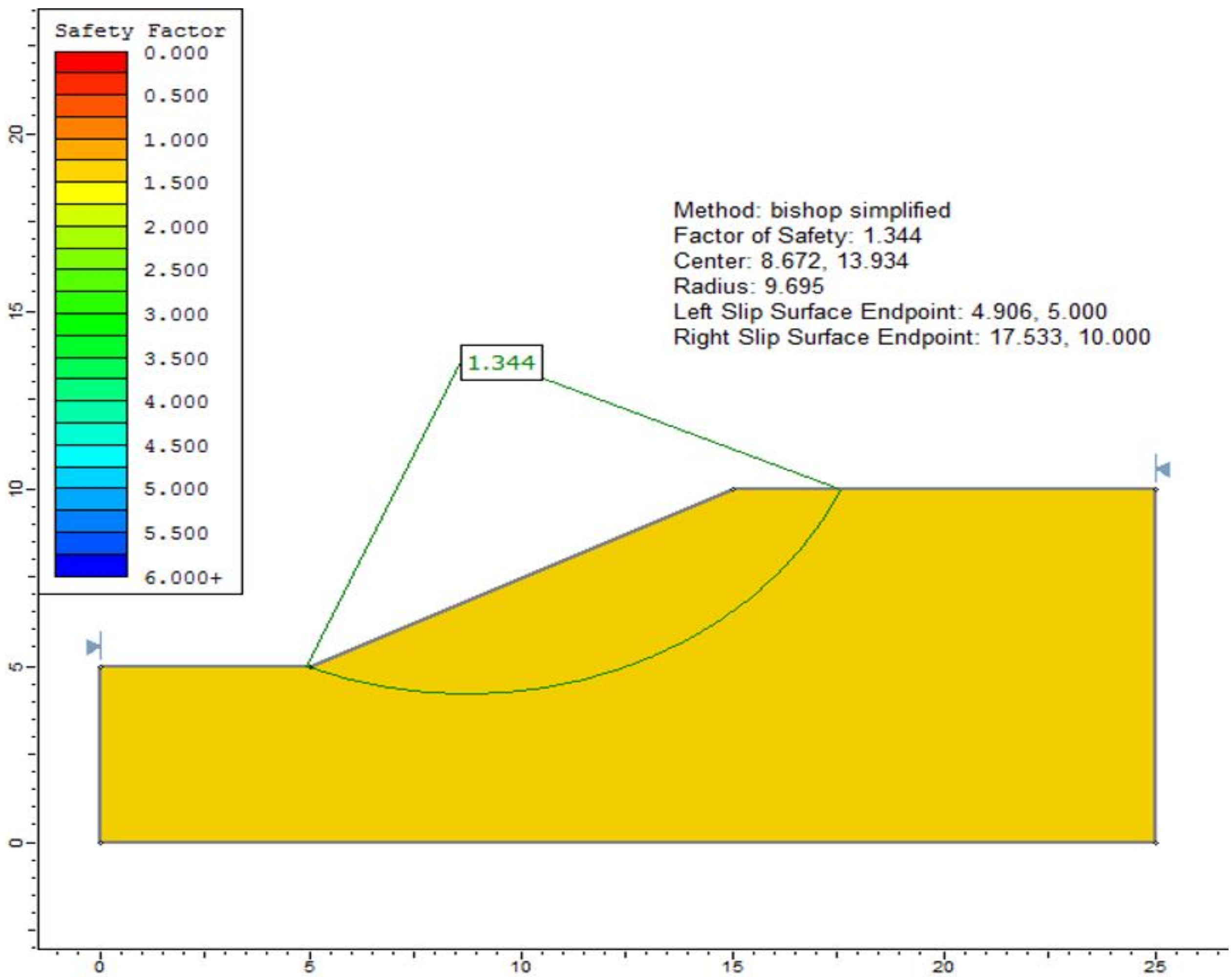


Figure 17.2: Circular failure surface, using the Bishop simplified method

Table 16.3: Noncircular – using Random search with Monte-Carlo optimization

Method	Factor of Safety
Janbu Simplified	1.178
Spencer	1.325

Note: Yamagami and Ueta (1988) Janbu Simplified Factor of Safety = 1.185

Yamagami and Ueta (1988) Spencer Factor of Safety = 1.339

Greco (1996) Spencer Factor of Safety = 1.33

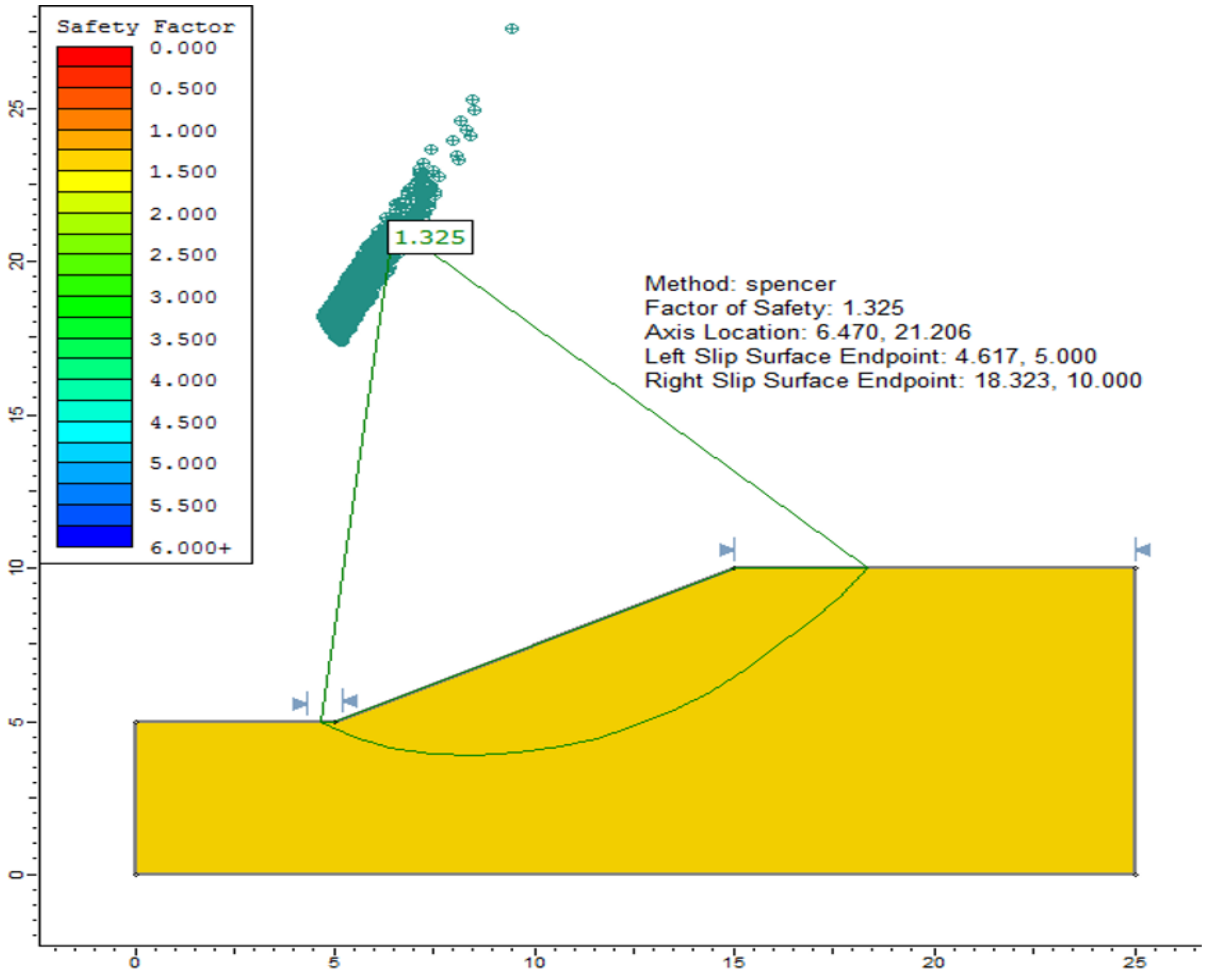


Figure 17.3: Noncircular failure surface, using the Spencer method

18. Slide Verification Problem #18

Slope, homogenous slope, ru pore pressure

18.1. Introduction

This model is taken from Baker (1980) and was originally published by Spencer (1969). It consists of a simple slope of homogeneous soil with pore pressure.

18.2. Problem Description

Verification problem #18 is shown in Figure 18.1. The material properties are given in Table 18.1. The position of the critical slip surface and the corresponding factor of safety is calculated for a noncircular slip surface. The pore pressure within the slope is modeled using a Ru value of 0.5.

18.3. Geometry and Material Properties

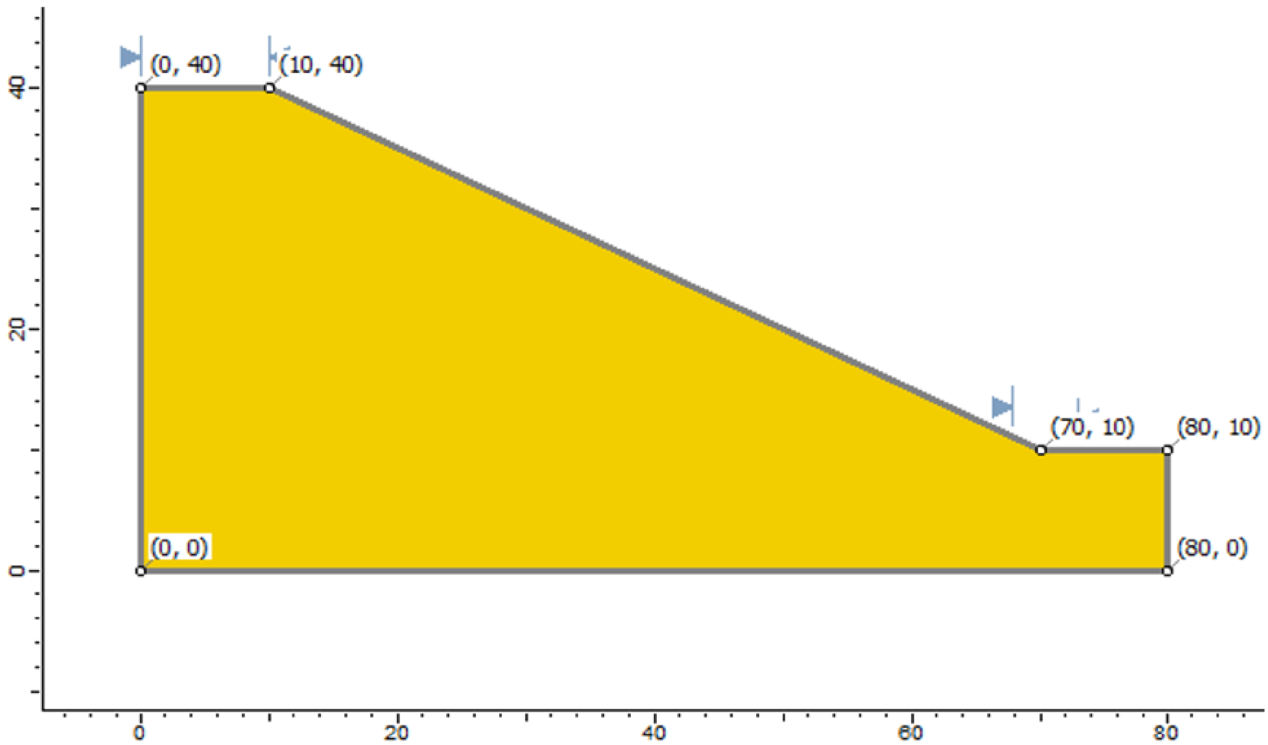


Figure 18.1: Geometry Setup in **Slide**

Table 18.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)	Ru
Soil	10.8	40	18	0.5

18.4. Results

Table 18.2: Noncircular – using Random search with Monte-Carlo optimization

Method	Factor of Safety
Spencer	1.010

Note: Baker (1980) Spencer factor of safety = 1.02

Spencer (1969) Spencer factor of safety = 1.08

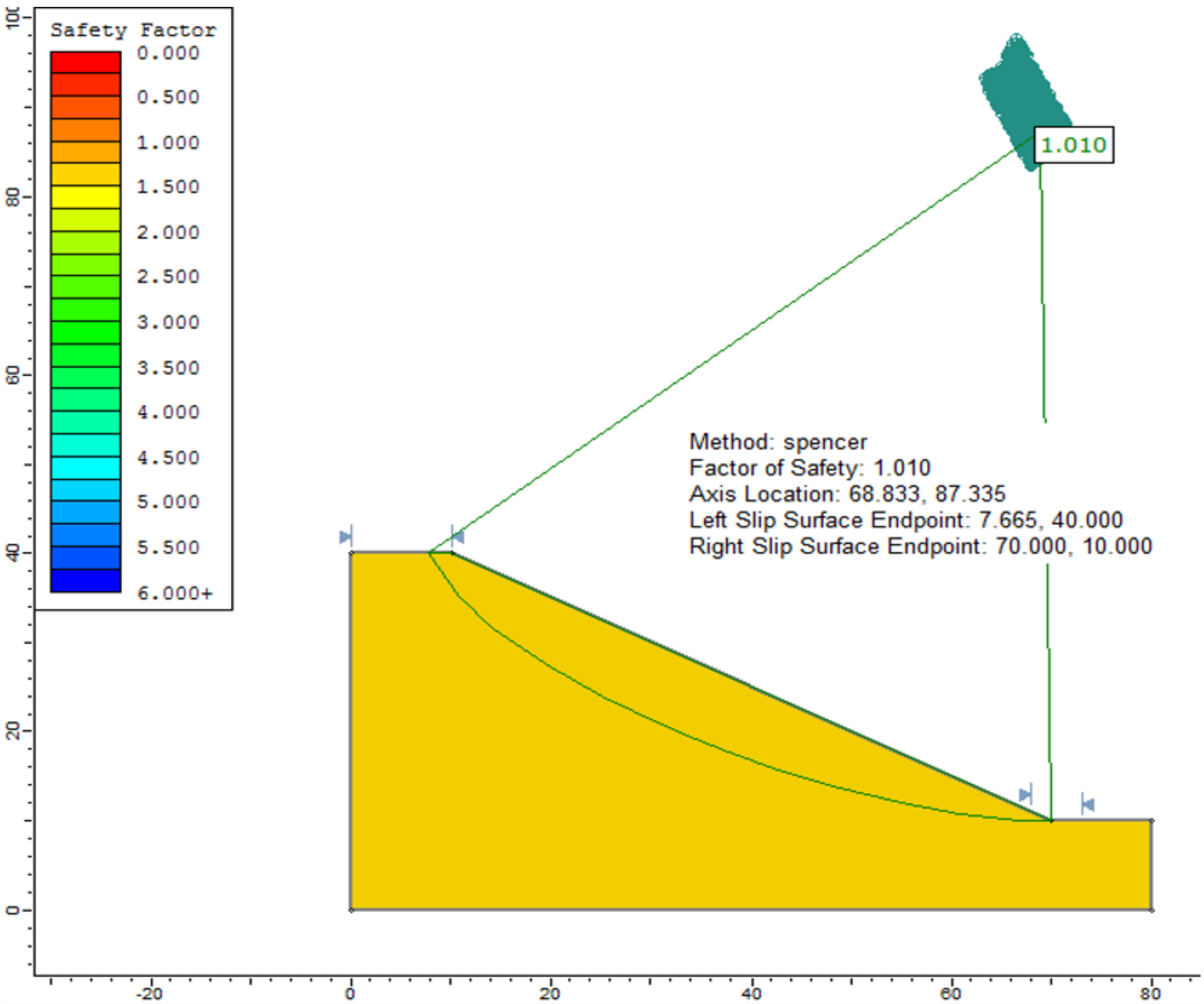


Figure 18.2: Noncircular failure surface, using the Spencer method

19. Slide 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

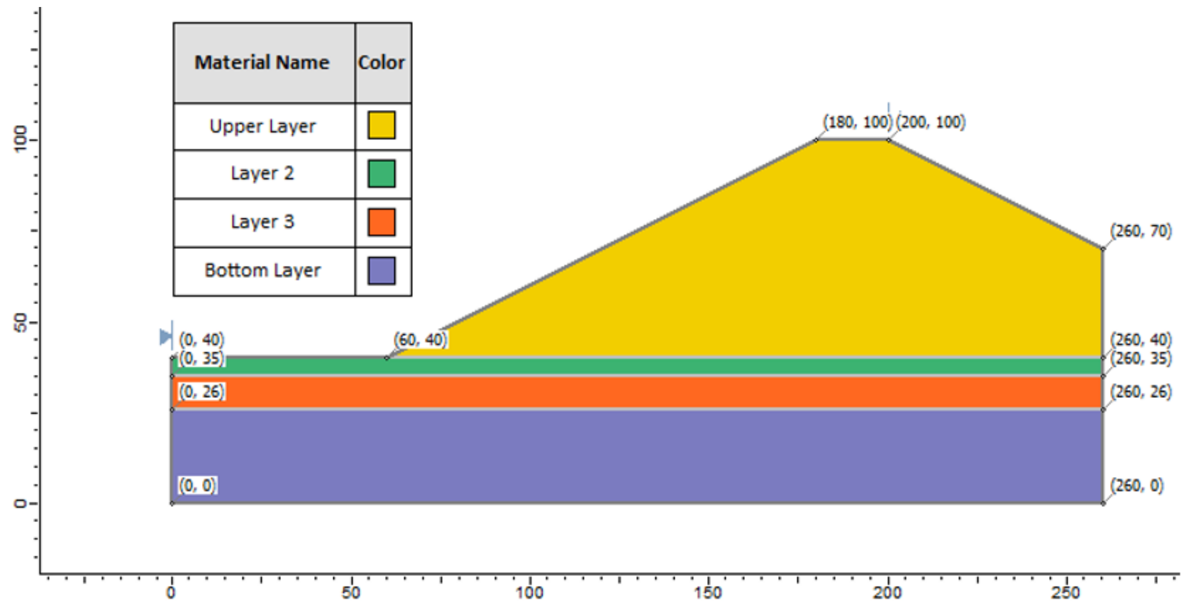


Figure 19.1: Geometry Setup in **Slide**

Table 19.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
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

19.4. Results

Table 18.2: Noncircular – using Random search with Monte-Carlo optimization, convex surfaces only

Method	Factor of Safety
Spencer	1.398

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

Spencer (1969) Spencer factor of safety = 1.40 - 1.42

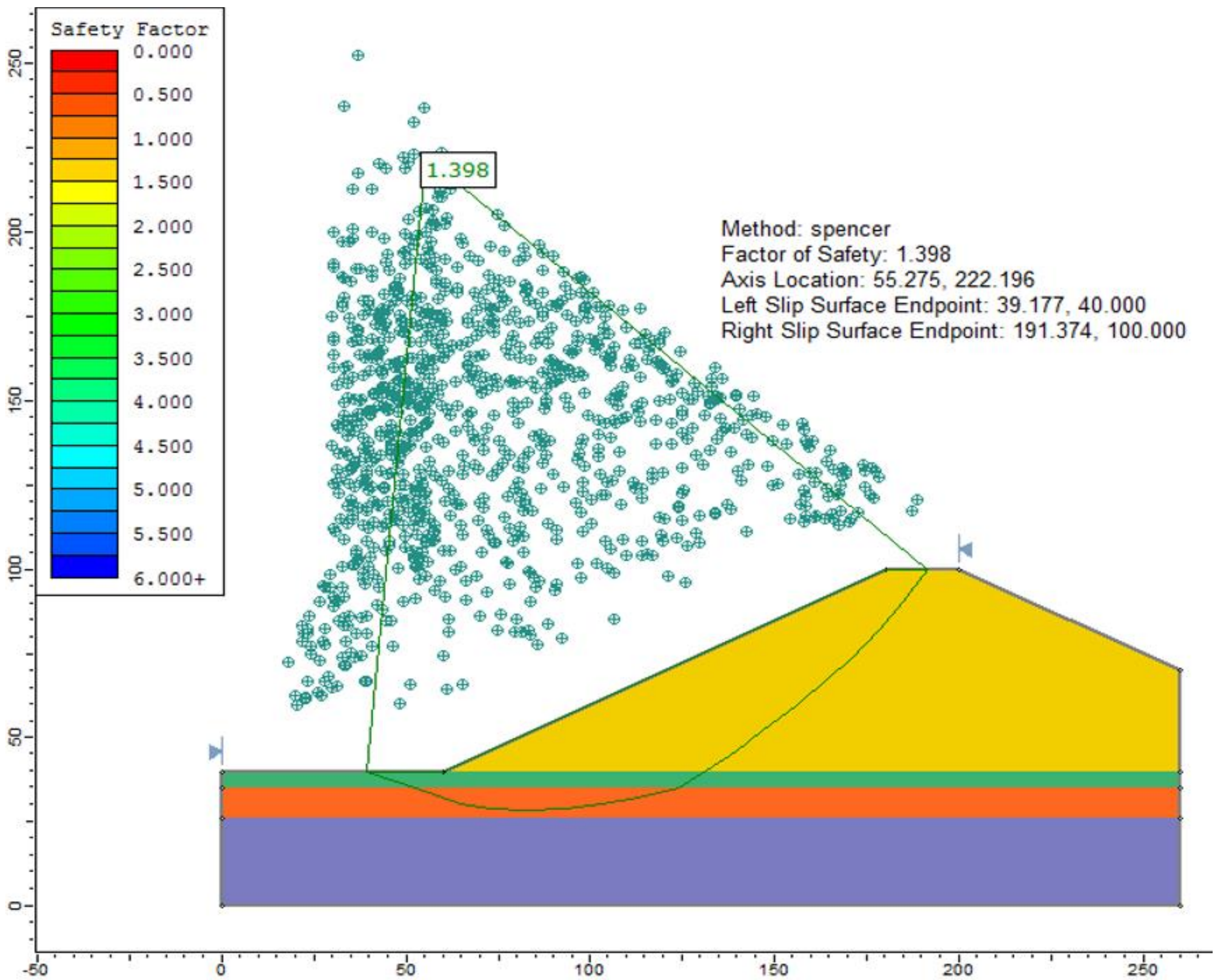


Figure 19.2: Noncircular failure surface, using the Spencer method

20. Slide Verification Problem #20

Slope, (4) materials, weak layer, water table

20.1. Introduction

This model is taken from Greco (1996) example #5, and it was originally published by Chen and Shao (1988). It consists of a layered slope with pore pressure and a weak seam.

20.2. Problem Description

Verification problem #20 is shown in Figure 20.1. The material properties are given in Table 20.1. The position of the critical slip surface and the corresponding factor of safety is calculated for a circular and noncircular slip surface. The weak seam is modeled as a 0.5m thick material layer at the base of the model.

20.3. Geometry and Material Properties

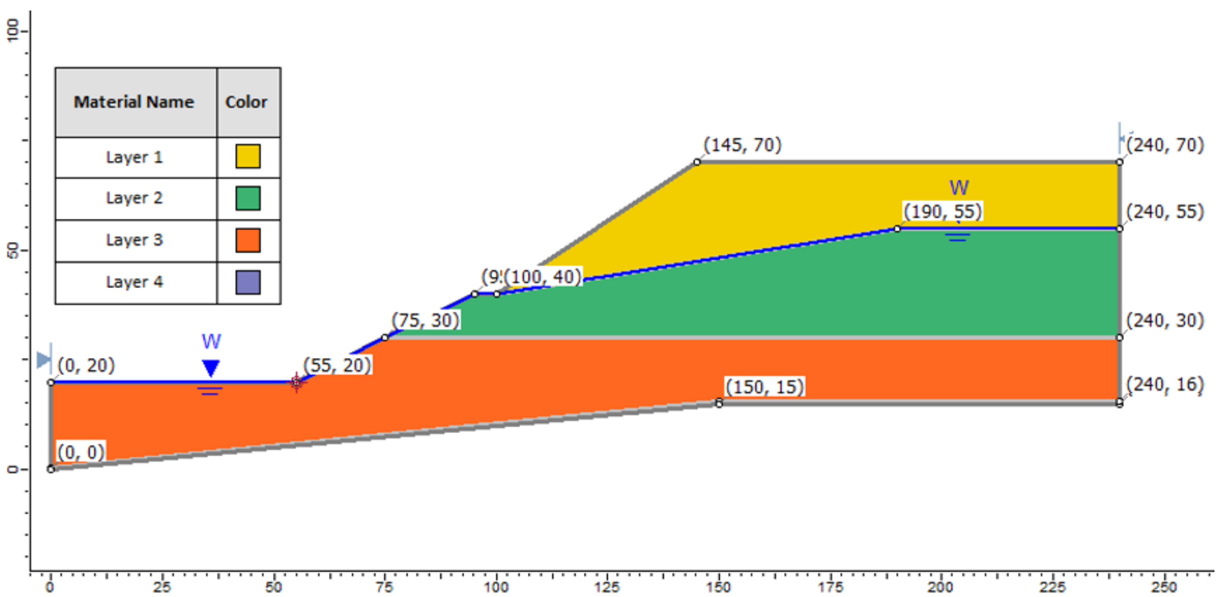


Figure 20.1: Geometry Setup in **Slide**

Table 20.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Layer 1	9.8	35	20
Layer 2	58.8	25	19
Layer 3	19.8	30	21.5
Layer 4	9.8	16	21.5

20.4. Results

Table 20.2: Circular – using grid search and a focus object at the toe (40x40 grid)

Method	Factor of Safety
Bishop	1.087
Spencer	1.093

Note: Greco (1996) Spencer factor of safety for nearly circular local critical surface = 1.08

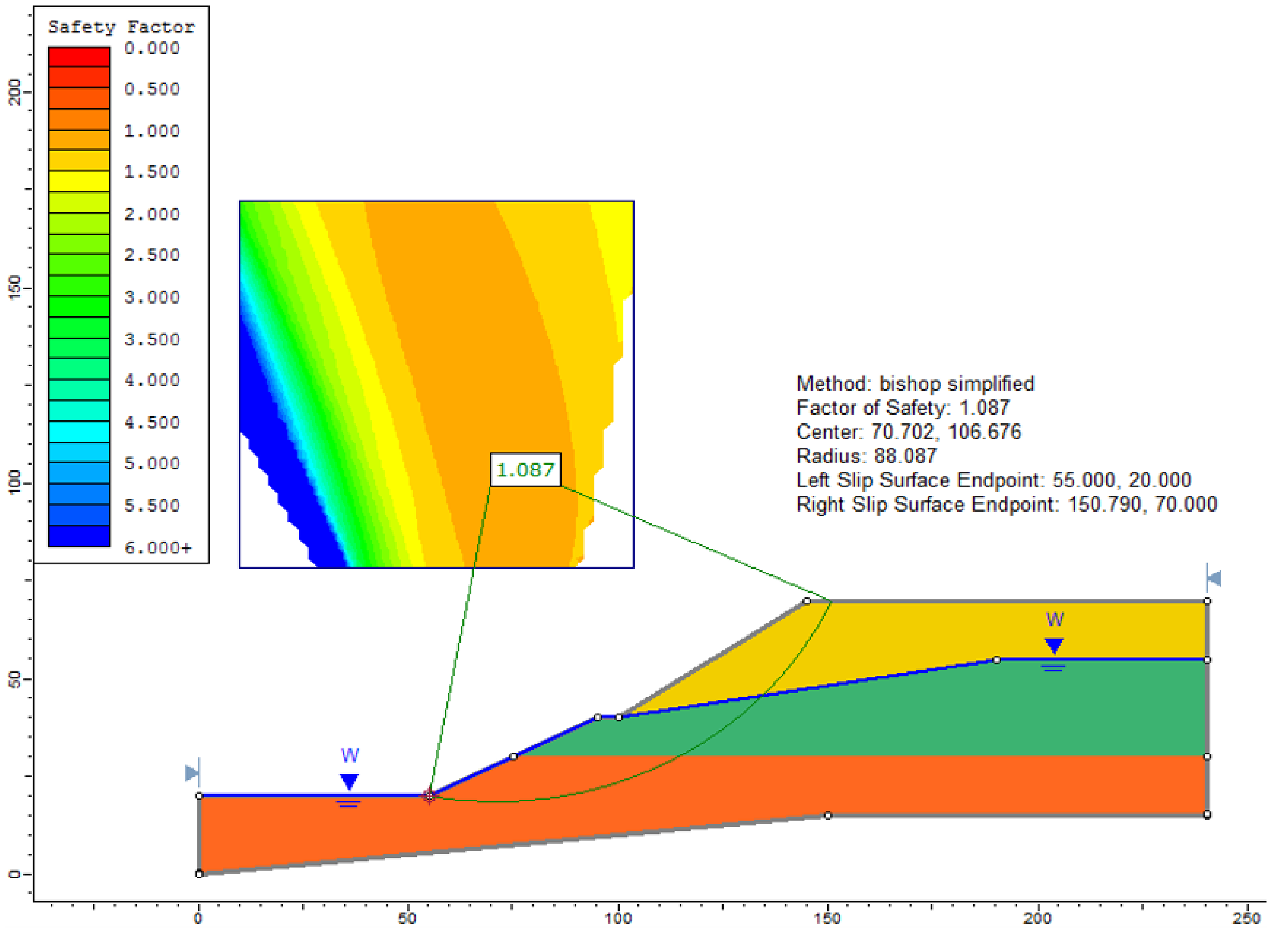


Figure 20.2: Circular failure surface, using the Bishop simplified method

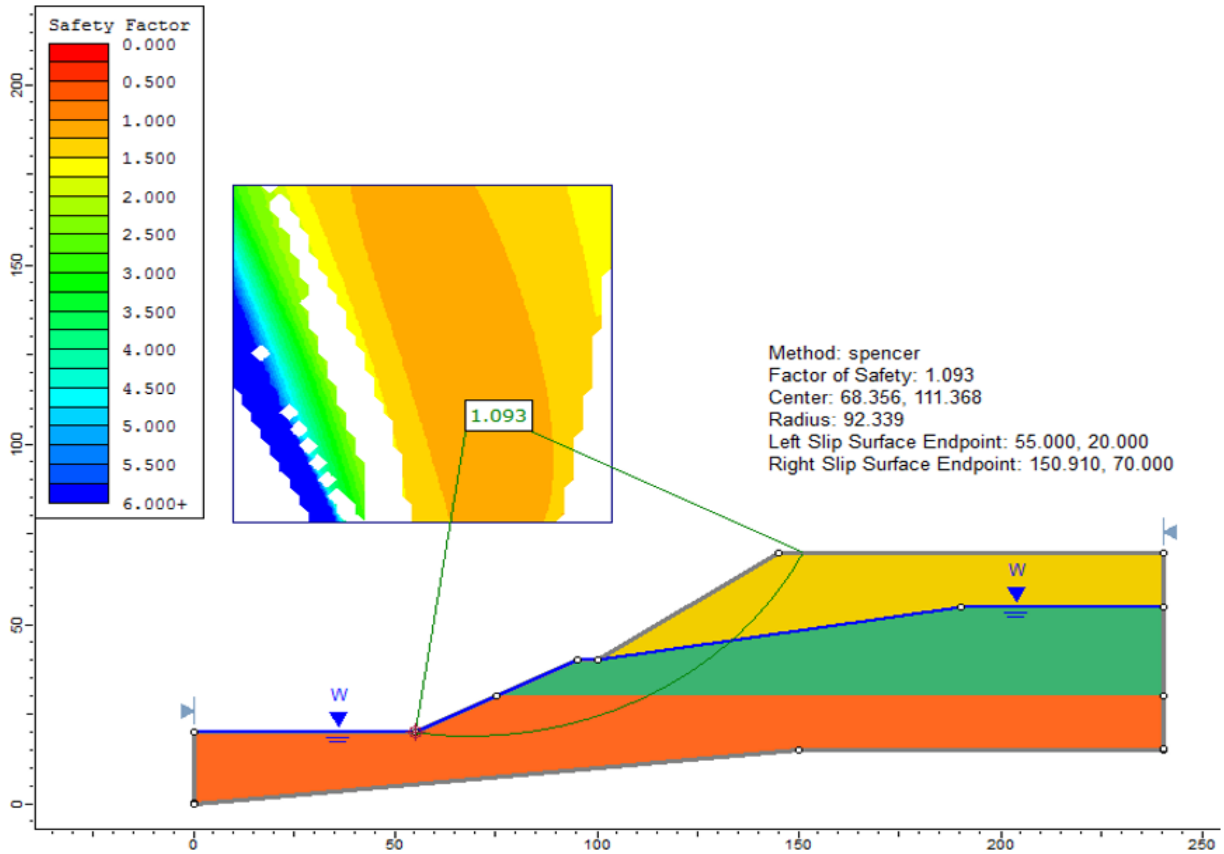


Figure 20.3: Circular failure surface using the Spencer method

Table 20.3: Noncircular – using Block search polyline in the weak seam and Monte-Carlo optimization

Method	Factor of Safety
Spencer	1.010

Note: Chen and Shao (1988) Spencer Factor of Safety = 1.01 - 1.03

Greco (1996) Spencer Factor of Safety = 0.973 - 1.1

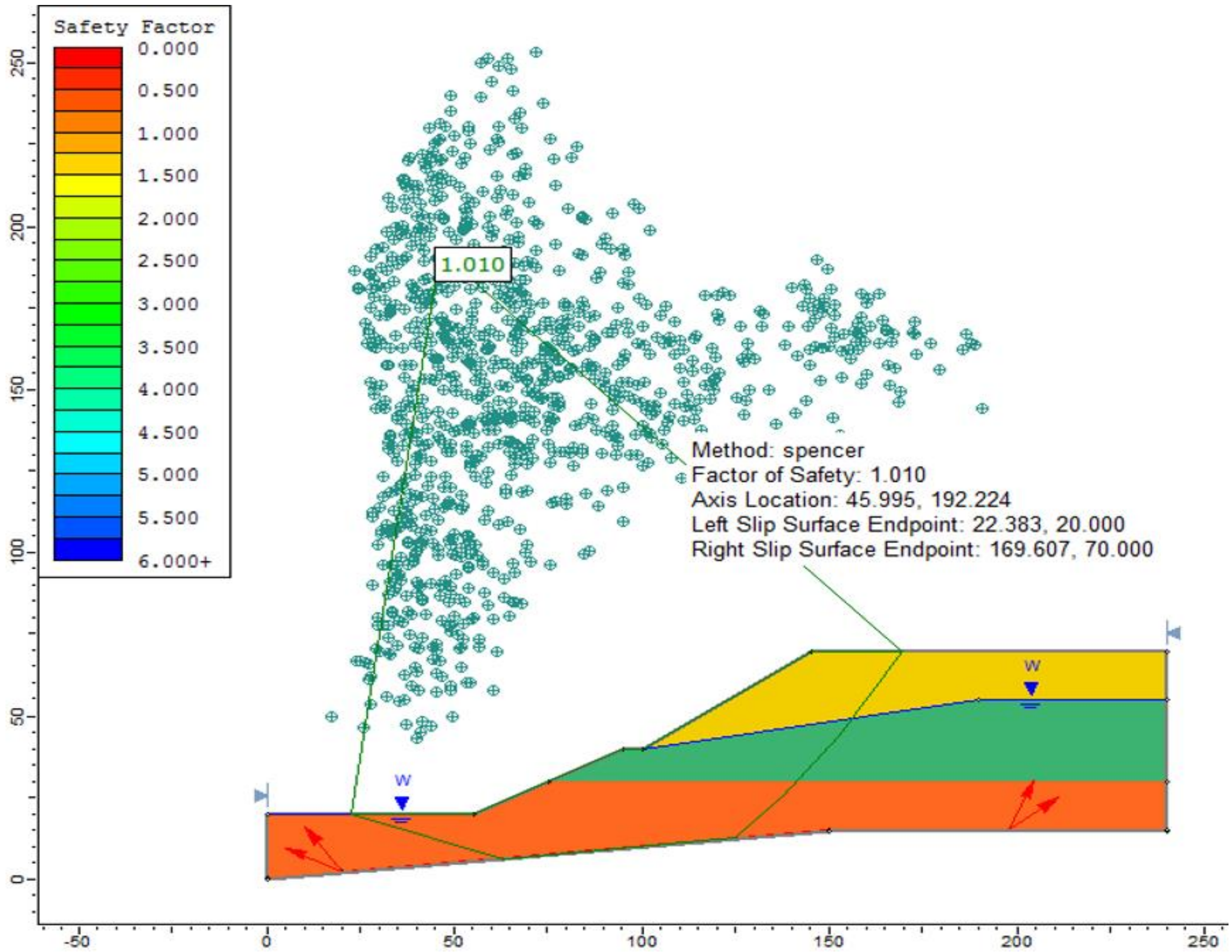


Figure 20.4: Noncircular failure surface using the Spencer method and block search

21. Slide Verification Problem #21

Slope, homogenous, 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.

21.3. Geometry and Material Properties

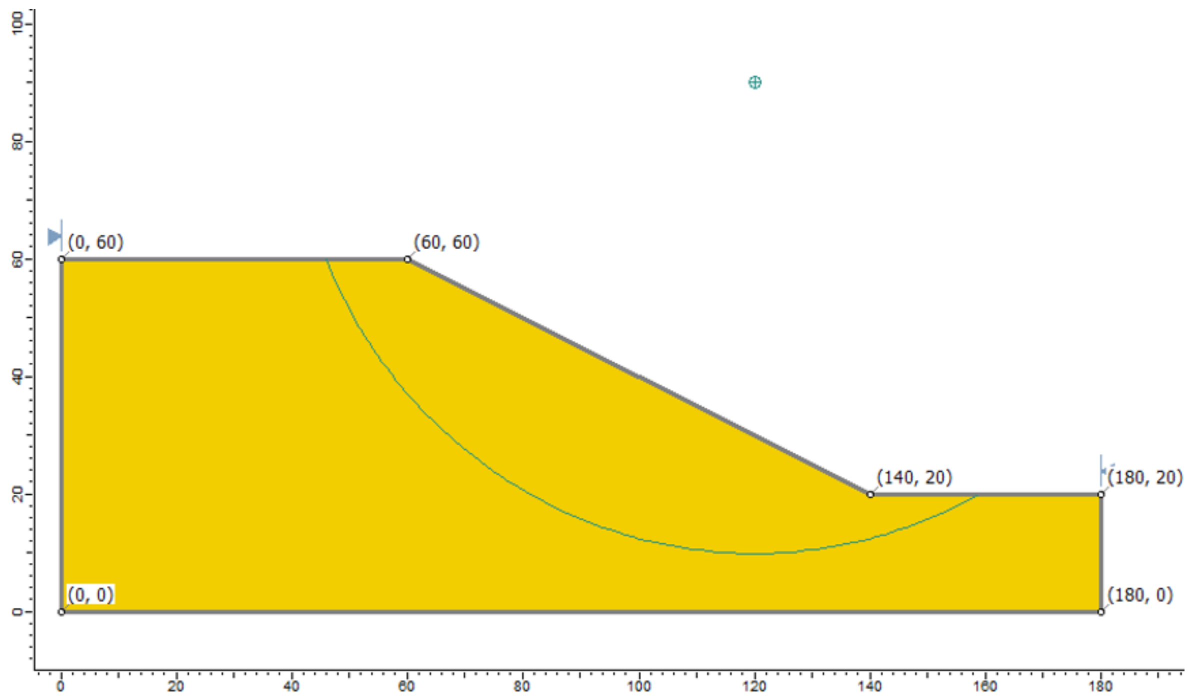


Figure 21.1: Geometry Setup in **Slide**

Table 21.1: Soil Properties

	c´ (psf)	ϕ´ (deg.)	γ (pcf)	Ru (case2)
Soil	600	20	120	0.25

21.4. Results

Table 21.2

Case	Ordinary (F&K)	Ordinary (*Slide*)	Bishop (F&K)	Bishop (*Slide*)	Spencer (F&K)	Spencer (*Slide*)	M-P (F&K)	M-P (*Slide*)
1-Dry	1.928	1.931	2.080	2.079	2.073	2.075	2.076	2.075
2-Ru	1.607	1.687	1.766	1.763	1.761	1.760	1.764	1.760
3-WT	1.693	1.716	1.834	1.833	1.830	1.831	1.832	1.831

22. Slide 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

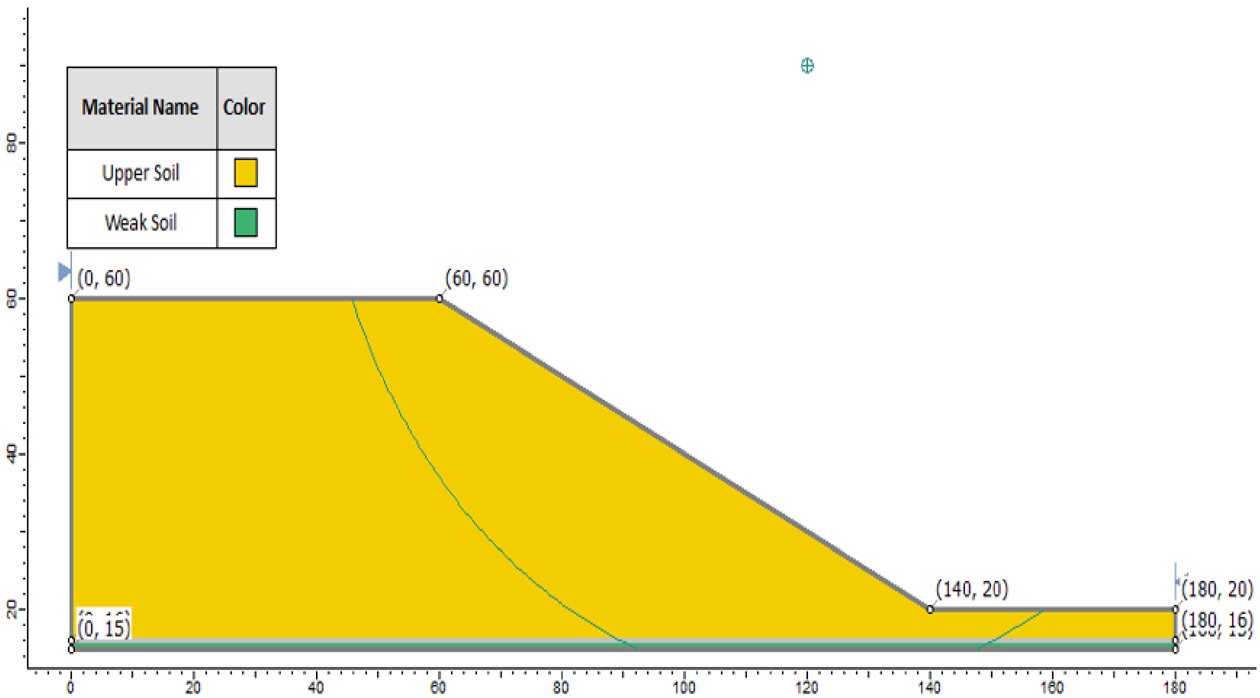


Figure 22.1: Geometry Setup in **Slide**

Table 22.1: Soil Properties

	c´ (psf)	ϕ´ (deg.)	γ (pcf)	Ru (case2)
Upper soil	600	20	120	0.25
Weak layer	0	10	120	0.25

22.4. Results

Table 22.2: Composite Circular - Slide

Method	Case 1: Dry	Case 2: Ru	Case 3: WT
Ordinary	1.300	1.121	1.188
Bishop Simplified	1.382	1.124	1.243
Spencer	1.382	1.124	1.244
GLE/Morgenstern-Price	1.372	1.114	1.237

Table 22.3: Composite Circular – Fredlund & Krahn

Method	Case 1: Dry	Case 2: Ru	Case 3: WT
Ordinary	1.288	1.029	1.171
Bishop Simplified	1.377	1.124	1.248
Spencer	1.373	1.118	1.245
GLE/Morgenstern-Price	1.370	1.118	1.245

Table 22.4: Composite Circular – Zhu, Lee, and Jiang

Method	Case 1: Dry	Case 2: Ru	Case 3: WT
Ordinary	1.300	1.038	1.192
Bishop Simplified	1.380	1.118	1.260
Spencer	1.381	1.119	1.261
GLE/Morgenstern-Price	1.371	1.109	1.254

23. Slide Verification Problem #23

Slope, (3) materials

23.1. Introduction

This model is taken from Low (1989). It consists of a slope overlaying two soil layers.

23.2. Problem Description

Verification problem #23 is shown in Figure 23.1. The material properties are given in Table 23.1. The middle and lower soils have constant and linearly varying undrained shear strength. The position of the critical slip surface and the corresponding factor of safety is calculated for a circular slip surface using both the bishop and ordinary/fellenius methods.

23.3. Geometry and Material Properties

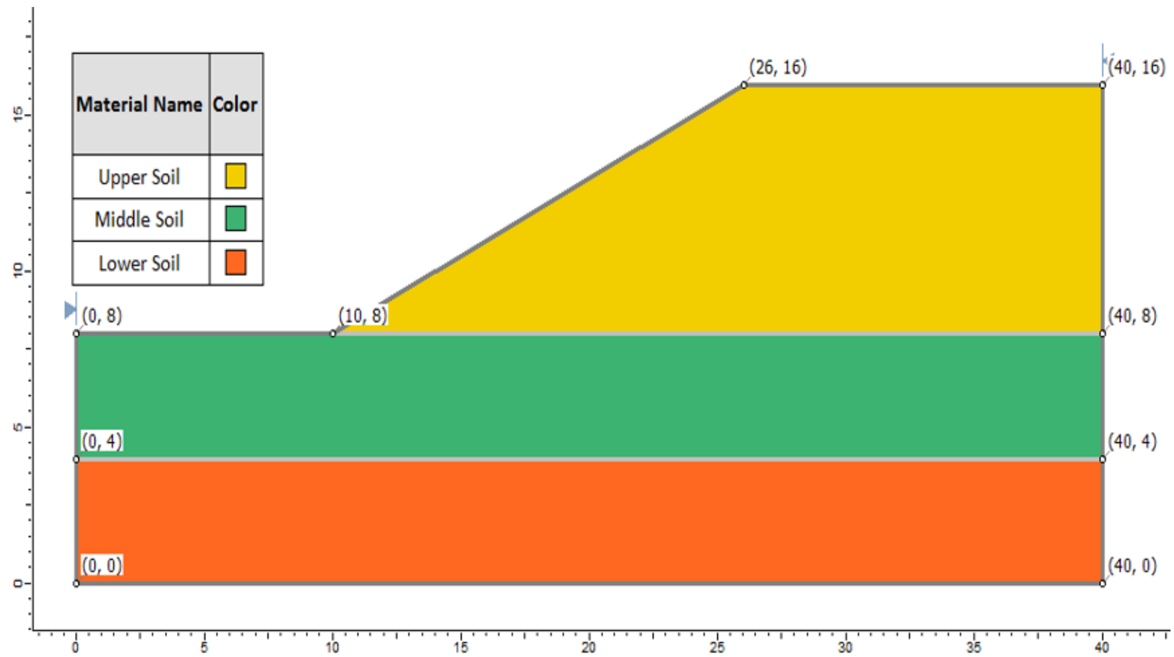


Figure 23.1: Geometry Setup in **Slide**

Table 23.1: Soil Properties

	Cu_{top} (kN/m^2)	Cu_{bottom} (kN/m^2)	ϕ (deg.)	γ (kN/m^3)
Upper Soil	95	95	15	20
Middle Soil	15	15	0	20
Lower Soil	15	30	0	20

23.4. Results

Table 23.2

Method	Factor of Safety
Ordinary	1.370
Bishop	1.192

Note: Low (1989) Ordinary factor of safety=1.36

Low (1989) Bishop factor of safety=1.14

Kim (2002) factor of safety=1.17

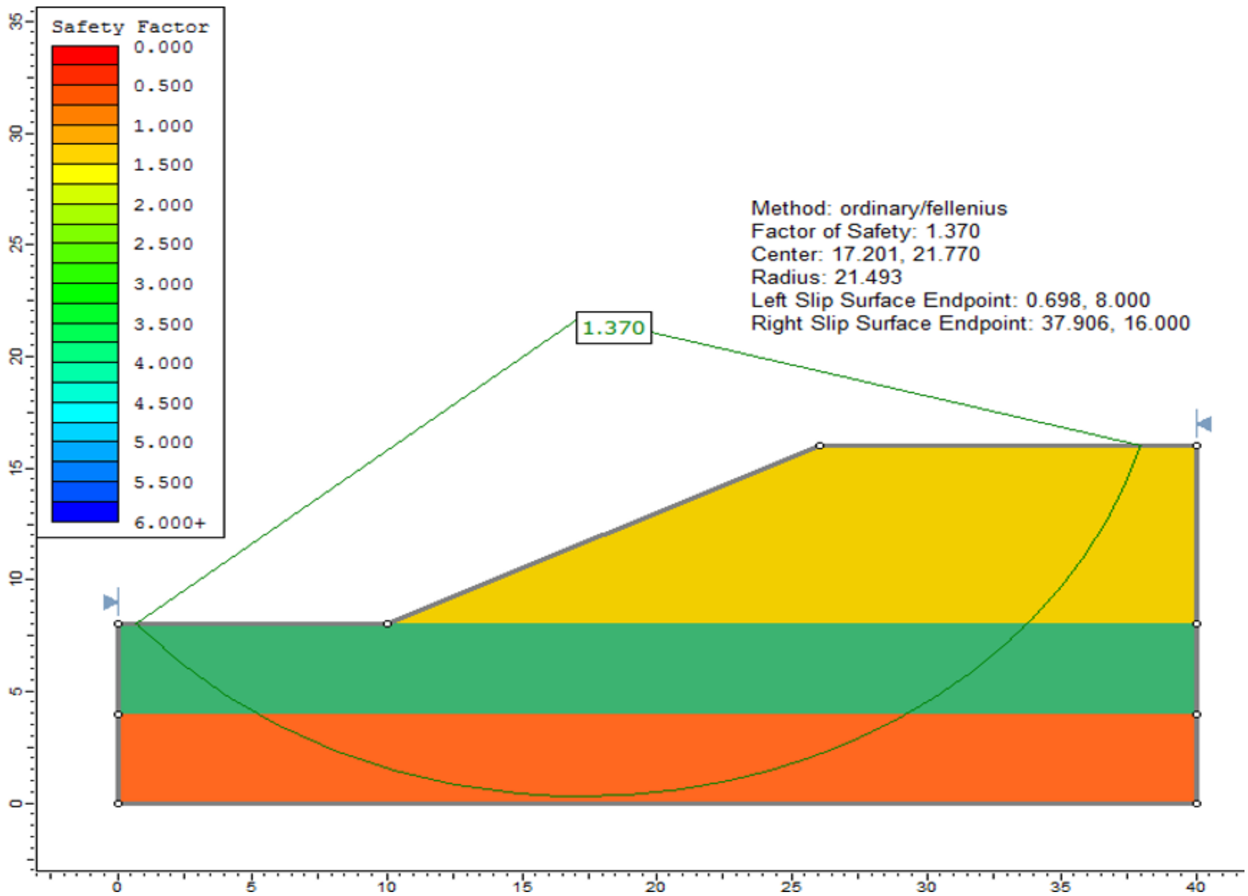


Figure 23.2: Circular failure surface using the Ordinary/Fellenius method

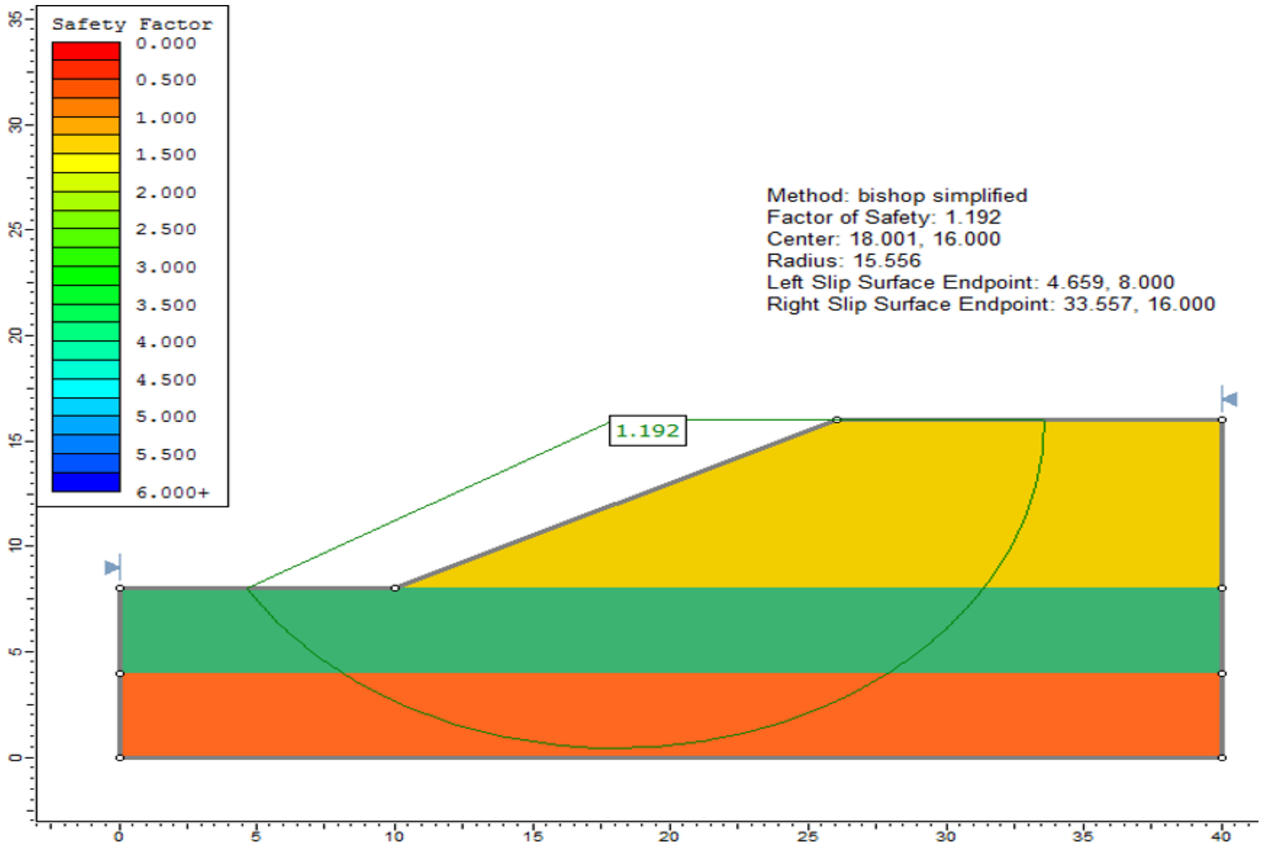


Figure 23.3: Circular failure surface using the Bishop simplified method

24. Slide 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, using both the bishop and ordinary/fellenius methods.

24.3. Geometry and Material Properties

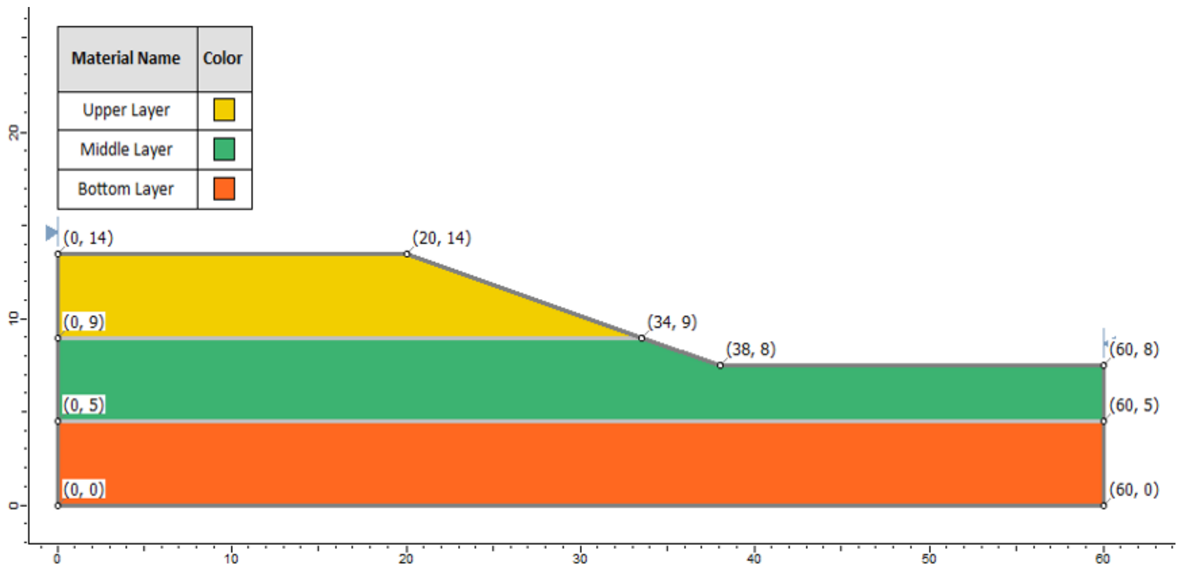


Figure 24.1: Geometry Setup in **Slide**

Table 24.1: Soil Properties

	c´ (kN/m^2)	γ (kN/m^3)
Upper Layer	30	18
Middle Layer	20	18
Bottom Layer	150	18

24.4. Results

Table 24.2

Method	Factor of Safety
Ordinary	1.439
Bishop	1.439

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

Low (1989) Bishop factor of safety = 1.44

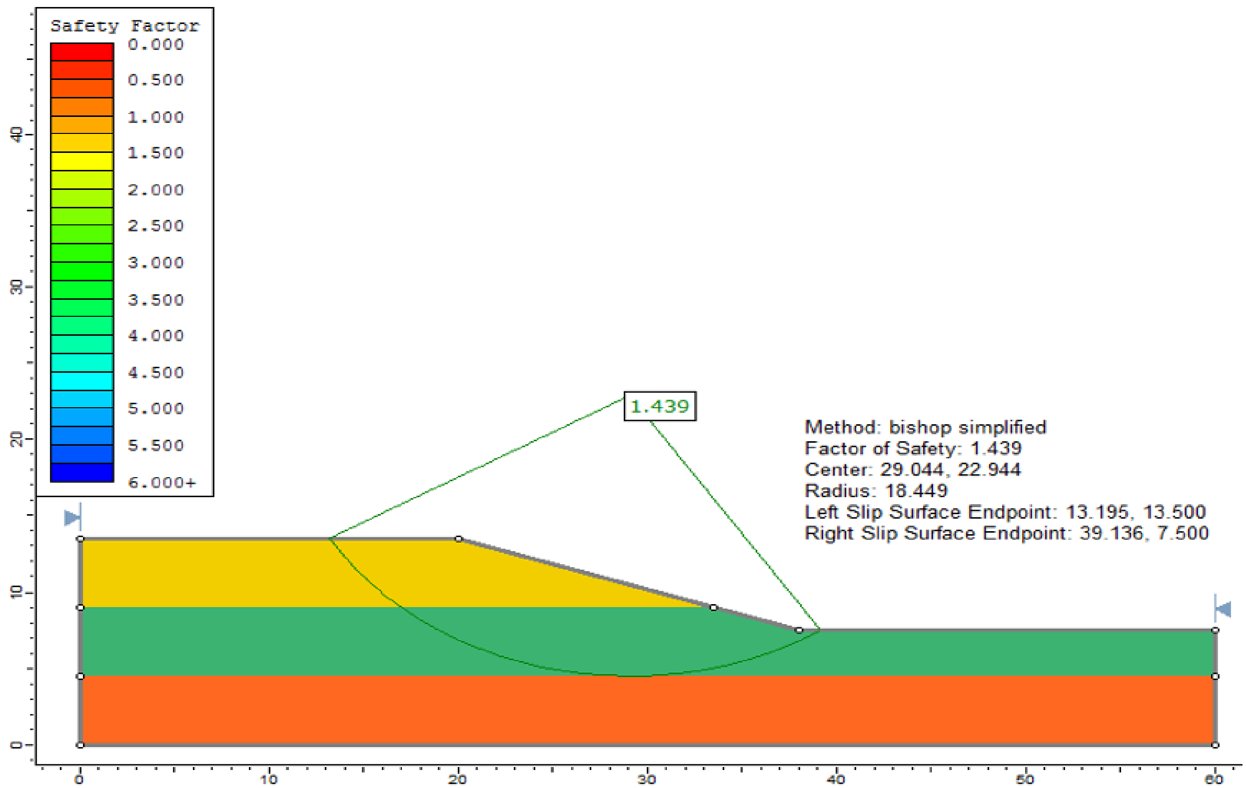


Figure 24.2: Circular failure surface, using the Bishop simplified method

25. Slide 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: Inter-slice force function

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

25.3. Geometry and Material Properties

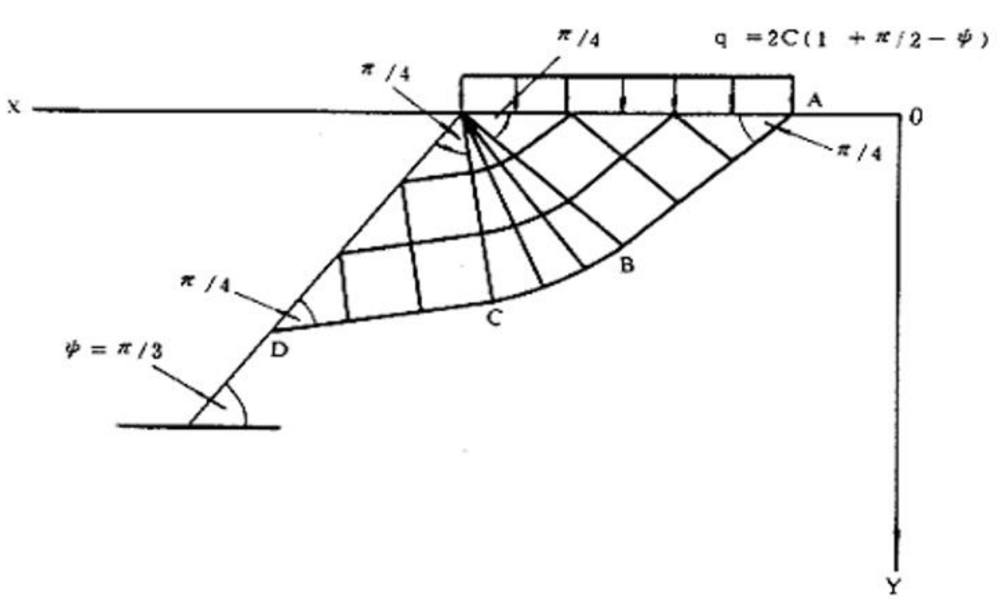


Figure 25.1: Closed-form solution (from Chen and Shao (1988))

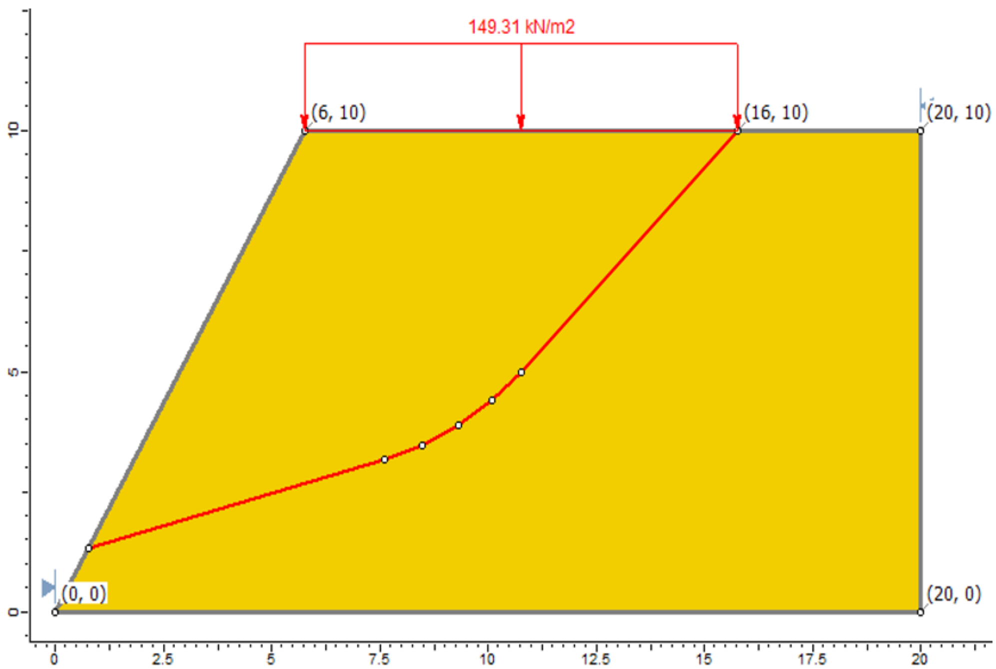


Figure 25.2: Geometry Setup in **Slide**

Table 25.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Soil	49	0	1e-6

25.4. Results

Table 25.2

Method	Factor of Safety
Spencer	1.051
GLE/M-P	1.009

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

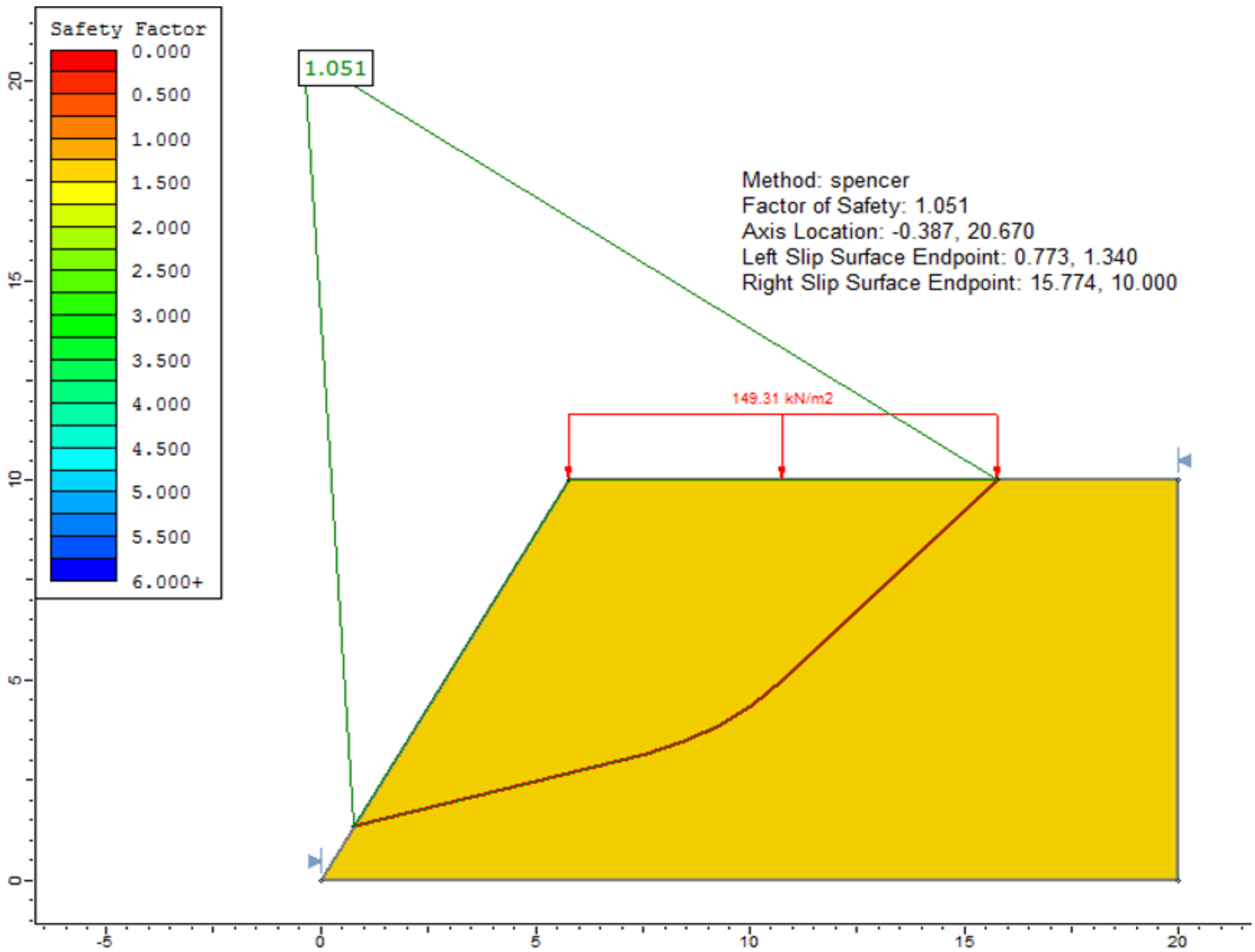


Figure 25.3: Non-Circular failure surface, by using the Spencer method

26. Slide 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: $q_c = 2C(1+\pi/2)$

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, q_c 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

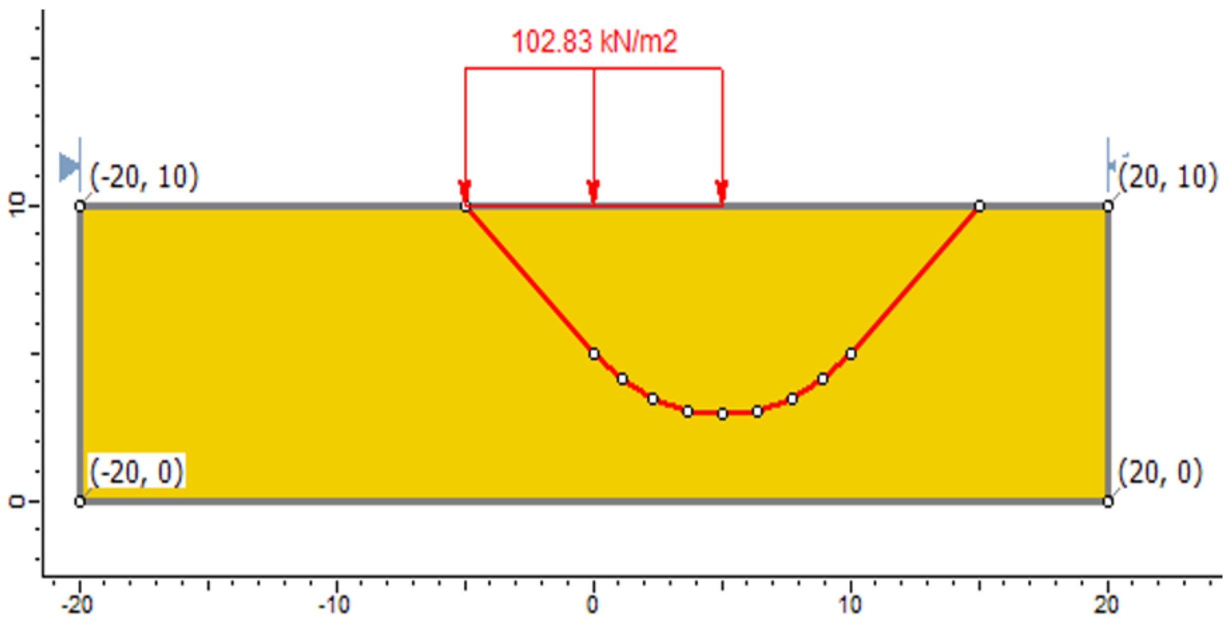


Figure 26.1: Geometry Setup in **Slide**

Table 26.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Soil	20	0	1e-6

26.4. Results

Table 25.2

Method	Factor of Safety
Spencer	0.940

Note: Theoretical factor of safety = 1.0

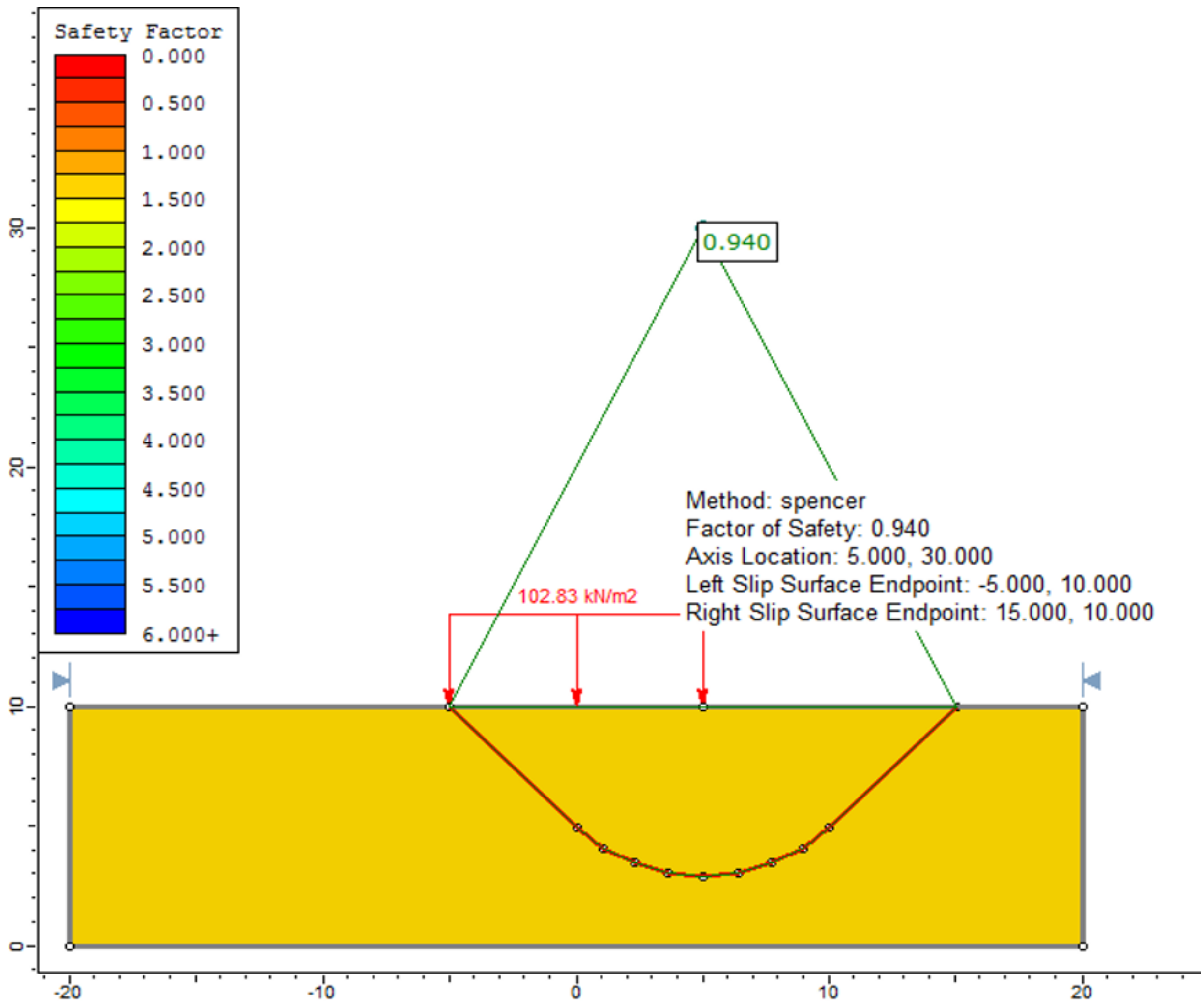


Figure 26.2: Non-Circular failure surface, by using the Spencer method

27. Slide Verification Problem #27

Slope, (2) materials, tension crack, water table (auto Hu)

27.1. Introduction

This model was taken from Malkawi, Hassan and Sarma (2001) who took it from the XSTABL version 5 reference manual (Sharma 1996). It consists of a 2 material slope overlaying undulating bedrock. There is a water table. Soil 1 has different moist and saturated unit weight. Soil 2 has zero strength. The model is done with imperial units (feet, psf, pcf) to be consistent with the original XSTABL analysis.

27.2. Problem Description

Verification problem #27 is shown in Figure 27.1. The material properties are given in Table 27.1. One of the interesting features of this model is the different unit weights of soil 1 below and above the water table. Another factor is the method of pore-pressure calculation. The pore pressures are calculated using a correction for the inclination of the phreatic surface and steady state seepage. Both *Slide* and XSTABL allow you to apply this correction. The pore pressures tend to be smaller than if a static head of water is assumed (measured straight up to the phreatic surface from the center of the base of a slice). The first analysis uses a single slip surface with x_c =59.52, y_c =219.21, and radius=157.68**.** The second analysis does a search with the restriction that the circular surface must exit the slope between 38<=x<=70 at the toe and 120<=x<=180 at the crest of the slope. The third analysis uses the same single slip surface as the first analysis but replaces soil 2 with an 11 foot deep tension crack zone instead of a zero strength material. The fourth analysis takes the third analysis and adds 6 feet of water in the tension crack.

27.3. Geometry and Material Properties

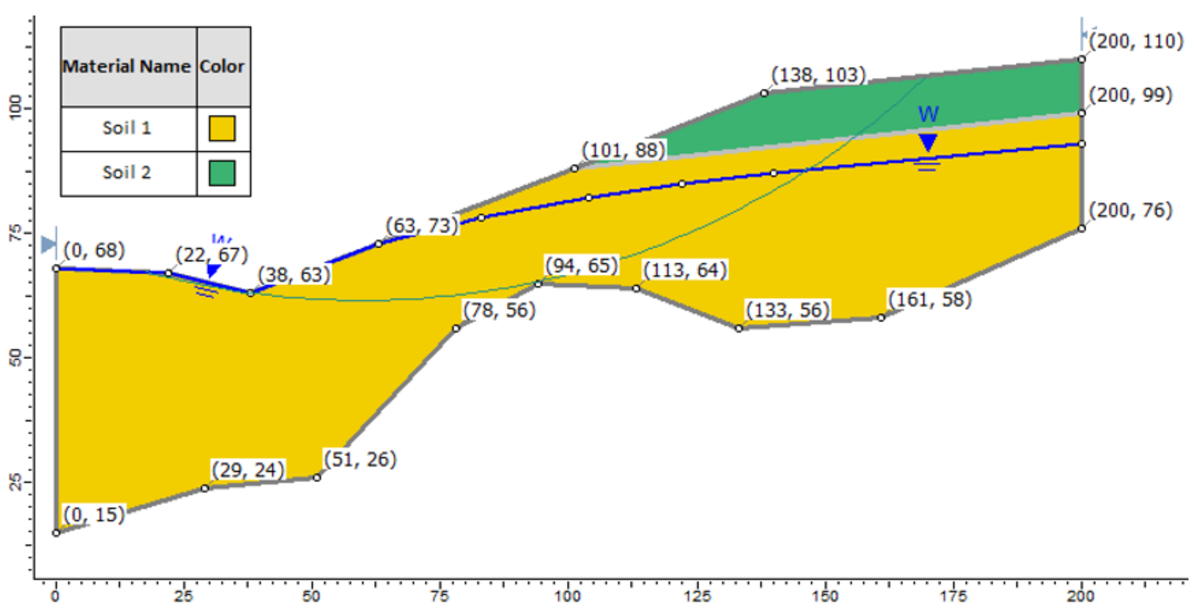


Figure 27.1: Geometry Setup in **Slide**

Table 27.1: Soil Properties

	c (psf)	ϕ (deg.)	γ moist (pcf)	γ saturated (pcf)
Soil 1	500	14	116.4	124.2
Soil 2	0	0	116.4	116.4

27.4. Results

Table 27.2: Circular – single center @ xc = 59.52, yc = 219.21, radius =157.68

Method	SLIDE	XSTABL
Bishop	1.396	1.397
Janbu Corrected	1.391	1.392
Corp. Engineers 1	1.411	1.413
Corp. Engineers 2	1.414	1.416
Lowe & Karafiath	1.411	1.413
Spencer	1.402	1.403
GLE/M-P (half-sine)	1.398	1.399

Table 27.3: Circular – auto search

Method	SLIDE
Bishop	1.376
Janbu Corrected	1.345
Corp. Engineers 1	1.394
Corp. Engineers 2	1.396
Lowe & Karafiath	1.392
Spencer	1.382
GLE/M-P (half-sine)	1.378

Note: Malkawi, Hassan and Sarma (2001), in comparing with XSTABL, quote a minimum Janbu factor of safety of 1.255 with the center and radius equal to x,y,r=62.63,160.96,101.02. However it is questionable whether this is the corrected Janbu or the uncorrected. It is also questionable whether they used the correct pore pressure distribution. If in *Slide*, you use a static pore pressure distribution and uncorrected simplified Janbu, you get a factor of safety of 1.254 (x,y,r=62.53,161.79,101.78) which is almost exactly what Malkawi, Hassan and Sarma calculated.

Table 27.4: Circular – single center @ xc = 59.52, yc = 219.21, radius = 157.68

An 11-foot tension crack is added to the analysis, replacing soil 2. The tension crack is dry. The Spencer results are shown in Figure 27.2

Method	SLIDE	XSTABL
Bishop	1.532	1.536
Janbu Corrected	1.544	1.569
Corp. Engineers 1	1.555	1.559
Corp. Engineers 2	1.562	1.566
Lowe & Karafiath	1.545	1.549
Spencer	1.532	1.535
GLE/M-P (half-sine)	1.532	1.535

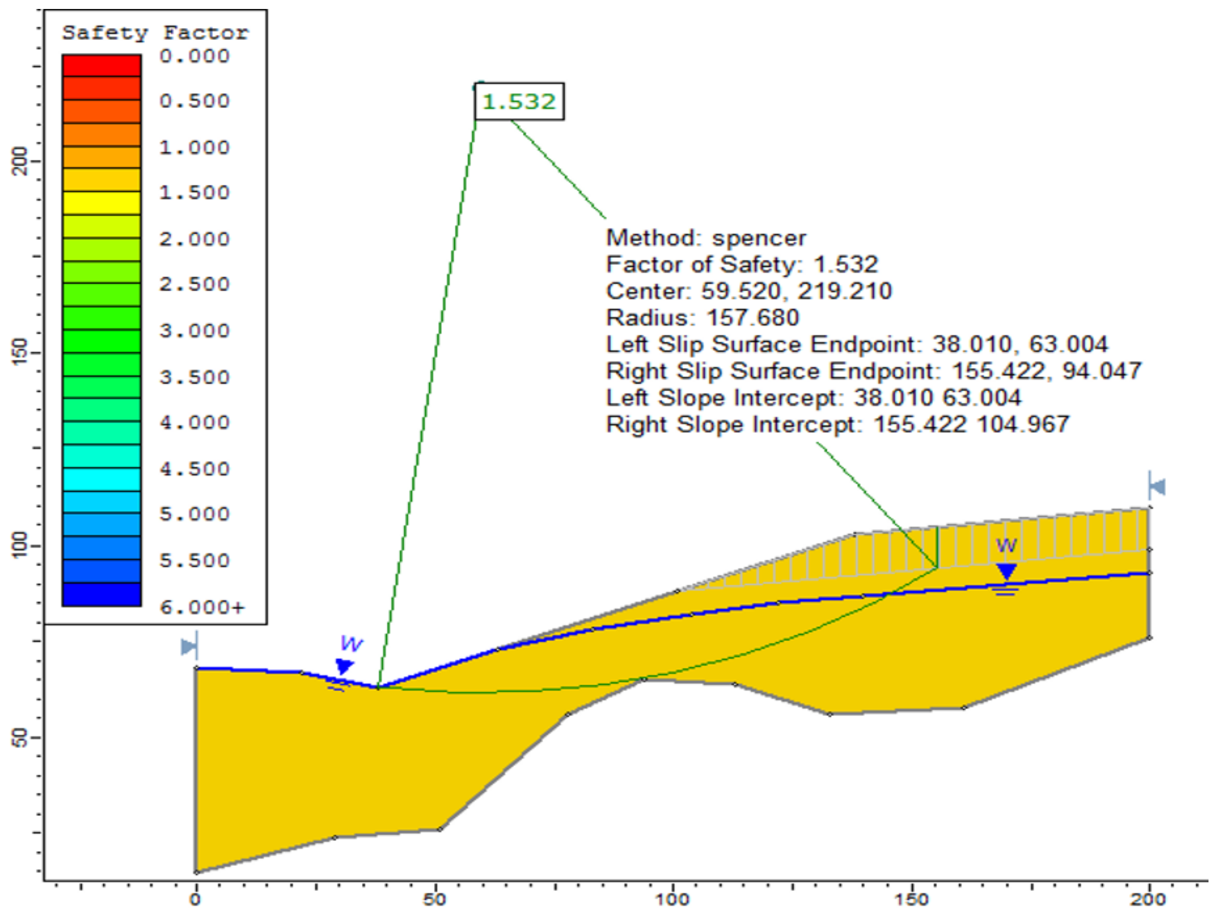


Figure 27.2: Results for the Spencer method

Table 27.4: Circular – single center @ xc = 59.52, yc = 219.21, radius = 157.68

The 11-foot tension crack added in analysis 3 is now partially filled with 6 feet of water

Method	SLIDE	XSTABL
Bishop	1.511	1.509
Janbu Corrected	1.520	1.543
Corp. Engineers 1	1.532	1.536
Corp. Engineers 2	1.538	1.542
Lowe & Karafiath	1.522	1.526
Spencer	1.510	1.513
GLE/M-P (half-sine)	1.510	1.513

28. Slide Verification Problem #28

Excavated slope and embankment, (3) materials and (5) materials, probabilistic analysis

28.1. Introduction

The set of models in this verification problem was taken from Chowdhury and Xu (1995). The geometry for the first four examples comes from the well-known Congress St. Cut model, first analyzed by Ireland (1954). All the examples in this verification evaluate the probability of failure of slopes given the means and standard deviations of some specified input parameters.

28.2. Problem Description

The geometry of Example 1 to 4 in Verification #28 is shown in Figure 28.1, and the geometry of Example 5 is shown in Figure 28.2. In each example two sets of circular slip surfaces are considered. The first set consists of potential failure surfaces tangential to the lower boundary of the Clay 2 layer, while the second considers slip surfaces tangential to the lower boundary of Clay 3. Both clays have constant undrained shear strength.

Chowdury and Xu do not consider the strength of the upper sand layer in Examples 1 to 4. They use the Bishop simplified method for all their analyses.

In their paper, Chowdury and Xu do not state the unit weight of the slope materials in Example 1 to 4. They also do not provide information on the geometry (radii and coordinates of the centers) of the critical surfaces. As a result, for each of these examples, we use material unit weights that enable us to obtain deterministic factor of safety values similar to those indicated in the paper. We then compare probability of failure values determined from *Slide* with the Chowdhury and Xu values.

In Example 5, Chowdhury and Xu examine the stability of an embankment on a soft clay foundation. Again they consider two sets of circular slip surfaces; one set is tangent to the interface of the embankment and the foundation, while the other is tangent to the lower boundary of the soft clay foundation.

The Chowdhury and Xu's probabilities of failure quoted in this verification problem are calculated using a commonly used definition of reliability index, and an assumption that factors of safety are normally distributed. **Slide** uses Monte Carlo analysis, with a minimum of five thousand samples to estimate probabilities of failure. The random variables in all *Slide* analyses were assumed to come from normal distributions.

28.3. Geometry

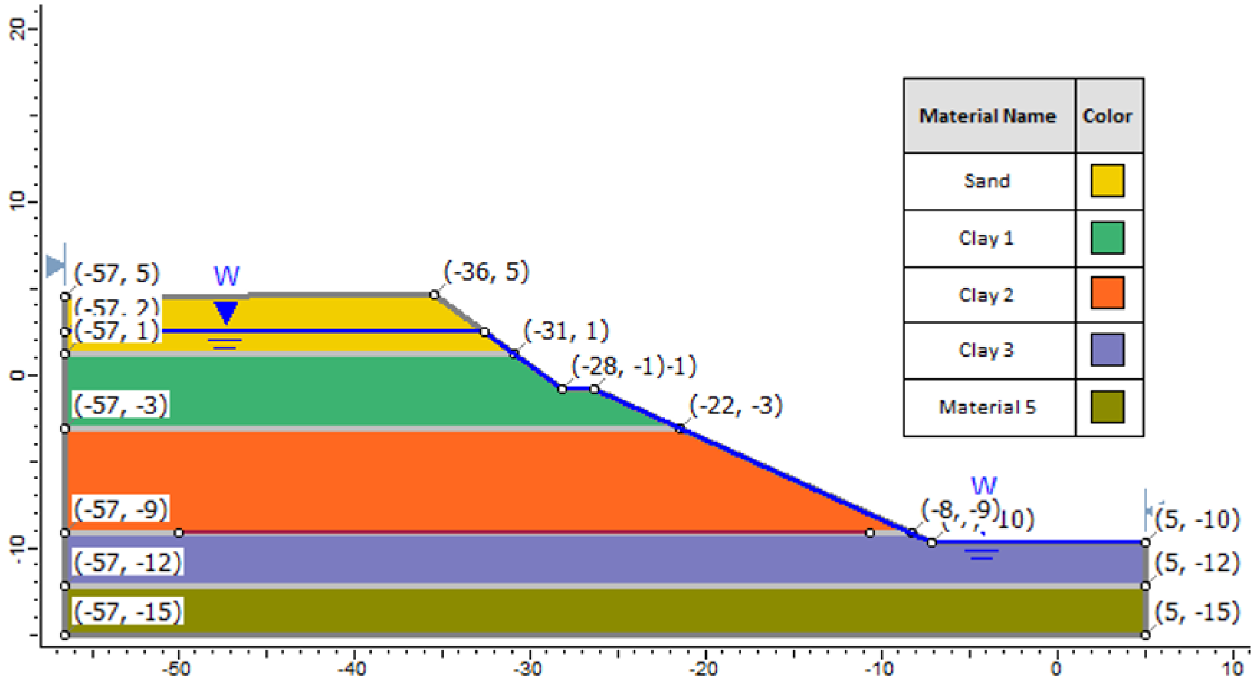


Figure 28.1: Geometry for Example 1 – 4 (excavated slope)

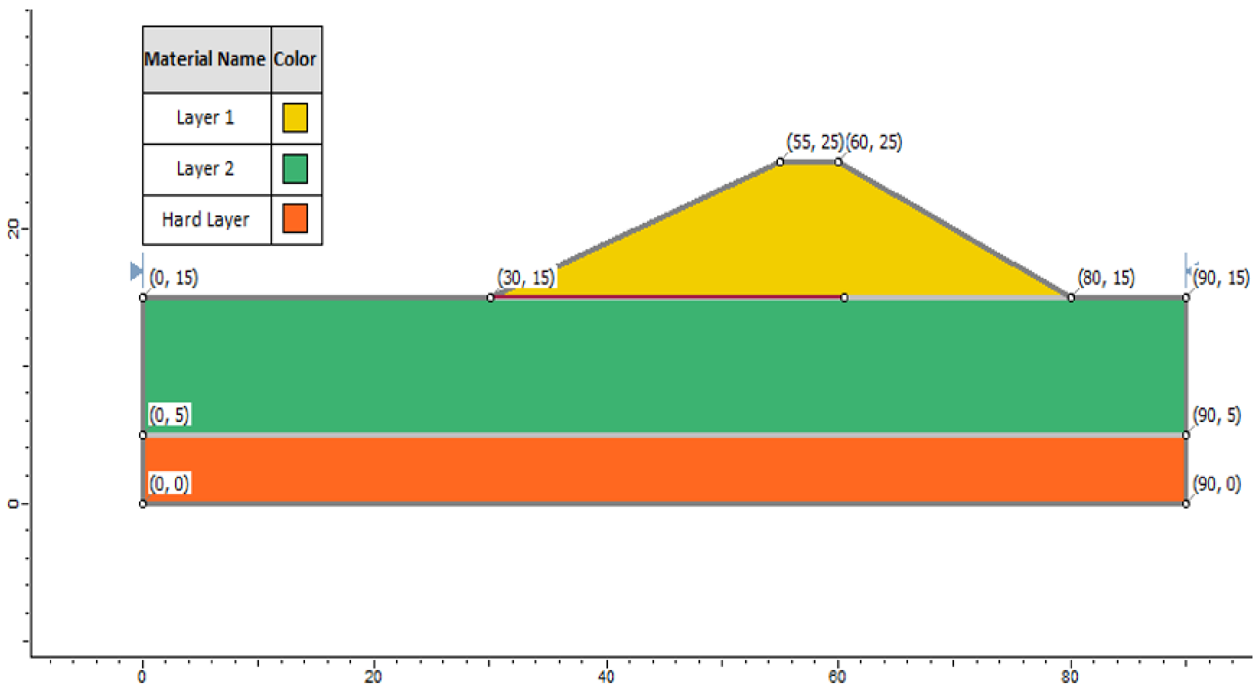


Figure 28.2: Geometry for Example 5 (an embankment on a soft clay foundation)

28.4. Results

Table 28.1: Example 1

	Soil Layer		
	Clay 1	Clay 2	Clay 3
	c_1	c_2	c_3
Mean (kPa)	55	43	56
Stdv. (kPa)	20.4	8.2	13.2
γ^* (kN/m^3)	21	22	22

Note: *The unit weight γ was not stated in the paper so we selected values that give us deterministic factors of safety close to those in the paper.

*The three clay layers are assumed frictionless.

Table 28.2: Results for Example 1

Failure Mode (Layer)	**Chowdhury & Xu**		**Slide**	
	Factor of Safety (Bishop simplified)	Probability of Failure	Factor of Safety (Bishop simplified)	Probability of Failure
Layer 2 (Clay 1)	1.128	0.26592	1.128	0.2461
Layer 3 (Clay 2)	1.109	0.27389	1.109	0.2789

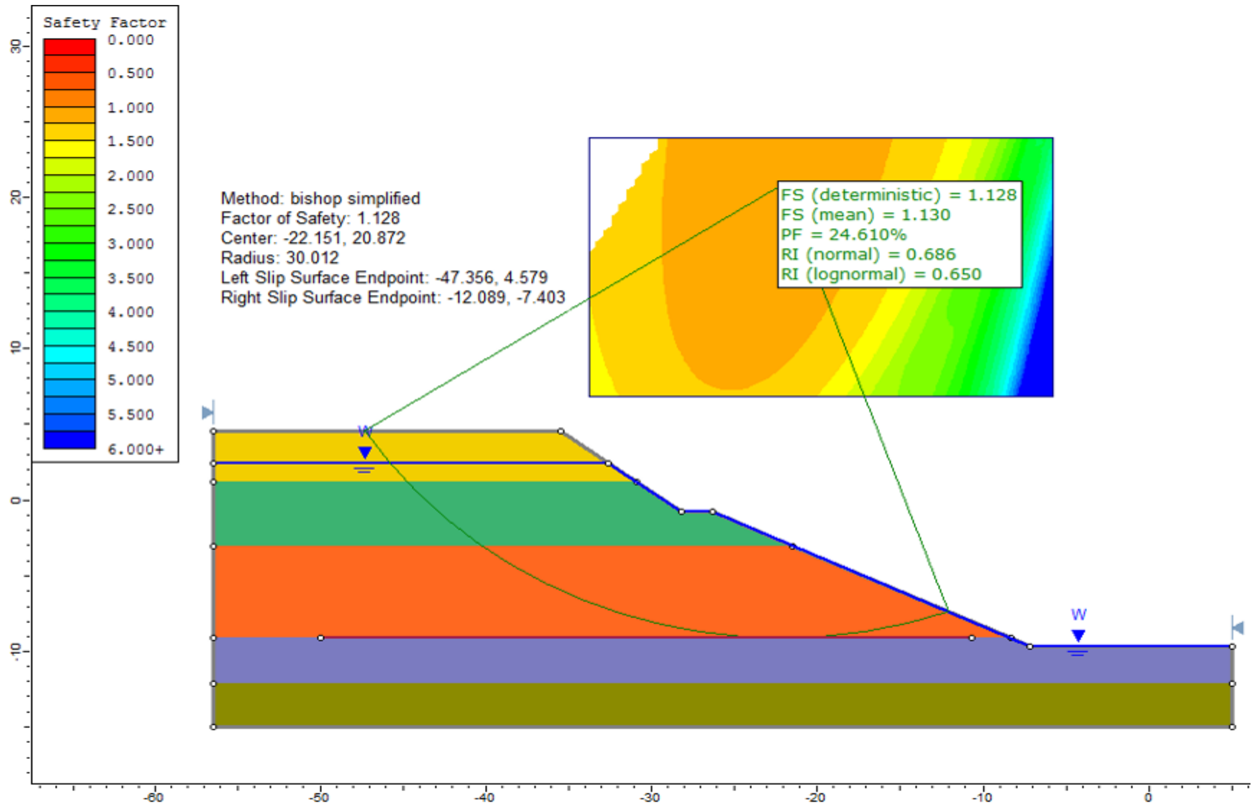


Figure 28.3: Critical slip circle tangential to lower boundary of clay layer 2

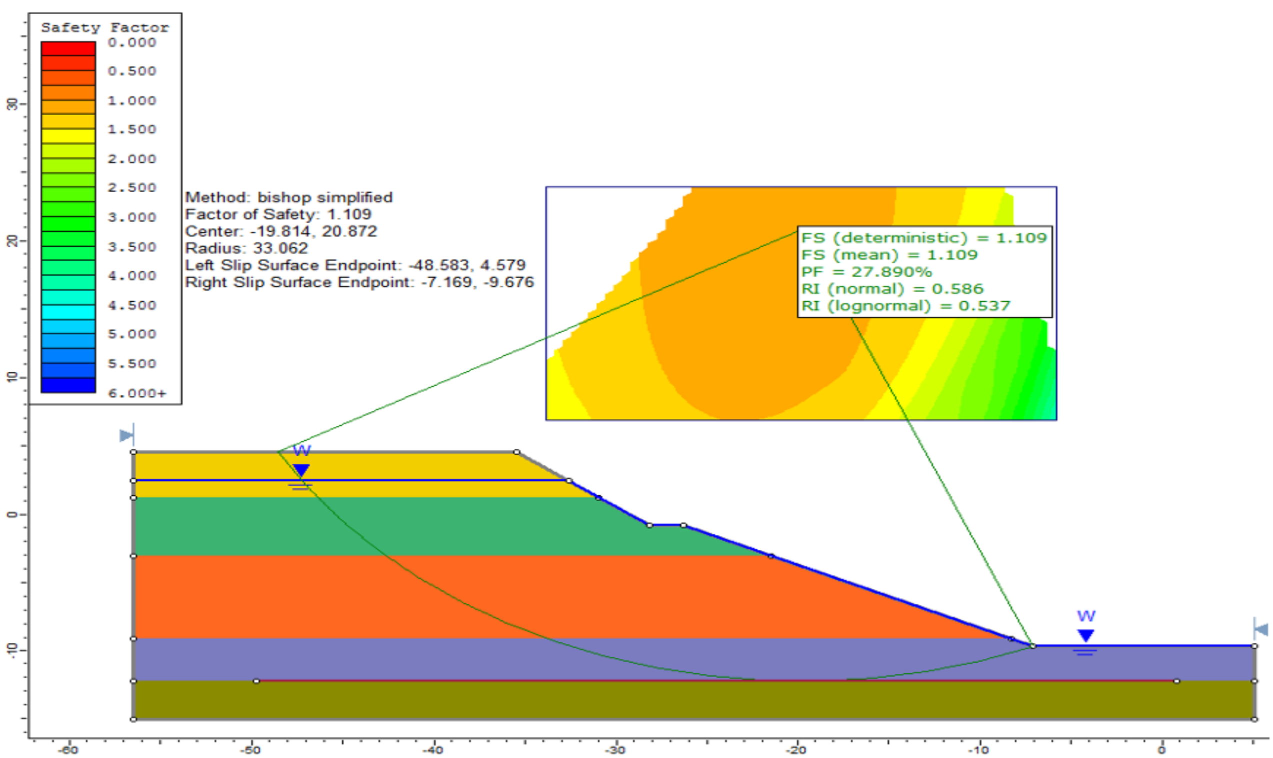


Figure 28.4: Critical slip circle tangential to lower boundary of clay layer 3

Table 28.3: Example 2

	Soil Layer		
	Clay 1	Clay 2	Clay 3
	c_1	c_2	c_3
Mean (kPa)	68.1	39.3	50.8
Stdv. (kPa)	6.6	1.4	1.5
γ^* (kN/m^3)	21	22	22

Note: *The unit weight γ was not stated in the paper so we selected values that give us deterministic factors of safety close to those in the paper.

*The three clay layers are assumed frictionless.

Table 28.4: Results for Example 2

Failure Mode (Layer)	Chowdhury & Xu		Slide	
	Factor of Safety (Bishop simplified)	Probability of Failure	Factor of Safety (Bishop simplified)	Probability of Failure
Layer 2 (Clay 1)	1.1096	0.0048	1.108	0.0037
Layer 3 (Clay 2)	1.0639	0.01305	1.058	0.0175

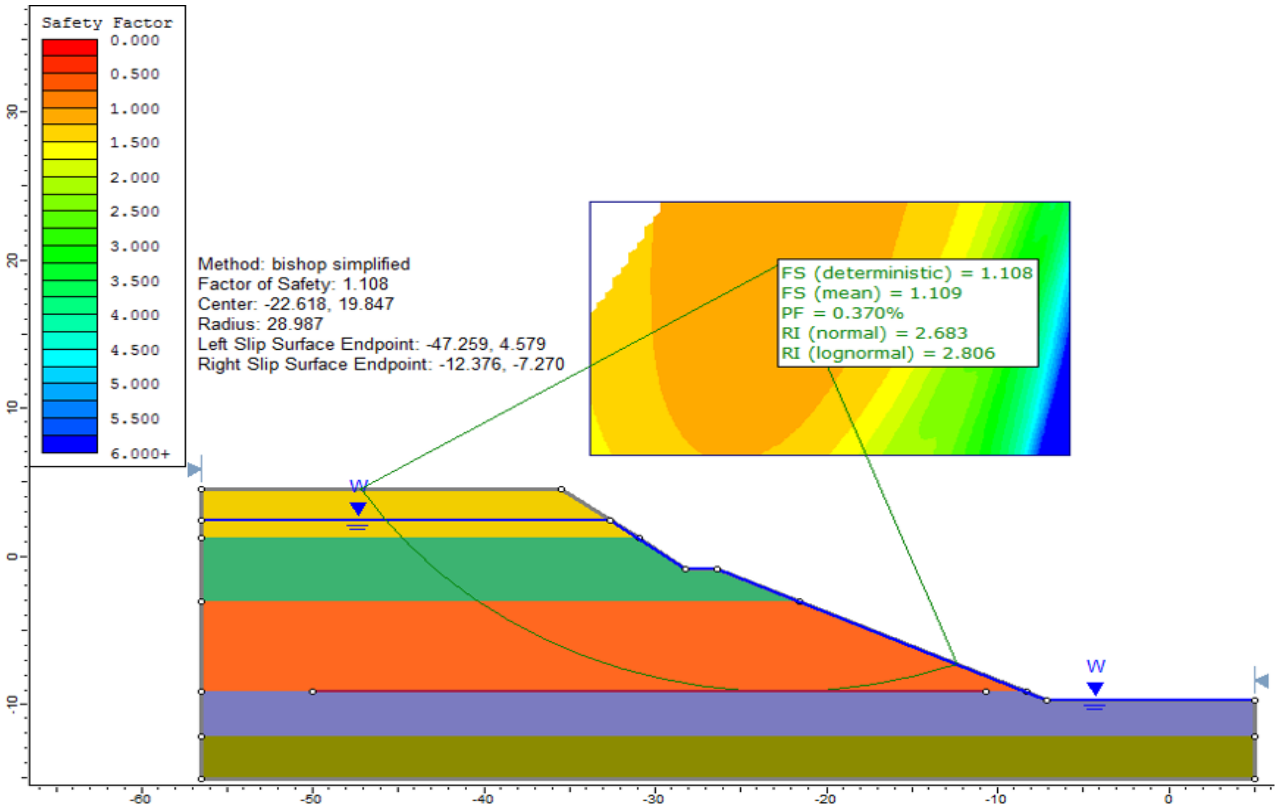


Figure 28.5: Critical slip circle tangential to lower boundary of clay layer

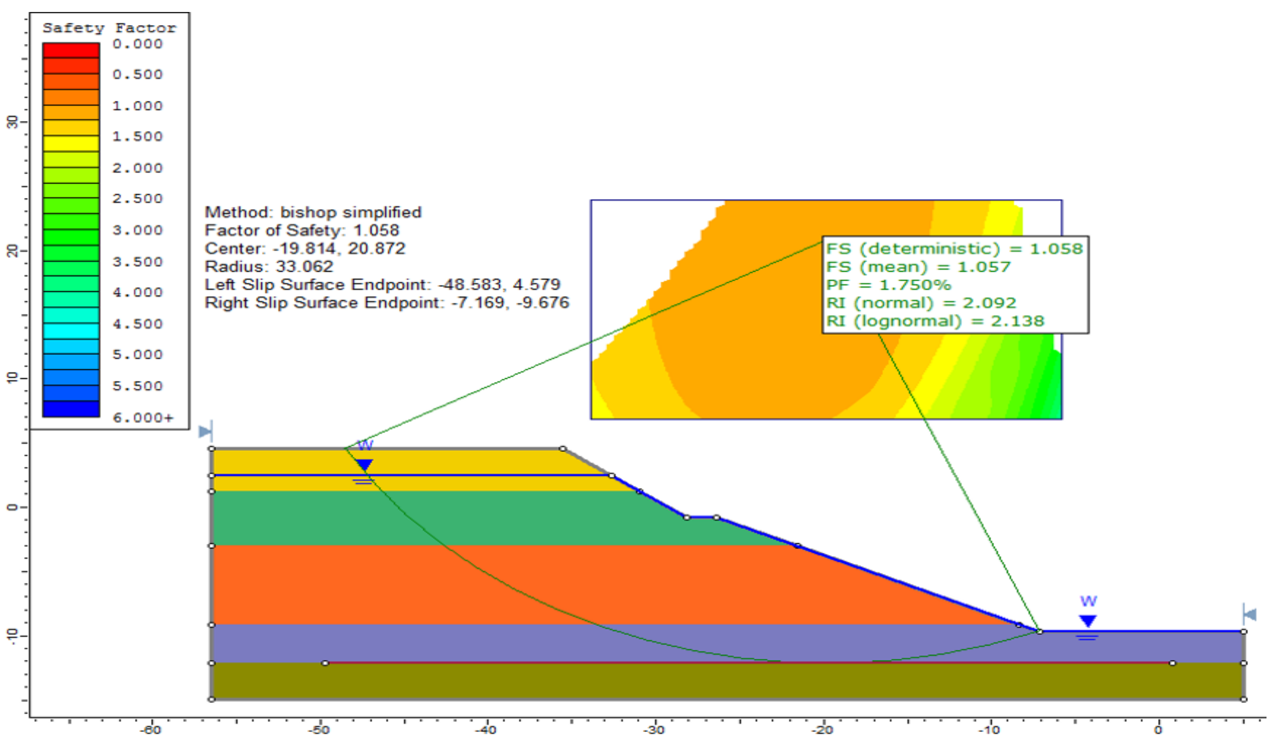


Figure 28.6: Critical slip circle tangential to lower boundary of clay layer 3

Table 28.5: Example 3

	Soil Layer		
	Clay 1	Clay 2	Clay 3
	c_1	c_2	c_3
Mean (kPa)	136	80	102
Stdv. (kPa)	50	15	24
γ^* (kN/m^3)	21	22	22

Note: *The unit weight γ was not stated in the paper so we selected values that give us deterministic factors of safety close to those in the paper.

*The three clay layers are assumed frictionless.

Table 28.6: Results for Example 3

Failure Mode (Layer)	**Chowdhury & Xu**		**Slide**	
	Factor of Safety (Bishop simplified)	Probability of Failure	Factor of Safety (Bishop simplified)	Probability of Failure
Layer 2 (Clay 1)	2.2343	0.01151	2.245	0.00044
Layer 3 (Clay 2)	2.1396	0.00242	2.128	0.0007

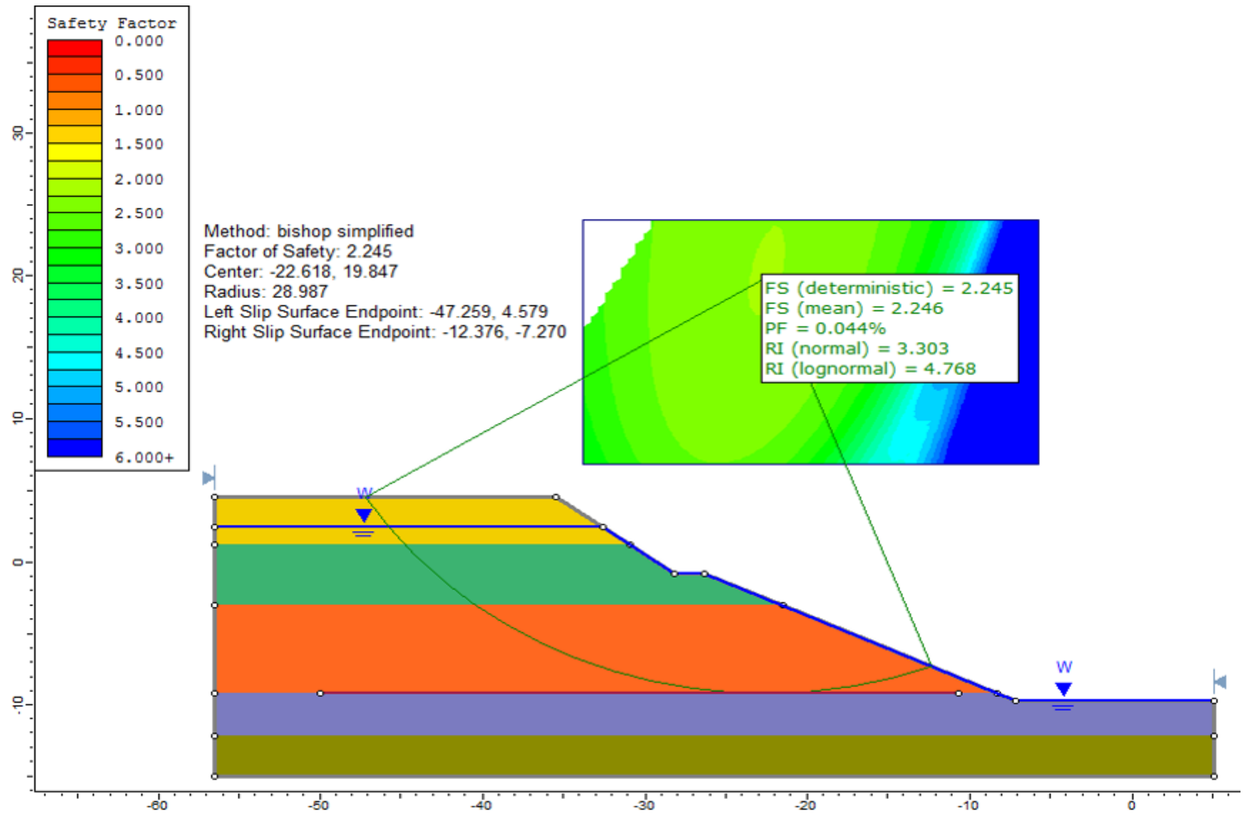


Figure 28.7: Critical slip circle tangential to lower boundary of clay layer 2

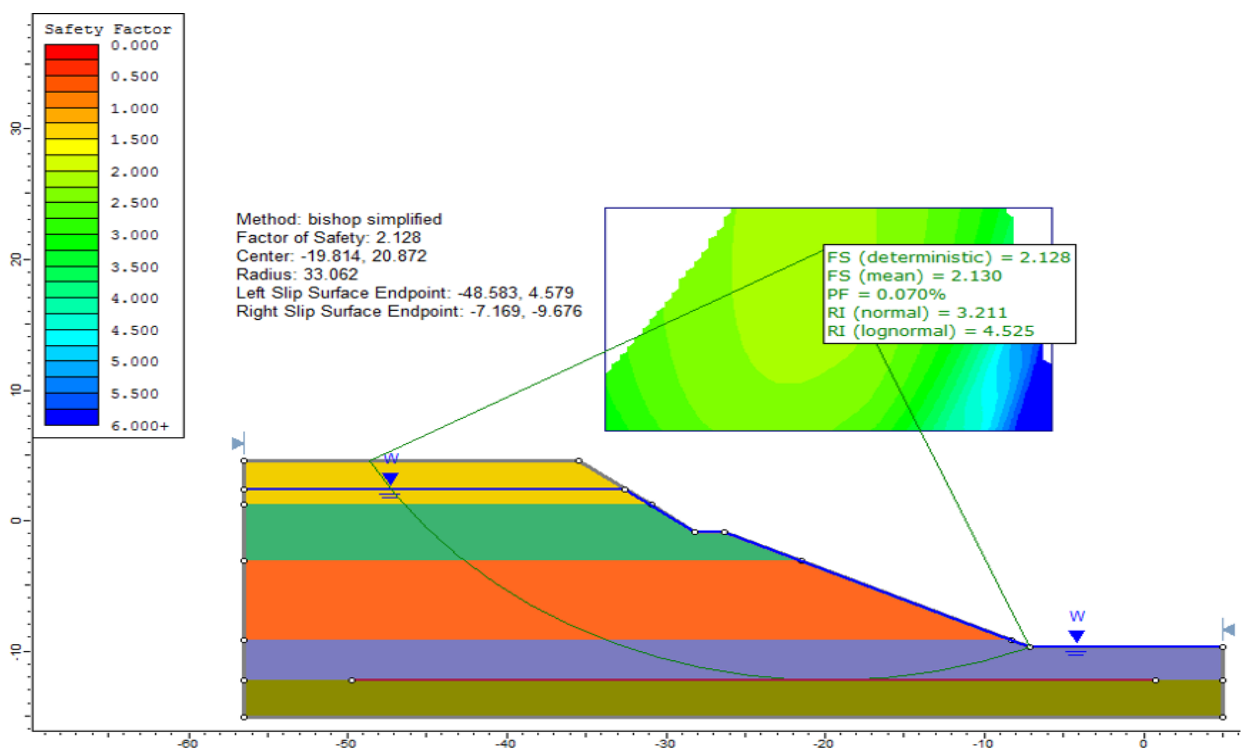


Figure 28.8: Critical slip circle tangential to lower boundary of clay layer 3

Table 28.7: Example 4

	Soil Layer					
	Clay 1		Clay 2		Clay 3	
	c_1		c_2		c_3	
Mean	55	5	43	7	56	8
Stdv.	20.4	1	8.7	1.5	13.2	1.7
γ^* (kN/m^3)	17		22		22	

Note: *The unit weight γ was not stated in the paper so we selected values that give us deterministic factors of safety close to those in the paper.

*The three clay layers are assumed frictionless.

Table 28.8: Results for Example 4

Failure Mode (Layer)	**Chowdhury & Xu** Factor of Safety (Bishop simplified)	**Chowdhury & Xu** Probability of Failure	**Slide** Factor of Safety (Bishop simplified)	**Slide** Probability of Failure
Layer 2 (Clay 1)	1.4239	0.01559	1.422	0.0211
Layer 3 (Clay 2)	1.5075	0.00468	1.503	0.0035

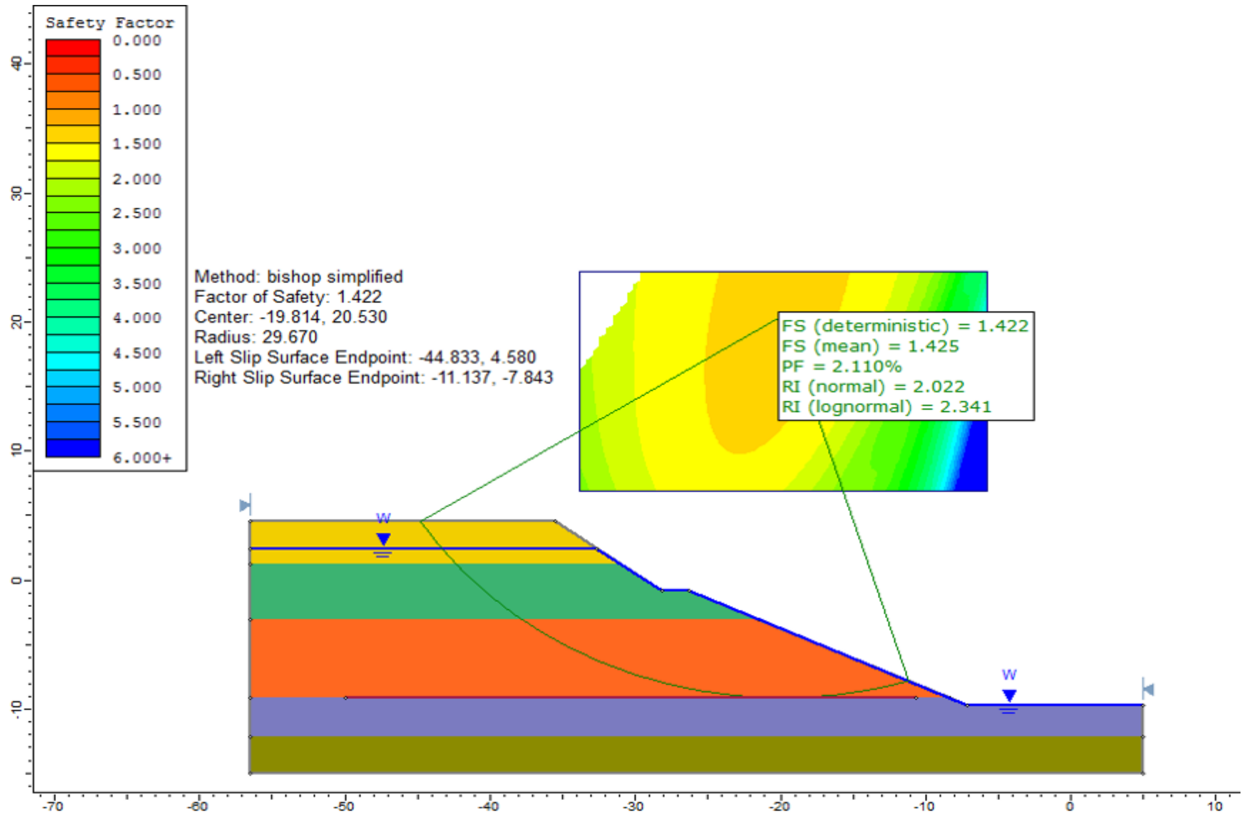


Figure 28.9: Critical slip circle tangential to lower boundary of clay layer 2

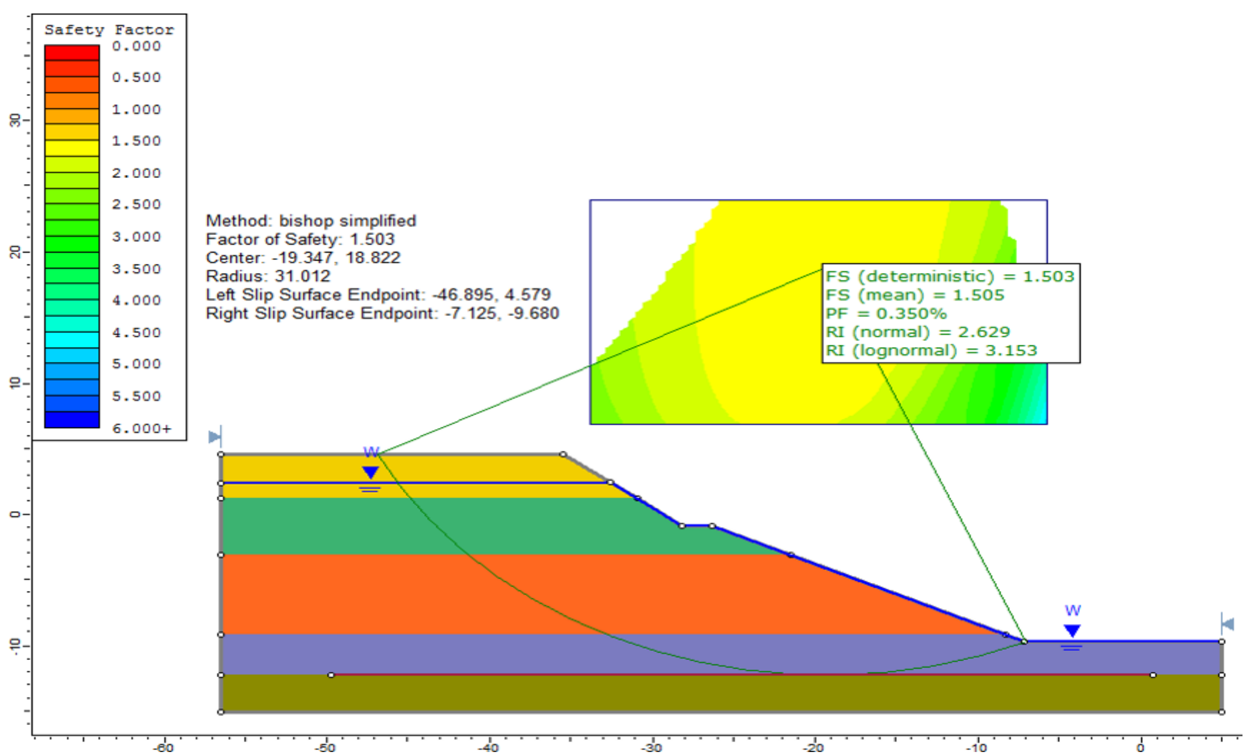


Figure 28.10: Critical slip circle tangential to lower boundary of clay layer 3

Table 28.7: Example 5

	Layer 1		Layer 2	
	c_1 (kPa)	ϕ_1 (°)	c_2 (kPa)	ϕ_2 (°)
Mean	10	12	40	0
Stdv.	2	3	8	0
γ^* (kN/m^3)	20		18	

Table 28.8: Results for Example 5

Failure Mode (Layer)	**Chowdhury & Xu**		**Slide**	
	Factor of Safety (Bishop simplified)	Probability of Failure	Factor of Safety (Bishop simplified)	Probability of Failure
Layer 2 (Clay 1)	1.1625	0.20225	1.16	0.2117
Layer 3 (Clay 2)	1.1479	0.19733	1.185	0.1992

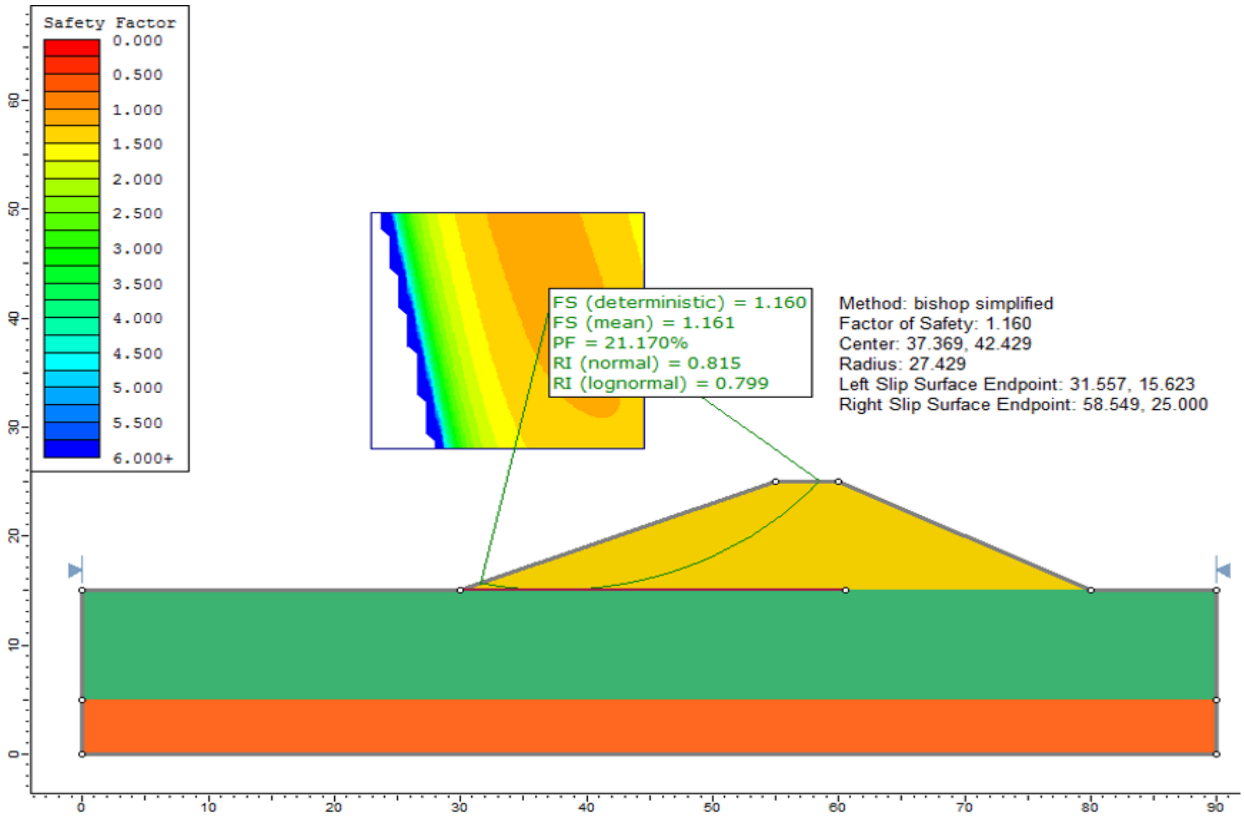


Figure 28.11: Critical slip circle tangential to interface of embankment and foundation

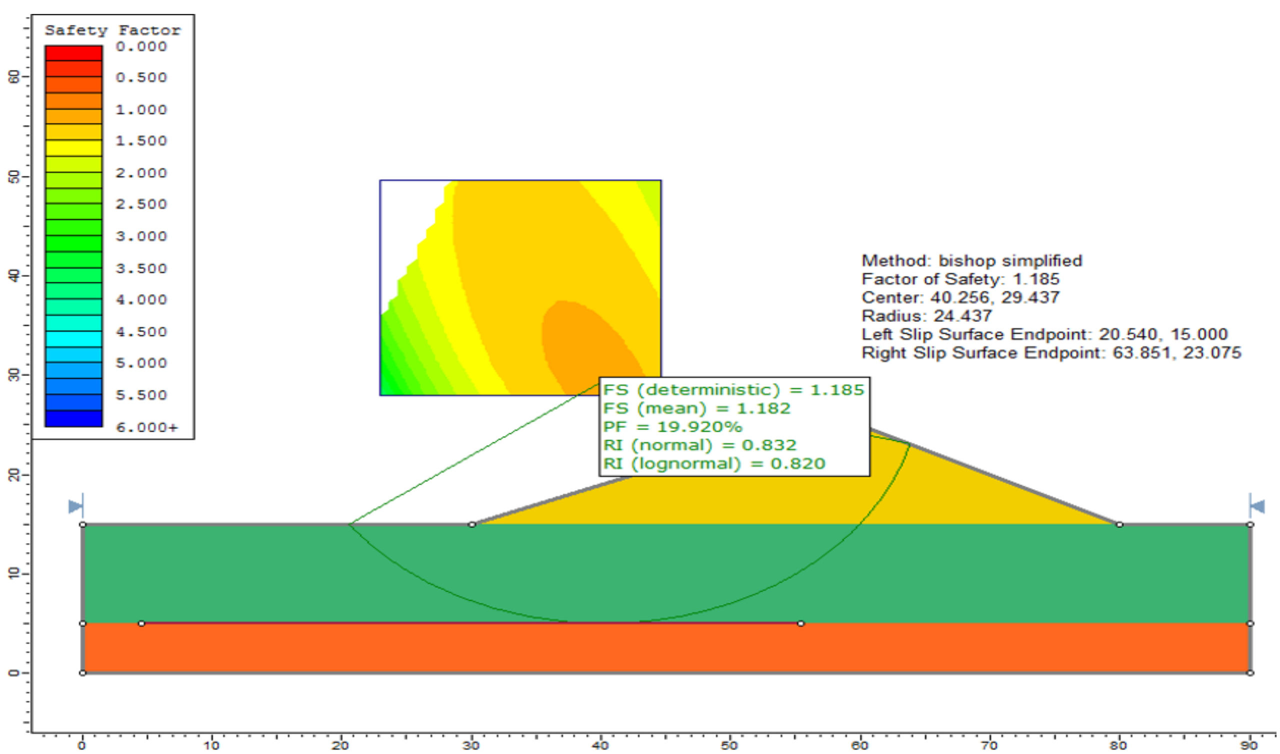


Figure 28.12: Critical slip circle tangential to lower boundary of soft foundation layer

29. Slide Verification Problem #29

Submerged slope, homogenous, probabilistic analysis, water table

29.1. Introduction

This model is taken from Duncan (2000). It looks at the failure of the 100 ft high underwater slope at the Lighter Aboard Ship (LASH) terminal at the Port of San Francisco.

29.2. Problem Description

Verification problem #29 is shown in Figure 29.1. All geometry and property values are determined using the figures and published data in Duncan (2000). The cohesion is taken to be 100 psf at an elevation of -20 ft and increase linearly with depth at a rate of 9.8 psf/ft. A probabilistic analysis using the latin-hypercube simulation technique is performed using 10000 samples to compute the probability of failure and reliability index of the estimated failure surface defined in Duncan (2000). These values are determined using the Janbu, Spencer, and GLE methods.

29.3. Geometry and Material Properties

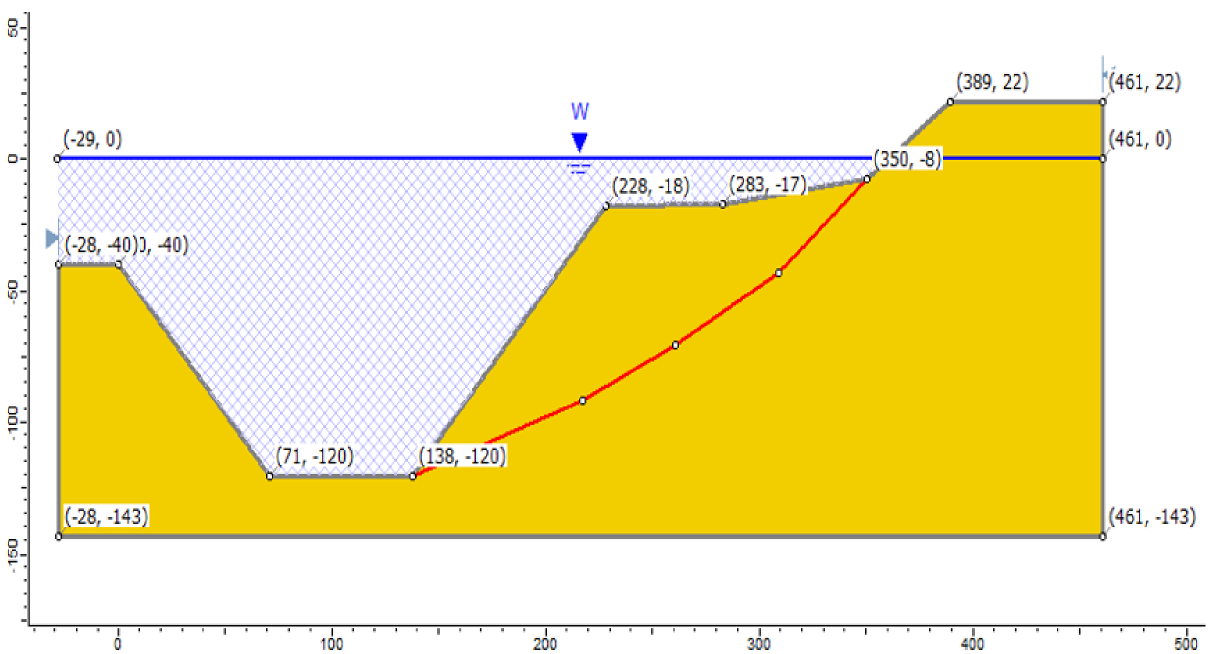


Figure 29.1: Geometry Setup in **Slide**

Table 29.1: Deterministic Soil Properties

	cohesion (datum) (psf)	Datum (ft)	Rate of change (psf/ft)	Unit Weight (pcf)
San Francisco Bay Mud	100	-20	9.8	100

Table 29.2: Probabilistic Soil Properties

San Francisco Bay Mud	Standard deviation	Absolute Minimum	Absolute Maximum
Unit Weight	3.3	99.1	109.9
Rate of change	1.2	5.8	13.8

29.4. Results

Table 29.3

Method	Deterministic Factor of Safety	Probability of Failure (%)	Reliability Index (lognormal)
Janbu Simplified	1.127	18	1.086
Janbu Corrected	1.168	15	1.0
Spencer	1.157	14	1.1
GLE	1.160	13	1.2

Note: Duncan (2000) quotes a deterministic factor of safety of 1.17 and a probability of failure of 18%. The probability of failure is calculated using the Taylor series technique.

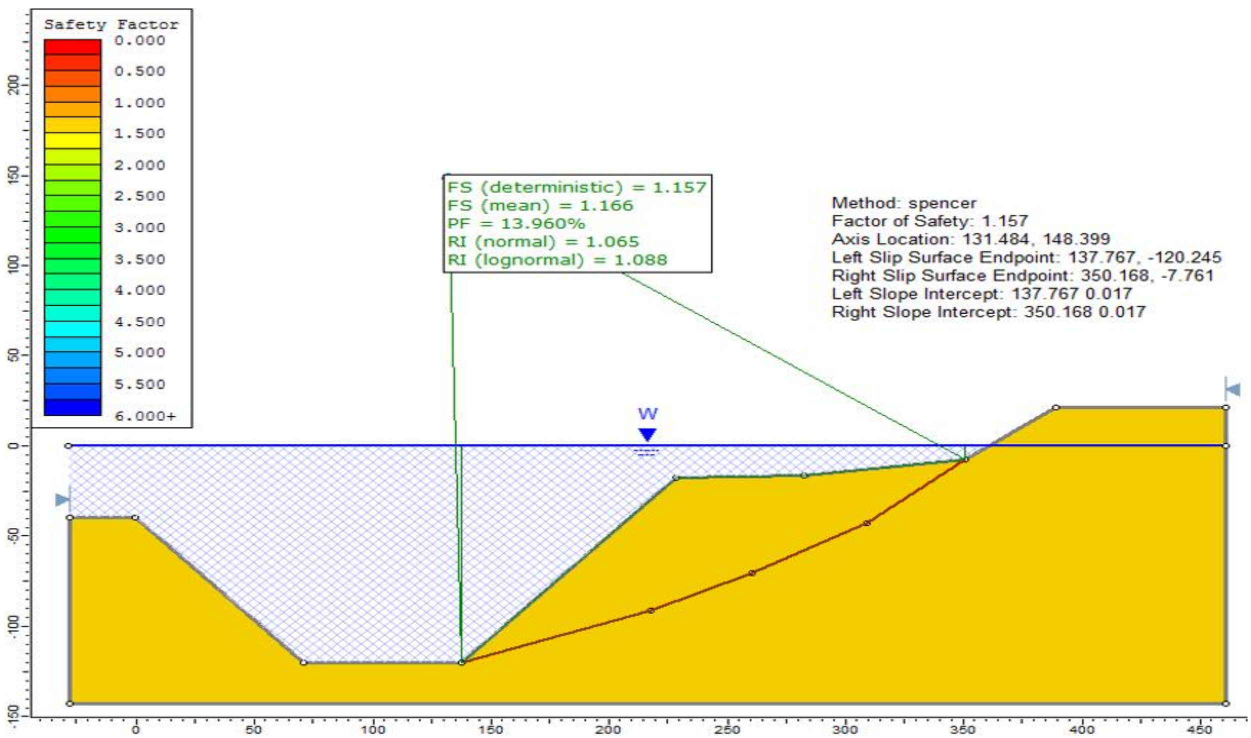


Figure 29.2: Noncircular failure surface, using the Spencer method

30. Slide Verification Problem #30

Reinforced embankment, (4) materials, tension crack, geosynthetic

30.1. Introduction

This model is taken from Borges and Cardoso (2002), their case 1 example. It looks at the stability of a geosynthetic-reinforced embankment on soft soil.

30.2. Problem Description

Verification problem #30 is shown in Figure 30.1. 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 is not anchored, has no adhesion, has a tensile strength of 200 kN/m, and frictional resistance against slip of 33.7 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 modelled as a passive force since this corresponds to how the authors implement the reinforcement force in their limit-equilibrium implementation.

30.3. Geometry and Material Properties

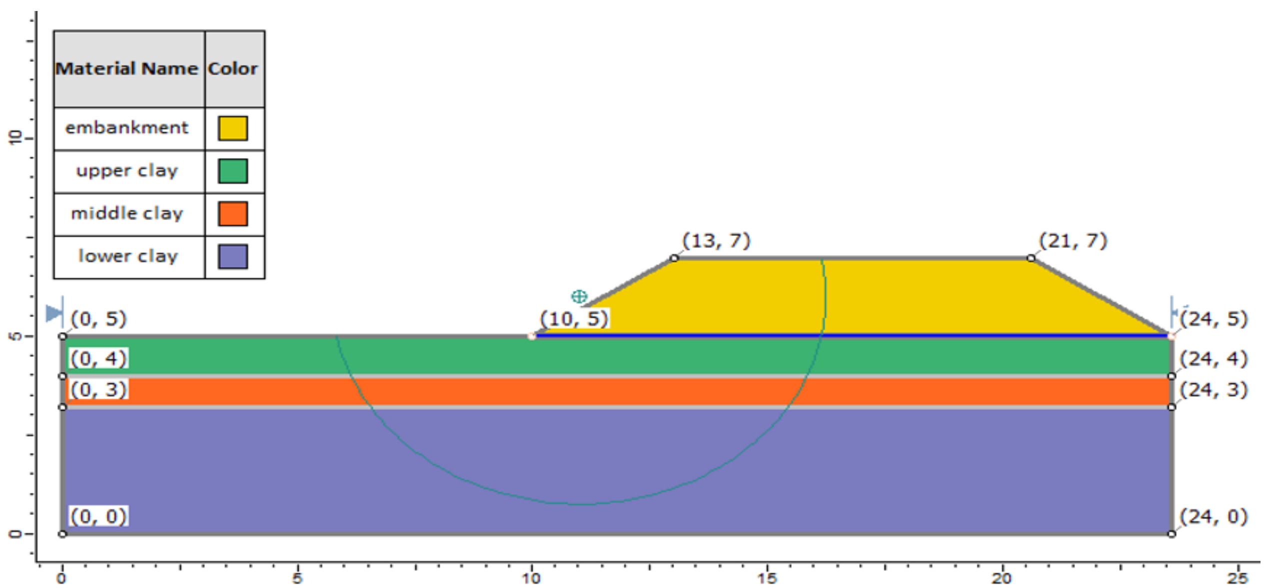


Figure 30.1: Geometry Setup in **Slide**

Table 30.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Embankment	0	35	20

Table 30.2

	Cu top (kN/m^2)	Cu bottom (kN/m^2)	γ (kN/m^3)
Upper Clay	8.49	8.49	17
Middle Clay	8.49	4.725	17
Lower Clay	4.725	13.125	17

30.4. Results

Table 30.3

	Factor of Safety	Overturning Moment (kN/m/m)	Resisting Moment (kN/m/m)
Circle A (Slide)	1.69	633	1071
Circle A (Borges)	1.77	631	1115
Circle B (Slide)	1.66	523	868
Circle B (Borges)	1.74	521	907

Note: Both circle A and B have reverse curvature. Since **Slide** automatically creates a tension crack in the portion of the circle with reverse curvature, the shear strength contribution in this region is removed. This is most likely the reason for the smaller factors of safety in **Slide**.

31. Slide Verification Problem #31

Reinforced embankment, (5) materials, geosynthetic

31.1. Introduction

This model is taken from Borges and Cardoso (2002), their case 2 example. It looks at the stability of a geosynthetic-reinforced embankment on soft soil.

31.2. Problem Description

Verification problem #31 is shown in Figure 31.1. 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 is not anchored, and it has no adhesion but a tensile strength of 200 KN/m and a frictional resistance against slip of 33.7 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.

31.3. Geometry and Material Properties

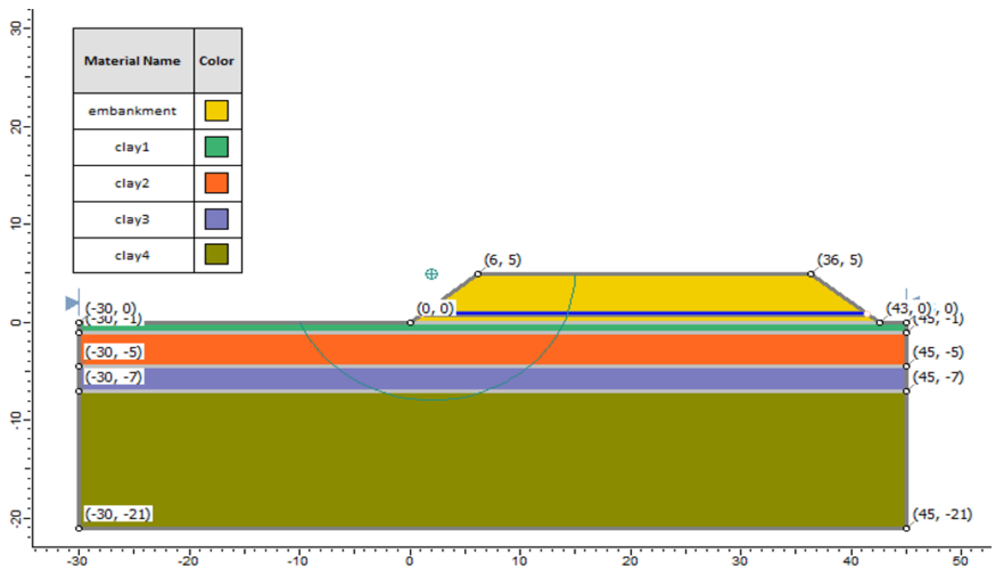


Figure 31.1: Geometry Setup in **Slide**

Table 31.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Embankment	0	35	20

Table 31.2

	Cu top (kN/m^2)	Cu bottom (kN/m^2)	γ (kN/m^3)
Clay1	33	33	17
Clay2	16	16	17
Clay3	16	18.375	17
Clay4	18.375	55.125	17

31.4. Results

Table 31.3

	Factor of Safety (Bishop Simplified)
Circle A (Slide)	1.18
Circle A (Borges)	1.19
Circle B (Slide)	1.16
Circle B (Borges)	1.15

32. Slide 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 and Figure 32.2 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

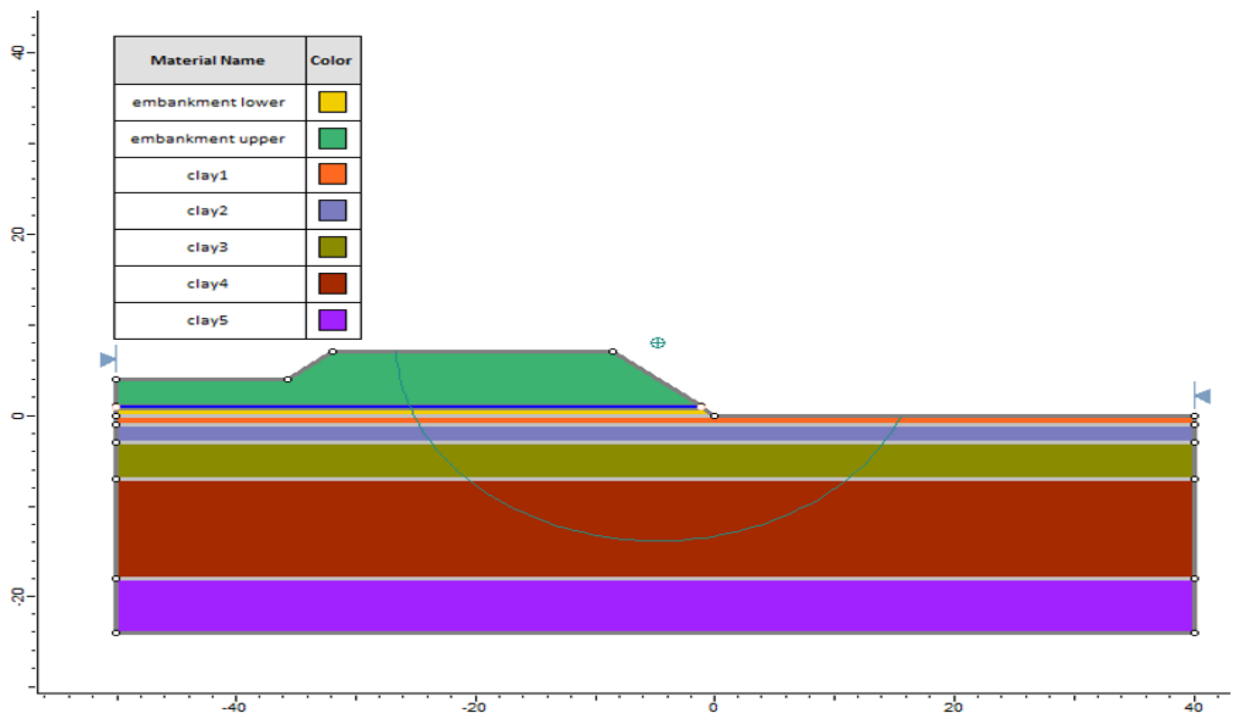


Figure 32.1: Case 1 – Embankment Height = 7 m

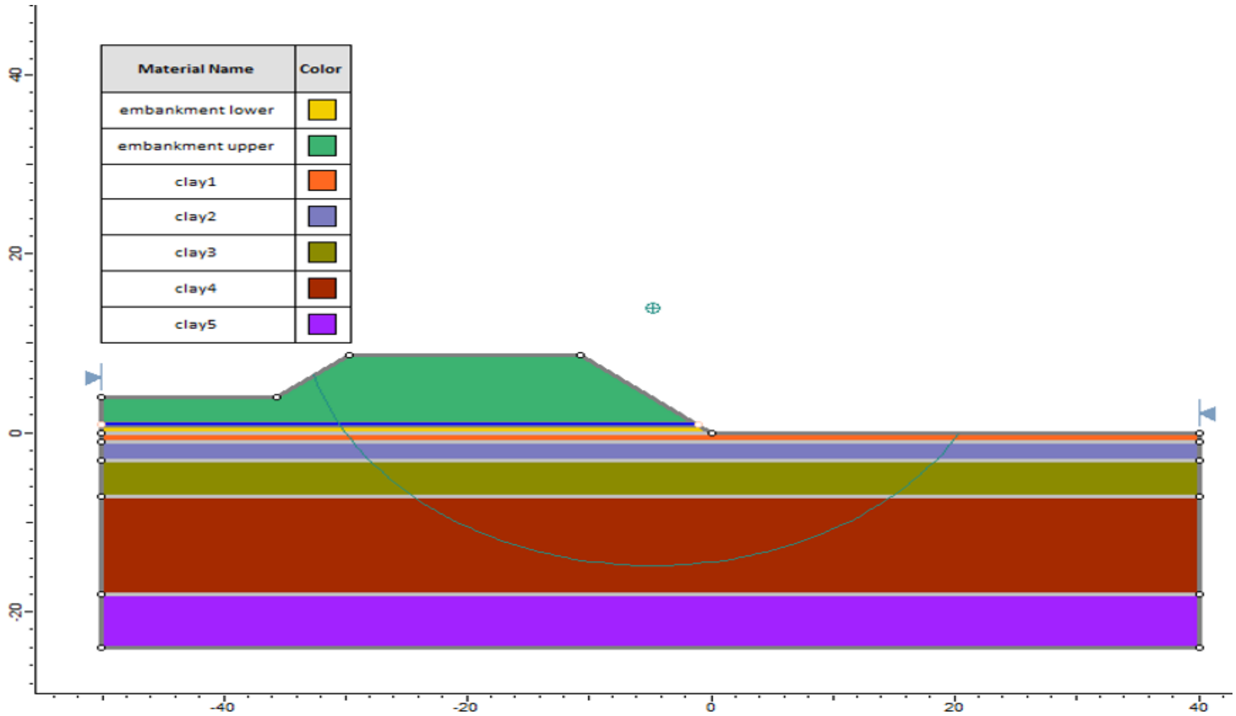


Figure 32.2: Case 2 – Embankment Height = 8.75 m

Table 32.1: Embankment Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Upper Embankment	0	35	21.9
Lower Embankment	0	33	17.2

Table 32.2: Soil Properties

	Cu (kN/m^2)	γ (kN/m^3)
Clay1	43	18
Clay2	31	16.6
Clay3	30	13.5
Clay4	32	17
Clay5	32	17.5

32.4. Results

Table 32.3: Case 1 – Embankment Height = 7 m

	Factor of Safety	Overturning Moment (kN/m/m)	Resisting Moment (kN/m/m)
Circle A (Slide)	1.23	32,832	40,231
Circle A (Borges)	1.25	34,166	42,695
Circle B (Slide)	1.22	61,765	75,300
Circle B (Borges)	1.19	63,870	75,754

Table 32.4: Case 2 – Embankment Height = 8.75 m

	Factor of Safety	Overturning Moment (kN/m/m)	Resisting Moment (kN/m/m)
Circle C (Slide)	0.98	64,873	63,846
Circle C (Borges)	0.99	65,116	64,784

33. Slide Verification Problem #33

Dike, (5) materials, probabilistic analysis, water table

33.1. Introduction

Verification #33 comes from El-Ramly et al (2003). It looks at the assessment of the probability of unsatisfactory performance (probability of failure) of a Syncrude tailings dyke in Canada. This example does not consider the spatial variation of soil properties and it is described in the paper as the simplified probabilistic analysis.

33.2. Problem Description

The original model from the El-Ramly et al paper is shown in Figure 33.1. The input parameters for the **Slide** model are provided in Table 33.1. El-Ramly et al considered five probabilistic parameters: the friction angle of the Kca clay-shale, the pore pressure ratio in the same layer, the friction angle of the Pgs sandy till layer, and the pore pressure ratios in this layer at the middle and at the toe of the dyke.

In our model we only consider the friction angles of the Kca clay-shale and Pgs sandy till as probabilistic parameters, and we use the phreatic surfaces indicated on Figure 33.2 in place of pore pressure ratios. We tested the influence of the phreatic surfaces (included them as piezometric lines with levels that are normal variables of unit standard deviation) and established that they had minimal impact on the probability of failure for this model. The **Slide** model is shown on Figure 33.2.

As in the El-Ramly et al paper, the Bishop simplified analysis method is used. **Slide** uses Monte Carlo analysis to calculate the probability of failure. It is assumed in the Slide model that all the probabilistic input variables are normally distributed.

33.3. Geometry and Material Properties

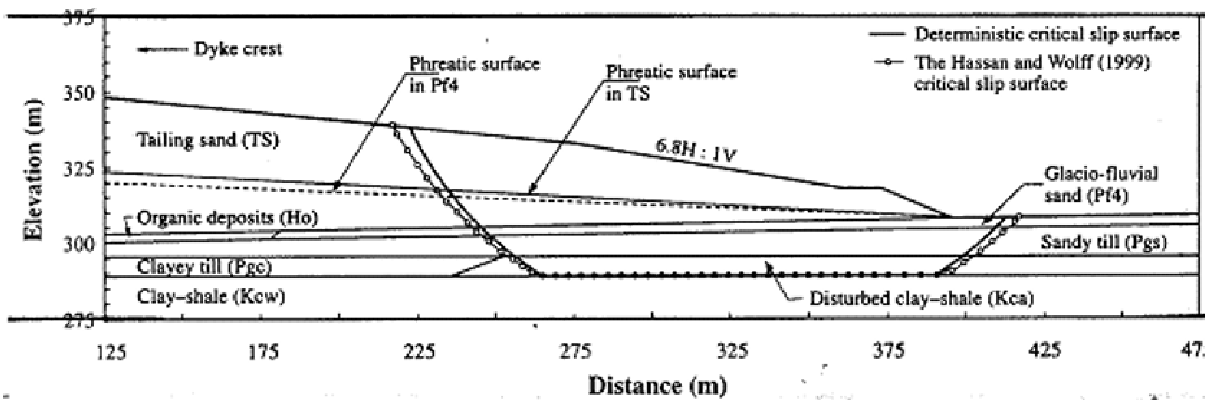


Figure 33.1: Original Model

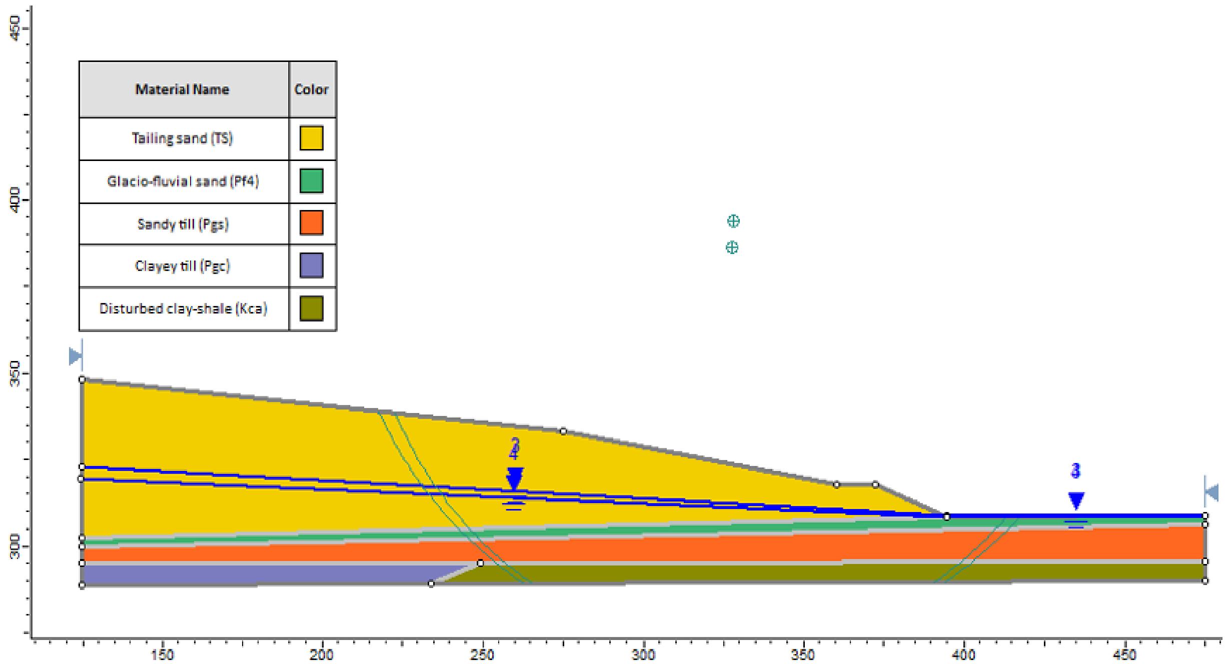


Figure 33.2: Geometry Setup in **Slide**

Table 33.1: Soil Properties

Material	c´ (kN/m^2)	ϕ´ (deg.)	Standard deviation of ϕ´ (deg.)	γ (kN/m^3)
Tailing sand (TS)	0	34	-	20
Glacio-fluvial sand (Pf4)	0	34	-	17
Sandy till (Pgs)	0	34	2	17
Disturbed clay-shale (Kca)	0	7.5	2.1	17

33.4. Results

Table 33.2

	Factor of Safety	Probability of Failure
Slide	1.305	1.54 x 10^{-3}
El-Ramly et al	1.31	1.6 x 10^{-3}

34. Slide Verification Problem #34

Dam, (3) materials, probabilistic analysis, water table

34.1. Introduction

This model is taken from Wolff and Harr (1987). It is a model of the Clarence Cannon Dam in northeastern Missouri, USA. This verification compares probabilistic results from *Slide* to those determined by Wolff and Harr for a non-circular critical surface.

34.2. Problem Description

Wolff and Harr used the point estimate method to evaluate the probability of failure of the Cannon Dam along the specified non-circular critical surface shown on Figure 34.1 (taken from their paper). From the probability concentrations provided in the paper, we calculated the probabilistic input parameters (cohesion, friction angle, and coefficient of correlation for the Phase I and Phase II fills) shown in Table 34.1. In the table we also provide the unit weights of the fills we had to use to match the factor of safety obtained by Wolff and Harr.

Since Wolff and Harr use an analysis method that satisfies force equilibrium only, we compare their results to those obtained from the GLE. We also show results for non-circular Spencer analysis. The *Slide* model is shown on Figure 34.2.

As in the El-Ramly et al paper, the Bishop simplified analysis method is used. *Slide* uses Monte Carlo analysis to calculate the probability of failure. It is assumed in the *Slide* model that all the probabilistic input variables are normally distributed.

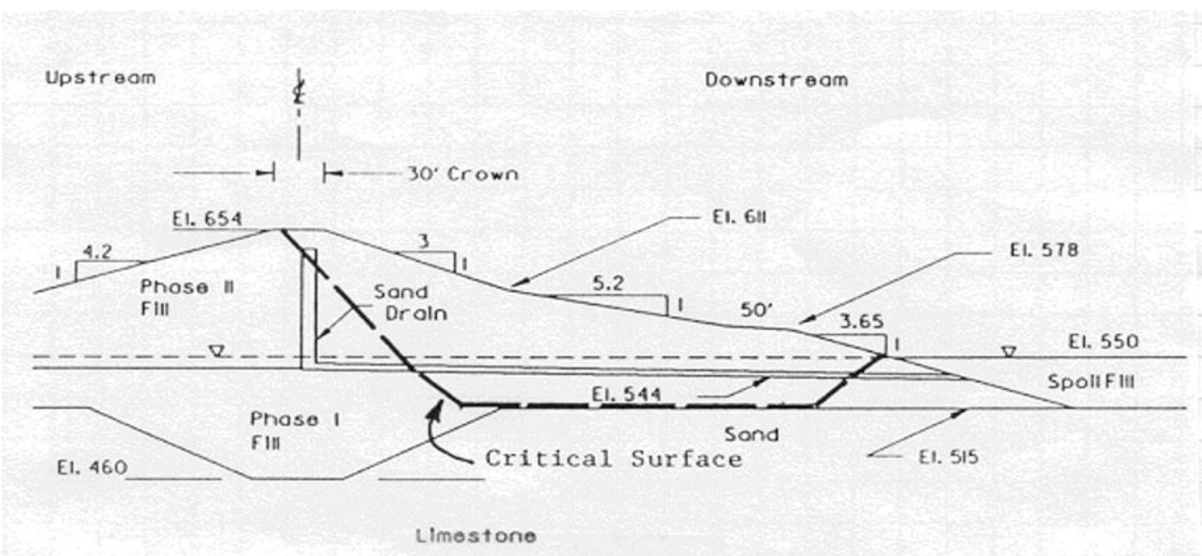


Figure 34.1: Original Model

34.3. Geometry and Material Properties

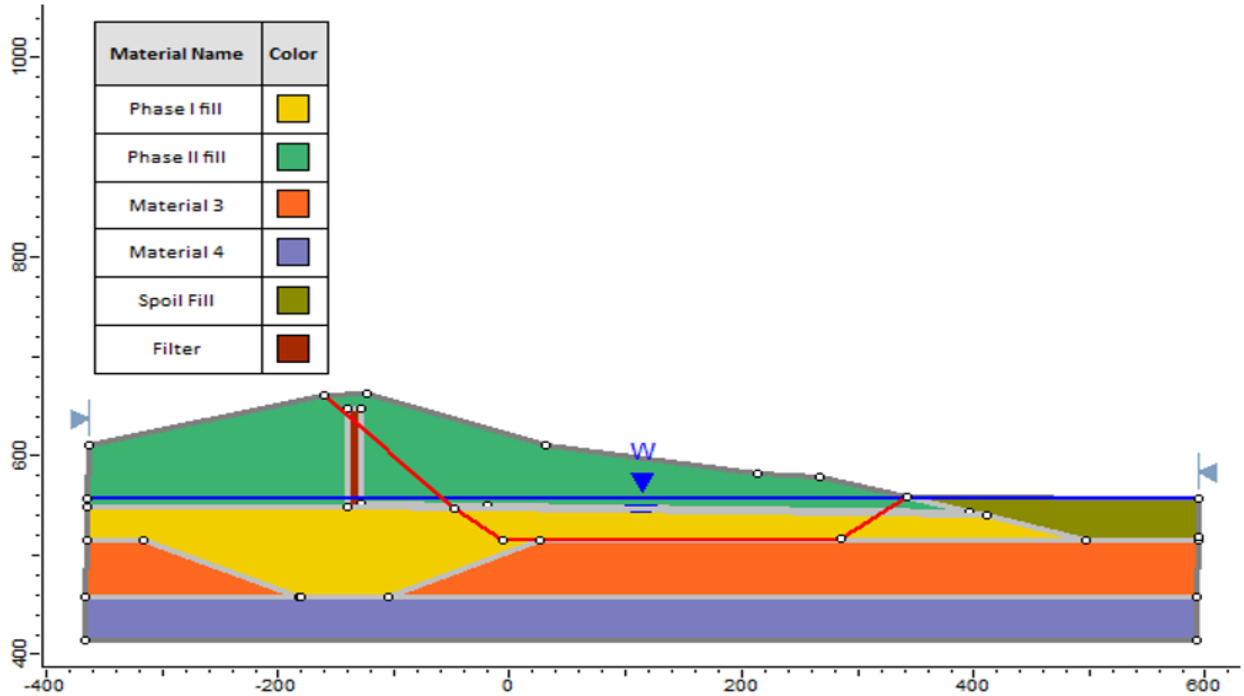


Figure 34.2: Geometry Setup in **Slide**

Table 34.1: Soil Properties*

Material	c´ (lb/ft^2)	Standard deviation of c´ (lb/ft^2)	ϕ´ (deg.)	Standard deviation of ϕ´ (deg.)	Correlation coefficient for c´ and ϕ´	γ (lb/ft^3)
Phase I fill	2,230	1,150	6.34	7.87	0.11	150
Phase II fill	2,901.6	1,079.8	14.8	9.44	-0.51	150
Sand drain	0	--	30	--	--	120

Note: *Information on the non-labeled soil layers in the model shown on Figure 34.2 is omitted because it has no influence on the factor of safety of the given critical surface.

34.4. Results

Table 34.2

	Deterministic Factor of Safety	Probability of Failure
Slide (GLE method)	2.333	3.55x 10^{-3}
Slide (Spencer method)	2.383	3.55x 10^{-3}
Wolff and Harr	2.36	4.55 x 10^{-2}

35. Slide Verification Problem #35

Dam, (5) materials, probabilistic analysis, reliability index

35.1. Introduction

This model is taken from Hassan and Wolff (1999). It is a model of the Clarence Cannon Dam in Missouri, USA. This verification problem looks at duplicating reliability index results for several circular failure surfaces specified in the Hassan and Wolff paper.

35.2. Problem Description

Hassan and Wolff applied a new reliability-based approach they had formulated to calculate reliability indices for slopes. The cross-section of the Cannon Dam they used is shown on Figure 35.1.

The Bishop simplified method of slices is used in all the cases discussed in this verification problem. We analyze two sets of slip surfaces, those shown on Figure 7 of the Hassan and Wolff paper and those on Figure 8. (Figures 7 and 8 from the paper are shown on Figure 35.2(a) and Figure 35.2(b) below.) Input parameters for the model are given in Table 35.1. Since the paper does not provide all the required input parameters, we selected values for the missing parameters that allowed us to match factors of safety for a few of the circles in Figure 7.

We assume all the probabilistic input variables to be normally distributed in performing Monte Carlo simulations. **Slide** calculates reliability indices based on the mean and standard deviation of the factor of safety values calculated in the simulations. The reliability indices shown in the results section are calculated with the assumption that factors of safety values are lognormally distributed (Hassan and Wolff (1999). Results obtained from Slide are compared to those from the Hassan and Wolff paper in Table 35.2.

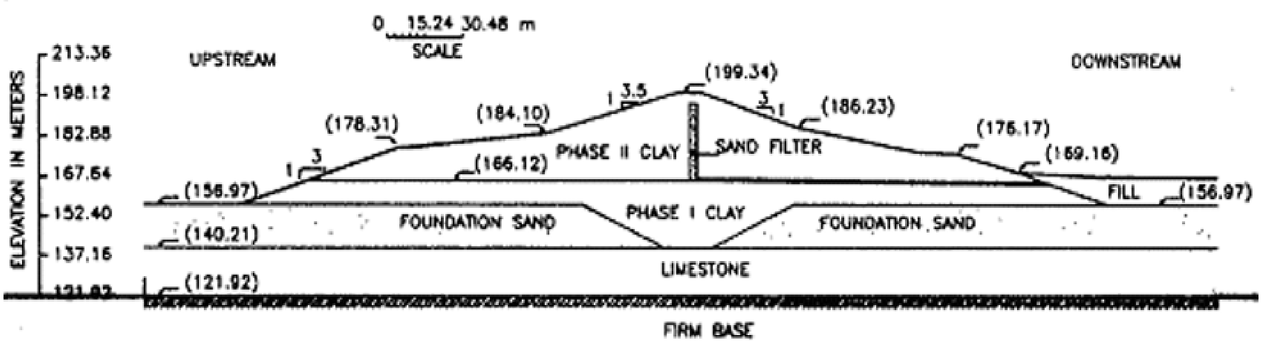


Figure 35.1: Original Model

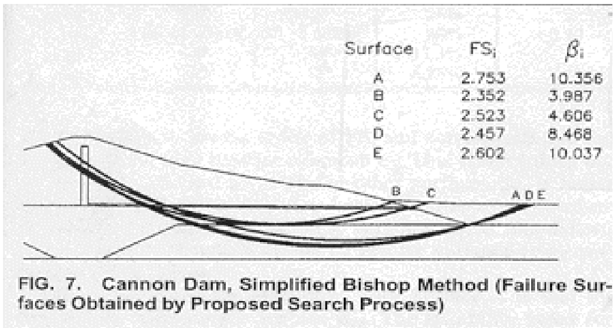


Figure 35.2. (a)

Figures 7 from the Hassan and Wolff (1999) paper

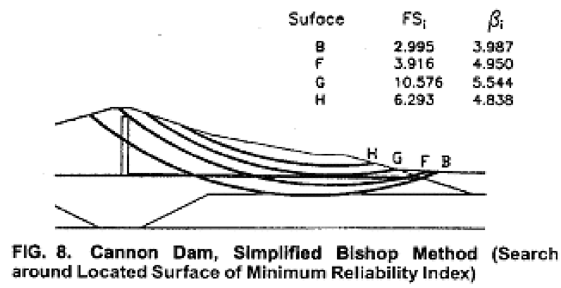


Figure 35.2. (b)

Figures 8 from the Hassan and Wolff (1999) paper

35.3. Geometry and Material Properties

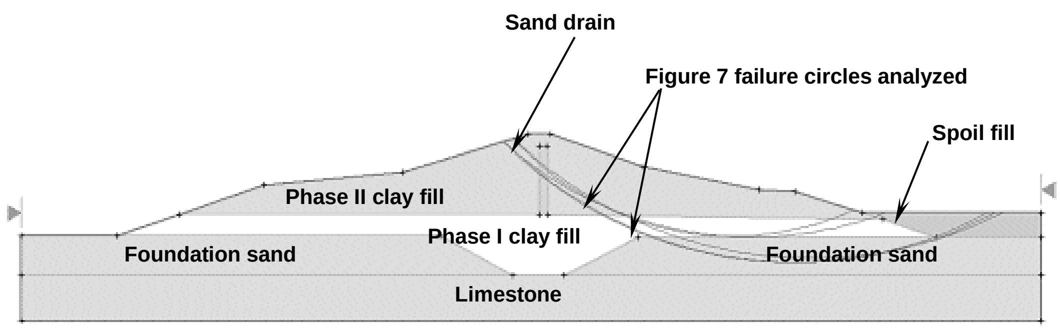


Figure 35.3 **Slide** Setup for the original Figure 7

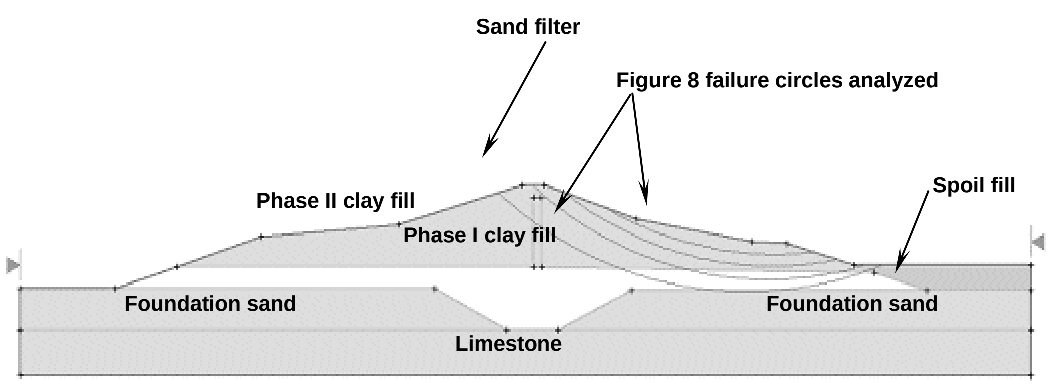


Figure 35.4 **Slide** Setup for the original Figure 8

Table 35.1: Material Properties*

Material	c' (kN/m^2)	Standard deviation of c' (kN/m^2)	ϕ' (deg.)	Standard deviation of ϕ' (deg.)	Correlation coefficient for c' and ϕ'	γ (kN/m^3)
Phase I clay fill	117.79	58.89	8.5	8.5	0.1	22
Phase II clay fill	143.64	79	15	9	-0.55	22
Sand filter	0	--	35	--	--	22
Foundation sand	5	--	18	--	--	20
Spoil fill	5	--	35	--	--	25

Note: *Properties of the limestone layer in the models shown on Figure 35.3 and 35.4 are omitted because they do not influence calculated factors of safety.

35.4. Results

Table 35.2

Surface	Slide Results		Hassan and Wolff Results	
	Deterministic Factor of Safety	Reliability Index (lognormal)	Deterministic Factor of Safety	Reliability Index (lognormal)
Fig. 7 Surface A	2.551	10.953	2.753	10.356
Fig. 7 Surface B	2.820	4.351	2.352	3.987
Fig. 7 Surface C	2.777	4.263	2.523	4.606
Fig. 7 Surface D	2.583	11.092	2.457	8.468
Fig. 7 Surface E	2.692	10.281	2.602	10.037
Fig. 8 Surface B	2.672	4.858	2.995	3.987
Fig. 8 Surface F	3.598	5.485	3.916	4.950
Fig. 8 Surface G	6.074	5.563	10.576	5.544
Fig. 8 Surface H	11.230	6.394	6.293	4.838

36. Slide Verification Problem #36

Slope, homogenous, probabilistic analysis, ru pore pressure, reliability index

36.1. Introduction

This model is taken from Li and Lumb (1987) and Hassan and Wolff (1999). It analyzes reliability indices of a simple homogeneous slope. This verification looks at comparing the reliability index of the deterministic global circular failure surface and the minimum reliability index value obtained from analysis of several failure surfaces.

36.2. Problem Description

The geometry of the homogeneous slope is shown in Figure 36.1 and soil parameters are provided in Table 36.1. The Bishop simplified method of analysis is used. Using Monte Carlo analysis that assumes all probabilistic variables to be normally distributed, reliability indices are calculated on the assumption that factors of safety values are distributed lognormally. This is consistent with the reliability index measures used by Hassan and Wolff (1999).

The reliability index calculated for the deterministic minimum factor of safety surface (critical deterministic surface), the minimum reliability index (critical probabilistic surface), and the overall reliability index of the slope are compared with reliability indices calculated by Hassan and Wolff in Table 36.2. Figure 36.2 and Figure 36.3 show the locations of the critical deterministic and probabilistic surfaces calculated by **Slide**.

36.3. Geometry and Material Properties

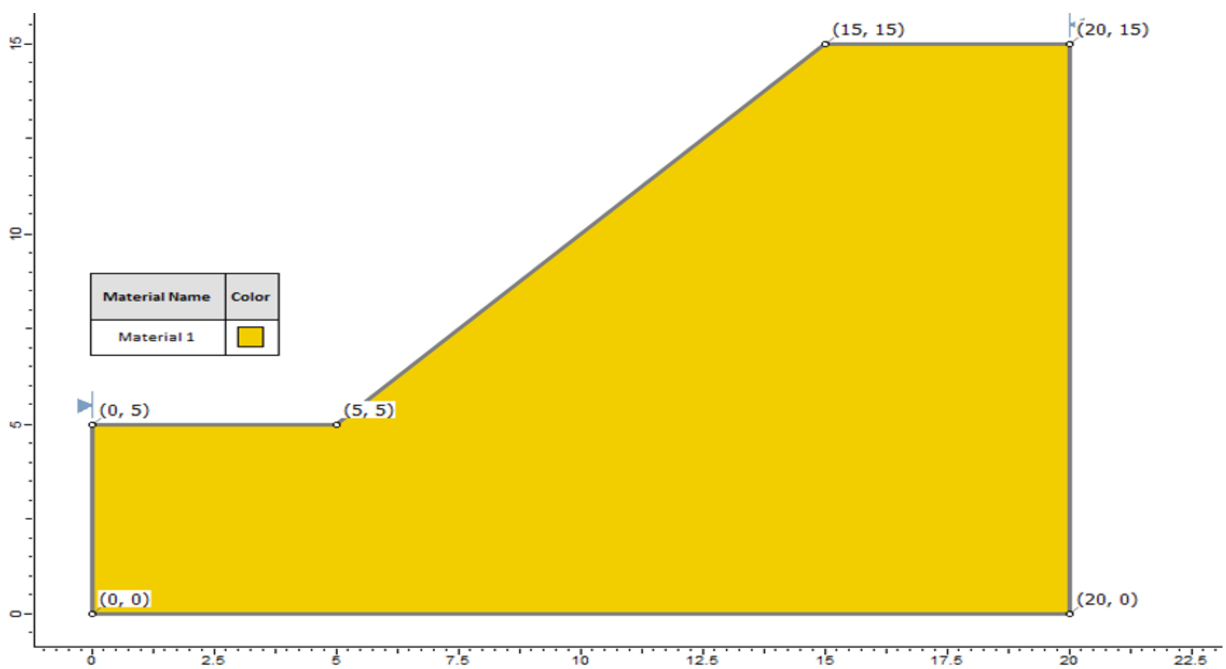


Figure 36.1: Geometry Setup in **Slide**

Table 36.1: Soil Properties

Property	Mean value	Standard deviation
c´ (kN/m^2)	18	3.6
ϕ´ (deg.)	30	3
γ (kN/m^3)	18	0.9
r_u	0.2	0.02

36.4. Results

Table 36.2

Slide Results by the Bishop Simplified method			Hasssan and Wolf Results	
Surface	Factor of Safety	Reliability Index (lognormal)	Factor of Safety	Reliability Index (lognormal)
Deterministic minimum factor of safety surface	1.340	2.482	1.334	2.336
Minimum reliability index surface	1.369	2.407	1.190	2.293
Overall slope (no particular surface)	1.350	2.393	--	--

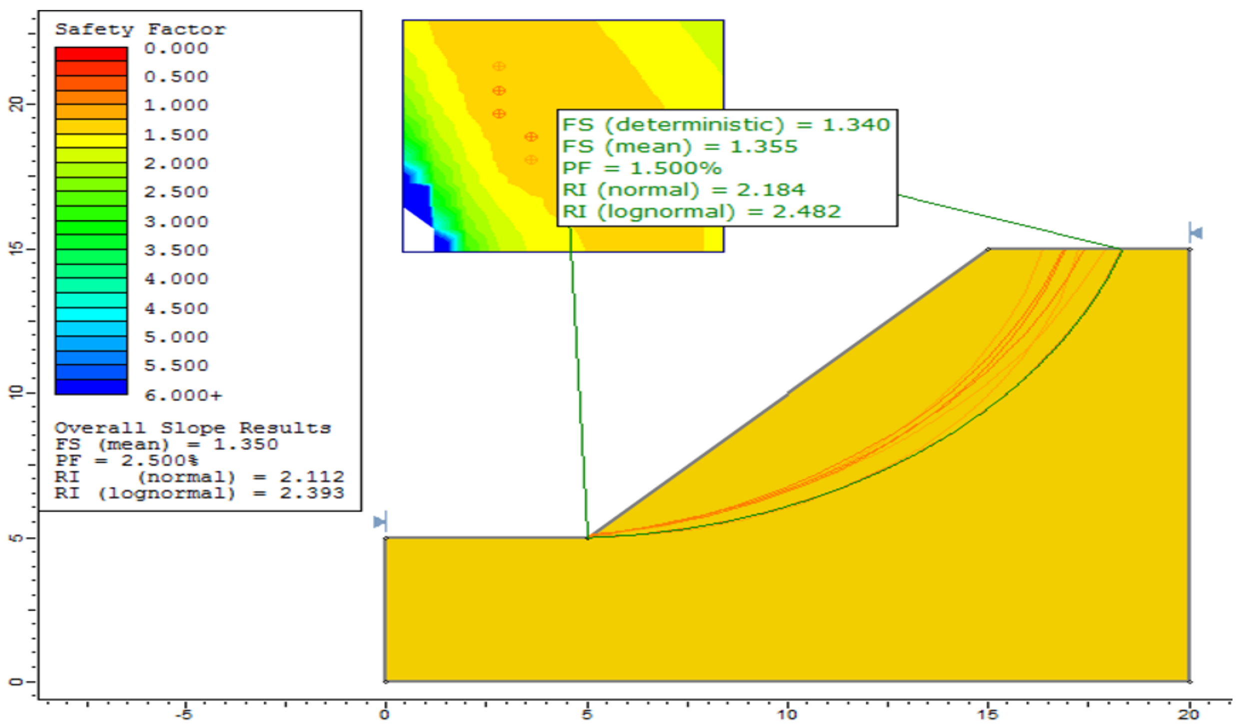


Figure 36.2: Critical deterministic surface and overall result

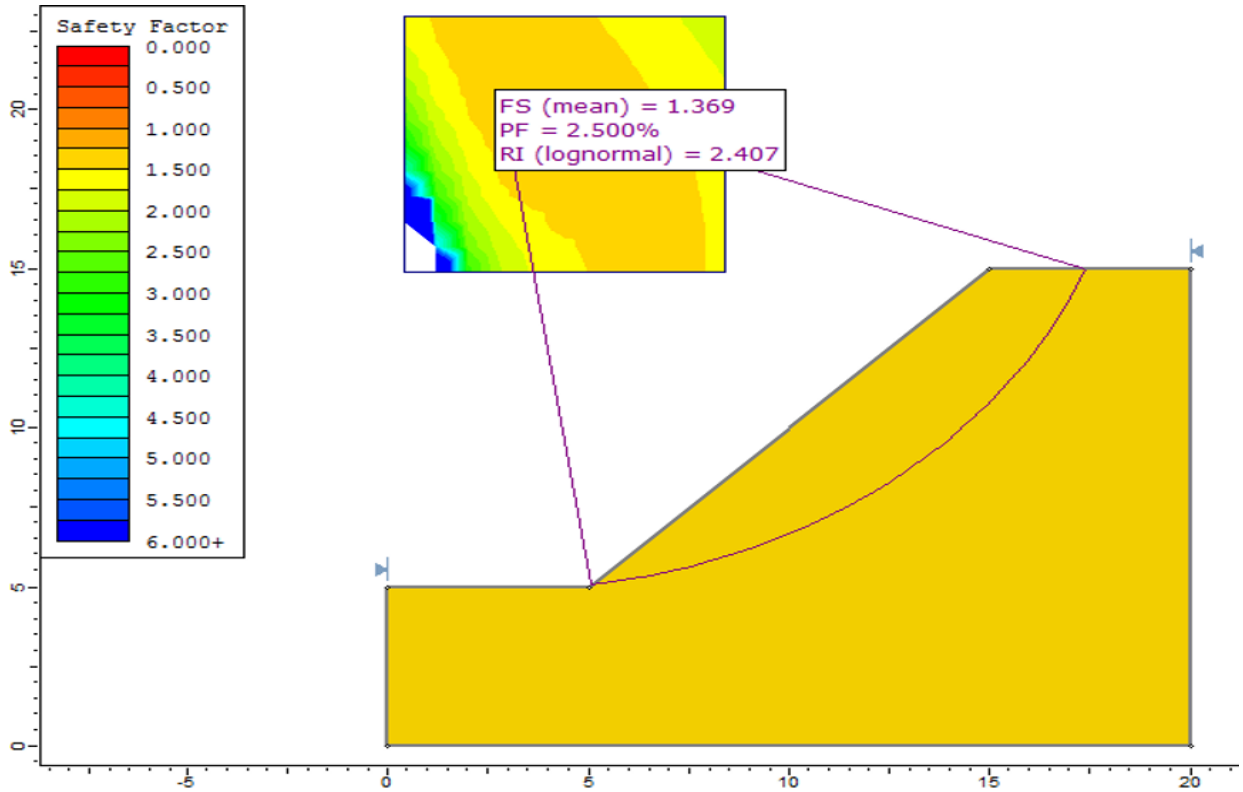


Figure 36.3: Critical probabilistic surface

37. Slide Verification Problem #37

Slope, homogenous, distributed load, back analysis of required support force and length

37.1. Introduction

Verification #37 models a slope reinforcement example described in the Reference Manual of the slope stability program XSTABL (1999). It illustrates the use of back analysis to determine the amount of reinforcement required to stabilize a slope to a specified factor of safety level.

37.2. Problem Description

The solution for this example of a simple slope, consisting solely of non-cohesive soil material, involved two steps:

a) Determining the reinforcement force needed to stabilize a slope to a factor of safety value of 1.5, and

b) Establishing the minimum required length of reinforced zone.

Figure 37.1 and Figure 37.2 describe the slope model. The solution in XSTABL examines failure surfaces that pass through the toe of the slope. To duplicate that in **Slide**, we placed a search focus point at the toe. In addition, to eliminate very small shallow failure surfaces of the slope face (slip circles that do not intersect the crest), only failure surfaces with a minimum depth of 2m were considered. Since the XSTABL solution considers a triangularly distributed reinforcement load along the slope height, the Slide model applies a concentrated force at a point above the toe that is a third of the slope height.

Next, we remodelled the slope, but this time we included a reinforced zone with a higher friction angle calculated from the formula (XSTABL Reference Manual (1999)).

$$\phi_{re\inf} = \tan^{-1}[F_r \tan(\phi)]$$

where $F_r = \dfrac{F_{min}}{F_{crit}}$.

We varied the length of the reinforced zone manually until we obtain a factor of safety value very close to 1.5. Again, we required all failure surfaces analyzed to pass through the toe and included a minimum slope depth to eliminate shallow, face failures.

37.3. Geometry

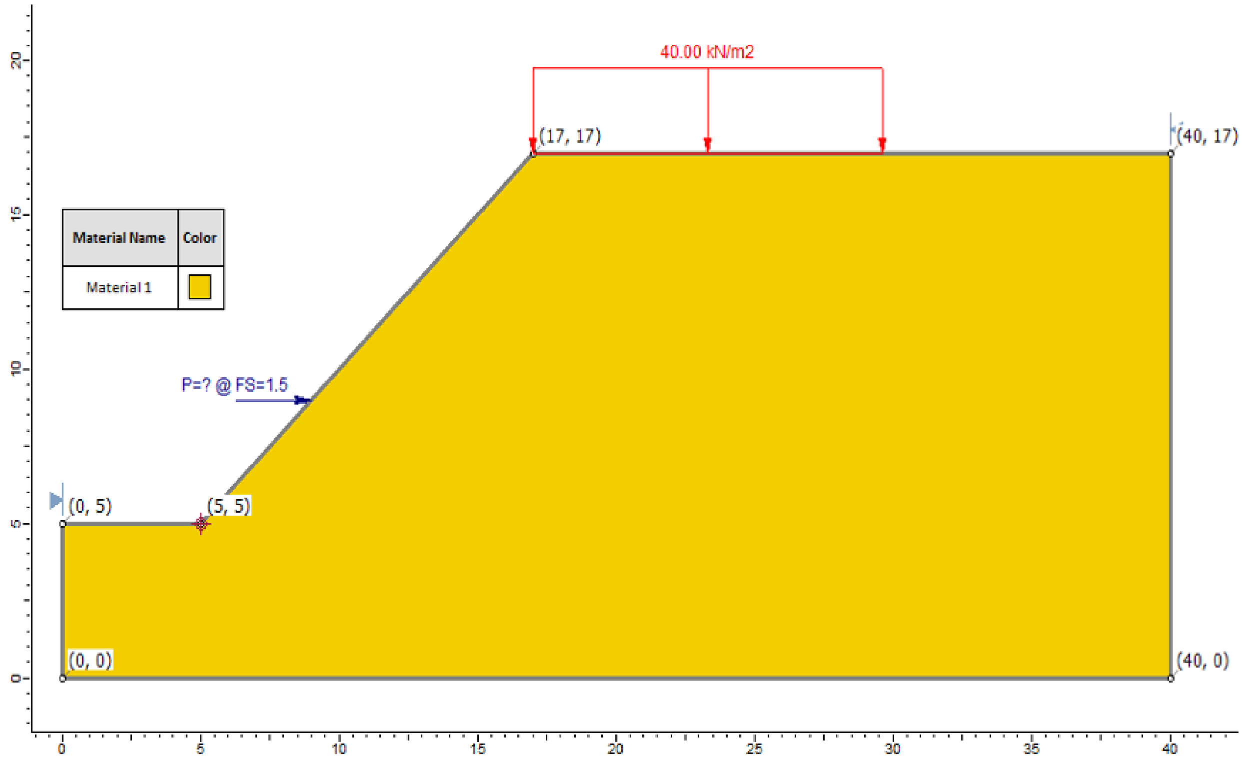


Figure 37.1: Geometry Setup in **Slide** (back analysis)

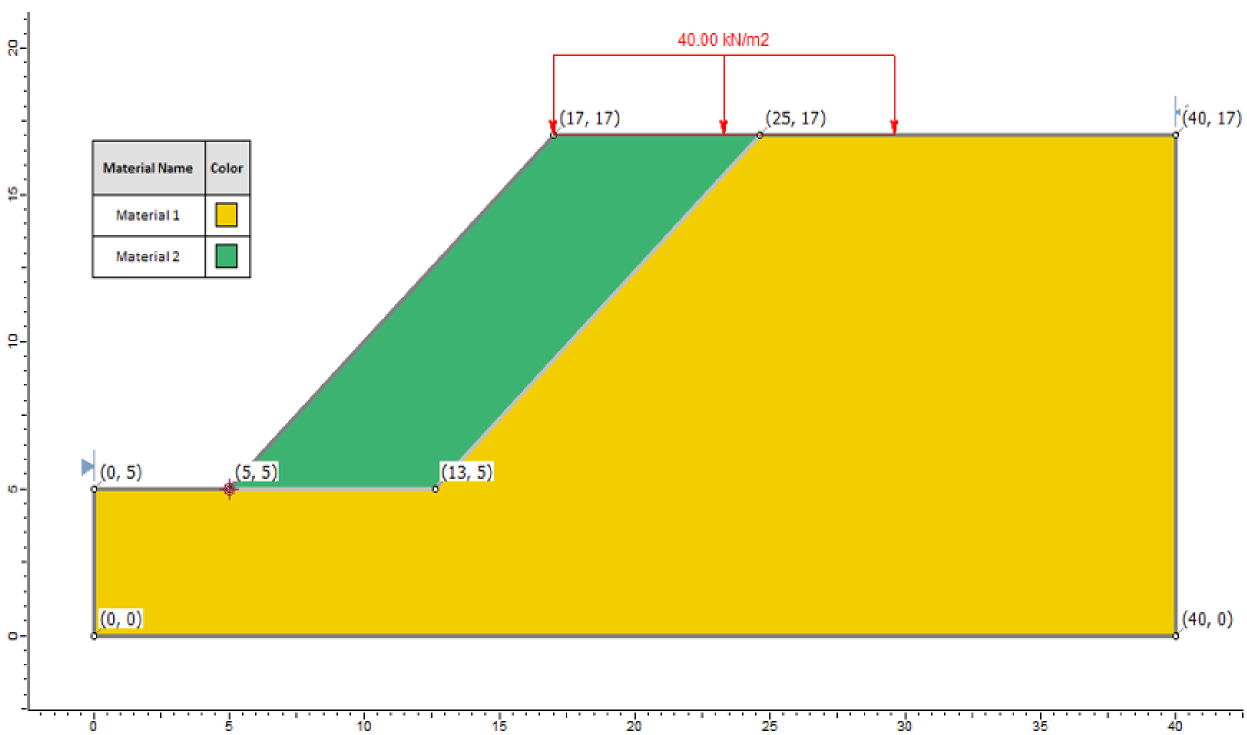


Figure 37.2: Geometry Setup in **Slide** (with reinforced zone)

37.4. Results

Table 37.1

	Slide	XSTABL
Required reinforcement force (kN)	351	345
F_r	1.96	2.044
f_{reinf} (°)	54.93	56.04
Length of reinforcement zone (m)	7.6	7.5

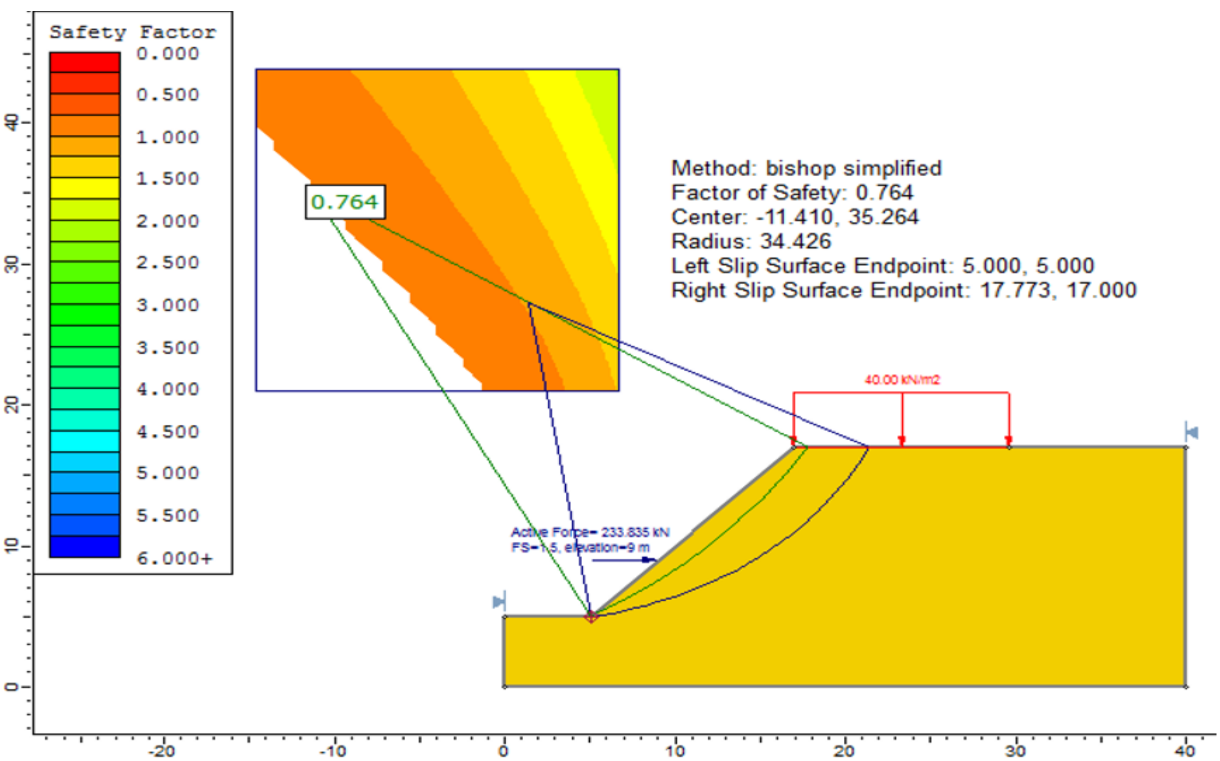


Figure 37.3: Critical Surface (back analysis)

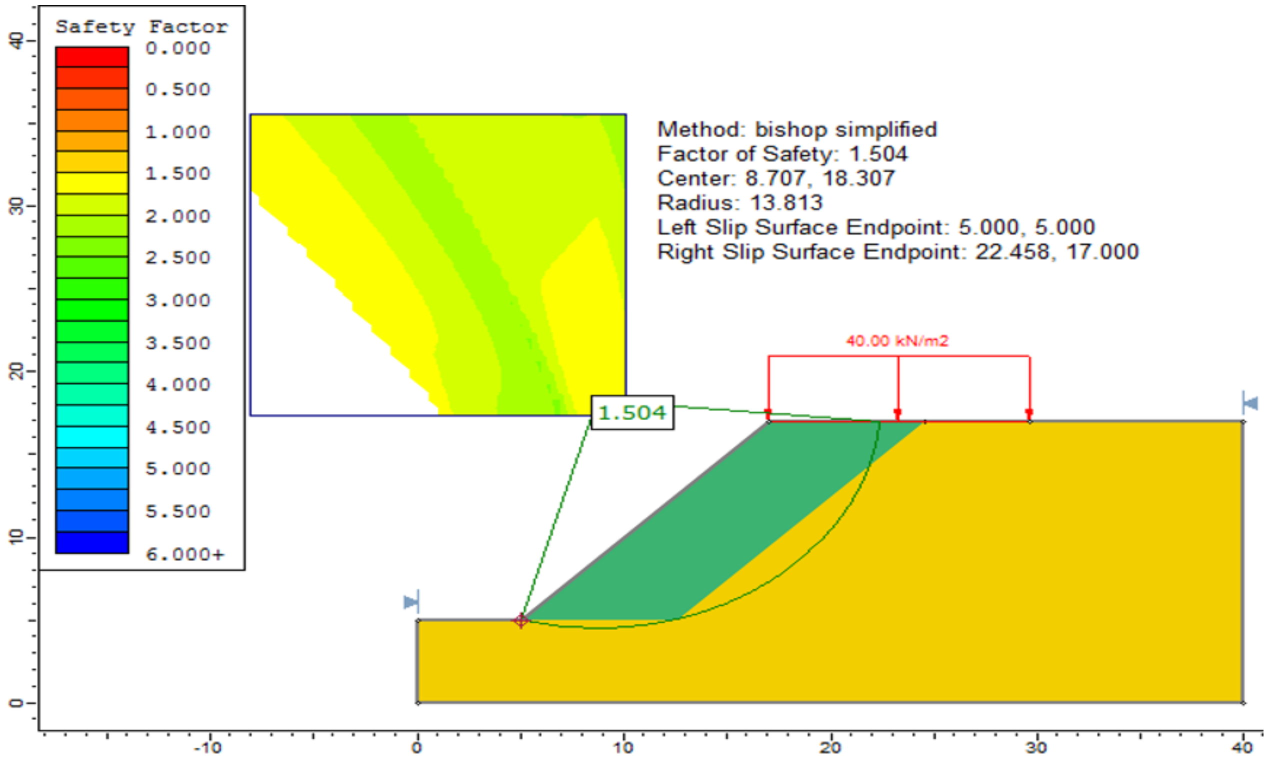


Figure 37.4: Critical Surface (with reinforced zone)

38. Slide Verification Problem #38

Excavated slope, homogenous, 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 28^o and it consists of a 24m thick soil layer, underlain by a 6m thick bedrock layer. Figure 38.1 describes the slope model in *Slide*.

Steady-state groundwater analysis is conducted using the finite element module in *Slide*. 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

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

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. The Bishop simplified method is used in this analysis.

38.3. Geometry and Material Properties

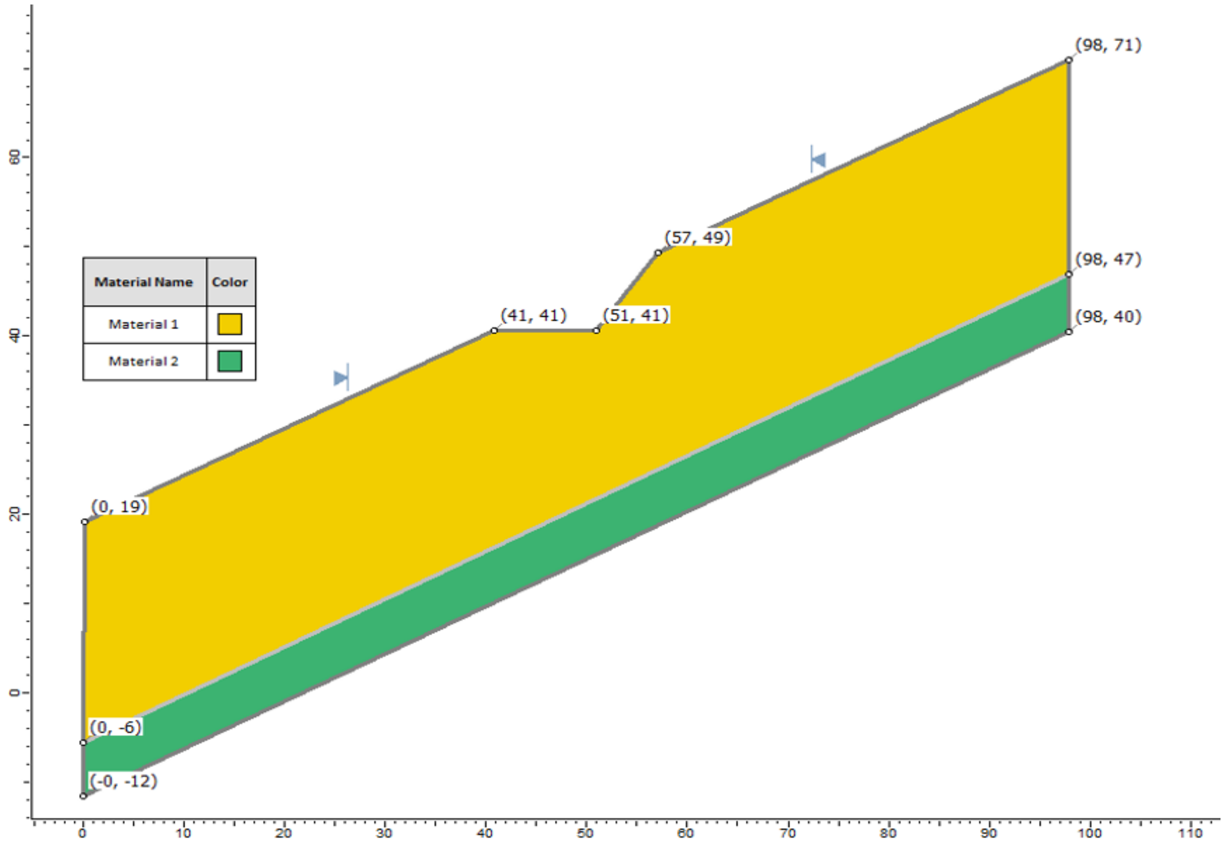


Figure 38.1: Geometry Setup in **Slide**

Table 38.1: Soil Properties

c' (kPa)	φ' (deg.)	φ_b (deg.)	γ (kN/m^3)
10	38	15	16

38.4. Results

Table 38.2

H (total head at right side of slope)	Slide	Ng. & Shi (1998)
61m	1.621	1.636
62m	1.538	1.527
63m	1.407	1.436

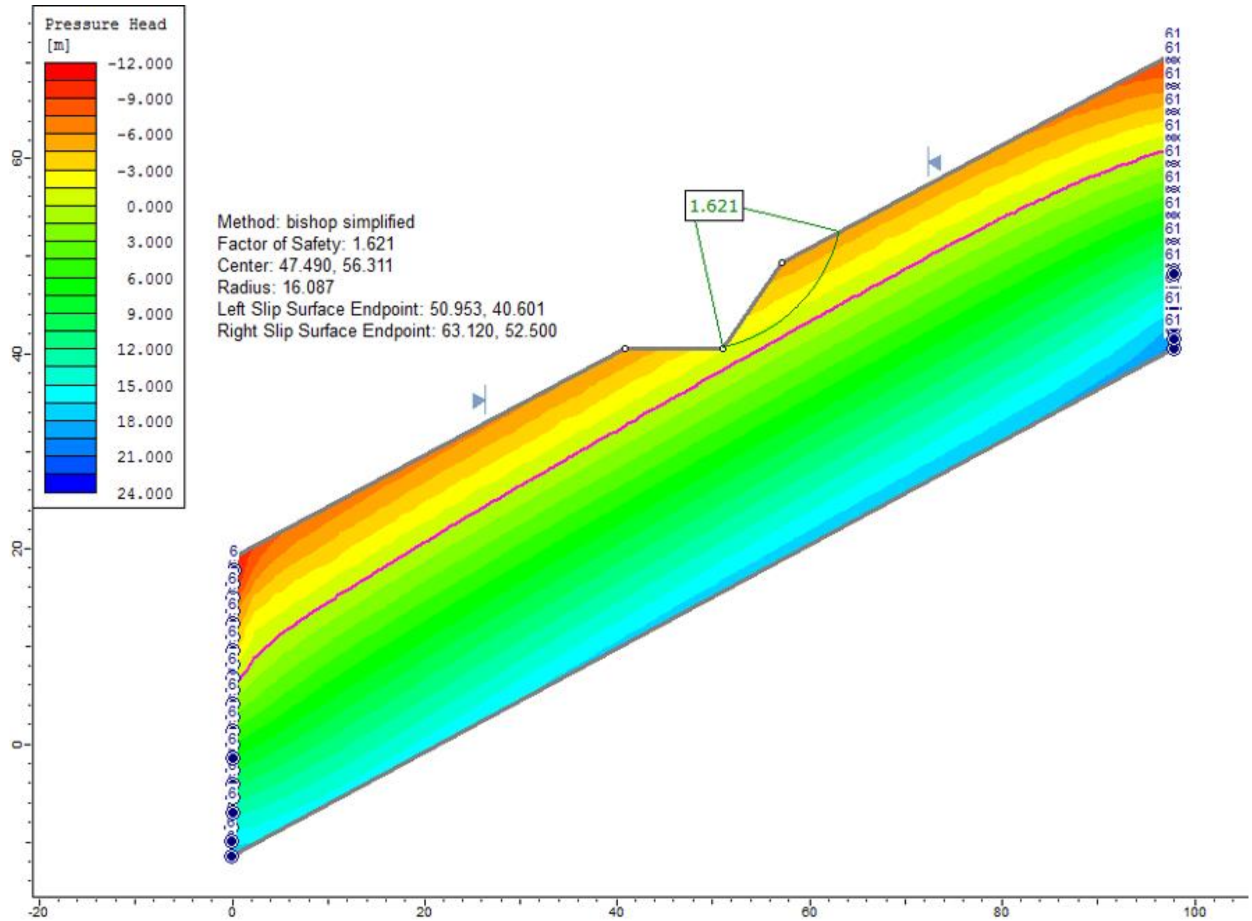


Figure 38.2: Groundwater and slope stability results for H = 61m

39. Slide 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

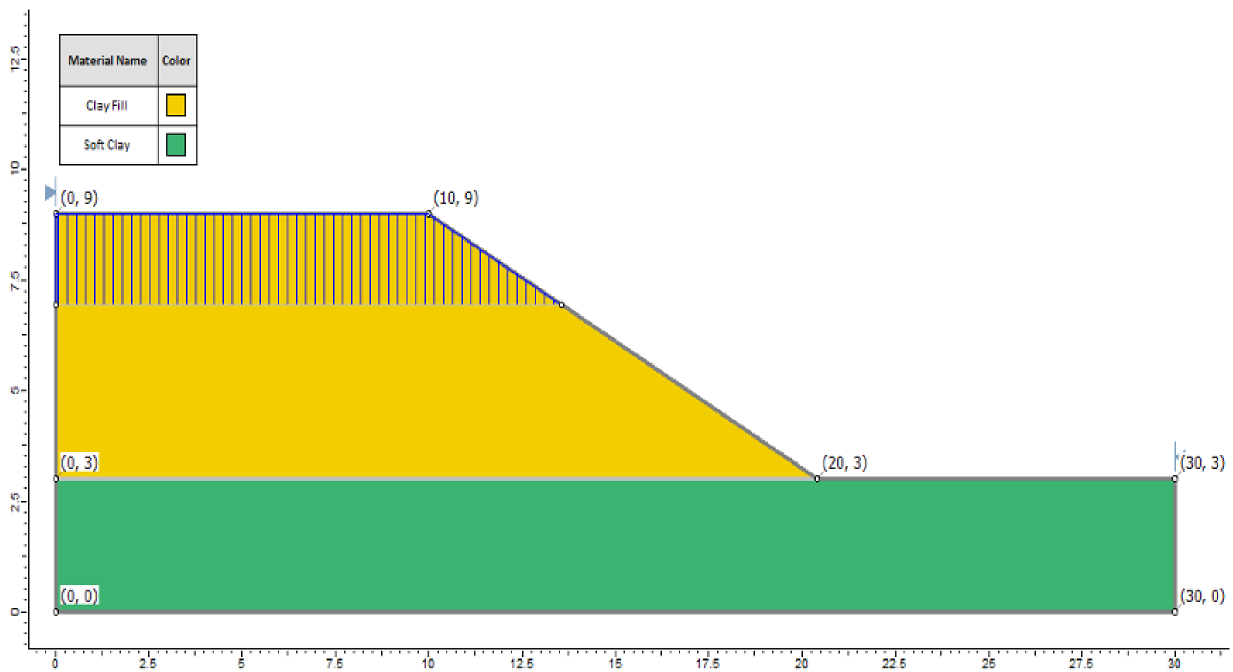


Figure 39.1: Clay Fill Embankment

Table 39.1: Clay fill model material properties

Material Name	c' (kPa)	φ' (deg.)	γ (kN/m^3)
Sand Fill	20	0	19.4
Soft Clay	20	0	19.4

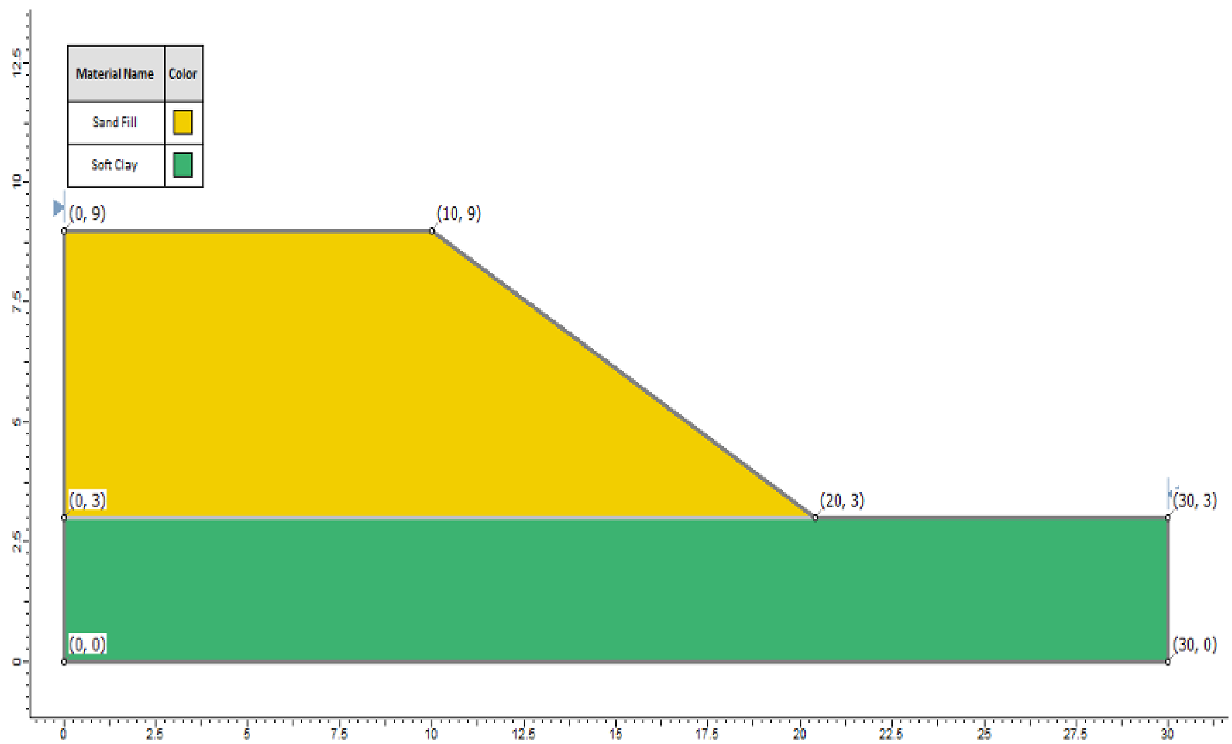


Figure 39.2: Sand Fill Embankment

Table 39.2: Sand fill model material properties

Material Name	c' (kPa)	φ' (deg.)	γ (kN/m^3)
Sand Fill	0	37	17
Soft Clay	20	0	20

39.4. Results

Table 39.2: Circular – Clay embankment with no reinforcement

Method	Factor of Safety
Spencer	0.975
GLE/M-P	0.975

Note: Tandiiria (2002) Spencer factor of safety = 0.981

Table 39.3: Noncircular – Clay embankment with no reinforcement

Method	Factor of Safety
Spencer	0.935
GLE/M-P	0.936

Note: Tandiiria (2002) Spencer factor of safety = 0.941

Table 39.4: Circular – Sand embankment with no reinforcement

Method	Factor of Safety
Spencer	1.209
GLE/M-P	1.218

Note: Tandiiria (2002) Spencer factor of safety = 1.219

Table 39.5: Noncircular Results – Sand embankment with no reinforcement

Method	Factor of Safety
Spencer	1.188
GLE/M-P	1.178

Note: Tandiiria (2002) Spencer factor of safety = 1.192

Table 39.6: Circular Results – Clay embankment with reinforcement

Method	Reinforcement Force (KN/m)	Factor of Safety
Spencer	169	1.35

Note: Tandiiria (2002) Reinforcement Force = 170 KN/m

Table 39.7: Noncircular Results – Clay embankment with reinforcement

Method	Reinforcement Force (KN/m)	Factor of Safety
Spencer	184	1.35

Note: Tandiiria (2002) Reinforcement Force = 190 KN/m

Table 39.8: Circular Results – Sand embankment with reinforcement

Method	Reinforcement Force (KN/m)	Factor of Safety
Spencer	44	1.35

Note: Tandiiria (2002) Reinforcement Force = 45 KN/m

Table 39.9: Noncircular Results – Sand embankment with reinforcement

Method	Reinforcement Force (KN/m)	Factor of Safety
Spencer	56	1.35

Note: Tandiiria (2002) Reinforcement Force = 56 KN/m

40. Slide Verification Problem #40

Slope, homogenous, 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 non-linear 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

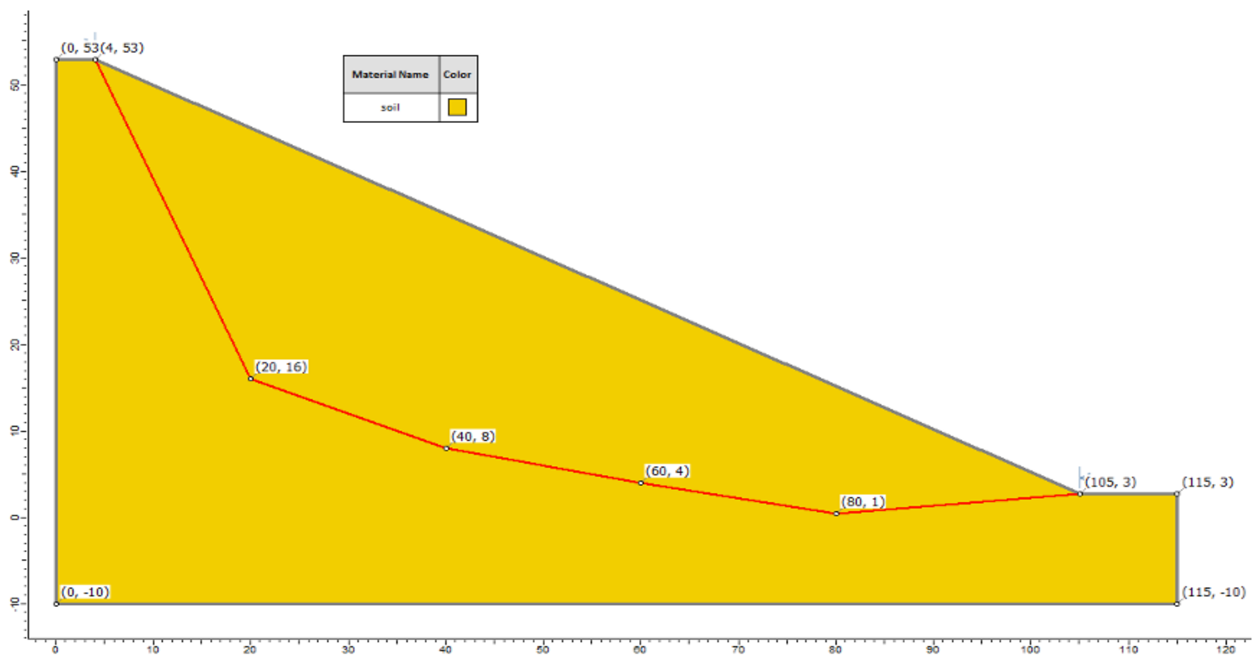


Figure 40.1: Geometry Setup in **Slide**

Table 40.1: Soil Properties

	A	b	γ (kN/m^3)
Mean	2	0.7	20.0
Rel. max/min	0.3	0.105	N/a

40.4. Results

Table 40.2

Method	Factor of Safety
Janbu Corrected	0.944

Note: Reference factor of safety = 0.98 [Perry]

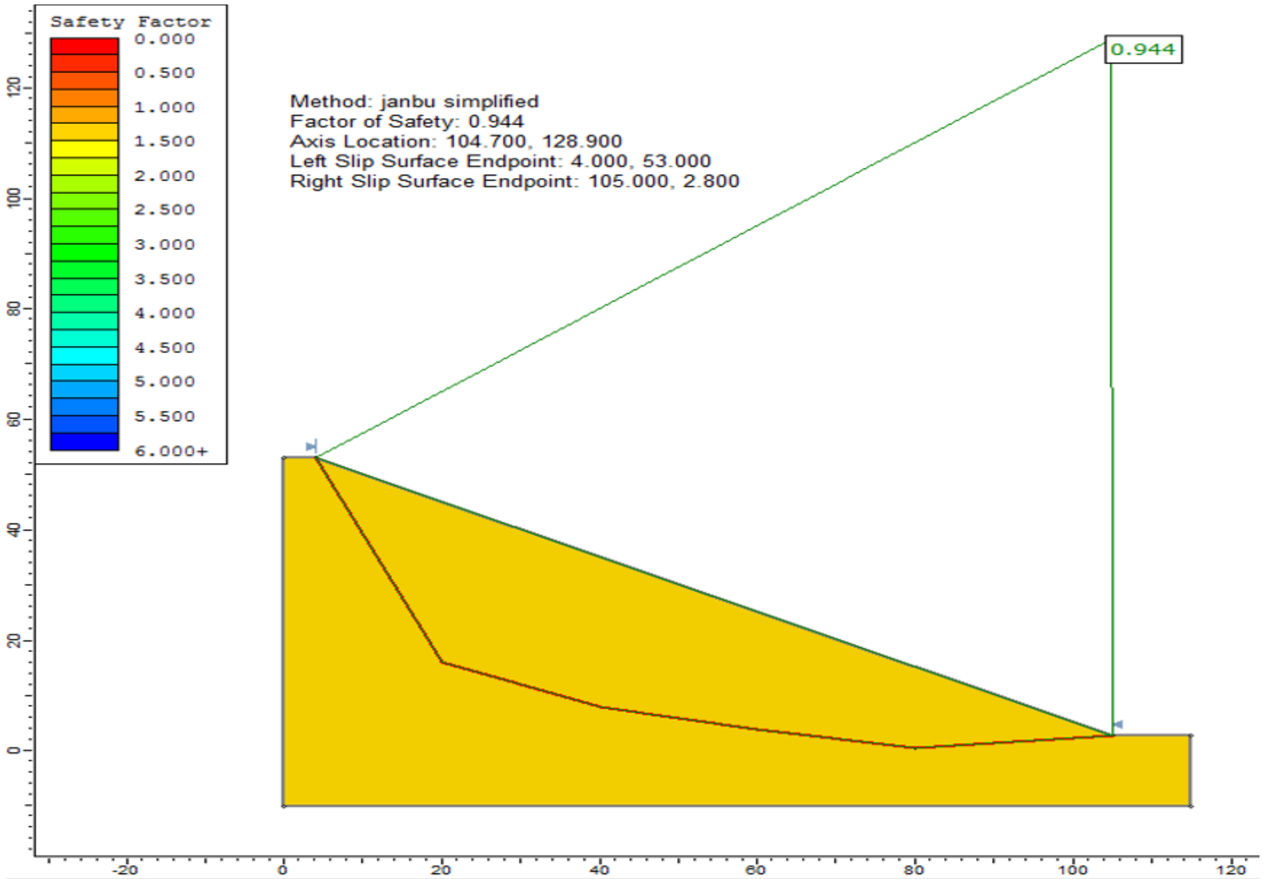


Figure 40.2: Solution, using the Bishop simplified method

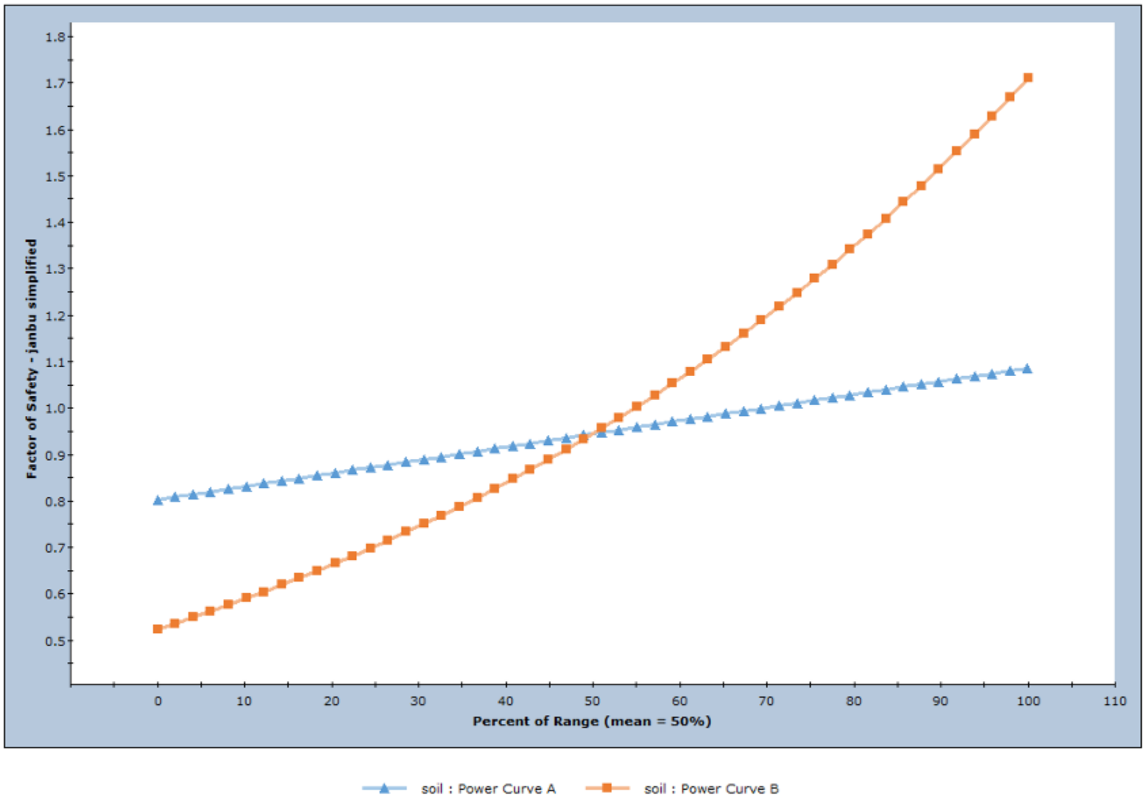


Figure 40.3: Sensitivity analysis on power curve A and power curve B

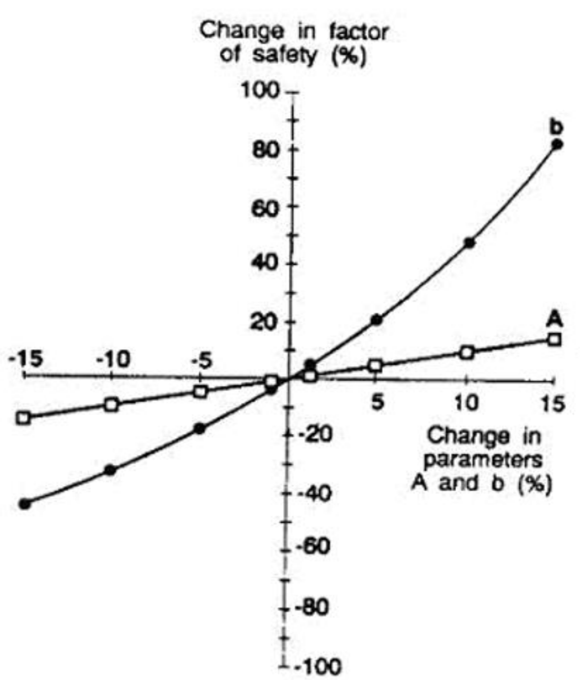


Figure 40.4: Perry's variation of factor safety with shear strength parameters

41. Slide Verification Problem #41

Slope, homogenous, 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

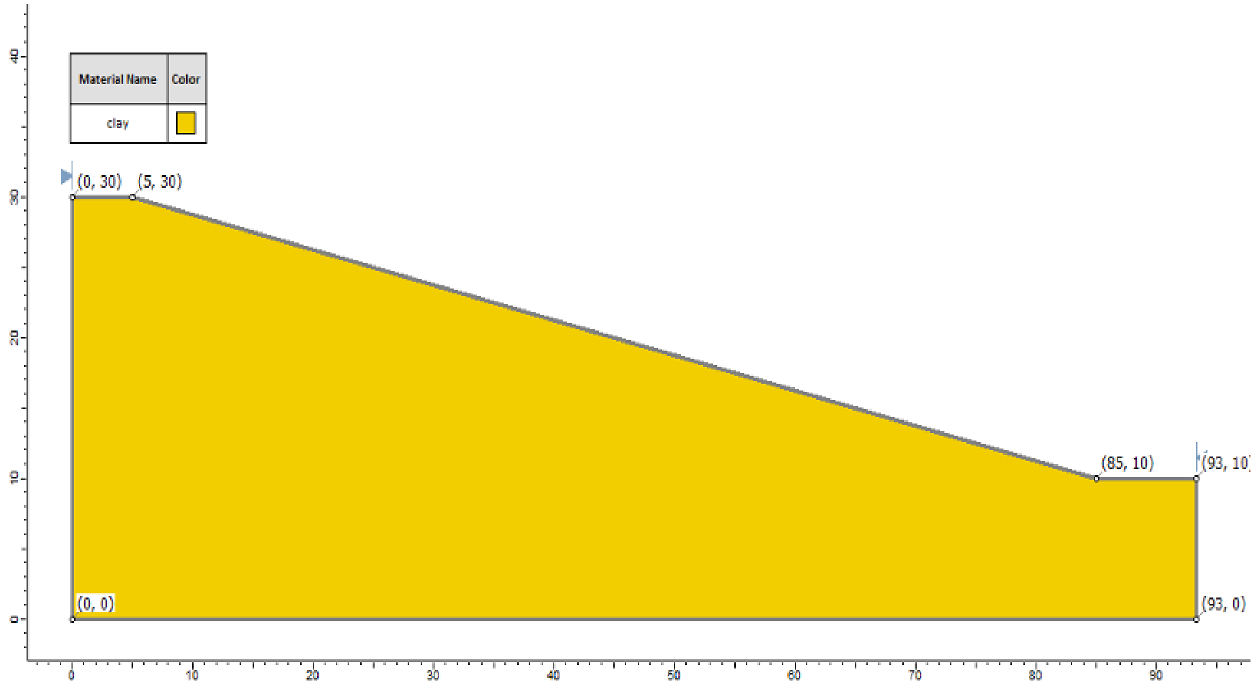


Figure 41.1: Geometry Setup in **Slide**

Table 41.1: Soil Properties

A	B	γ (kN/m^3)
1.4	0.8	20.0

41.4. Results

Table 41.2

Method	Factor of Safety
Bishop	1.656
Janbu Simplified	1.563

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

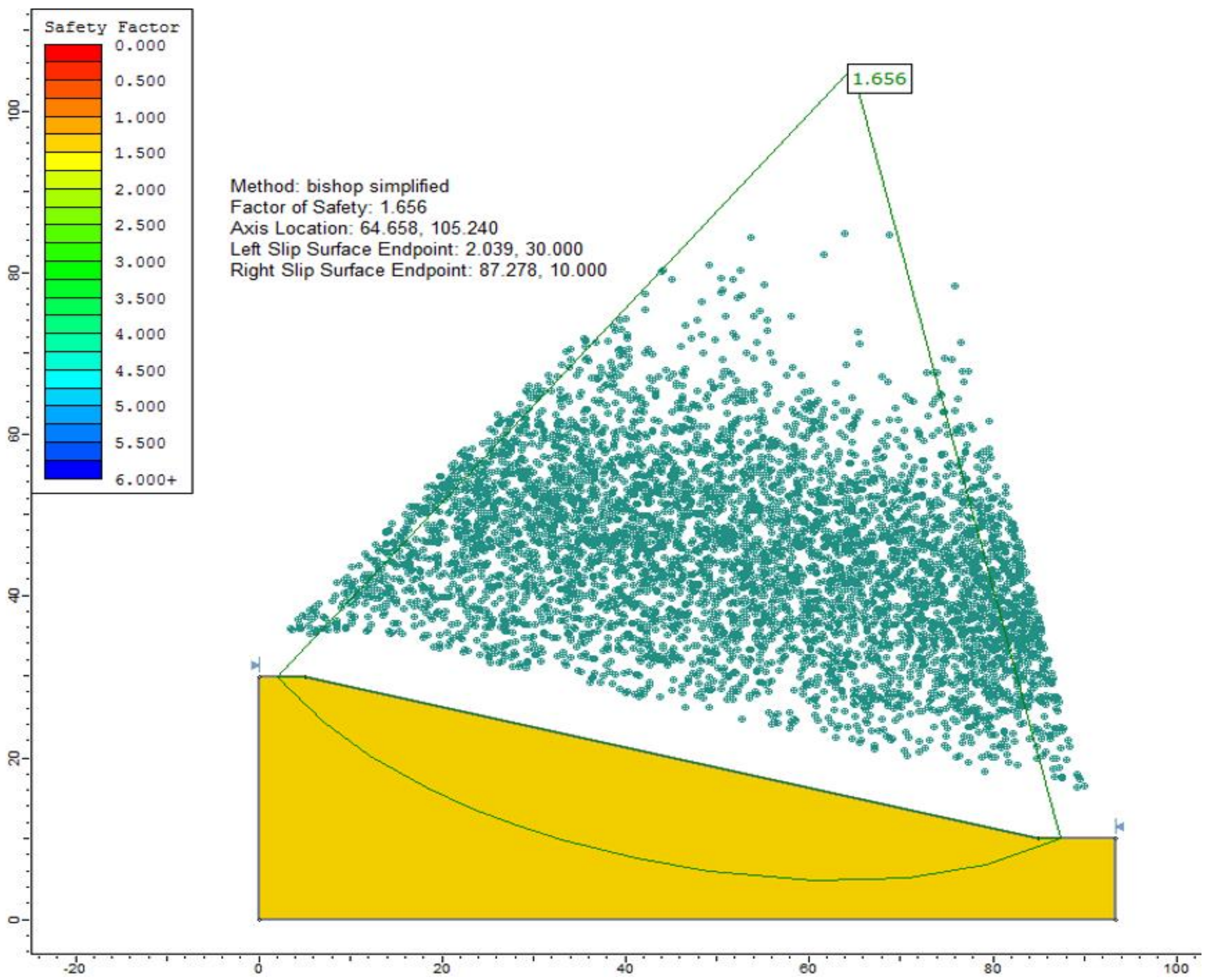


Figure 41.2: Solution, using the Bishop simplified method

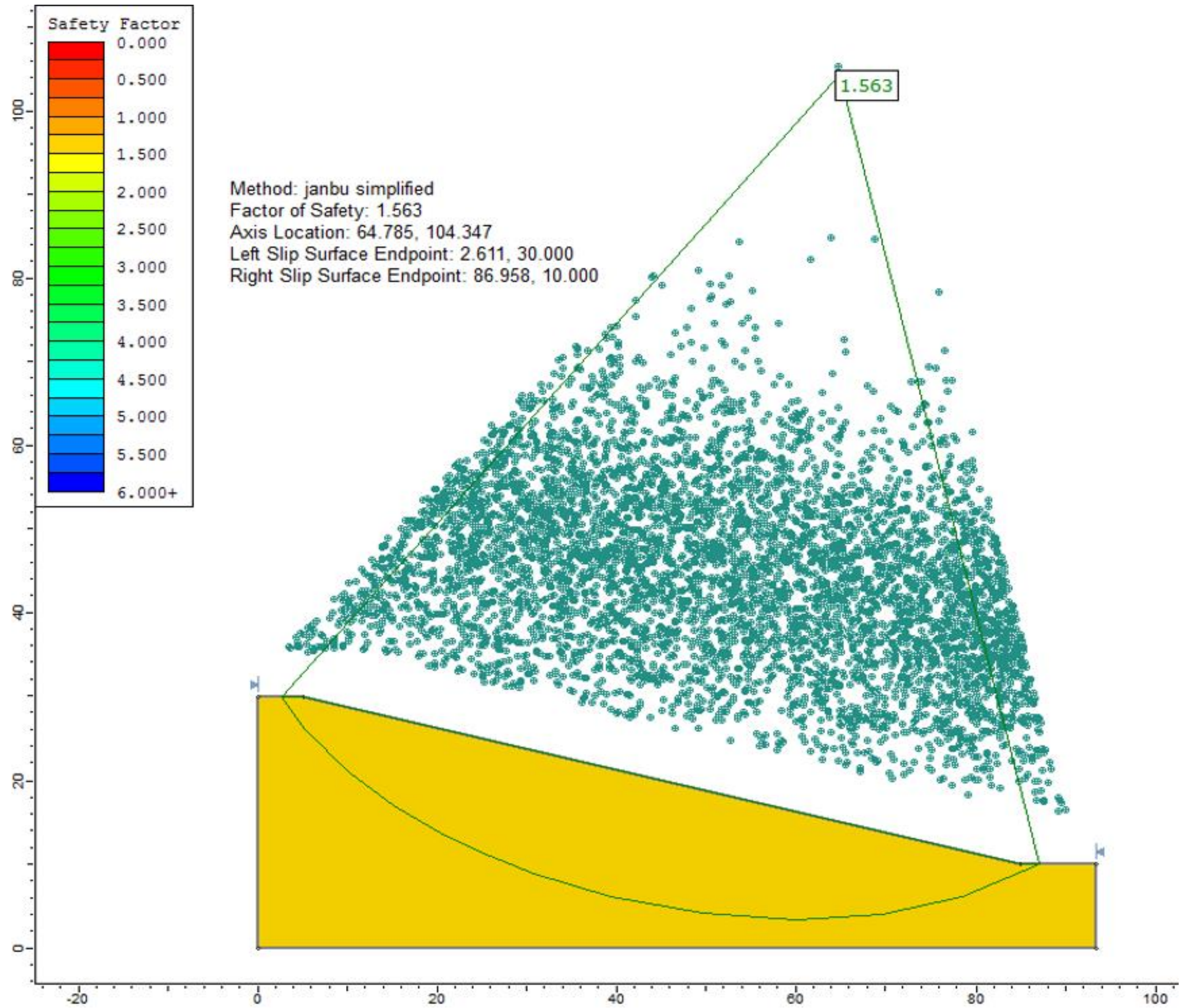


Figure 41.3: Solution, using the Janbu simplified method

42. Slide 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

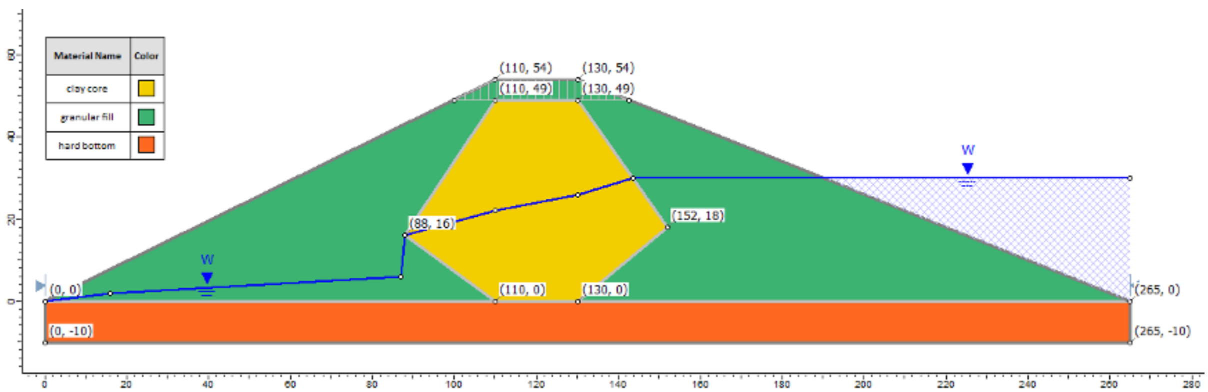


Figure 42.1: Geometry Setup in **Slide**

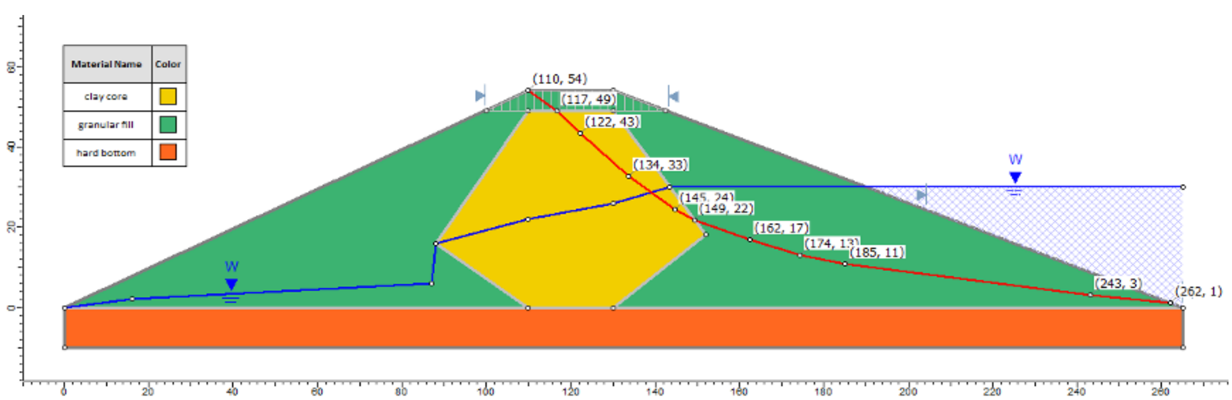


Figure 42.2: Location of noncircular failure surface

Table 42.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Clay core	20	20	20
Granular fill	0	40	21.5
Hard base	200	45	24

42.4. Results

Table 42.2: Circular failure surface, 80x80 grid

Method	Factor of Safety
Spencer	1.925

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

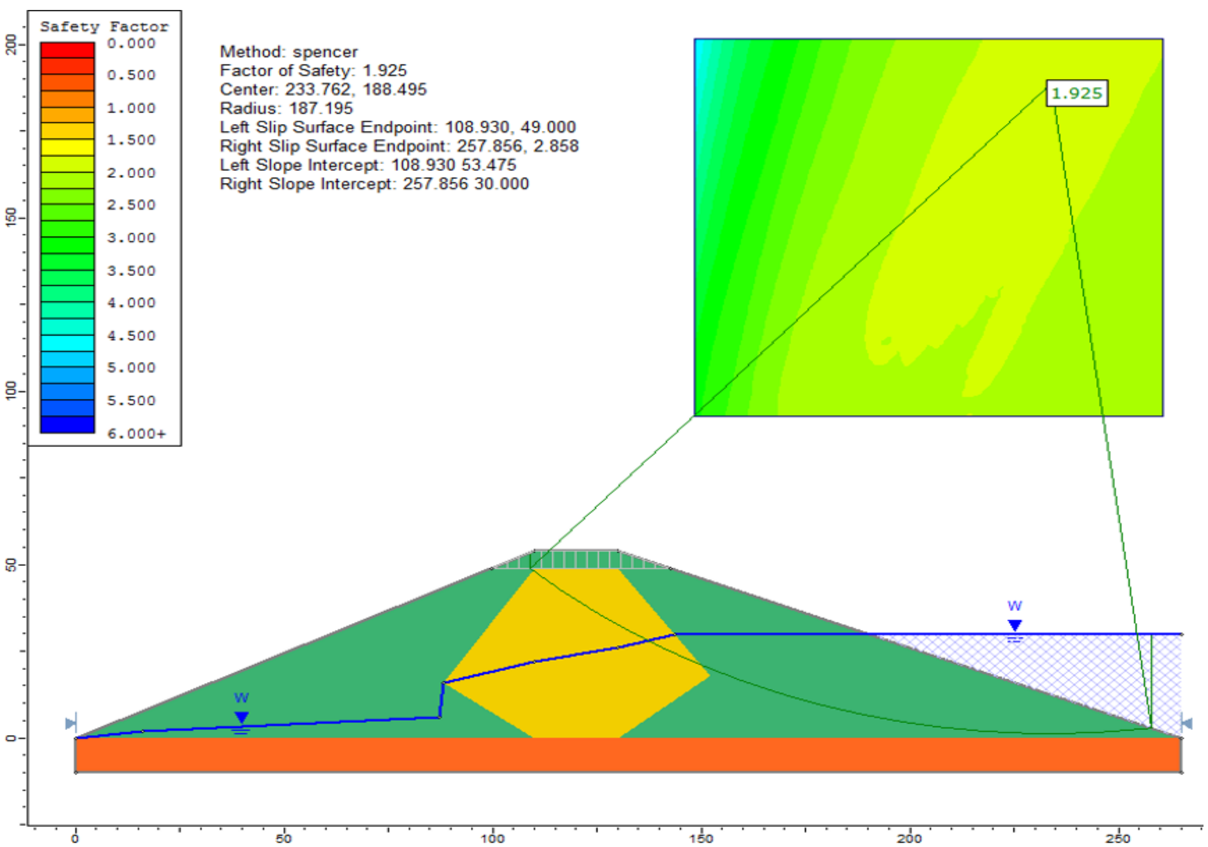


Figure 42.3: Safety map featuring global minimum zone using Spencer method

Table 42.3: Noncircular using Random search with Optimization (zero faces)

Method	Factor of Safety
Spencer	1.877

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

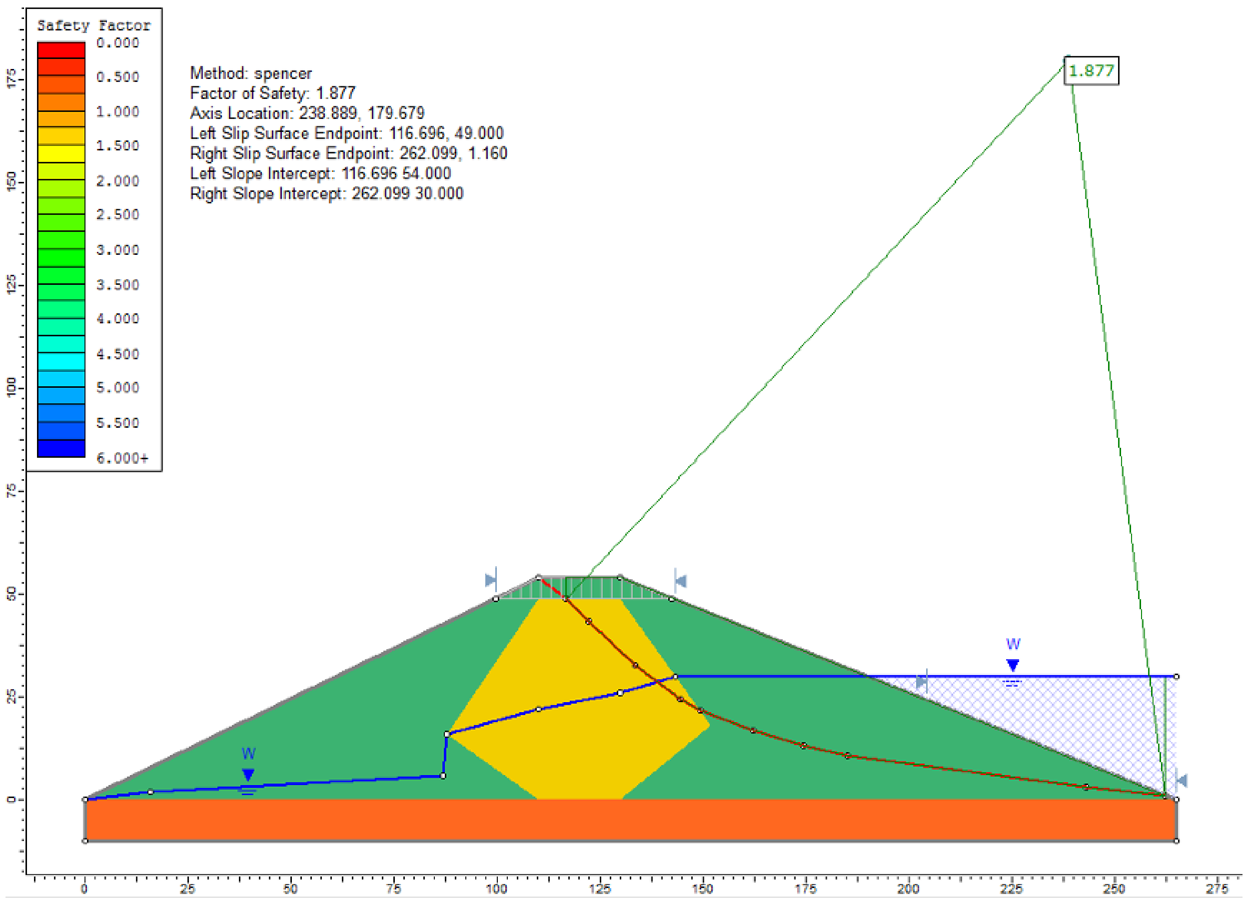


Figure 42.4: Noncircular failure surface using Random search with optimization

43. Slide Verification Problem #43

Slope, homogenous, planar surface, RocPlane comparison

43.1. Introduction

This problem was taken from Baker (2001). It looks at planar failure surface safety factors relative to varying failure plane angles.

43.2. Problem Description

The slope in this problem is homogeneous and dry. The geometry is given in Figure 43.1. There are two tests that must be run on this slope: first, the plot of safety factor vs. x-coordinate is required for all critical failure planes passing through the toe of the slope. Then, the critical circular failure surfaces in Zone A must be determined, at which point the safety factor vs. x-coordinate for Zone A must be plotted. The goal of this problem is to locate the minimum safety factor and its variation as the function of failure plane angle changes.

43.3. Geometry and Material Properties

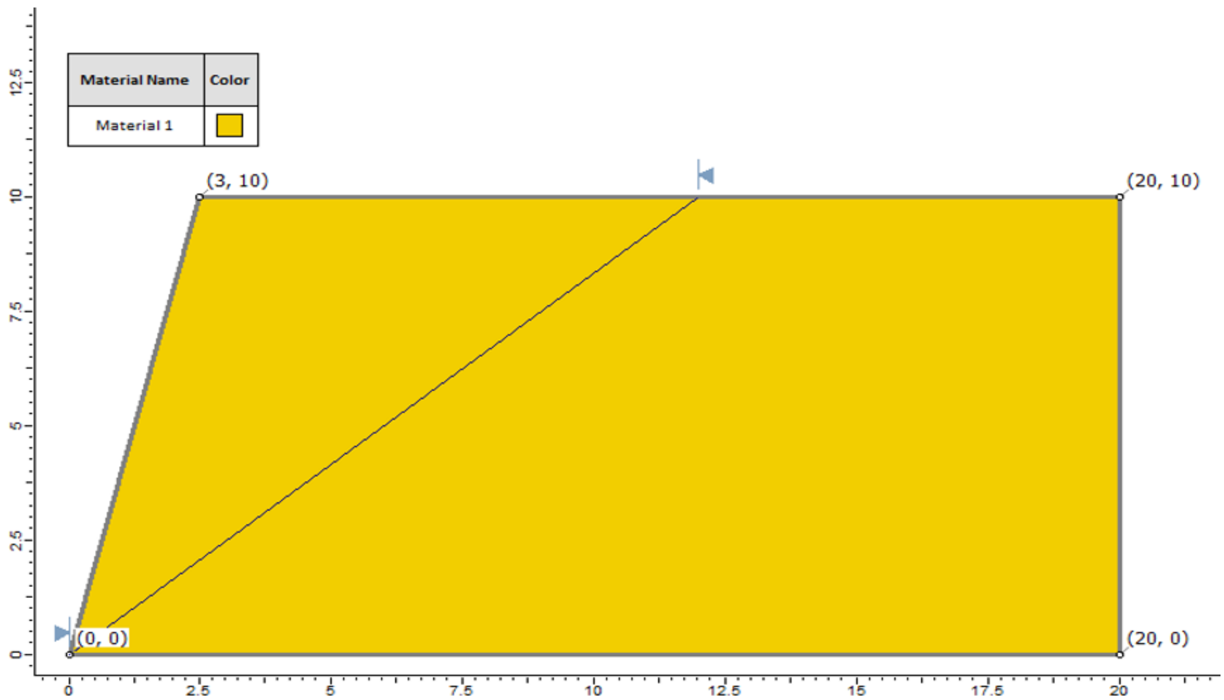


Figure 43.1: Geometry Setup in **Slide**

Note: For critical planar surface solution, use a block search with a focus point at the toe and a focus line along the bench. For the circular search, move the right limit (12, 10) to only include Zone A. Grid should go no higher than 17.5 to avoid anomalous results. Janbu simplified must be used to coincide with the author's use of the Culmann method.

Table 43.1: Soil Properties

	c´ (kN/m²)	ϕ´ (deg.)	γ (kN/m³)
Material 1	30	30	20

43.4. Results

Table 43.2

Method	Factor of Safety	Angle (deg)
Janbu Simplified (Non-circular)	1.352	49.5
Janbu Simplified (Circular)	1.329	49.5
RocPlane 2.0	1.351	49.5

Note: Baker (2001) Culmann FS = 1.35

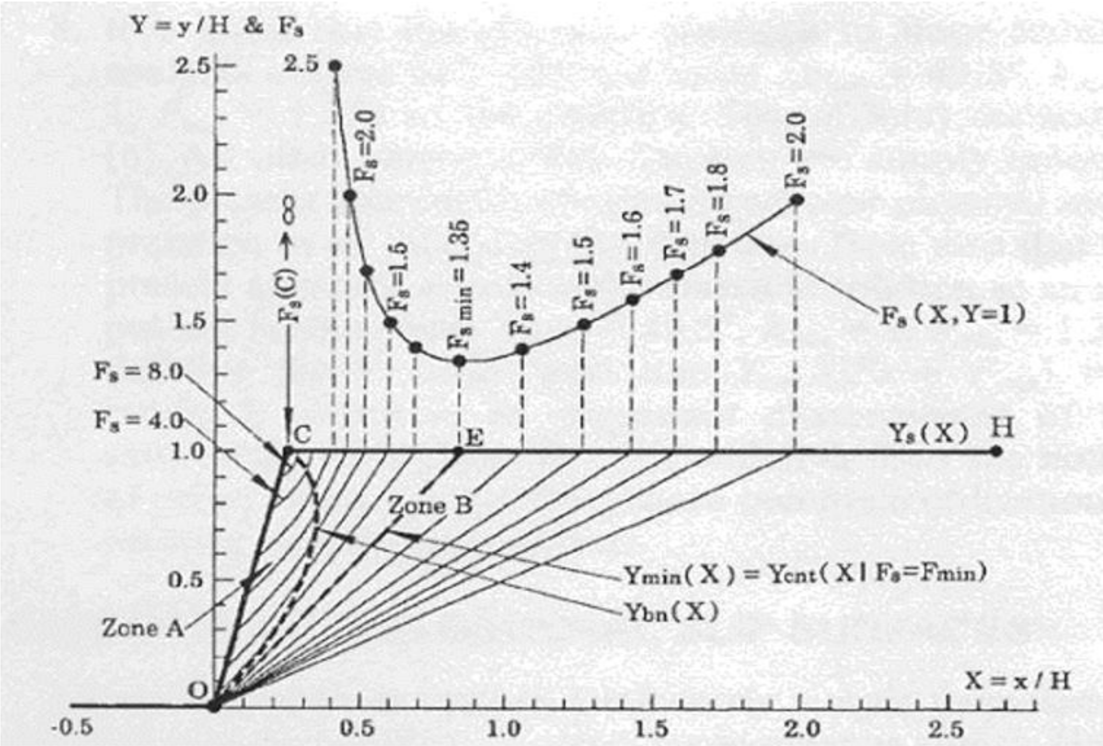
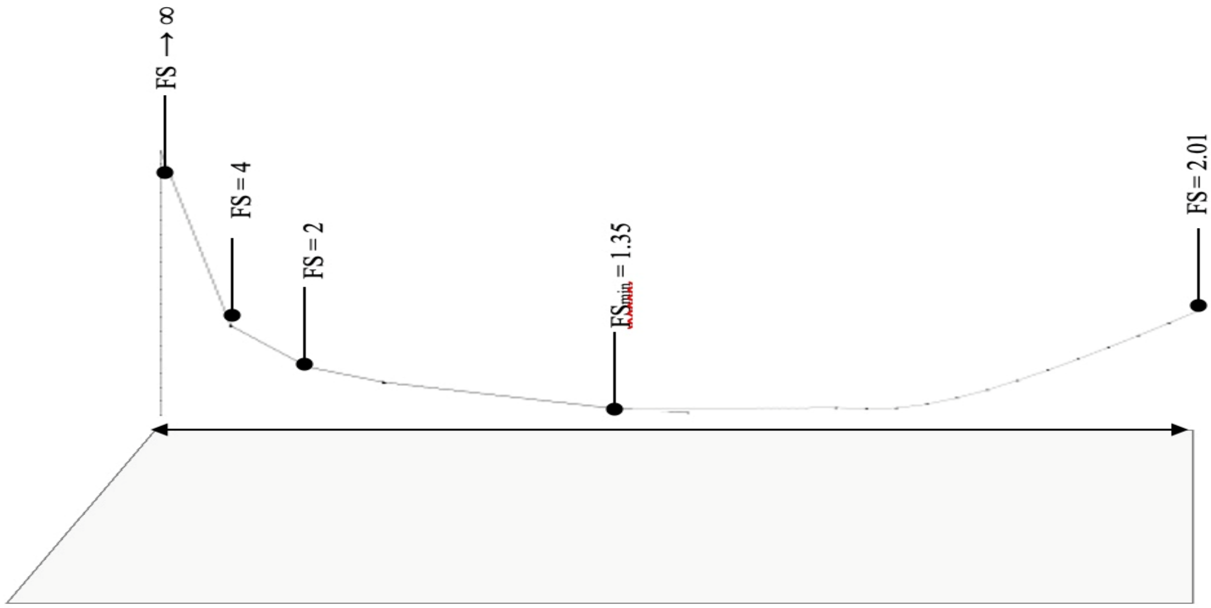


Figure 43.2: Baker's Distribution (Reference plot)



Note: Vertical scales are not the same on both sides of the minimum.

Figure 43.3: FS spatial distribution with failure surface distribution along x-axis.

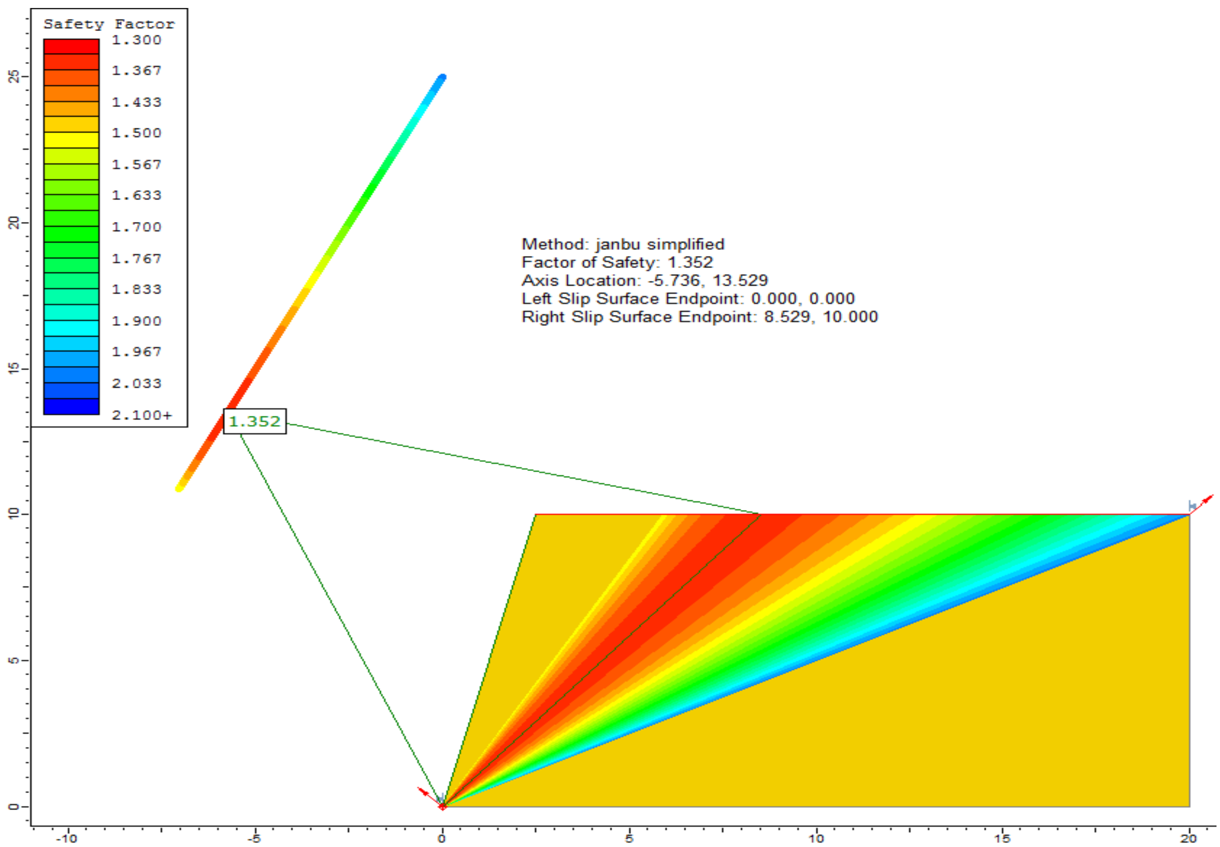


Figure 43.4 – Planar failure surfaces, using Janbu simplified method

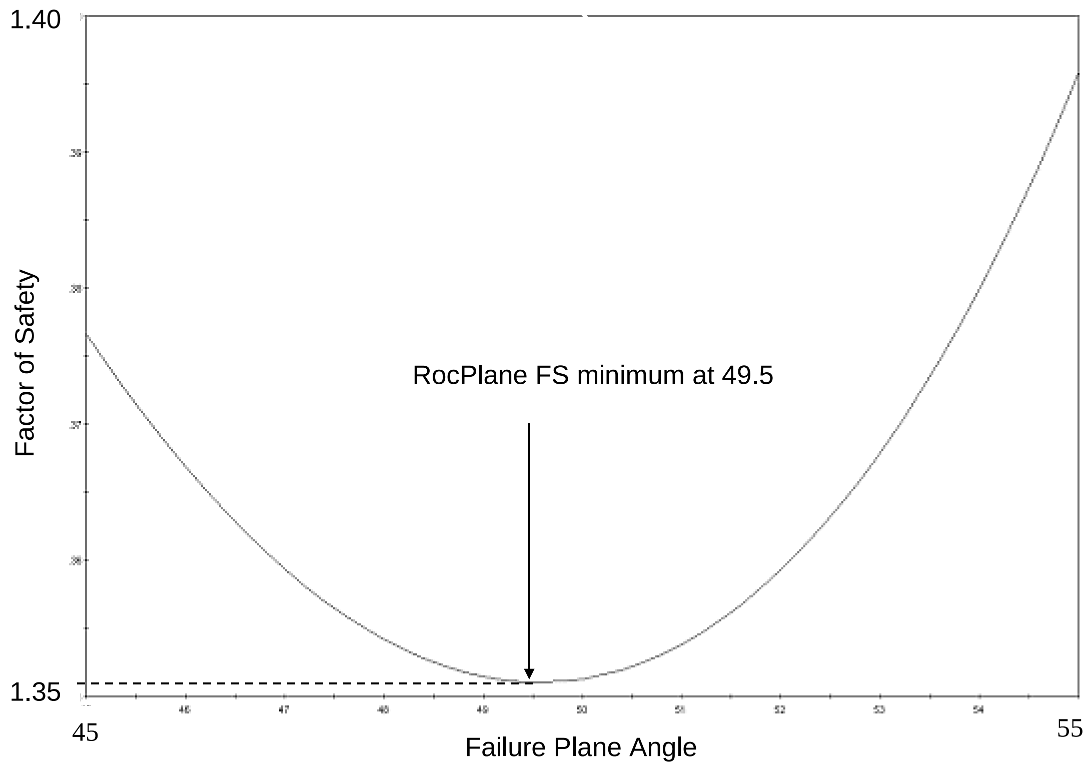


Figure 43.5– Solution using RocPlane 2.0

44. Slide Verification Problem #44

Slope, homogenous

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 Mohr-Coulomb strength criterion and Power Curve criterion. The power curve criterion was derived from Baker's own non-linear function:

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

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

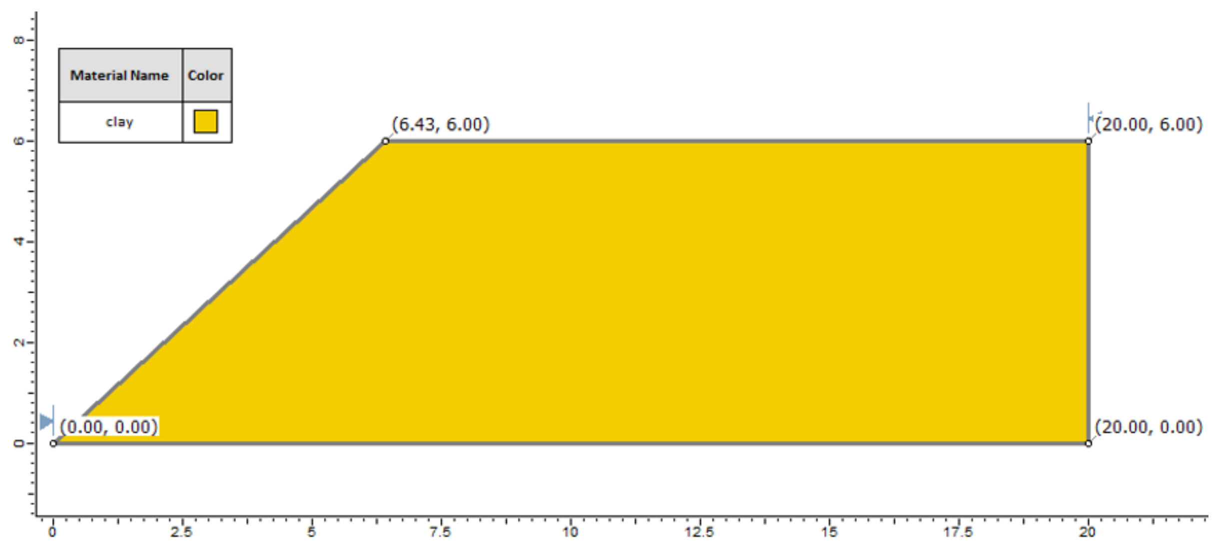


Figure 44.1: Geometry Setup in **Slide**

Table 44.1: Soil Properties

	c´ (kN/m²)	ϕ´ (deg.)	γ (kN/m³)	A	n	T	a	b	c
Soil #1	0.0	38.0	19.5	0.58	0.86	0	1.107	0.86	0
Soil #2	5.3	23.0	19.5						

44.4. Results

Table 44.2

Strength Type	Method	Factor of Safety	Maximum effective normal stress (kPa)
Power Curve/non-linear	Janbu Simplified	0.921	15.40
	Spencer	0.960	11.51
Mohr-Coulomb	Janbu Simplified	1.469	41.88
	Spencer	1.536	37.55
Mohr-Coulomb with iteration results (c´ = 0.39 kPa, ϕ´ = 38.6 °)	Janbu simplified	0.957	9.62
	Spencer	0.981	8.83

Note: Baker (2003) non-linear results: FS = 0.97, σ_{max} = 8.7

Baker (2003) M-C results: FS = 1.50, σ_{max} = 40.2

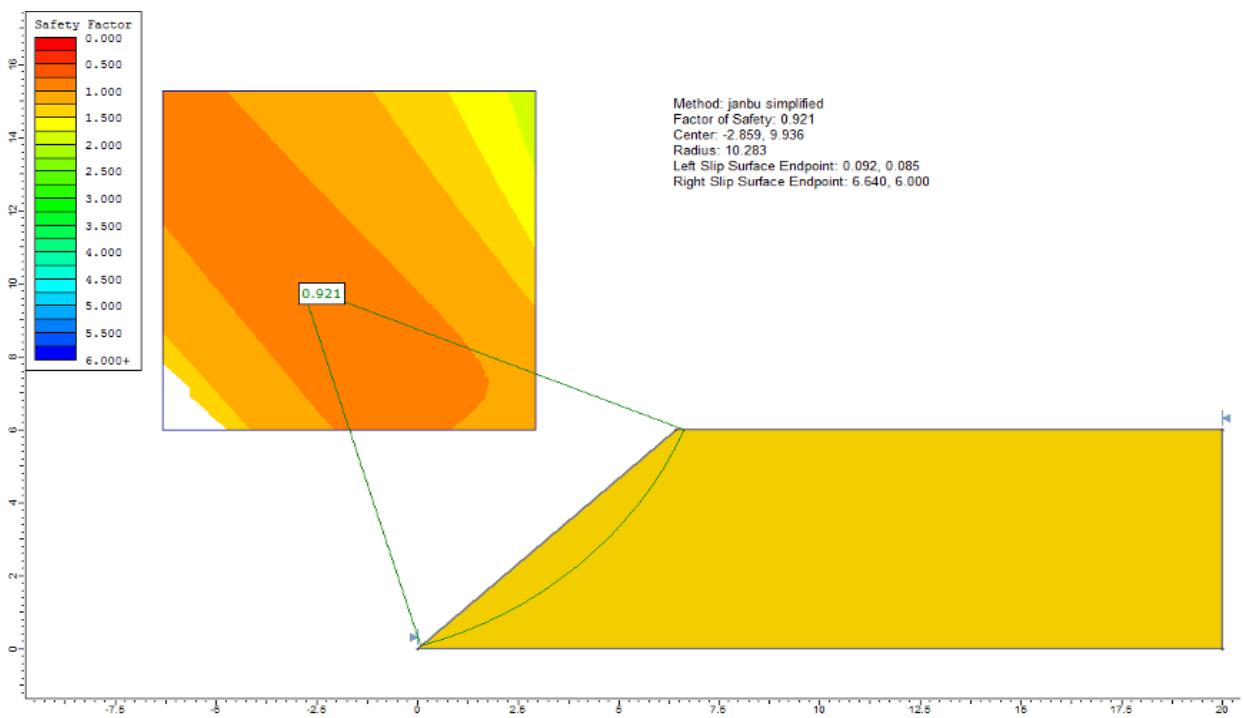


Figure 44.2: Critical failure surface, using the power curve criterion, Janbu simplified

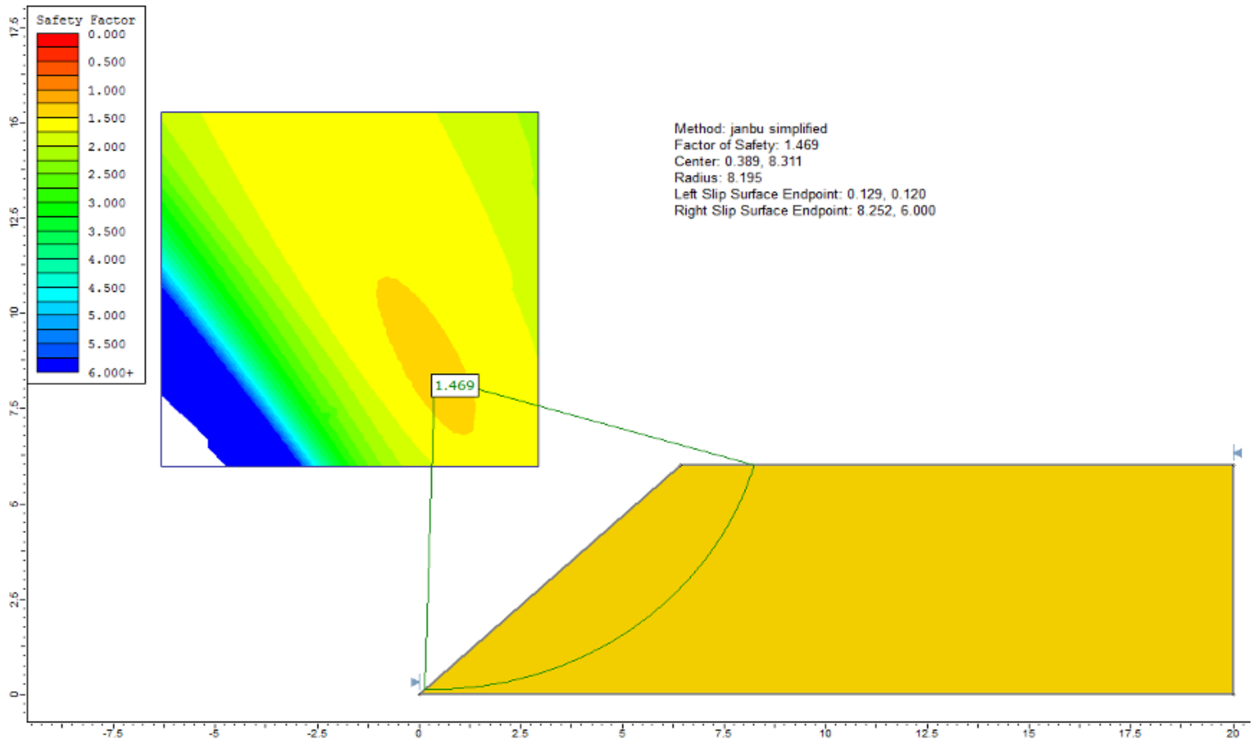


Figure 44.3: Critical failure surface, using the Mohr-Coulomb criterion, Janbu simplified

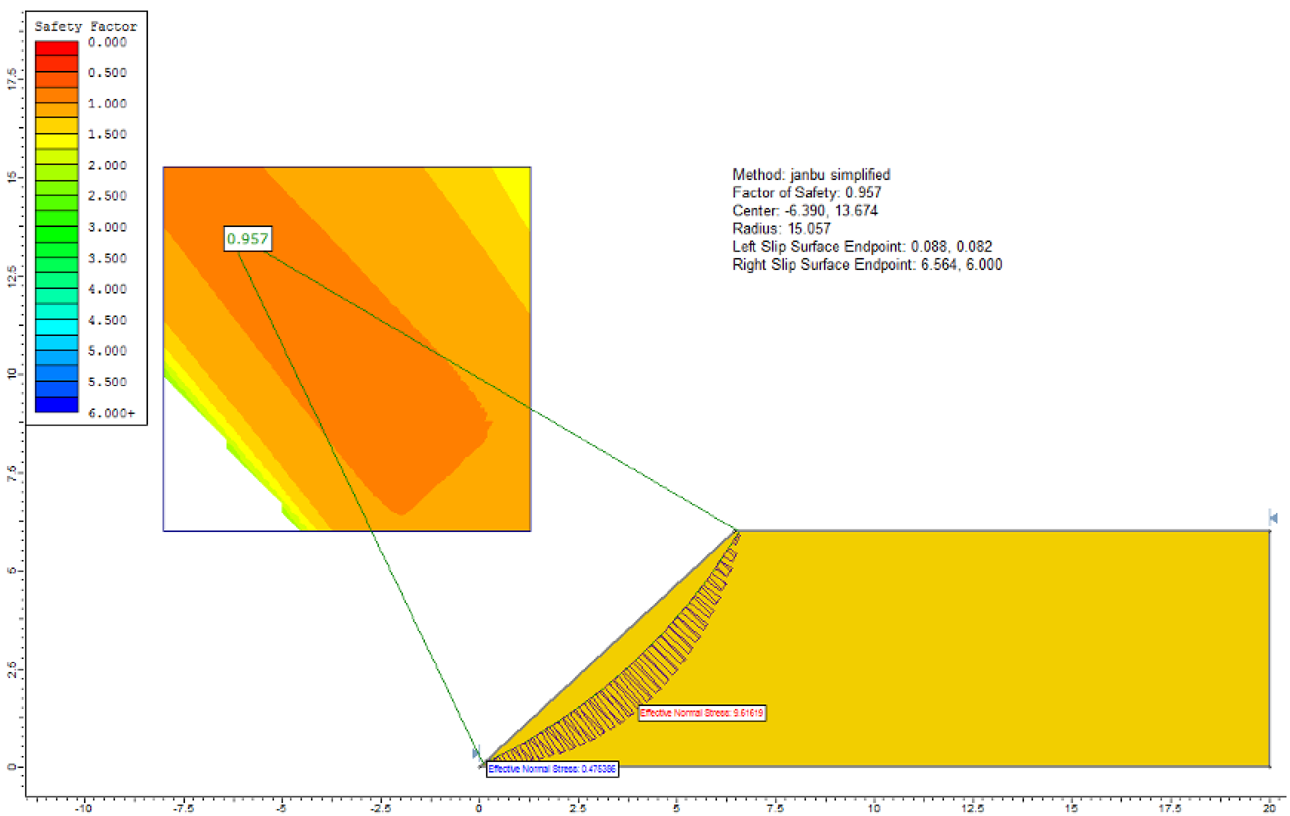


Figure 44.4: Mohr-Coulomb criterion with iterations, Janbu simplified

45. Slide Verification Problem #45

Slope, homogenous

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:

$$\tau = P_a A\left(\frac{\sigma}{P_a} + T\right)^n$$ … 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

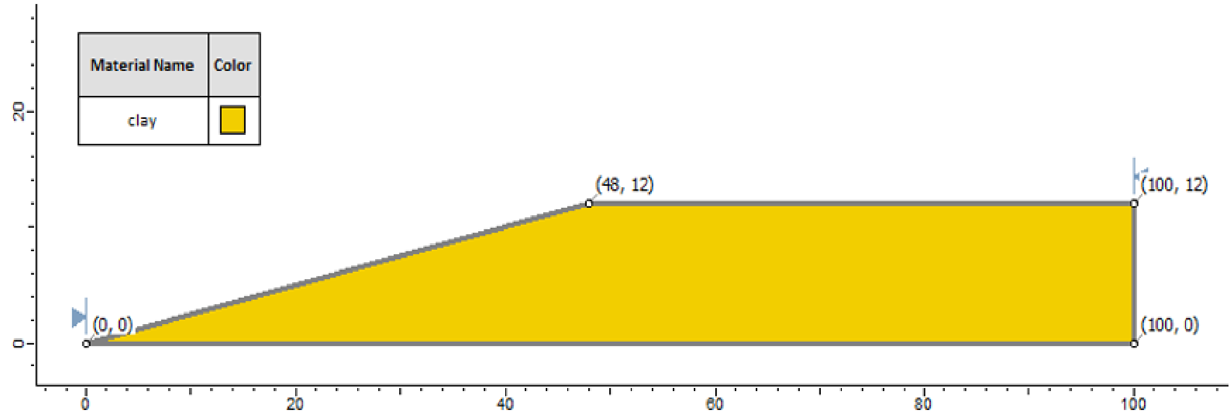


Figure 45.1: Geometry Setup in **Slide**

Table 45.1: Soil Properties

Material	c´ (kN/m²)	ϕ´ (deg.)	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						

45.4. Results

Table 45.2

Strength Type	Method	Factor of Safety	Maximum effective normal stress (kPa)
Power Curve	Janbu Simplified	2.559	99.50
	Spencer	2.662	93.03
Mohr-Coulomb	Janbu Simplified	2.662	118.63
	Spencer	2.794	106.26
Mohr-Coulomb with iteration results (c´ = 2.439kPa, ϕ´ = 30.392°)	Janbu simplified	2.610	84.64
	Spencer	2.696	82.25

Note: Baker (2003) non-linear results: FS = 2.64, σ_{max} = 78.1

Baker (2003) M-C results: FS = 2.66, σ_{max} = 140.3

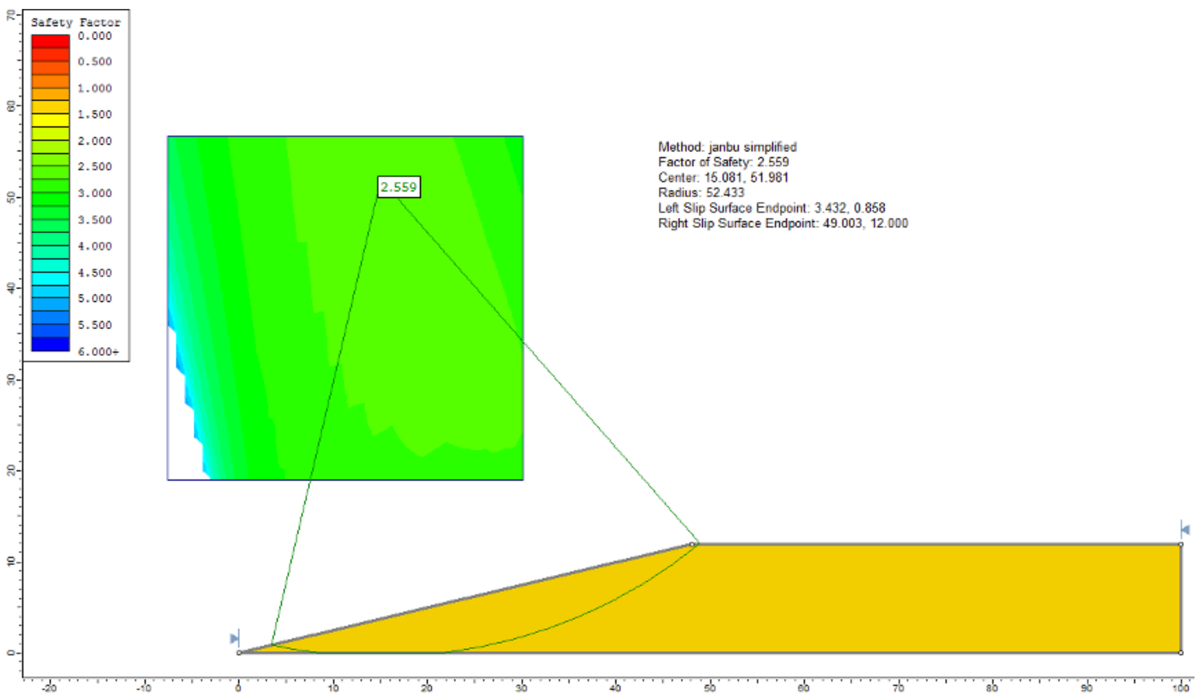


Figure 45.2: Critical failure surface, using the power curve criterion, Janbu simplified

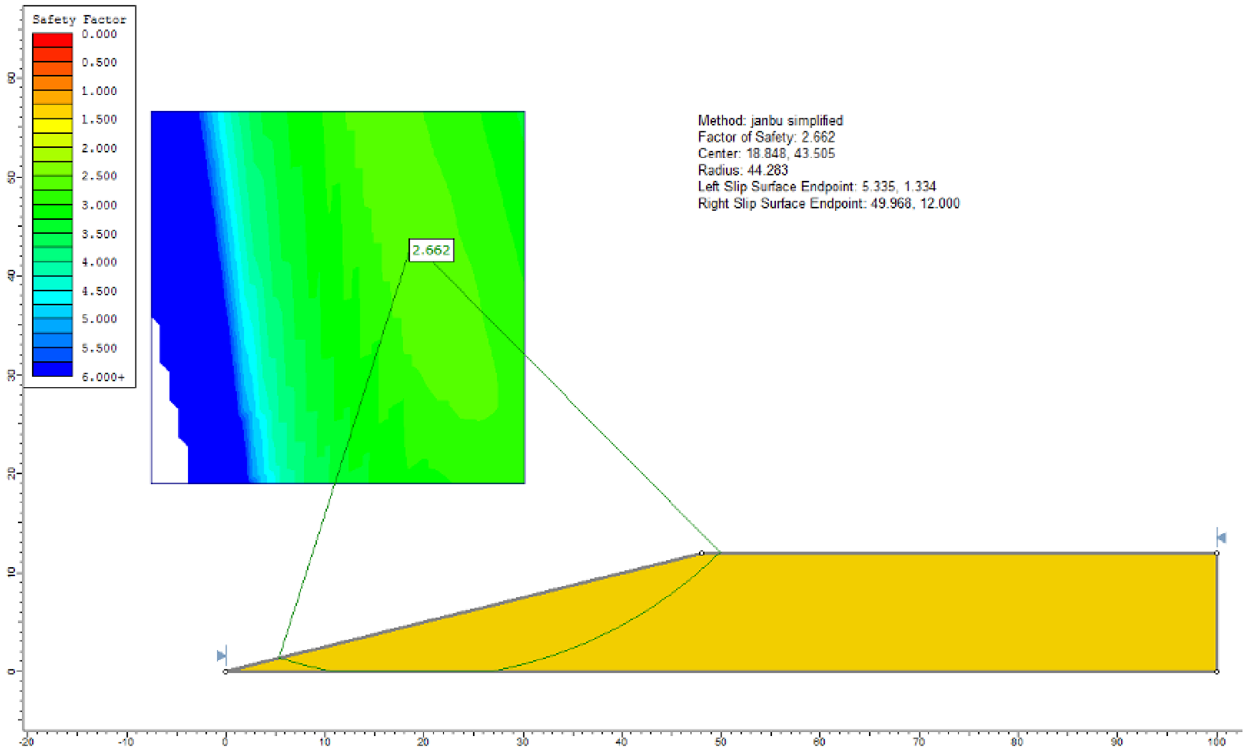


Figure 45.3: Critical failure surface, using the Mohr-Coulomb criterion, Janbu simplified

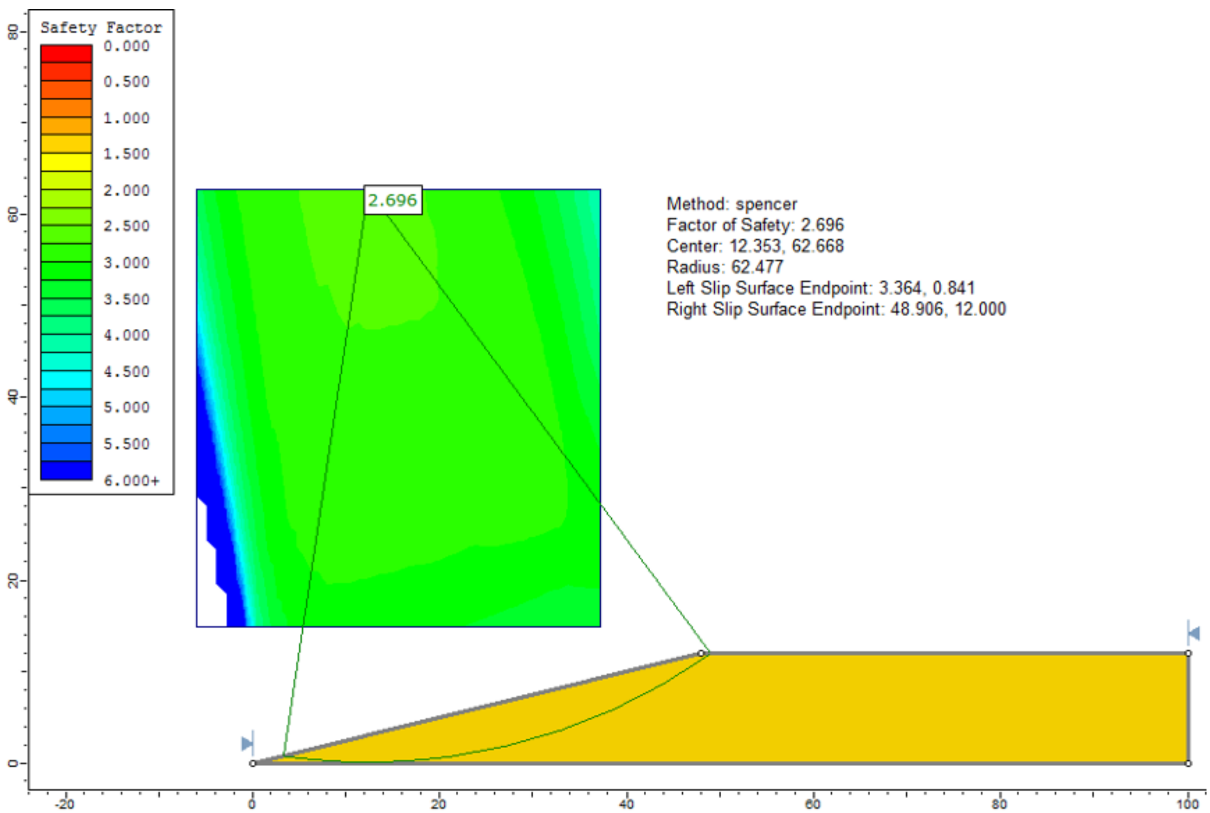


Figure 45.4: Mohr-Coulomb criterion with iterations, Spencer

46. Slide Verification Problem #46

Dam, (2) materials, rapid drawdown, finite element groundwater seepage analysis, ponded water

46.1. Introduction

This problem was taken from Baker (1993). It examines the slope stability analysis of a dam under three loading conditions: 1) End of construction with an empty reservoir, 2) steady state with a full reservoir, and 3) rapid drawdown. It should be noted that this problem is actually a Validation Problem, as many of the clay permeability parameters used here were not given in Baker's paper, thus preventing exact reproduction of his calculations.

46.2. Problem Description

Problem #46 is divided into three loading conditions. All stages analyze the same dam (Figure 46.1, Figure 46.2) with the same soil properties (Table 1), given in Baker (1993).

Stage 1 requires the factor of safety and noncircular critical surface of the dam when the reservoir is dry and empty (i.e., post-construction).

Stage 2 utilizes a finite element groundwater analysis, and the factor of safety and noncircular critical surface of the dam is calculated under steady state conditions. The water is 10 m deep, and the water table is horizontal at elevation 0 m.

Stage 3 requires the factor of safety and noncircular failure surface of the dam after it has been subjected to rapid drawdown (i.e., undrained loading conditions). Undrained shear strength is not known at this stage and must be manually extracted from the author's data (Figure 46.3). This data can also be found as <Compacted Clay.fn6> and <Natural Clay.fn6>, which can be accessed under the discrete function in the modeller.

46.3. Geometry and Material Properties

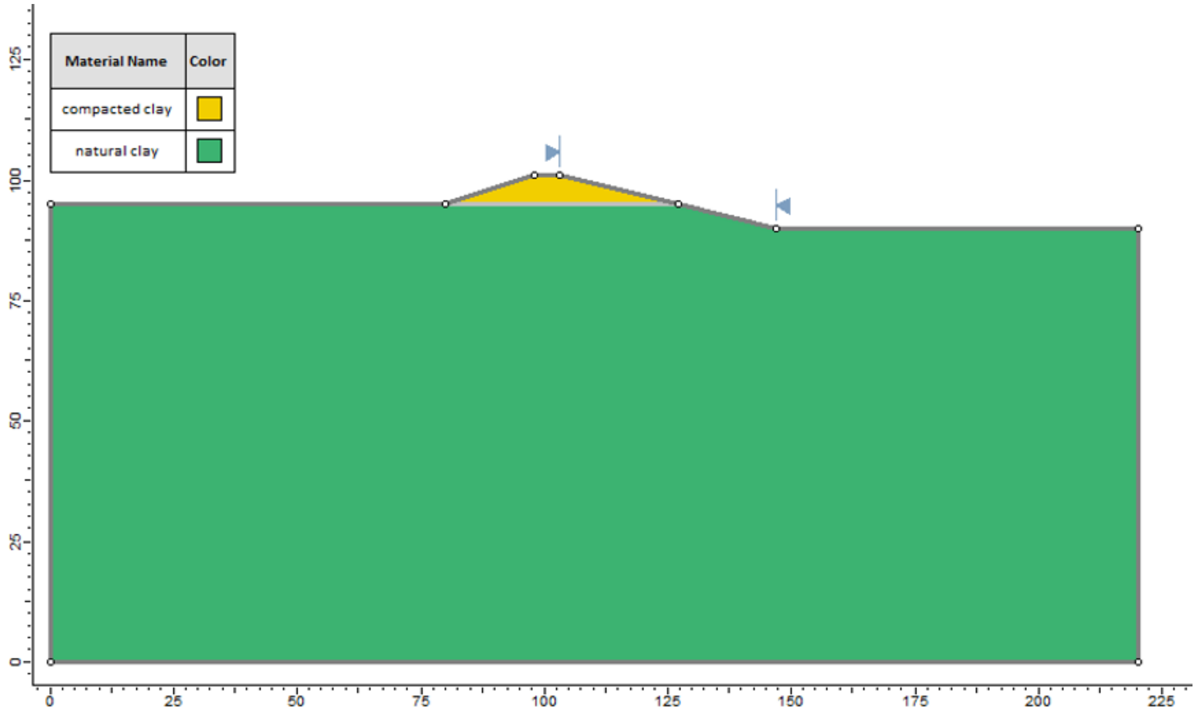


Figure 46.1: Geometry Setup in **Slide** – Stage 1

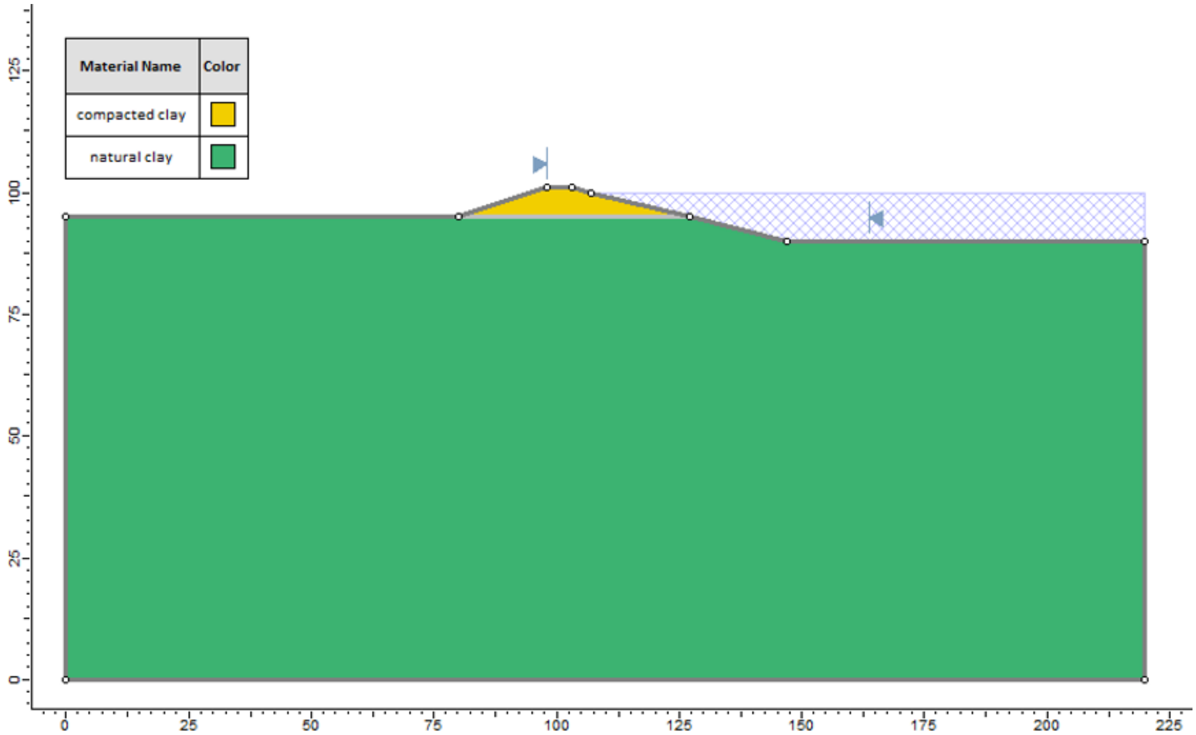


Figure 46.2: Geometry Setup in **Slide** – Stage 2

Note: Mesh = 6 noded triangles. Tolerance = 1e-5. Minimum depth of noncircular surface is 5m. Limits are as they were before.

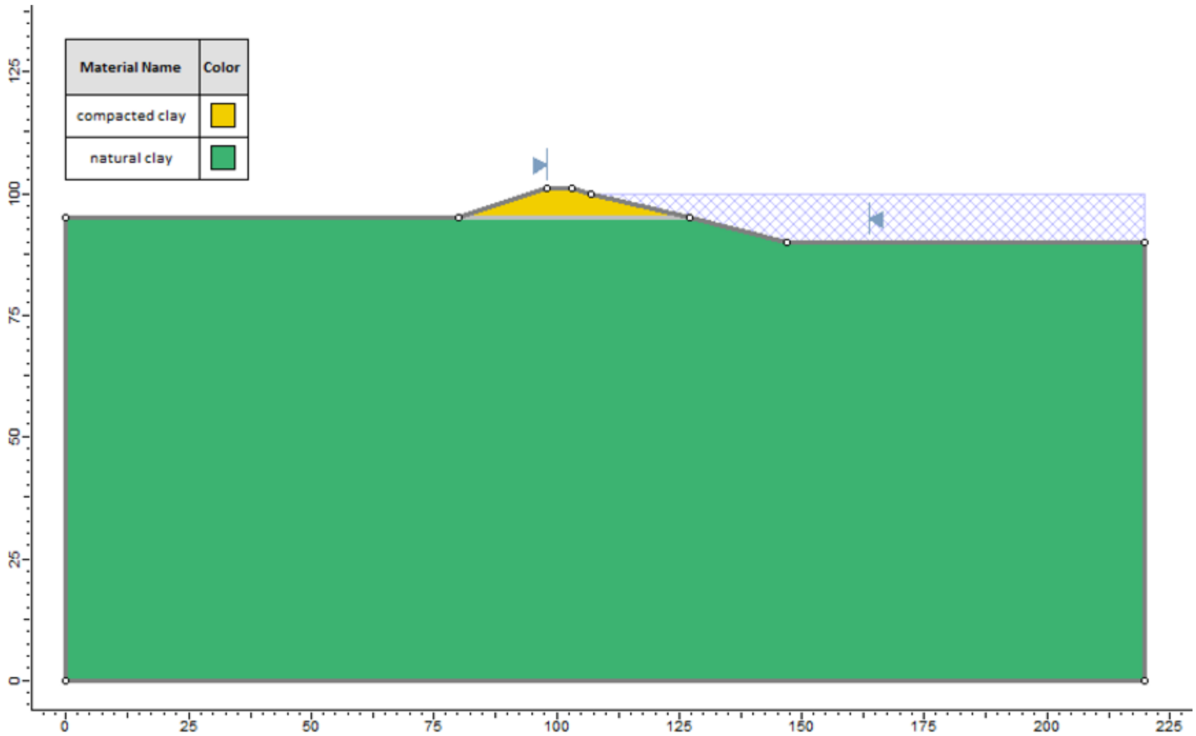


Figure 46.3: Baker's parameters for stage 3

Note: there should be no ponded water in stage 3, as the dam is subjected to rapid drawdown

Table 46.1: Soil Properties

Material	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m3)	Ks	K2/K1	K1 Angle	a	n
Compacted Clay	6.5	40	18	7e-5	0.1	0	0	0
Natural Clay	0	32	18	7e-5	0.1	0	0.06	2

Note: Permeability values were not given in Baker (1993), so they were estimated. Estimated values are given in the dark box.

46.4. Results

Table 46.2: Stage 1 – Post-construction, Random search

Method	Factor of Safety
Spencer	2.534

Note: Baker (1993) FS = 2.41

Theoretical FS = 2.5

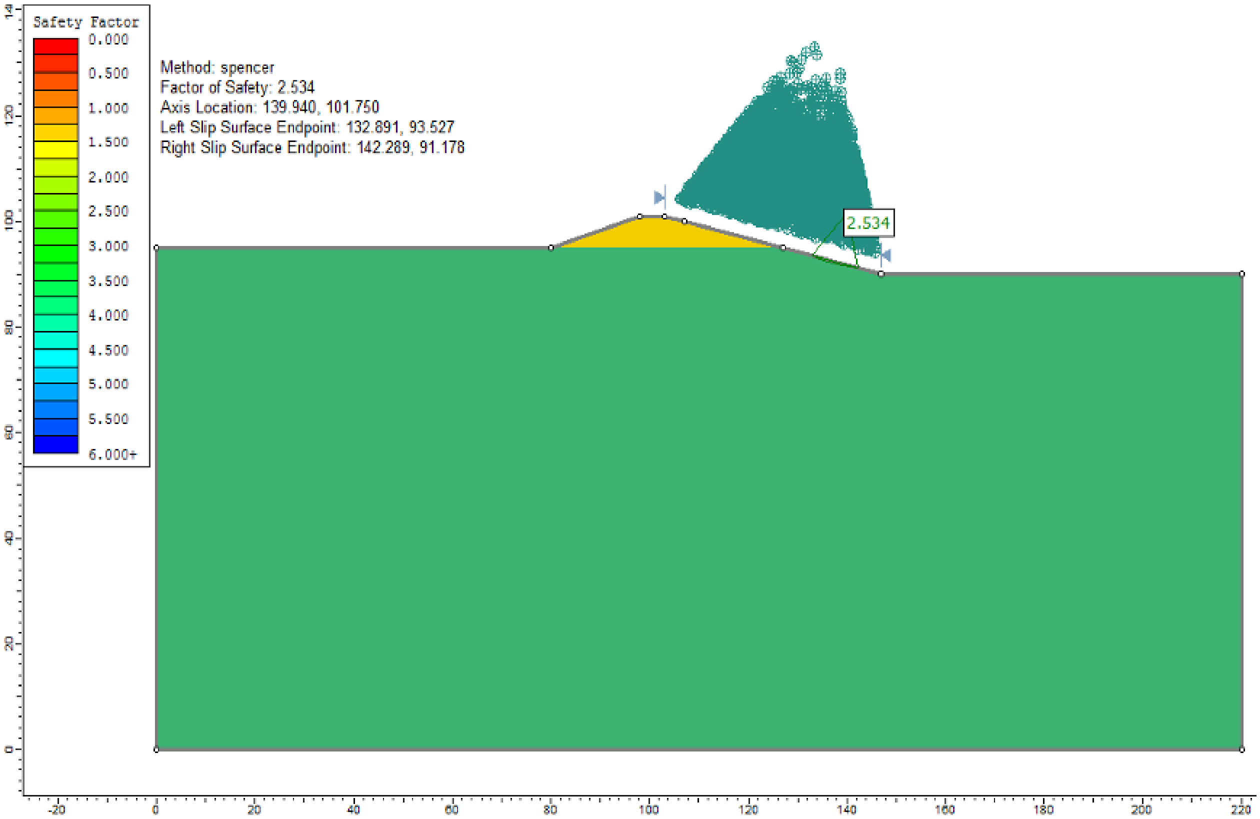


Figure 46.4: Critical failure surface, using the Spencer method

Table 46.2: Stage 2 – steady state conditions, random search

Method	Factor of Safety
Spencer	7.003

Note: Baker (1993) FS = 6.98

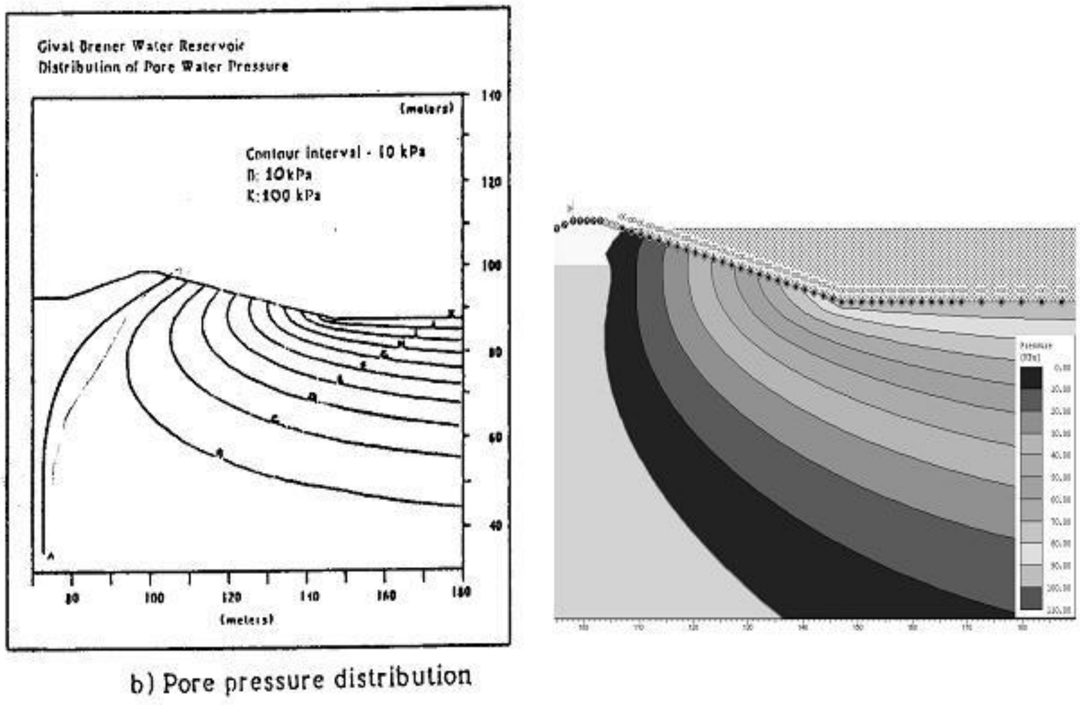


Figure 46.5: Comparison of Baker's pore pressure contours with SLIDE's

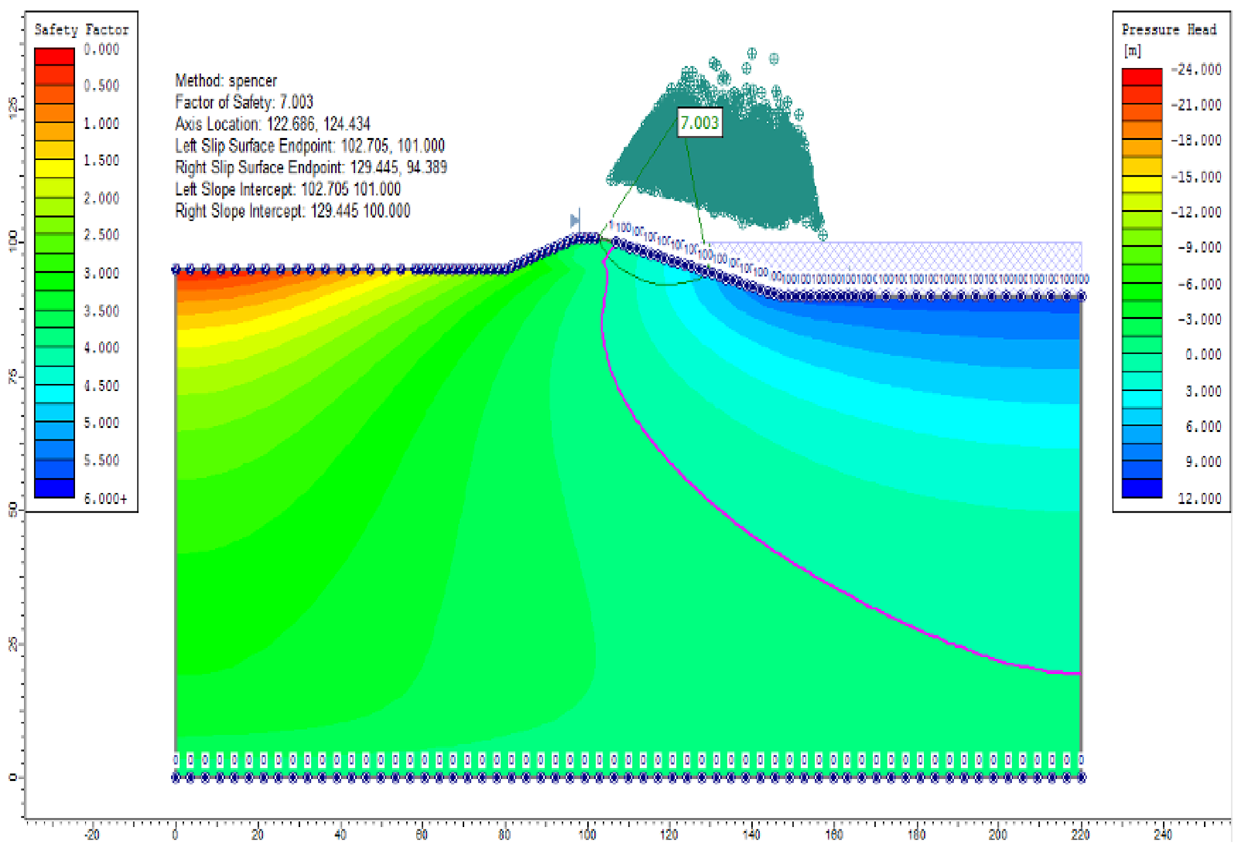
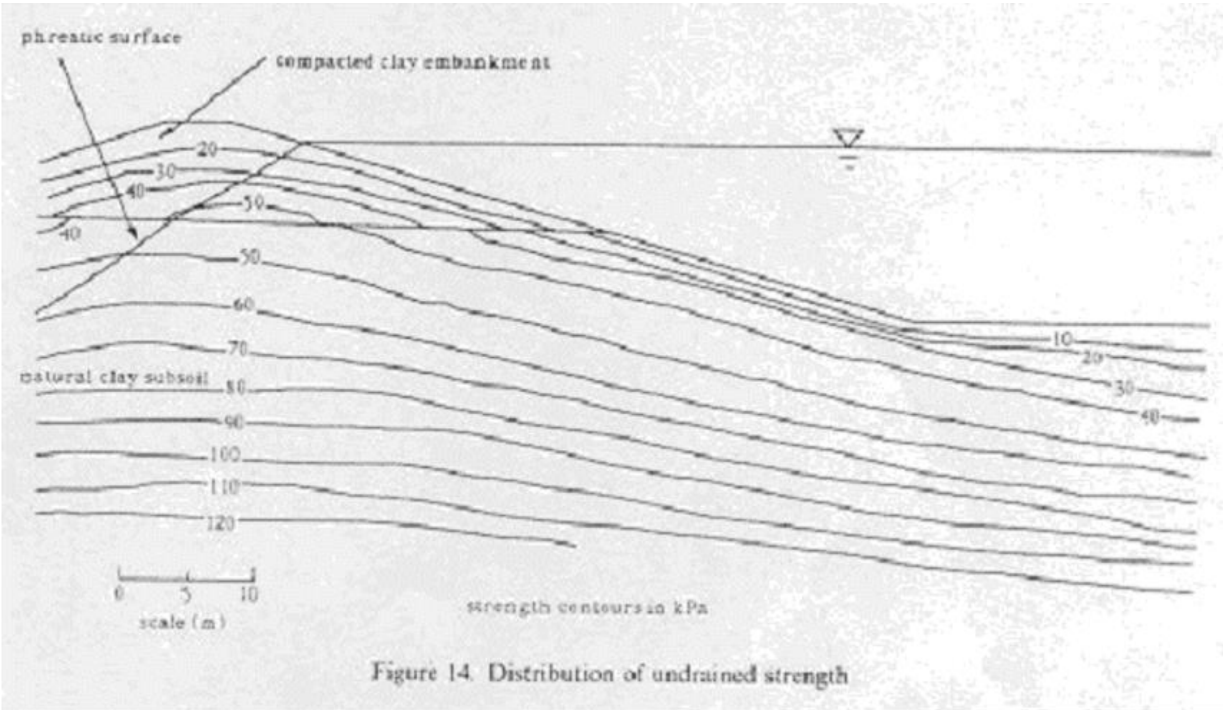


Figure 46.6: Critical failure surface, using the Spencer method

Table 46.2: Stage 3 – Rapid draw-down conditions, random search with optimization

Method	Factor of Safety
Spencer	2.181

Note: Baker (1993) FS = 2.18



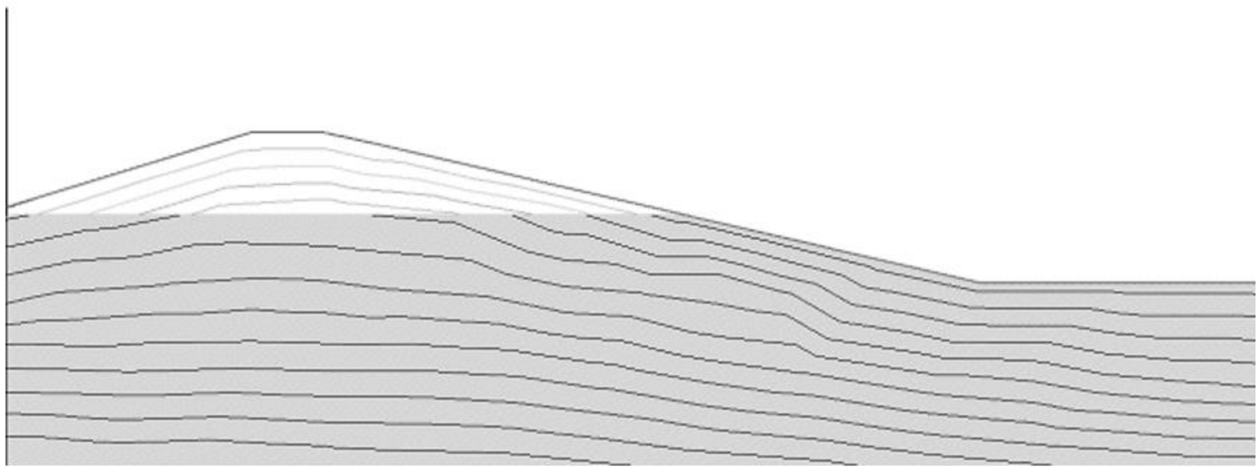


Figure 46.7: Comparison of Baker's pore pressure contours with SLIDE's

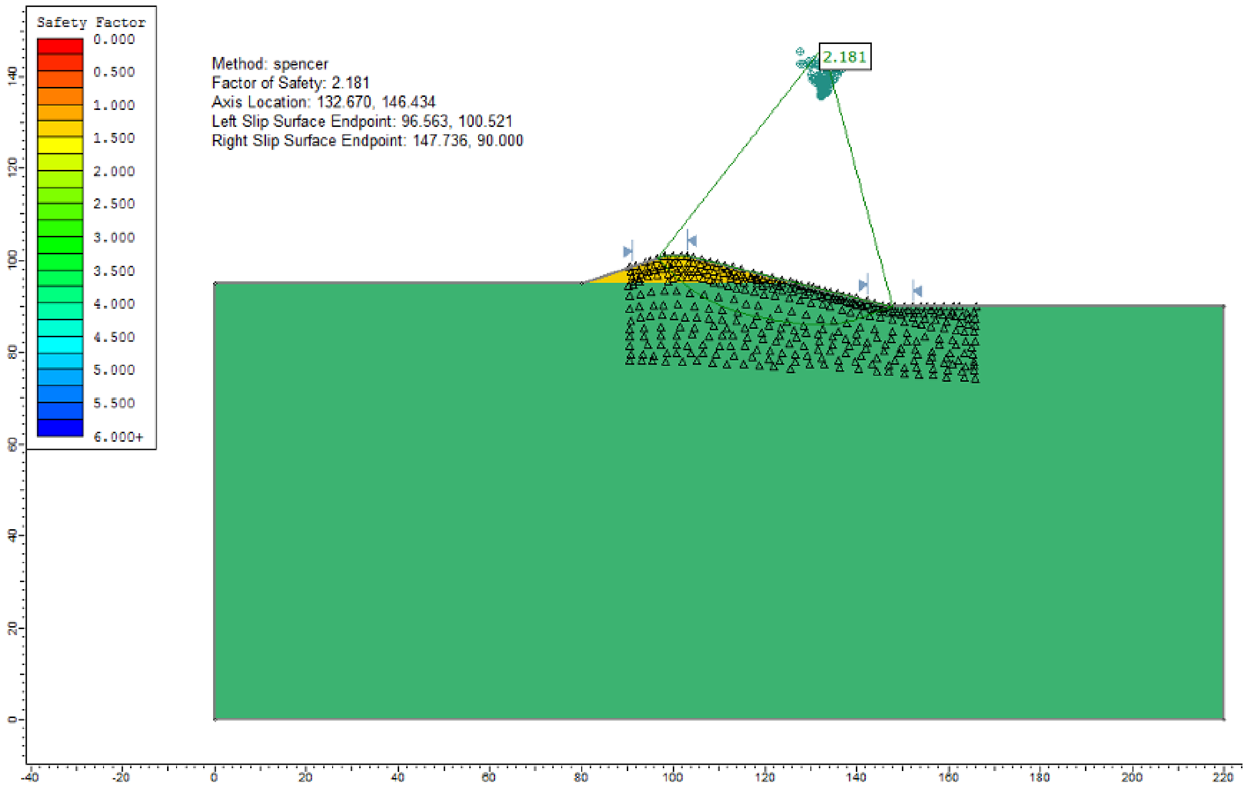


Figure 46.8: Critical failure surface, using the Spencer method

47. Slide Verification Problem #47

Retaining wall, homogenous, planar failure, line load, shotcrete, soil nails

47.1. Introduction

This problem was taken from Sheahan (2003). It examines the Amherst test wall, a soil nailed wall in clay that was failed due to over-excavation.

47.2. Problem Description

Verification Problem #47 examines planar failure of a soil nailed wall, and its associated factor of safety. The wall is undrained and homogeneous (Table 47.1), and is reinforced by two rows of soil nails (Table 47.2). The shotcrete plate on the soil nails has a weight of 14.6 kN/m, which is modeled as a point load on top of the wall face. The critical planar slip surface and associated factor of safety are required.

47.3. Geometry and Material Properties

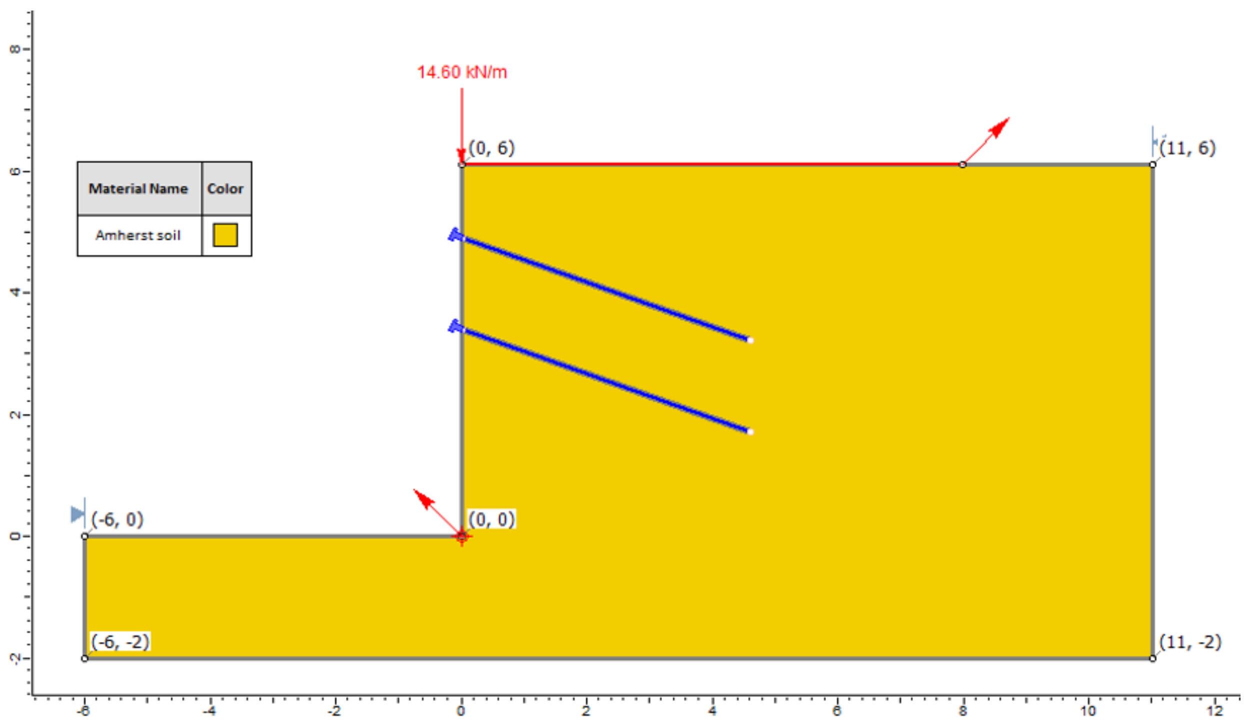


Figure 47.1: Geometry Setup in **Slide**

Table 47.1: Soil Properties

	c´ (kN/m²)	γ (kN/m³)
Amherst Clay	25	18.9

Table 47.2: Soil Nail Properties

Type	Out-of-plane Spacing (m)	Tensile Strength (kN)	Plate Strength (kN)	Bond Strength (kN)	Length (m)	Number of rows
Passive	1.5	118	86	15	4.9	2

47.4. Results

Table 47.3: Block search

Method	Factor of Safety
Janbu Simplified	0.890
Janbu corrected	0.890

Note: Sheahan (2003) FS = 0.887

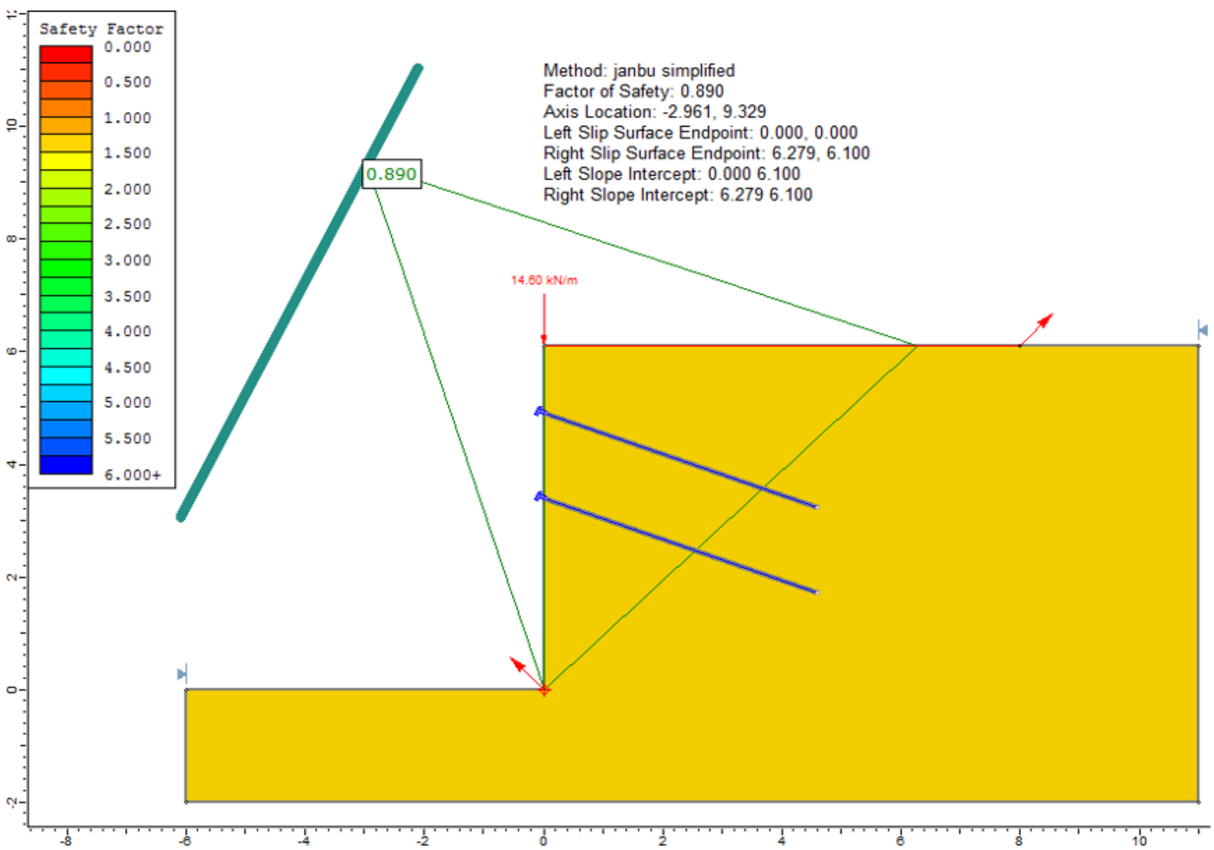


Figure 47.2: Critical failure surface, using the Janbu simplified method

48. Slide Verification Problem #48

Retaining wall, homogenous, planar failure, line load, soil nails, shotcrete

48.1. Introduction

This problem was taken from Sheahan (2003). It examines the Clouterre Test Wall, constructed in Fontainebleau sand and failed by backfill saturation. This test was carried out as part of the French national project on soil nailing.

48.2. Problem Description

Verification Problem #48 examines the relationship between failure plane angle and factor of safety for a homogeneous slope in which the primary resistance against failure is friction generated by soil weight. The test wall is reinforced by seven rows of soil nails, with a shotcrete plate weighing 13.2 kN/m, which is modeled as a point load acting on the wall face. The geometry, soil properties, and reinforcement properties are given in Section 48.3. The factor of safety is calculated for six different failure plane angles, ranging from 45–70 degrees.

48.3. Geometry and Material Properties

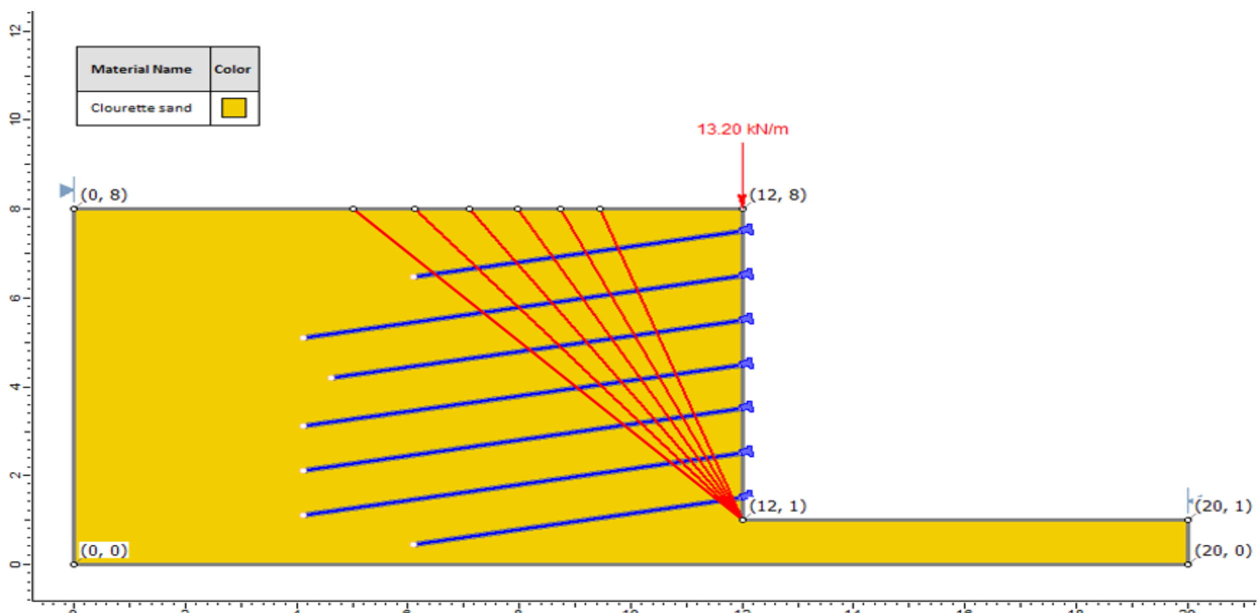


Figure 48.1: Geometry Setup in **Slide**

Table 48.1: Soil Properties

Material	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Fontainebleau Sand	3	38	20

Table 48.2: Soil Nail Properties

Type	Out-of-plane Spacing (m)	Tensile Strength (kN)	Plate Strength (kN)	Bond Strength (kN)
Passive	1.5	15	59	7.5

48.4. Results

Table 48.3

Failure Plane Angle (deg.)	Slide Factor of Safety	Sheahan Factor of Safety
45	1.123	1.176
50	1.043	1.070
55	0.989	0.989
60	0.945	0.929
65	0.922	0.893
70	0.923	0.887

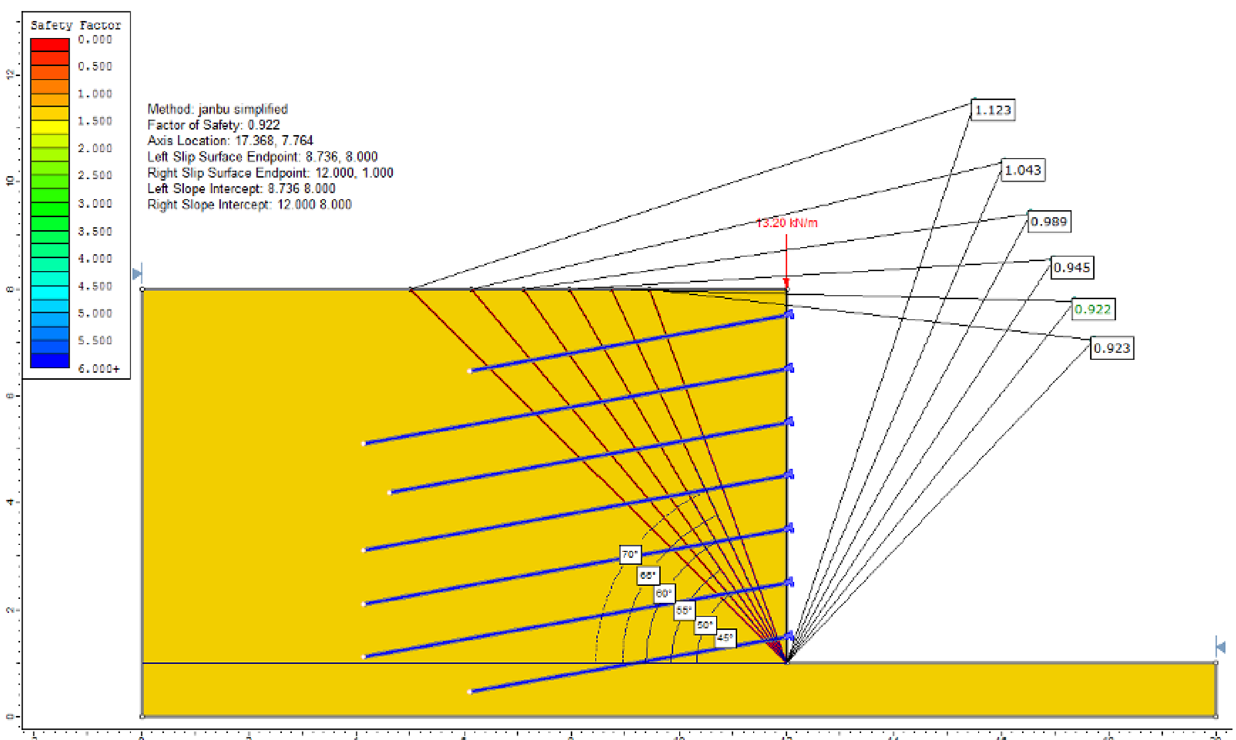


Figure 48.2: Failure planes and corresponding safety factors

49. Slide Verification Problem #49

Retaining wall, (2) materials, grouted tiebacks, soldier piles

49.1. Introduction

This problem was taken from the SNAILZ reference manual (http://www.dot.ca.gov/hq/esc/geotech). It consists of a 2-material slope reinforced with a soldier pile tieback wall. This problem is done in imperial units.

49.2. Problem Description

Verification problem #49 consists of a slope with 2 materials and variable types of reinforcement. Each of the two rows of tiebacks have different bar diameters, resulting in different tensile capacities. The soldier pile in the SNAILZ problem is modeled using a micro-pile in **Slide**. The factor of safety for the given failure surface is calculated.

49.3. Geometry and Material Properties

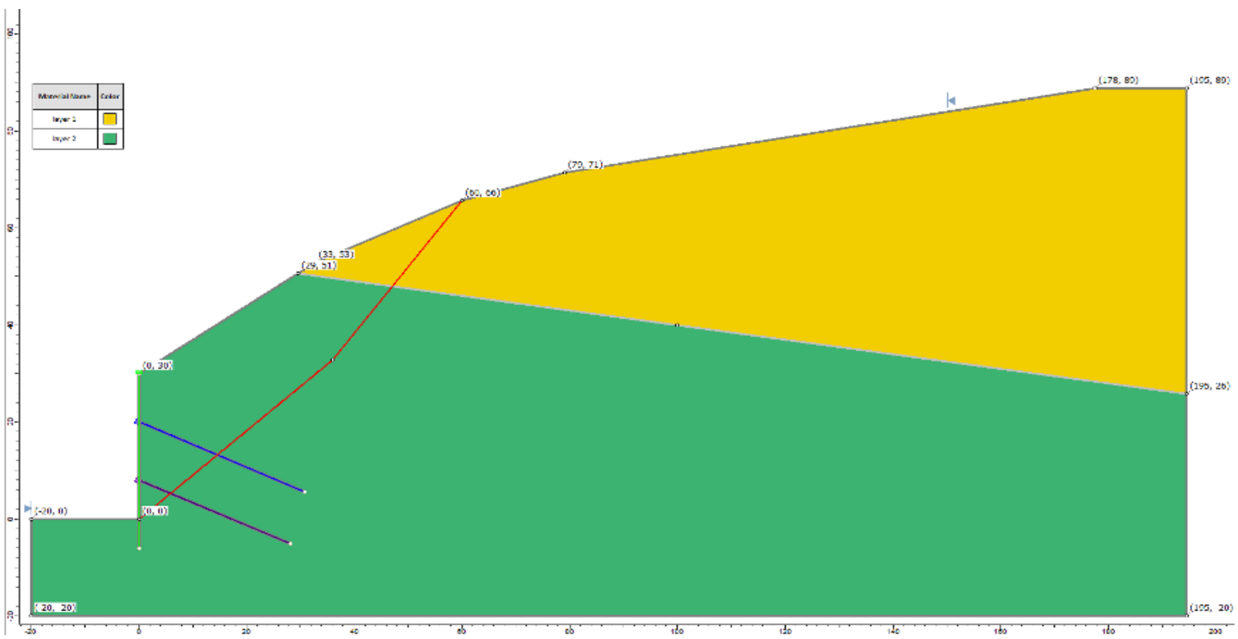


Figure 49.1: Geometry Setup in **Slide**

Table 49.1: Soil Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Layer 1	600	24	120
Layer 2	300	34	130

Table 49.2: Soil Nail Properties

	Out-of plane Spacing (ft)	Tensile Strength (lb)	Plate Strength (lb)	Bond Strength (lb/ft)
Grouted Tieback: top row	8	120344.9	120344.9	13571.68
Grouted Tieback: bottom row	8	164217.3	164217.3	13571.68
Micro-pile (active)	1	Pile shear strength: 5900 lb.		

49.4. Results

Table 49.3

Method	Factor of Safety
Janbu simplified	1.446
Janbu corrected	1.479

Note: SNAILZ factor of safety = 1.52

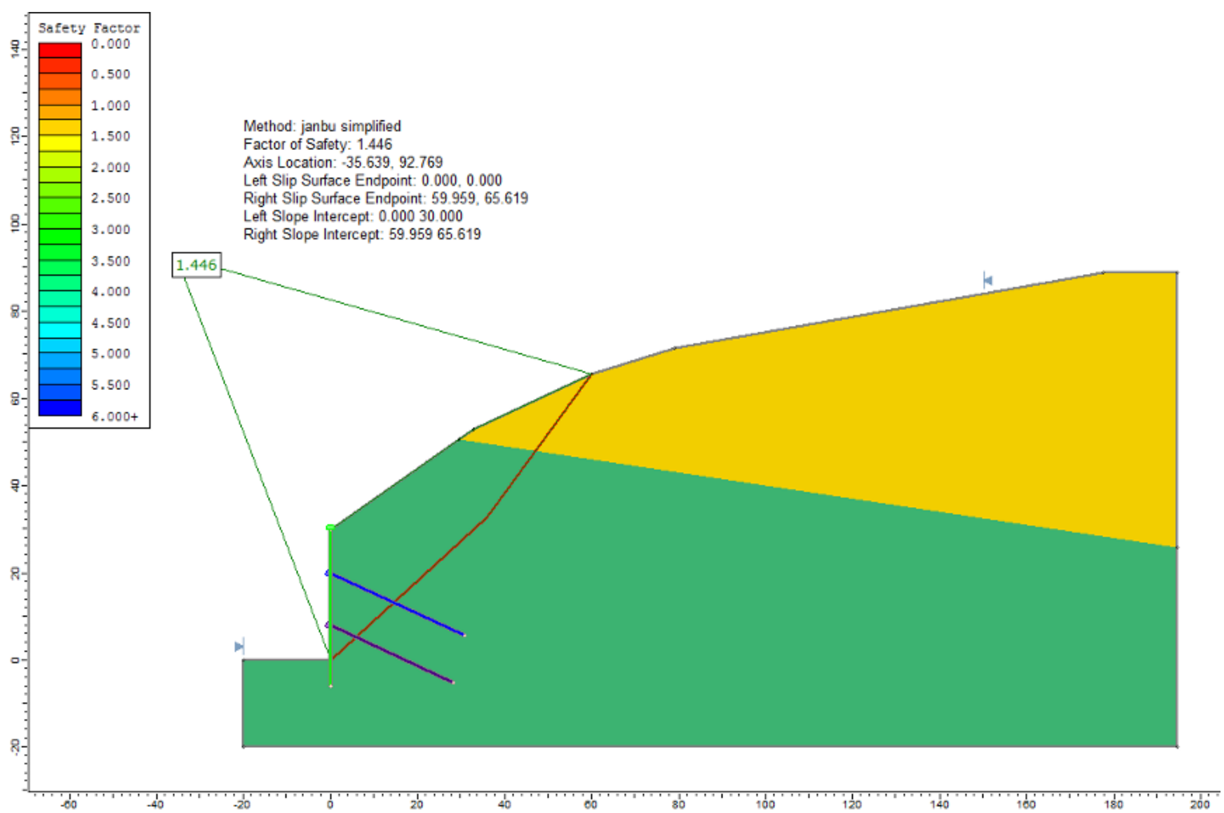


Figure 49.2: Critical failure surface, using the Janbu simplified method

50. Slide Verification Problem #50

Reinforced slope, (2) materials, predefined slip surface, geosynthetic

50.1. Introduction

This problem was taken from the SNAILZ reference manual. It examines a slope which has been reinforced with geotextile layers. SNAILZ models the geotextile characteristics with soil nails that have equivalent parameters, as it is not equipped with a geotextile reinforcement option. This verification example attempts to replicate this model with **Slide**.

50.2. Problem Description

Verification problem #50 examines a 2-layer slope with multiple reinforcement parameters (Figure 50.1). Each horizontal, parallel row varies in length, tensile capacity, and bond strength (Table 50.2). The rows are all evenly spaced (1.8 ft) except for row 14 (1.6 ft). The rows are numbered starting at the crest. The factor of safety is required for the two failure surfaces given in Figure 50.2.

50.3. Geometry and Material Properties

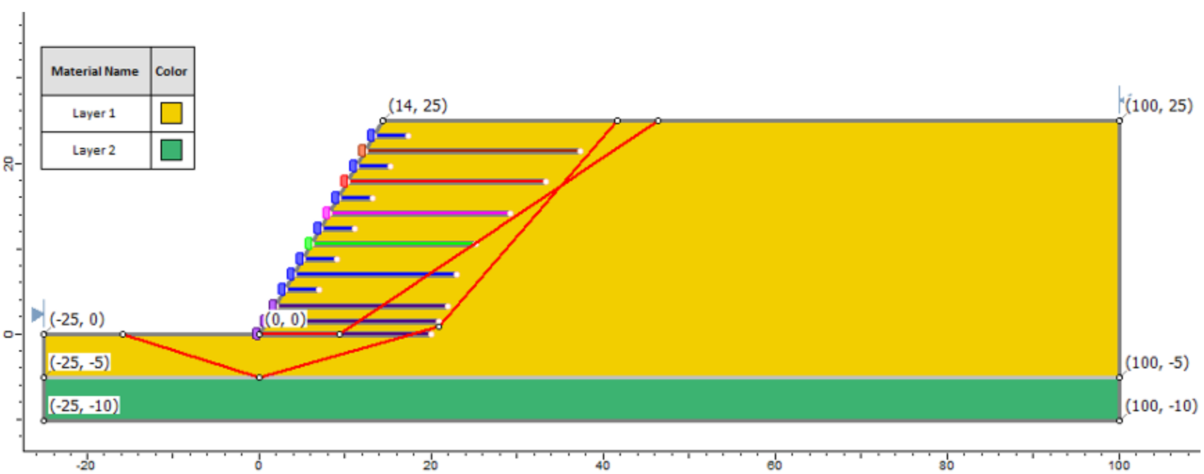


Figure 50.1: Geometry Setup in **Slide**

Table 50.1: Soil Properties

Material	c´ (psf)	ϕ´ (deg.)	γ (pcf)
Layer 1	0	32	125
Layer 2	500	35	128

Table 50.2: Soil Nail Properties (Active)

	Out-of-plane Spacing (ft)	Tensile Strength (lb)	Plate Strength (lb)	Bond Strength (lb/ft)	Length (ft)
Rows: 1,3,5,7,9,11	1	1103	1103	1206.37	4
Rows: 12,13,14	1	2212	2212	1206.37	20
Rows: 8	1	1103	1103	965.096	19
Rows: 6	1	1103	1103	732.822	21
Rows: 4	1	1103	1103	482.548	23
Rows: 2	1	1103	1103	241.274	25
Rows: 10	1	1103	1103	1206.31	19

50.4. Results

Table 50.3

Failure Plane (designated by point on surface)	Slide Factor of Safety	SNAILZ Factor of Safety
(0,0)	1.577	1.60
(0, -5)	1.417	1.46

Table 50.4: Nail force

Nail Row	Max Force (lb)
1-11	1103
12-14	2212

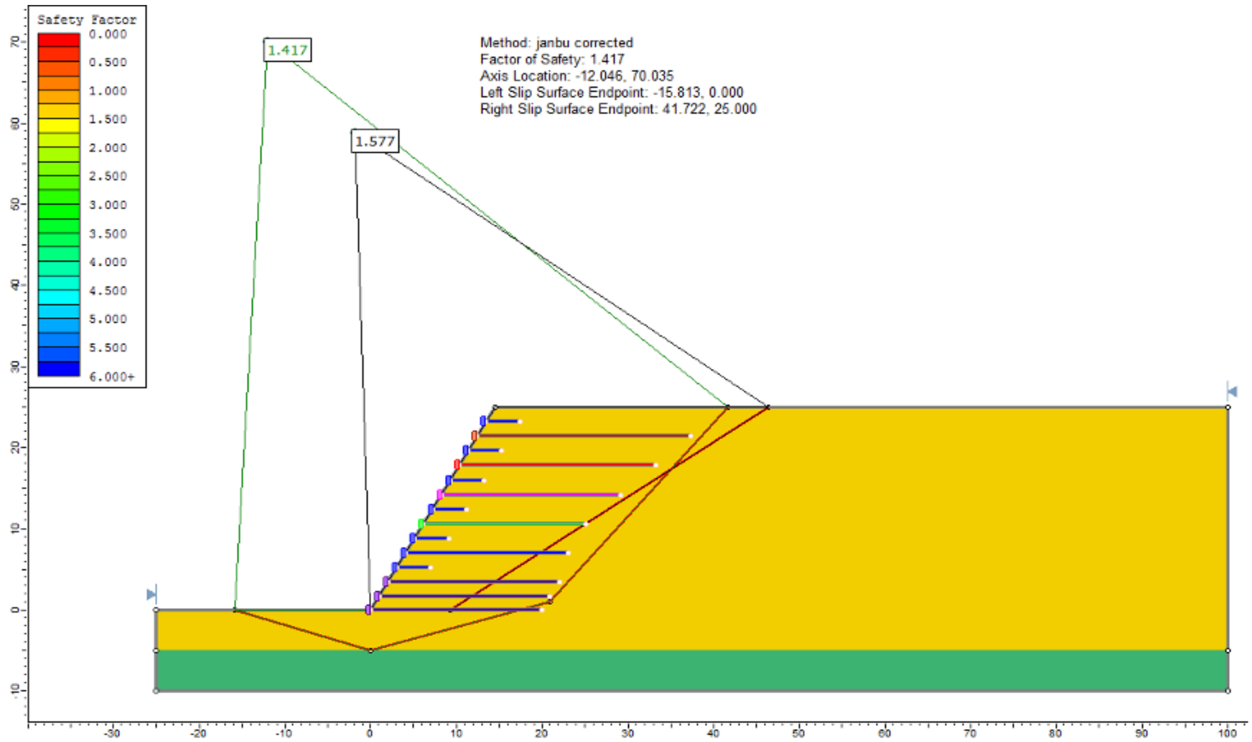


Figure 50.2: Safety factors for the given failure surfaces

51. Slide 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, using all methods of analysis. A tolerance of 0.001 is used.

51.3. Geometry and Material Properties

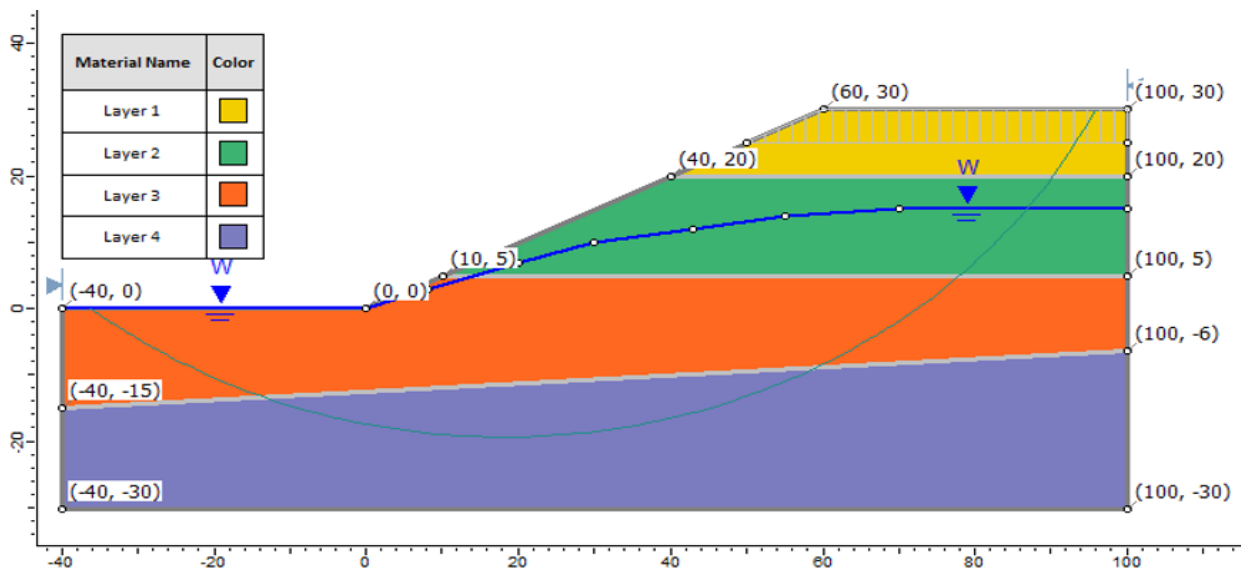


Figure 51.1: Geometry Setup in **Slide**

Table 51.1: Soil Properties

	c´ (kN/m^2)	**ϕ´ (deg.)**	**γ (kN/m^3)**
Material	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Layer 1 (top)	20	32	18.2
Layer 2	25	30	18
Layer 3	40	18	18.5

51.4. Results

Table 51.2

Method	Slide Factor of Safety	Zhu Factor of Safety
Ordinary	1.145	1.066
Bishop Simplified	1.278	1.278
Janbu Simplified	1.112	1.112
Corps of Engineers 2	1.422	1.377
Lowe & Karafiath	1.288	1.290
Spencer	1.293	1.293
GLE/Morgenstern & Price	1.304	1.303

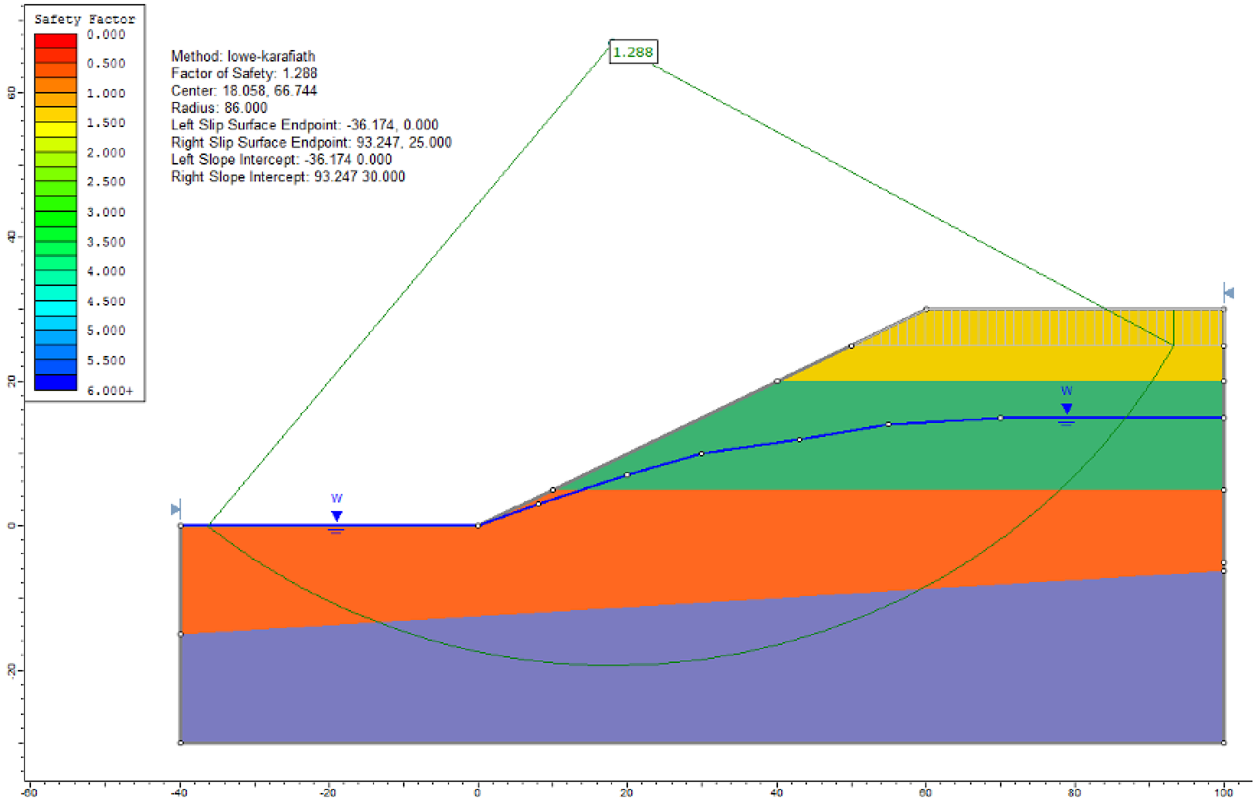


Figure 51.2: Safety factor using the Lowe & Karafiath method

52. Slide Verification Problem #52

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

52.1. Introduction

This problem was taken from Zhu and Lee (2002). It analyzes a heterogeneous slope under wet and dry conditions. For each condition, 4 different failure surfaces were analyzed.

52.2. Problem Description

Verification problem #52 is a 4-material slope with a dry tension crack in the top (Figure 52.1). The factor of safety is calculated for 8 separate cases: 4 distinct failure surfaces under dry conditions, and the same 4 failure surfaces when a water table is included (Table 52.2). Surfaces 1 and 3 are circular, while 2 and 4 are noncircular. Surfaces 1 and 2 are shallow, and surfaces 3 and 4 are deep.

52.3. Geometry and Material Properties

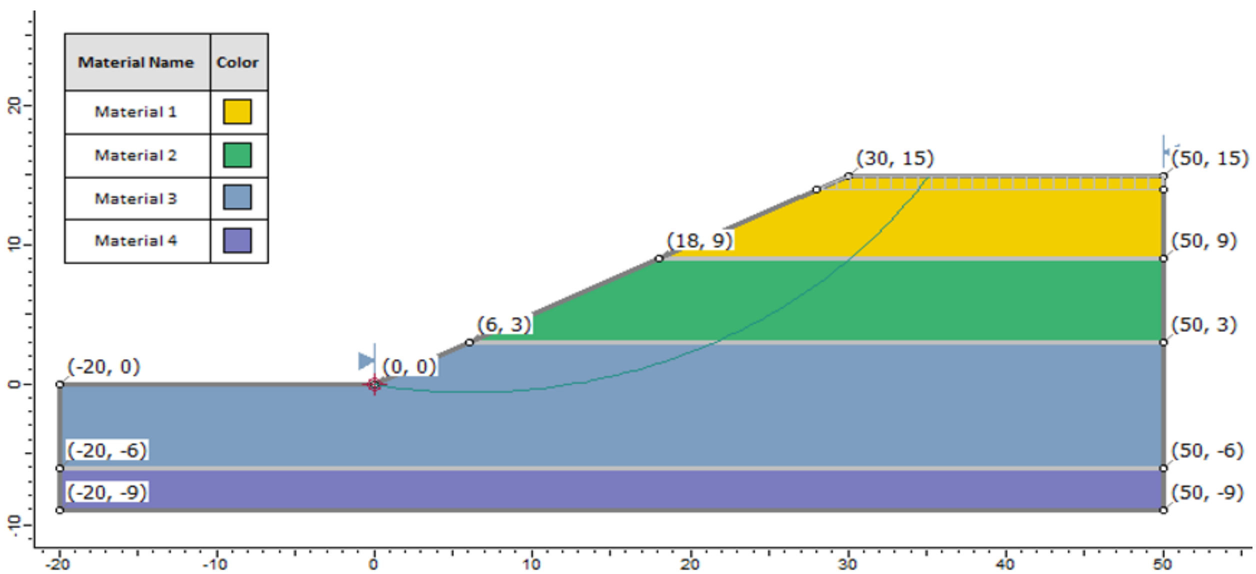


Figure 52.1: Geometry Setup in **Slide** (dry condition)

Note: Surfaces 1 and 2 are done using the limits shown, however 3 and 4 are analyzed with 2 sets of limits forcing the failure surface to intersect the top and bottom bench through the middle of the bench. Surfaces 1 and 2 must pass through toe of slope; a search point is added to the toe. Surface 2 requires a block search window to be added, to keep the search shallow.

Table 52.1: Soil Properties

Material	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Layer 1 (top)	20	18	18.8
Layer 2	40	22	18.5
Layer 3	25	26	18.4
Layer 4 (bottom)	10	12	18

Table 52.2: Water Table Geometry – wet condition

Coordinates	Arc
(0, -20)	--
(0, 0)	--
(6, 3)	--
--	(10.568, 5.284)
--	(25.314, 9.002)
--	(39.149, 10.269)
(50, 10.269)	--

52.4. Results

Table 52.3: Surface 1 – Circular, shallow (Dry Condition)

Method	**Slide** **Factor of Safety**	**Zhu** **Factor of Safety**
Bishop simplified	2.010	2.011
Ordinary	1.934	1.935
Morgenstern-Price	2.017	2.035
Spencer	2.017	2.035

Note: Zhu’s limit equilibrium factor of safety = 2.035

Table 52.4: Surface 1 – Circular, shallow (Wet Condition)

Method	**Slide** **Factor of Safety**	**Zhu** **Factor of Safety**
Bishop simplified	1.526	1.534
Ordinary	1.514	1.496
Morgenstern-Price	1.533	1.559
Spencer	1.533	1.559

Note: Zhu’s limit equilibrium factor of safety = 1.560

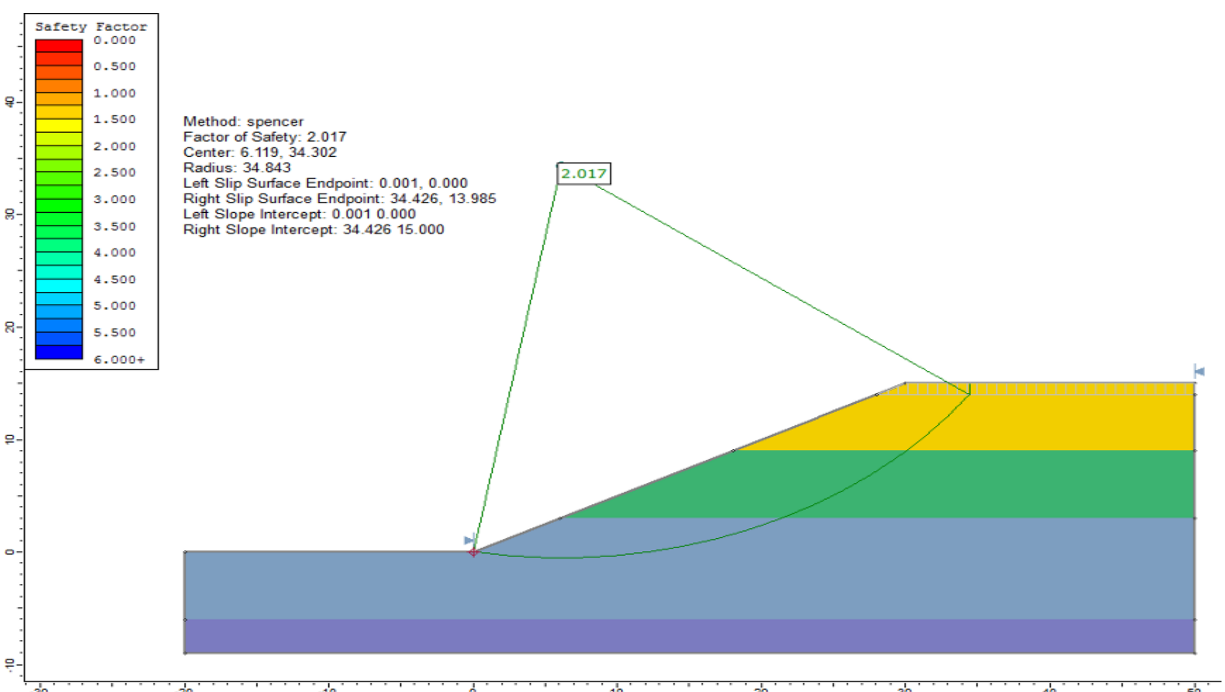


Figure 52.2: Solution, using the Bishop simplified method

Table 52.5: Surface 2 – Noncircular, shallow – Block search (Dry Condition)

Method	Slide Factor of Safety	Zhu Factor of Safety
Bishop simplified	2.069	N/a
Ordinary	1.977	N/a
Morgenstern-Price	2.167	2.104
Spencer	2.163	2.087

Note: Zhu’s limit equilibrium factor of safety = 2.049

Table 52.6: Surface 2 – Noncircular, shallow – Block search (Wet Condition)

Method	Slide Factor of Safety	Zhu Factor of Safety
Bishop simplified	1.479	N/a
Ordinary	1.471	N/a
Morgenstern-Price	1.561	1.628
Spencer	1.554	1.616

Note: Zhu’s limit equilibrium factor of safety = 1.584

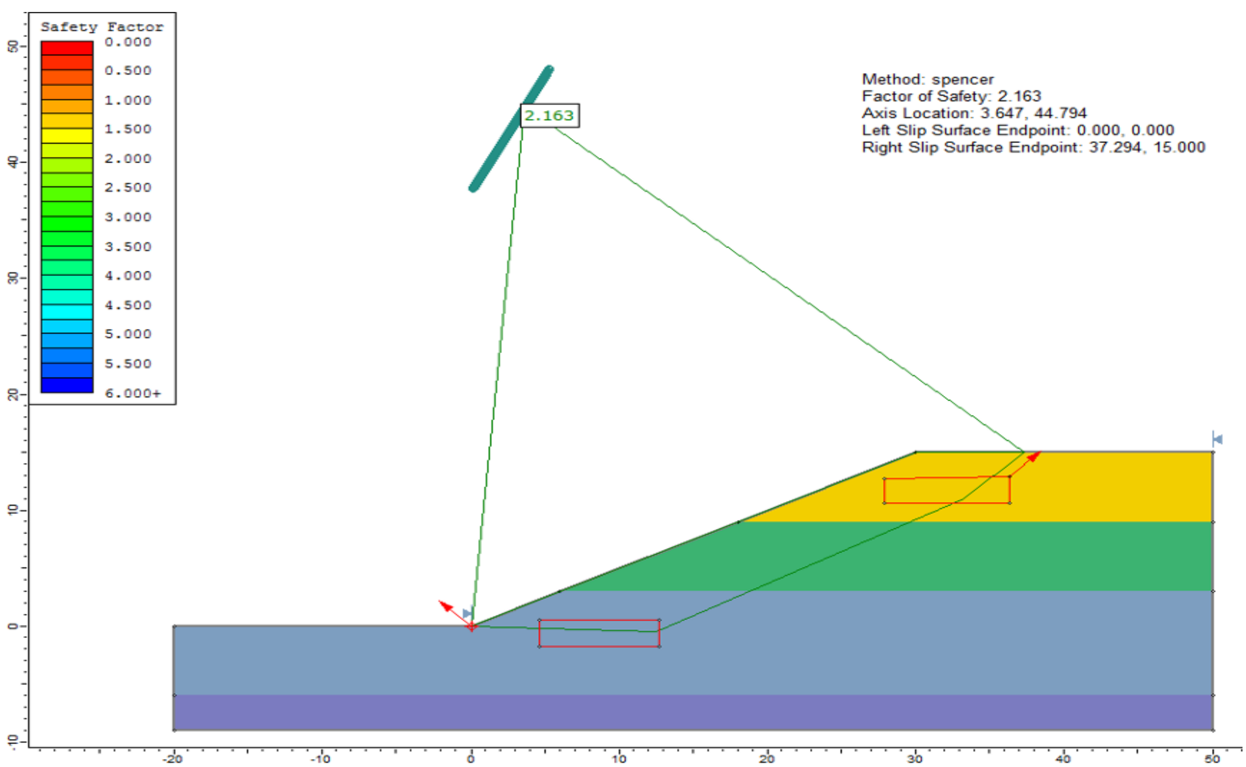


Figure 52.3: Solution, using the Bishop simplified method

Table 52.7: Surface 3 – Circular, deep – Grid search (30x30) (Dry Condition)

Method	Slide Factor of Safety	Zhu Factor of Safety
Bishop simplified	1.804	1.429
Ordinary	1.495	1.229
Morgenstern-Price	1.790	1.823
Spencer	1.804	1.836

Note: Zhu's limit equilibrium factor of safety = 1.744

Table 52.8: Surface 3 – Circular, deep – Grid search (30x30) (Wet Condition)

Method	Slide Factor of Safety	Zhu Factor of Safety
Bishop simplified	1.176	1.079
Ordinary	1.036	0.922
Morgenstern-Price	1.174	1.197
Spencer	1.189	1.211

Note: Zhu's limit equilibrium factor of safety = 1.166

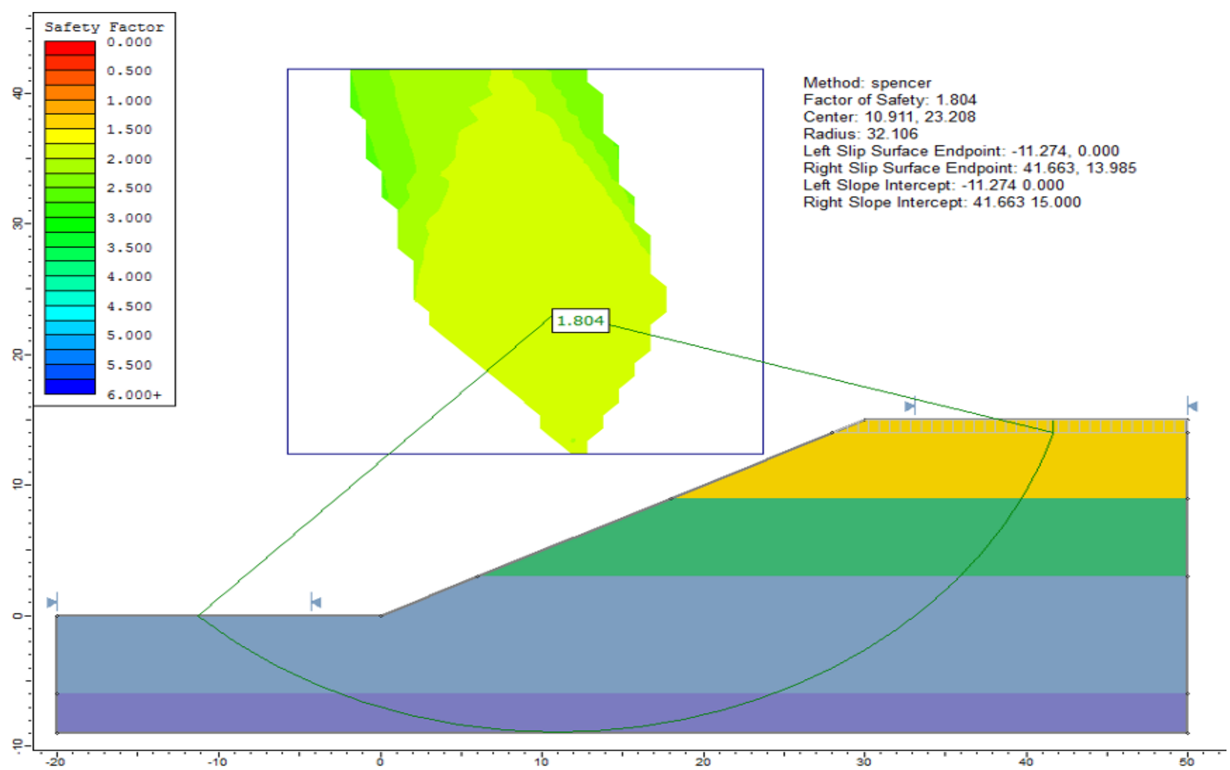


Figure 52.4: Surface 3(dry condition), using the Spencer method

Table 52.9: Surface 4 – Noncircular, deep – Path search (Dry Condition)

Method	Slide Factor of Safety	Zhu Factor of Safety
Bishop simplified	1.624	N/a
Ordinary	1.150	N/a
Morgenstern-Price	1.776	1.765
Spencer	1.796	1.772

Note: Zhu's limit equilibrium factor of safety = 1.709

Table 52.10: Surface 4 – Noncircular, deep – Path search (Wet Condition)

Method	Slide Factor of Safety	Zhu Factor of Safety
Bishop simplified	1.073	N/a
Ordinary	0.799	N/a
Morgenstern-Price	1.162	1.141
Spencer	1.175	1.150

Note: Zhu's limit equilibrium factor of safety = 1.109

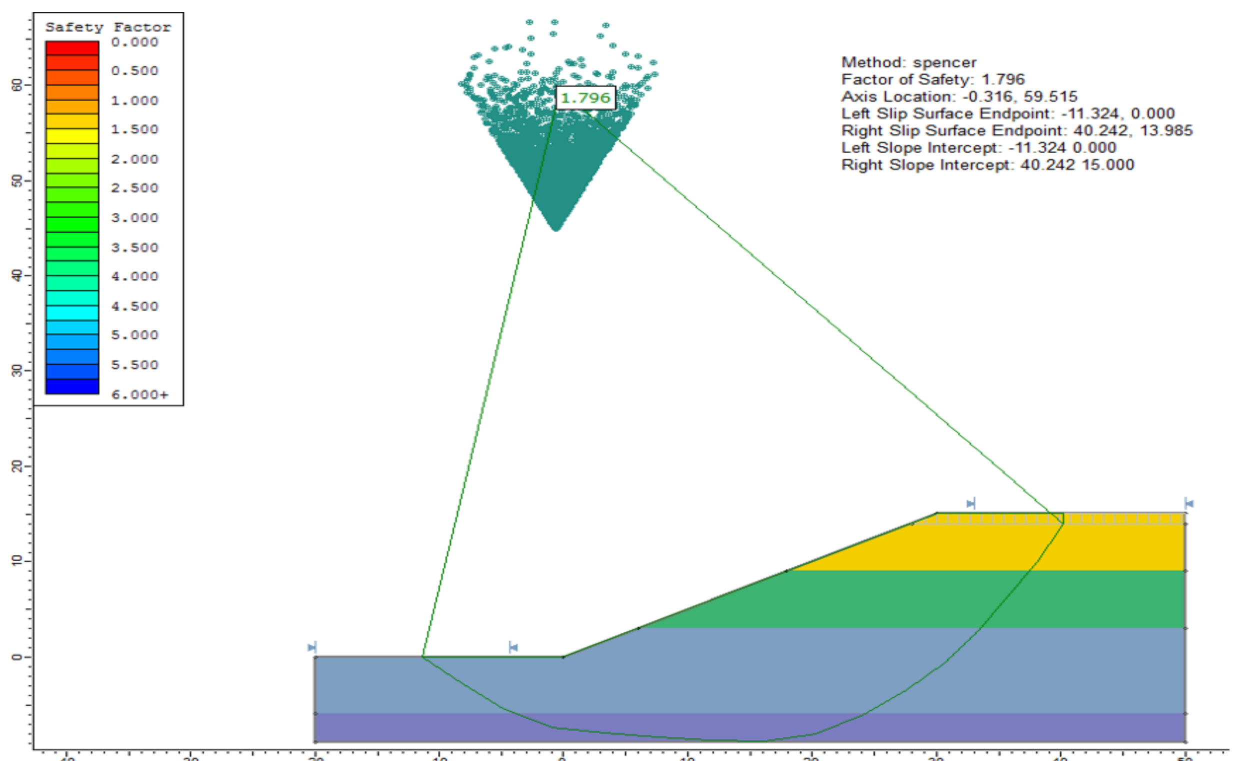


Figure 52.5: Surface 4 (dry condition), using Spencer method

53. Slide Verification Problem #53

Slope, homogenous, water table, tension crack, planar failure, RocPlane comparison

53.1. Introduction

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

53.2. Problem Description

Verification problem #53 analyzes a homogeneous slope undergoing failure along a specified noncircular surface (Figure 53.1). The slope has a tension crack at the crest 15m deep. A water table is also present, filling the tension crack 25% at the line of failure. Starting at the right, the water table is horizontal until it passes over the intersection between the tension crack and the failure plane, at which point it linearly approaches the toe. The factor of safety for the block is calculated.

53.3. Geometry and Material Properties

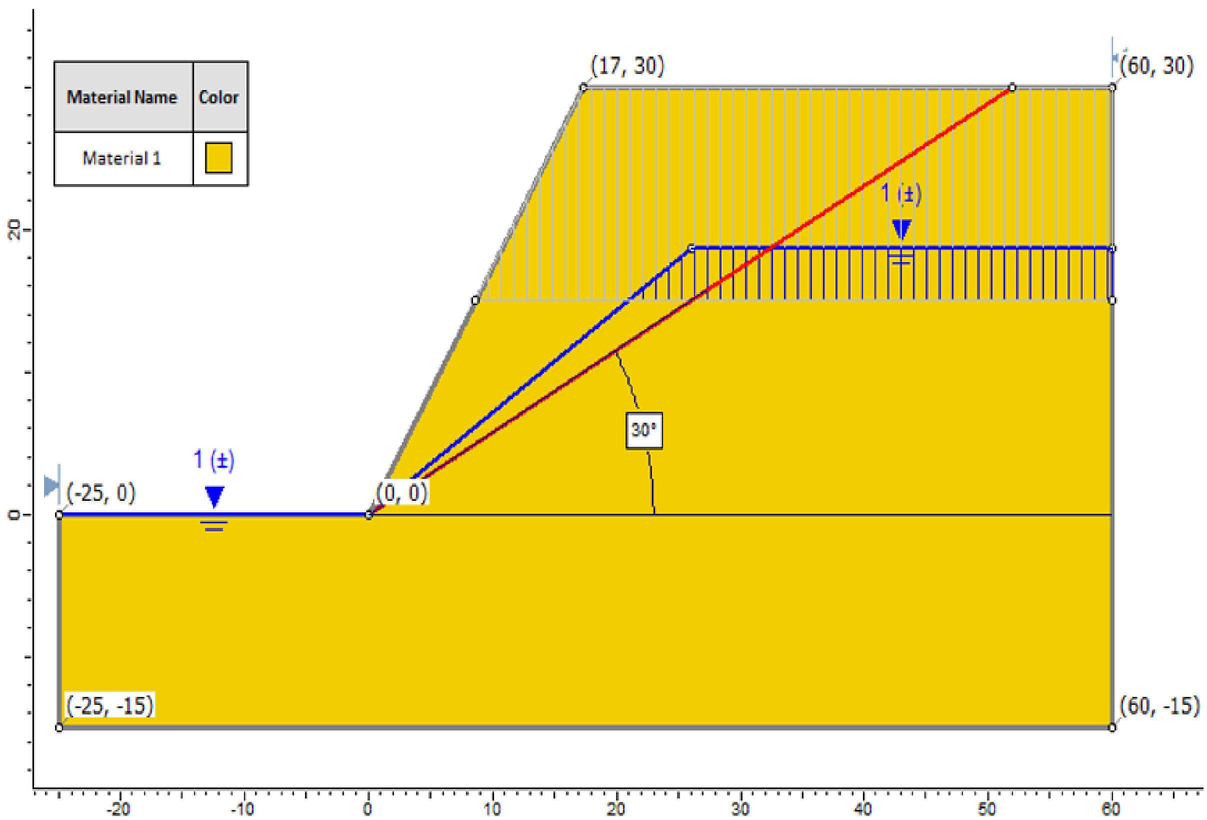


Figure 53.1: Geometry Setup in **Slide**

Table 53.1: Soil Properties

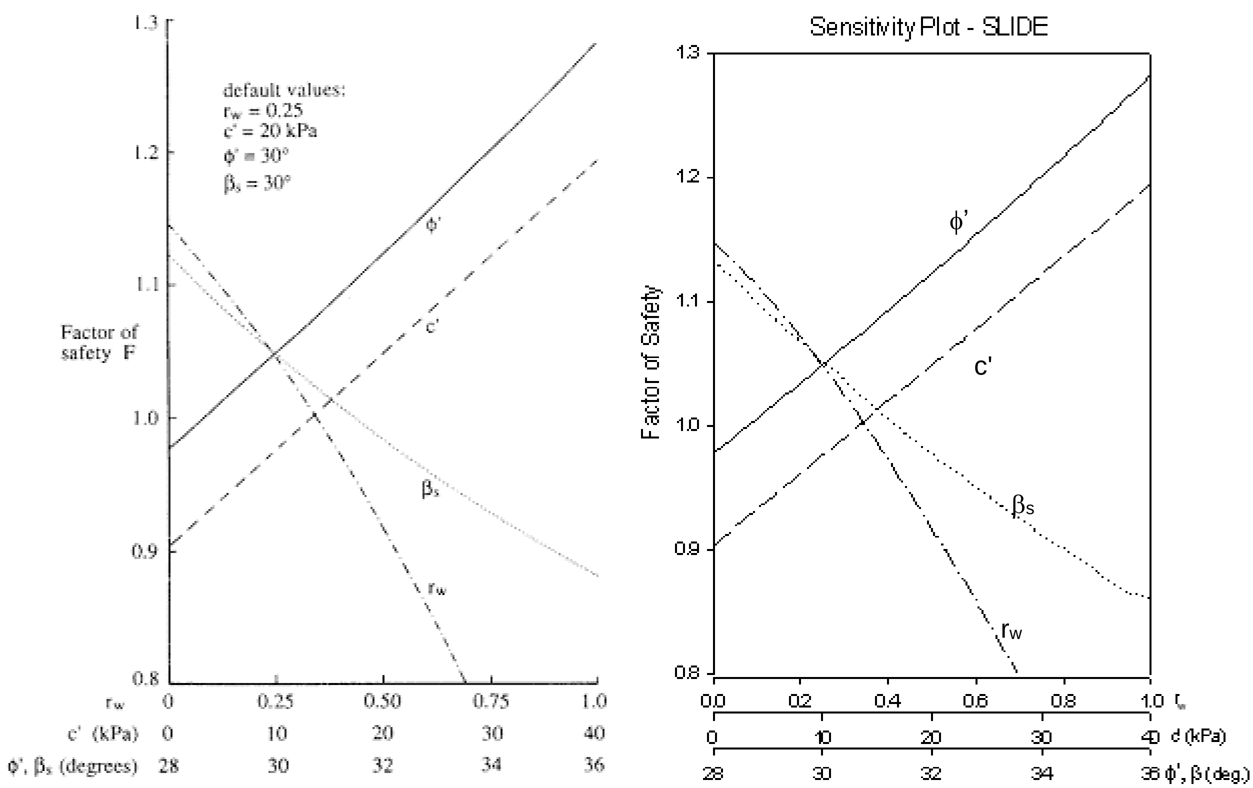
Material	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Material 1	20	30	25

53.4. Results

Table 53.2

Method	Factor of Safety
Slide - Janbu Simplified	1.049
RocPlane	1.049

Note: Priest’s factor of safety = 1.049



(a) (b)

Figure 53.2 Comparison for sensitivity results in rw c’, ϕ’ and βs: (a) Reference’s results from Priest (1993); (b) results from **Slide**

54. Slide Verification Problem #54

Slope, homogenous, micro piles

54.1. Introduction

This problem was taken from Yamagami (2000). It looks at the reinforcement of an unstable slope, using stabilizing piles.

54.2. Problem Description

Verification problem #54 analyzes a homogeneous slope (Figure 54.1) with a circular failure surface. The single row of micro-piles acts as passive reinforcement. The piles are spaced 1 m horizontally, with a shear strength of 10.7 kN. The factors of safety for the slope with and without reinforcement is calculated.

54.3. Geometry and Material Properties

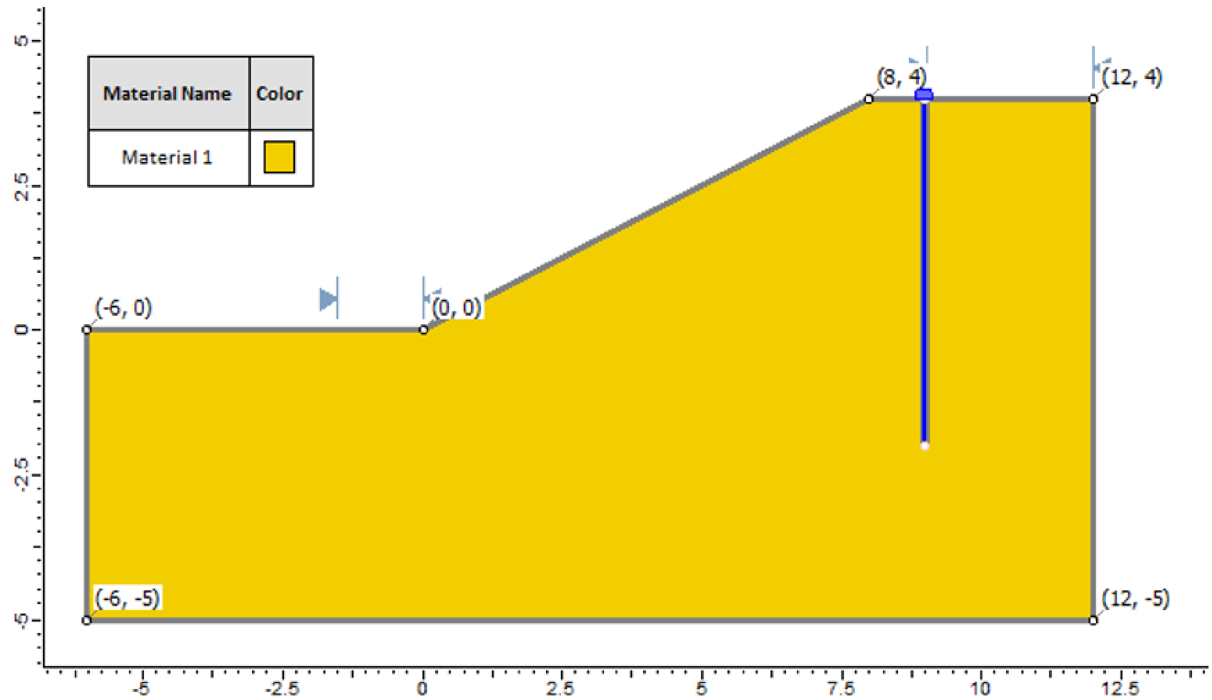


Figure 54.1: Geometry Setup in **Slide**

Table 54.1: Soil Properties

Material	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Material 1	4.9	10	15.68

54.4. Results

Table 54.2

Method	Factor of Safety
Slide – no pile	1.102
Slide – with pile	1.193
Yamagami – no pile	1.10
Yamagami – with pile	1.20

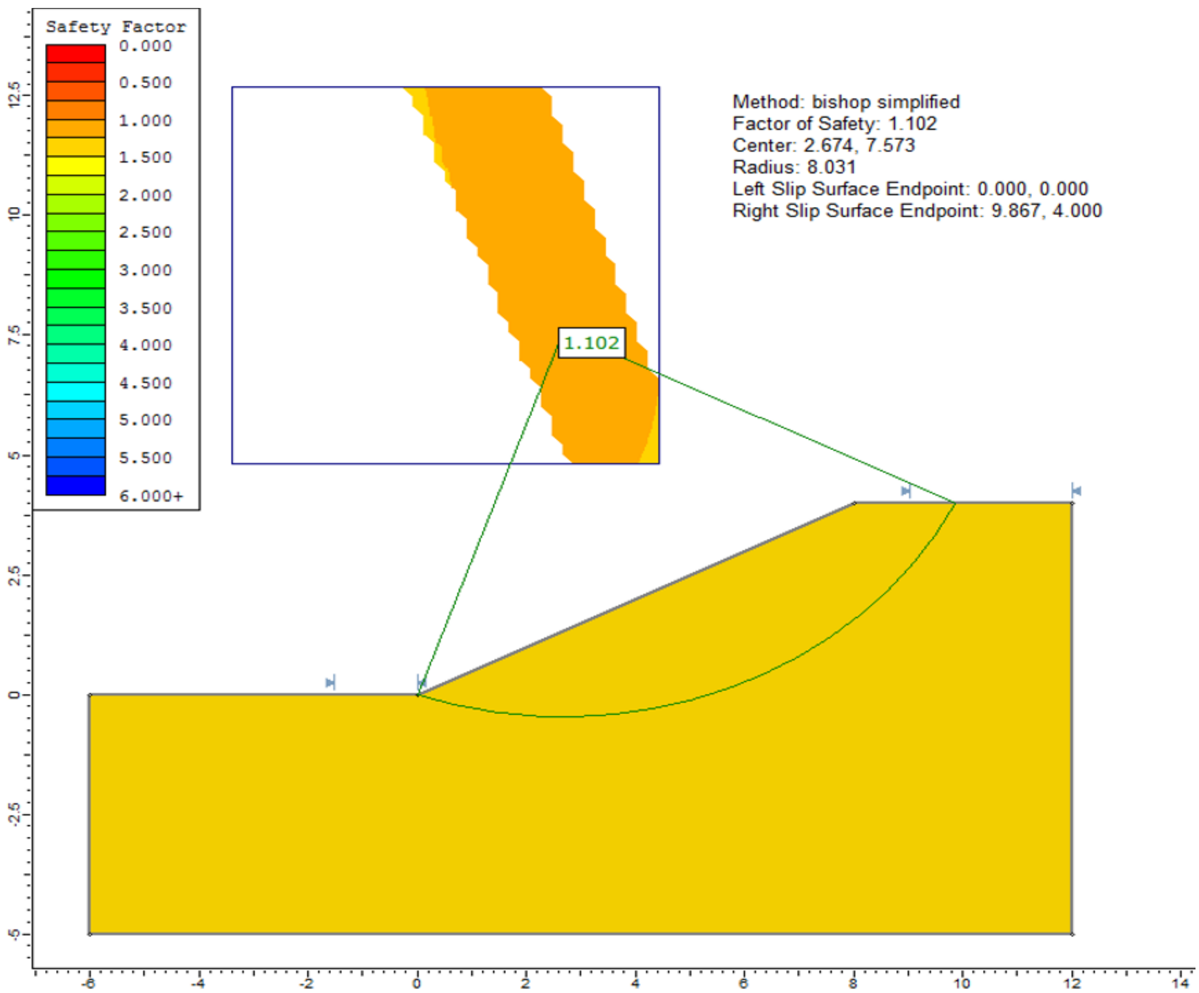


Figure 54.2: Circular failure surface, no pile

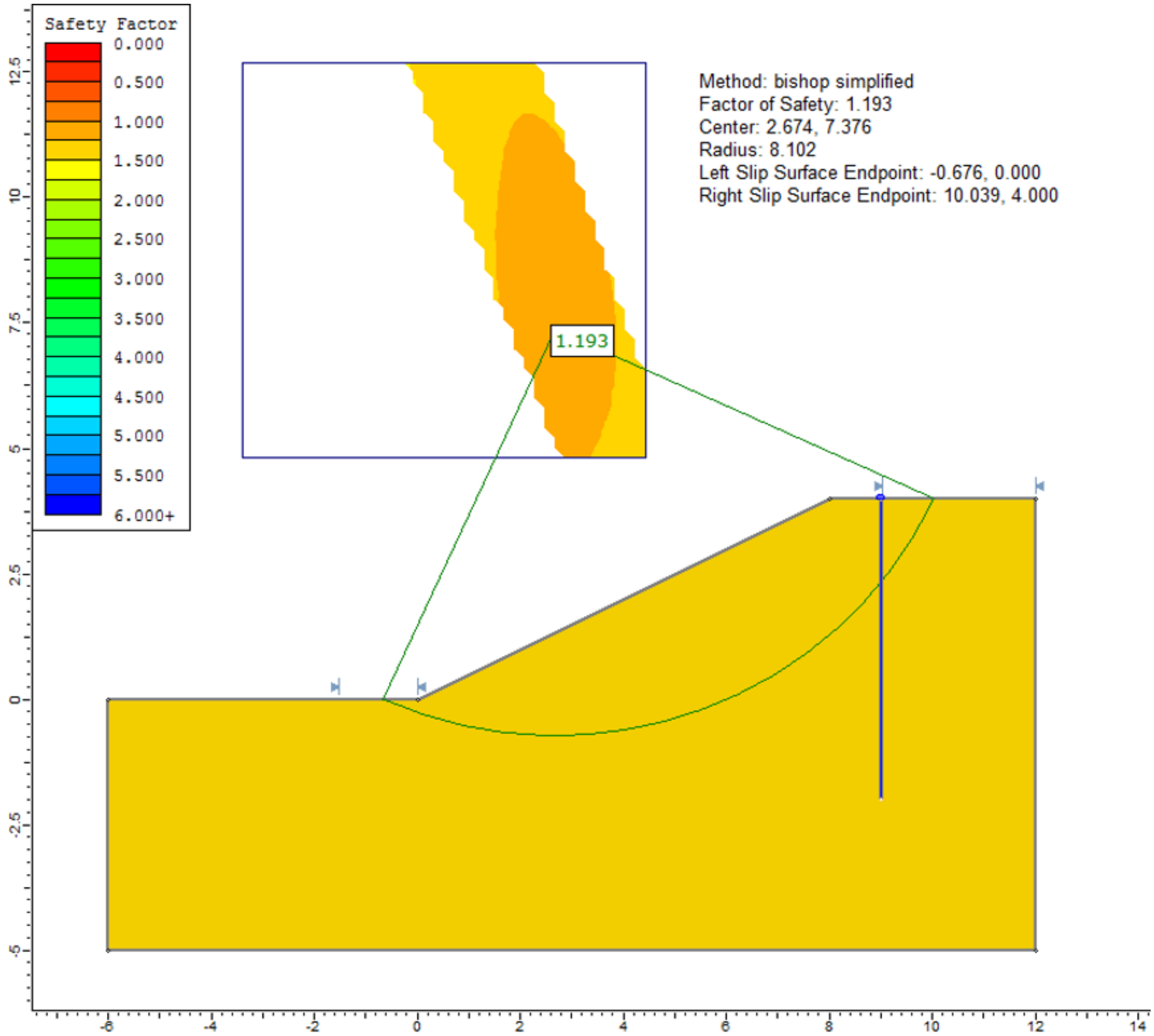


Figure 54.3: Circular failure surface, with reinforcing pile

55. Slide Verification Problem #55

Slope, homogenous, water table

55.1. Introduction

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

55.2. Problem Description

Verification problem #55 analyses a homogeneous, unreinforced slope. A water table is present (Figure 55.1). The circular critical surface and factor of safety is required.

Note: For this paper, Slide was optimized for maximum precision. An 80x80 grid was used with a tolerance of 0.0001. Analysis methods used were: Bishop, Janbu simplified, Ordinary/Fellenius, Spencer, and Lowe-Karafiath.

55.3. Geometry and Material Properties

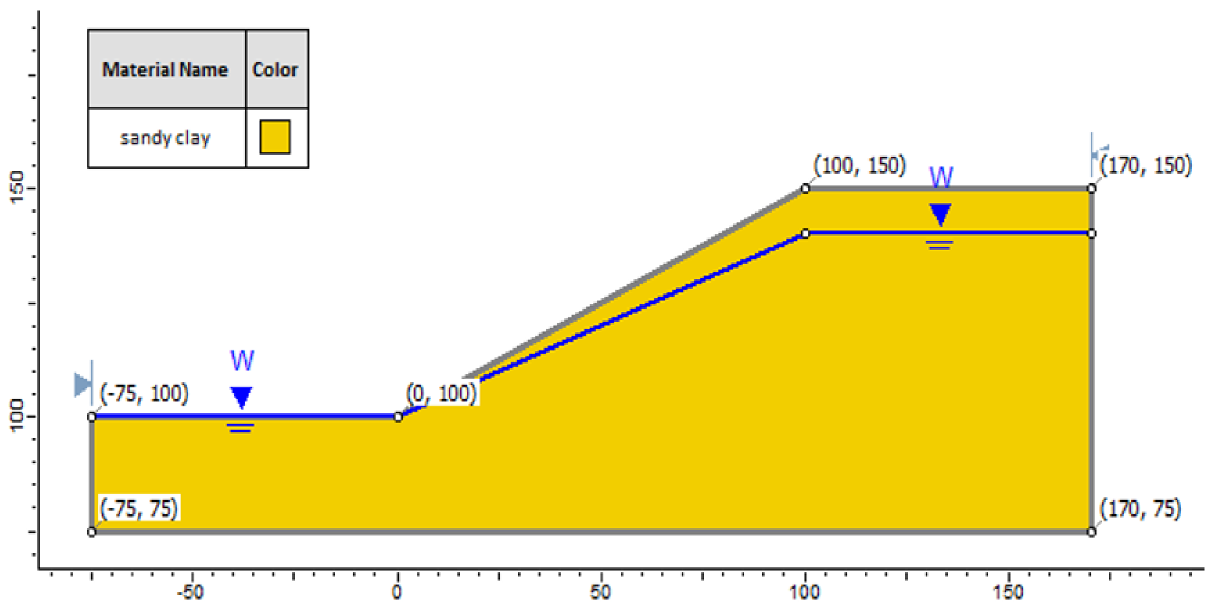


Figure 55.1: Geometry Setup in **Slide**

Table 55.1: Soil Properties

Material	c´ (psf)	ϕ´ (deg.)	γ (pcf)
Sandy clay	300	30	120

55.4. Results

Table 55.2

Method	Slide	UTEXAS4	SLOPE/W	WINSTABL	XSTABL	RSS
Spencer	1.300	1.30	1.30	1.34	--	--
Bishop simplified	1.293	1.29	1.29	1.34	1.29	1.29
Janbu simplified	1.151	1.15	1.15	1.20	1.24	1.15
Lowe-Karafiath	1.318	1.32	--	--	-	---

Note: SNAIL FS = 1.22 (Wedge method)

GOLD-NAIL FS = 1.32 (Circular method)

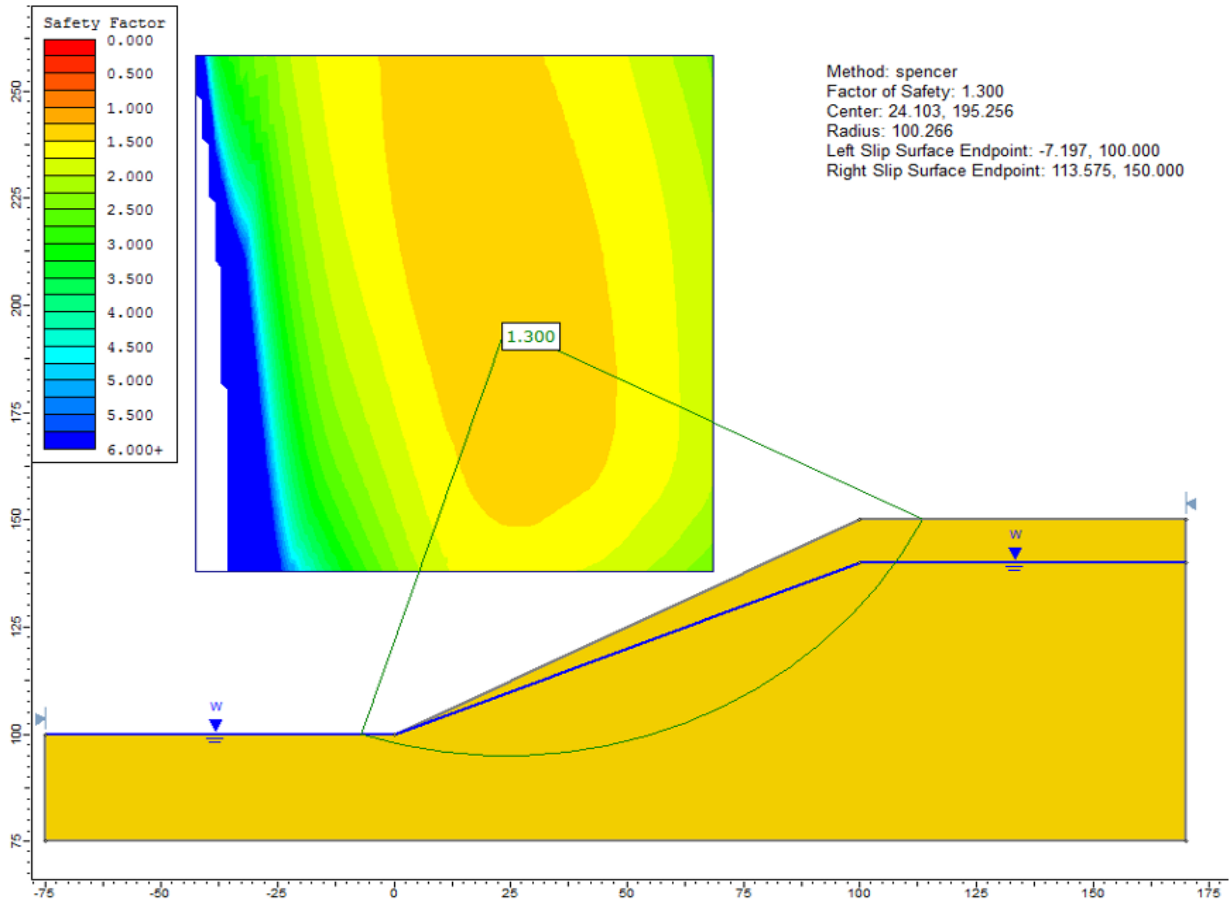


Figure 55.2: Circular failure surface, using Spencer method

56. Slide Verification Problem #56

Slope, homogenous, 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

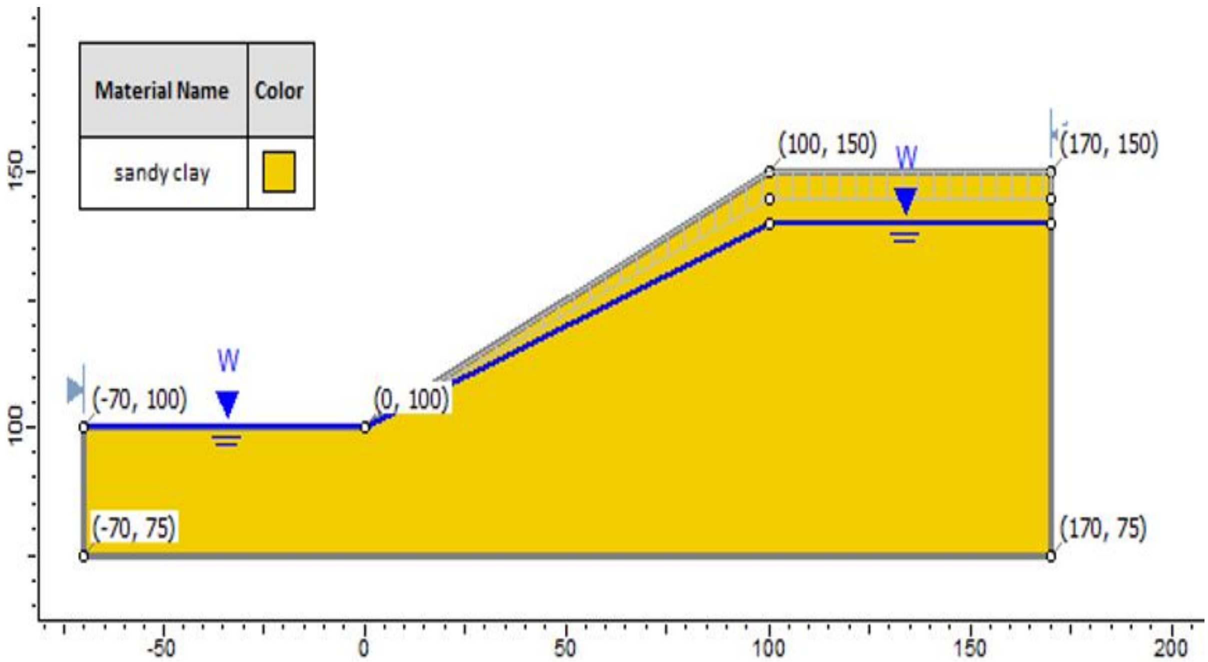


Figure 56.1: Geometry Setup in **Slide**

Table 56.1: Soil Properties

Material	c´ (psf)	ϕ´ (deg.)	γ (pcf)
Sandy clay	300	30	120

56.4. Results

Table 56.2

Method	Slide	UTEXAS4	SLOPE/W	WINSTABL	XSTABL	RSS
Spencer	1.290	1.29	1.29	1.32	--	--
Bishop simplified	1.285	1.28	1.28	1.31	1.28	1.28
Janbu simplified	1.141	1.14	1.14	1.18	1.23	1.13
Lowe-Karafiath	1.304	1.31	--	--	--	--

Note: SNAIL FS = 1.18 (Wedge method)

GOLD-NAIL FS = 1.30 (Circular method)

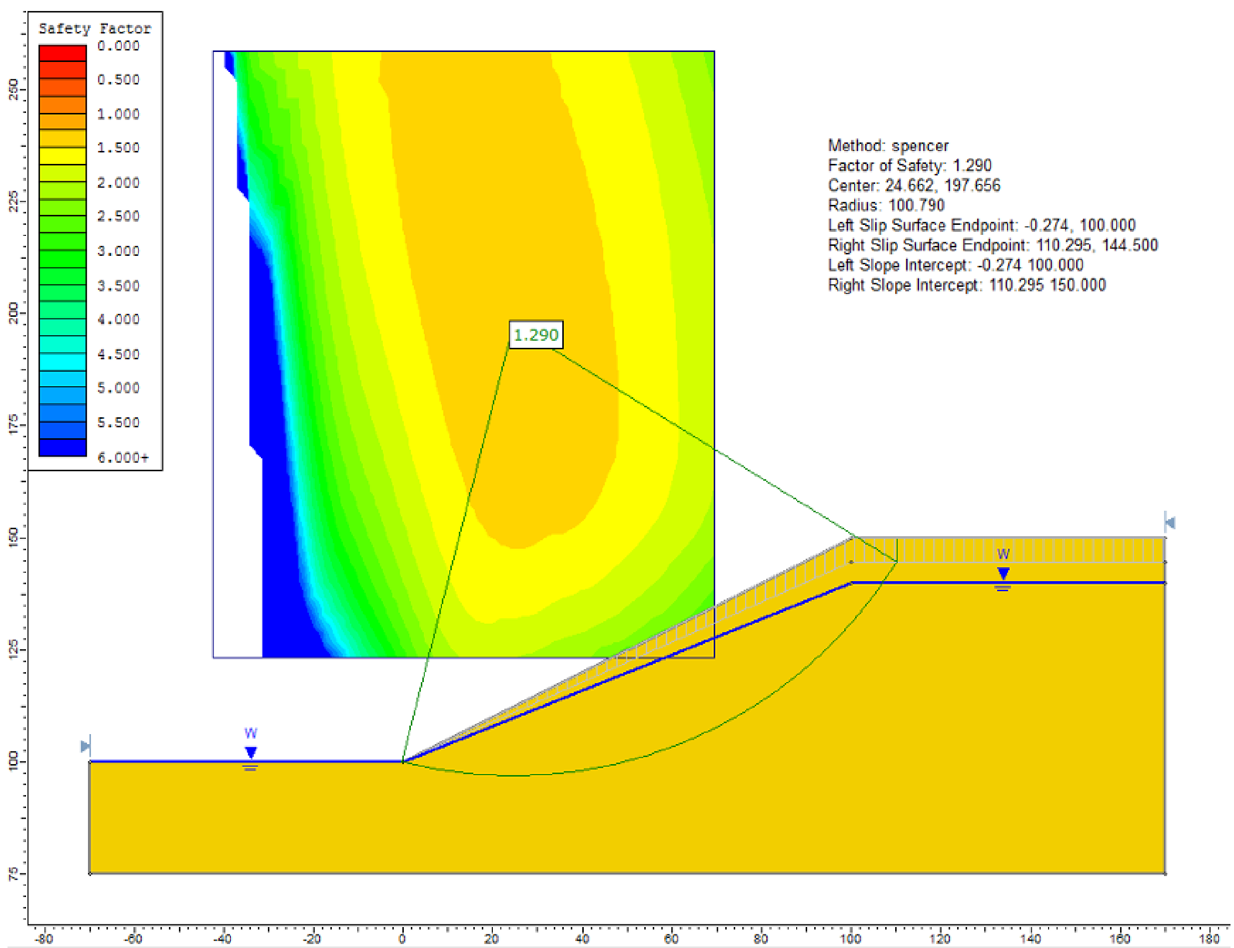


Figure 56.2: Circular failure surface, using the Spencer method

57. Slide Verification Problem #57

Slope, (2) materials, water table, tension crack, composite surfaces

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

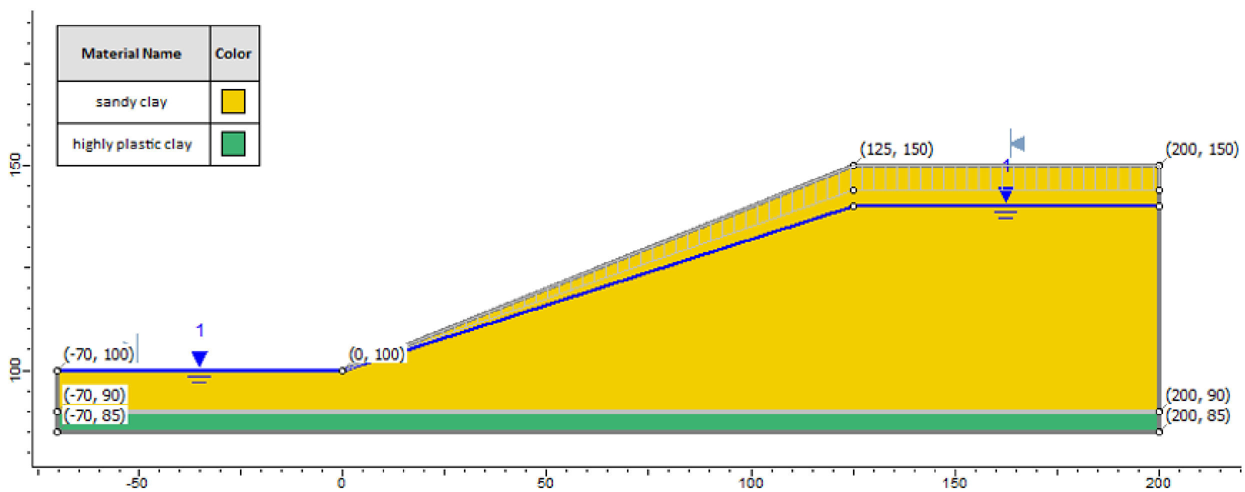


Figure 57.1: Geometry Setup in **Slide**

Table 57.1: Soil Properties

Material	c´ (psf)	ϕ´ (deg.)	γ (pcf)
Sandy clay	300	35	130
Highly Plastic Clay	0	25	130

57.4. Results

Table 57.2: Composite surfaces/Noncircular

Method	Slide	SLOPE/W	XSTABL
Spencer	1.400	1.40	--
Bishop simplified	1.392	1.39	1.41
Janbu simplified	1.222	1.21	1.34
Lowe-Karafiath	1.385	--	--
Ordinary	1.257	0.85	--

Note: SNAIL FS = 1.39 (Wedge method)

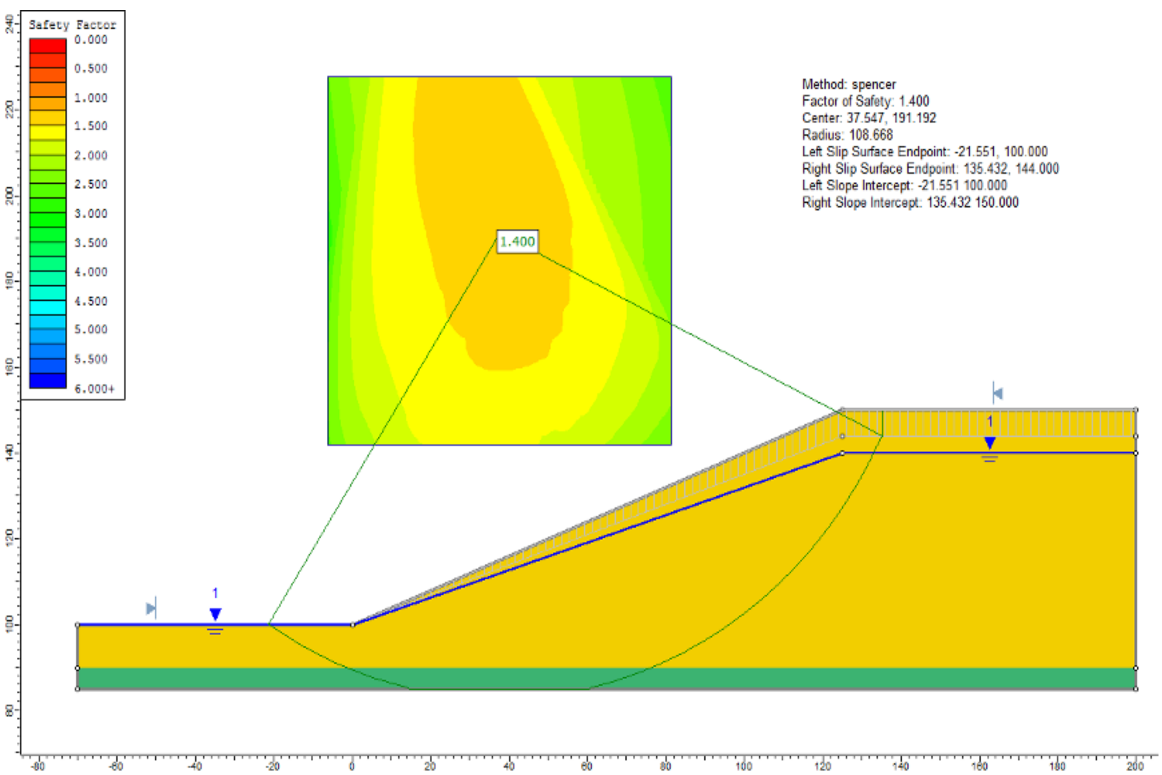


Figure 57.2: Noncircular failure surface, using Spencer method

Table 57.3: No composite surfaces/Circular

Method	Slide	UTEXAS4	WINSTABL	RSS
Spencer	1.422	1.42	1.45	--
Bishop simplified	1.417	1.41	1.39	1.41
Janbu simplified	1.263	1.20	1.23	1.24
Lowe-Karafiath	1.414	1.12	--	--
Ordinary	1.319	--	--	--

Note: GOLD-NAIL FS = 1.40 (Circular method)

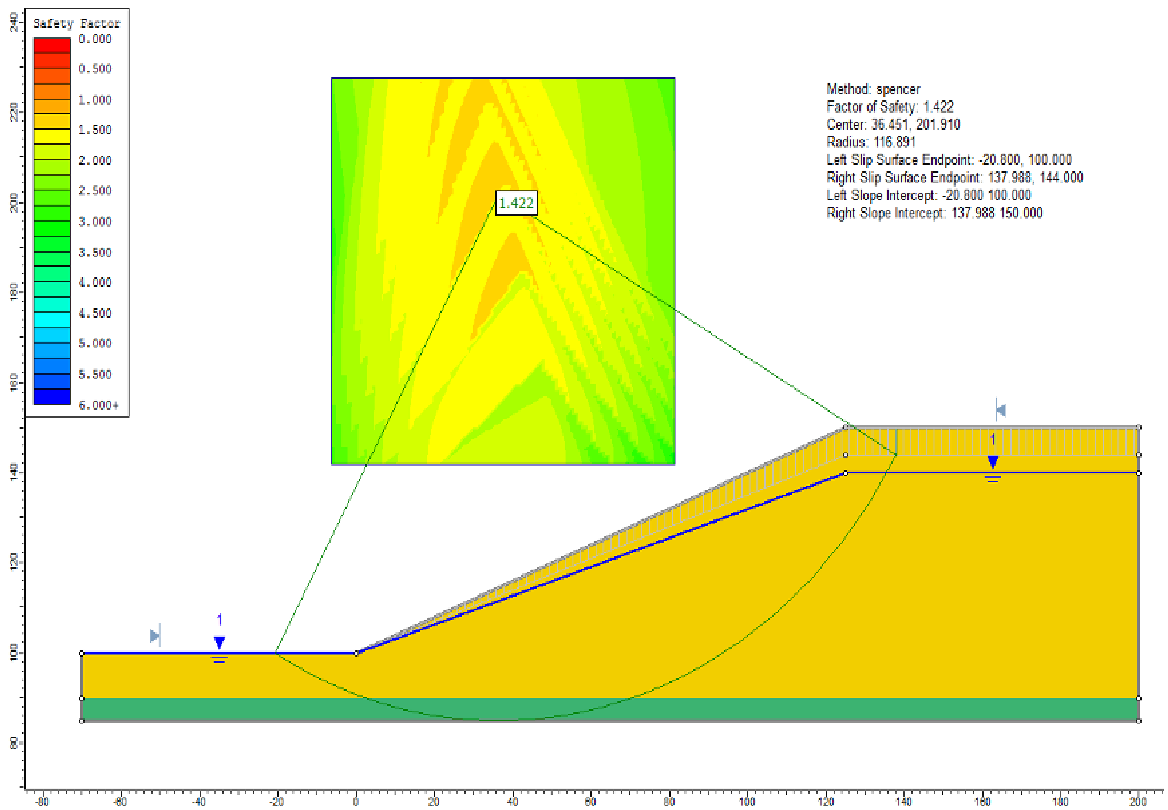


Figure 57.3: Circular failure surface, using Spencer method

58. Slide Verification Problem #58

Retaining wall, (8) materials, water table, grouted tieback

58.1. Introduction

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

58.2. Problem Description

Verification problem #58 analyzes a tied-back wall in layered soil. A water table is present. Each layer lies horizontal. The tied-back wall is modelled by three identical rows of active grouted tieback reinforcement (Table 58.2). The circular critical failure surface (surface must be at least 25 ft deep) and factor of safety is calculated.

<u>Note:</u>

The problem gives reinforcement parameters in the form:

Tieback Spacing 4 ft.

1.08” Diameter 270 ksi Steel

4 k/ft Allowable Pullout

In order to convert these to **Slide** parameters for grouted tieback reinforcement:

Out-of-plane Spacing = Tieback spacing

Tensile *and* Plate Capacity = Yield strength * πr^2 (lbs)

Bond Strength = Allowable pullout (lbs/ft)***

***Allowable pullout is given in ft^{-1}. The conversion that one must undergo to get Bond Strength gives the exact same number in lbs/ft. This conversion method must be applied to all questions pertaining to this paper.

58.3. Geometry and Material Properties

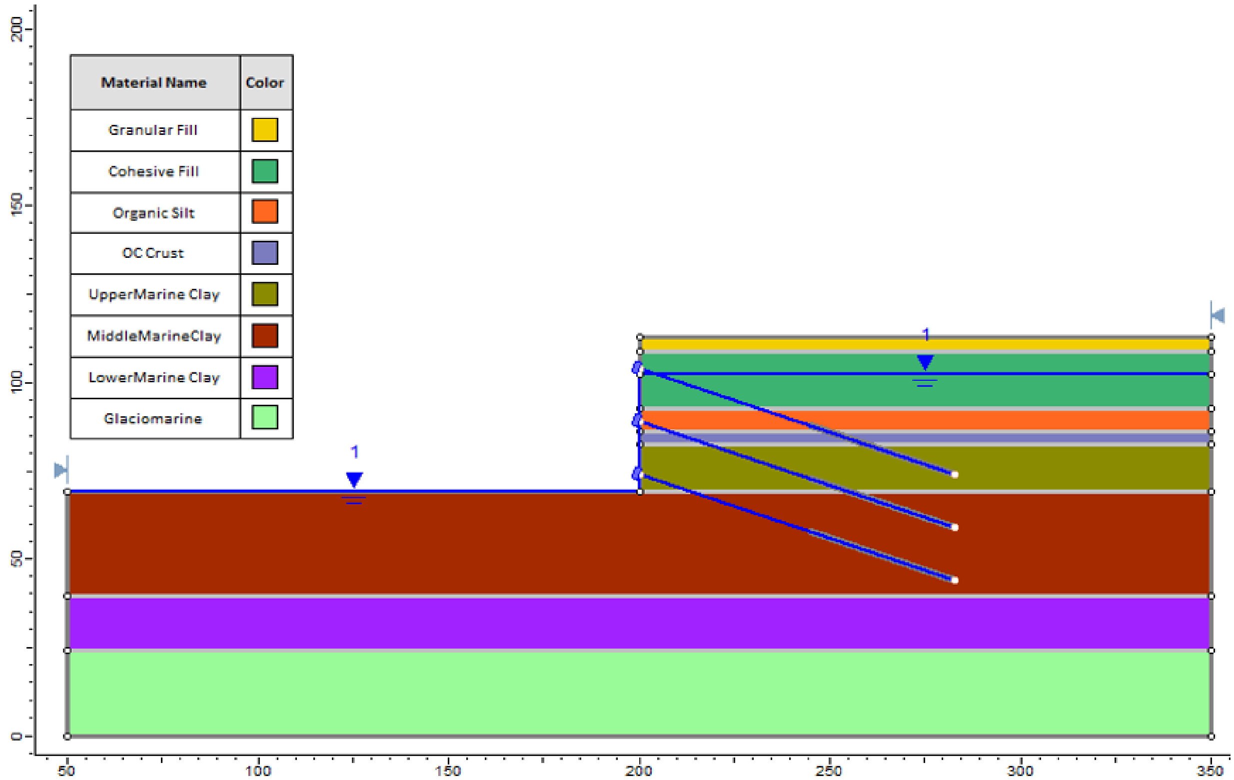


Figure 58.1: Geometry Setup in **Slide**

Table 58.1: Soil Properties

Layer	c´ (psf)	ϕ´ (deg.)	γ (pcf)
Granular Fill (GF)	0	30	120.4
Cohesive Fill (CF)	0	30	114.7
Organic Silt (OS)	900	0	110.2
OC Crust (OC)	2485	0	117.8
Upper Marine Clay (UM)	1670	0	117.8
Middle Marine Clay (MM)	960	0	117.8
Lower Marine Clay (LM)	1085	0	117.8
Glaciomarine Deposits (GD)	1500	0	147.1

Table 58.2: Grouted Tieback Properties – All Rows

Tensile Cap. (lbs)	Plate Cap. (lbs)	Bond Strength (lb/ft)	Bond Length (ft)	Out-of-Plane spacing (ft)
247343.87	247343.87	4000	40	4

58.4. Results

Table 58.3: Circular Method

Method	Slide	UTEXAS4	SLOPE/W	WINSTABL
Spencer	1.145	1.14	1.14	1.20
Bishop simplified	1.147	1.14	1.14	1.16
Janbu simplified	1.061	1.13	1.05	1.12
Lowe-Karafiath	1.175	1.20	--	--
Ordinary	1.129	--	1.12	--

Note: GOLD-NAIL FS = 1.19 (Circular method)
RSS only allows horizontal reinforcement
XSTABL does not allow for reinforcement
SNAIL FS = 1.03 (Wedge method – noncircular)

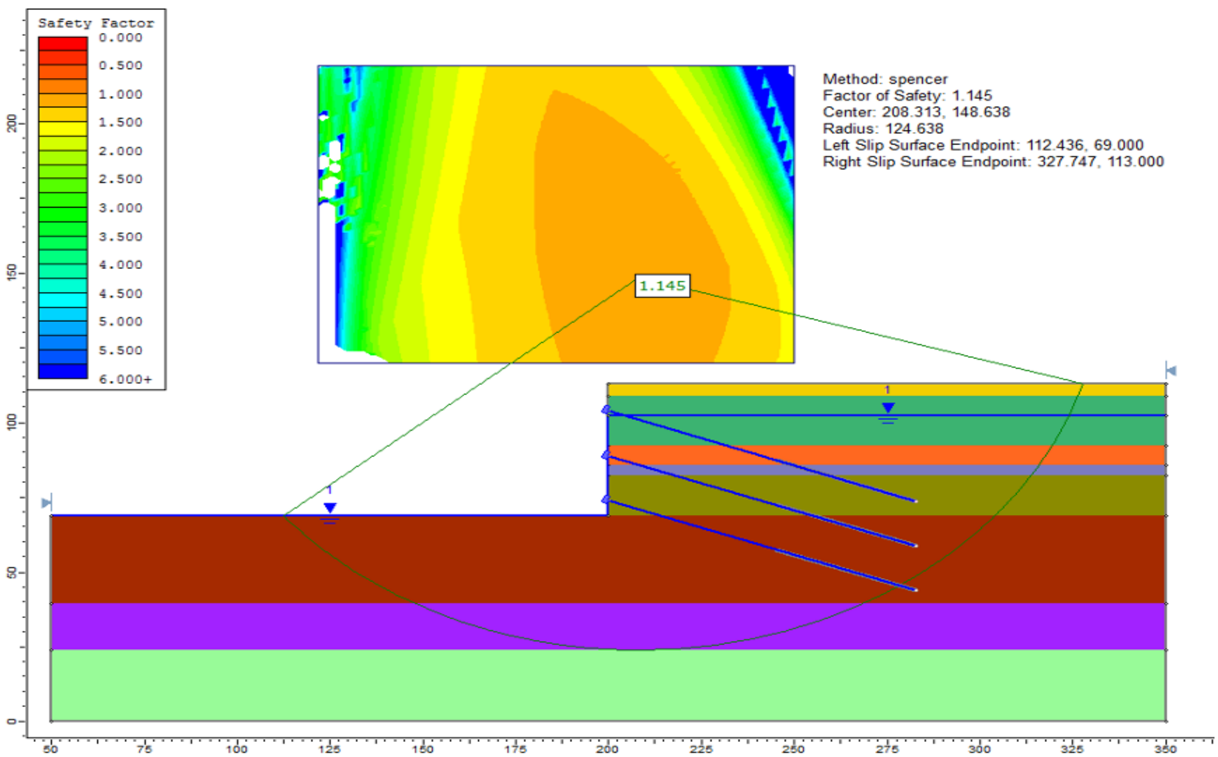


Figure 58.2: Circular failure surface, using the Spencer method

59. Slide Verification Problem #59

Retaining wall, homogenous, water table, grouted tieback

59.1. Introduction

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

59.2. Problem Description

Verification Problem #59 analyzes a tieback wall in homogeneous sand. One row of active grouted tieback support is used. A water table is present. The circular critical failure surface and factor of safety is calculated. To eliminate undesirable critical surfaces, do not allow for tension cracks caused by reverse curvature, and place a focus search point at the toe of the wall.

59.3. Geometry and Material Properties

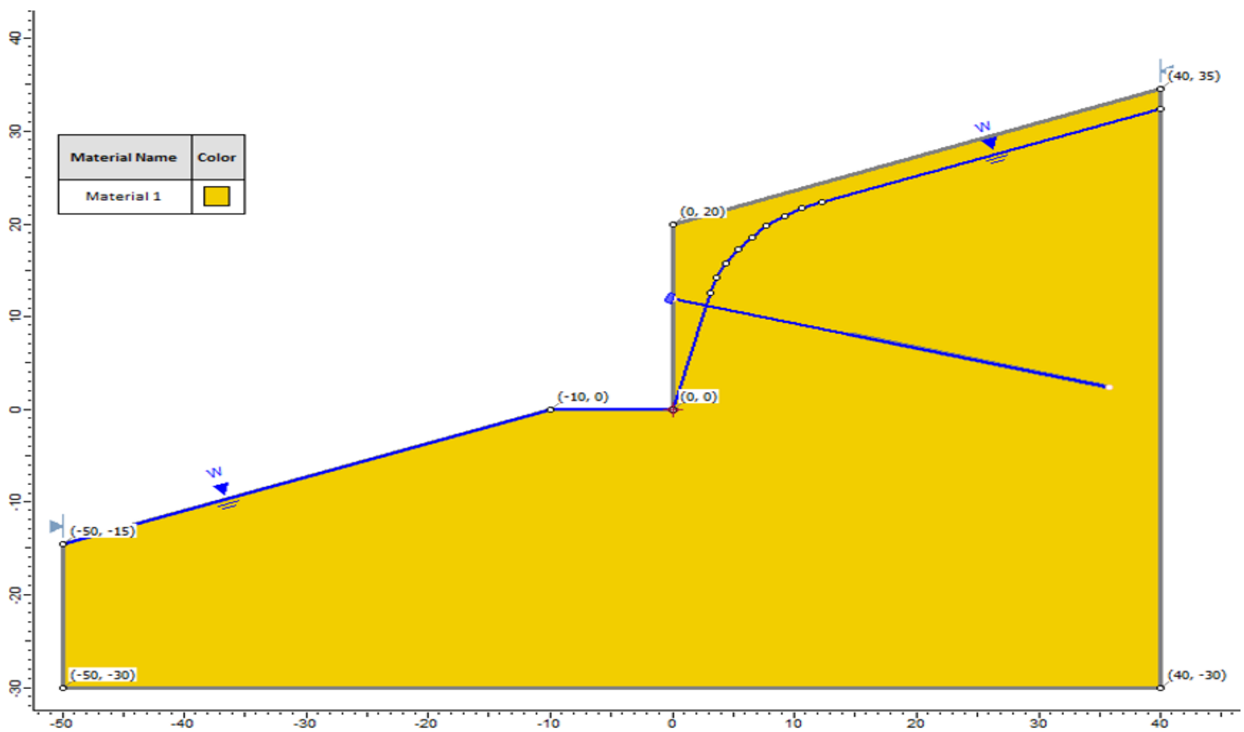


Figure 59.1: Geometry Setup in **Slide**

Table 59.1: Soil Properties

Material	c´ (psf)	ϕ´ (deg.)	γ (pcf)
Sand	0	30	120

Table 59.2: Grouted Tieback Properties

Tensile Cap. (lbs)	Plate Cap. (lbs)	Bond Strength (lb/ft)	Bond Length (ft)	Out-of-Plane spacing (ft)
184077.69	184077.69	5000	22	8

59.4. Results

Table 59.3

Method	Slide	UTEXAS4	SLOPE/W	WINSTABL
Spencer	0.596	0.65	0.60	0.59
Bishop simplified	0.582	0.56	0.60	0.74
Janbu simplified	0.583	0.64	0.61	0.76
Lowe-Karafiath	0.588	0.76	--	--
Ordinary	0.859	--	0.62	--

Note: GOLD-NAIL FS = 0.62 (Circular method)
RSS only allows horizontal reinforcement
XSTABL does not allow for reinforcement
SNAIL FS = 0.62 (Wedge method – noncircular)

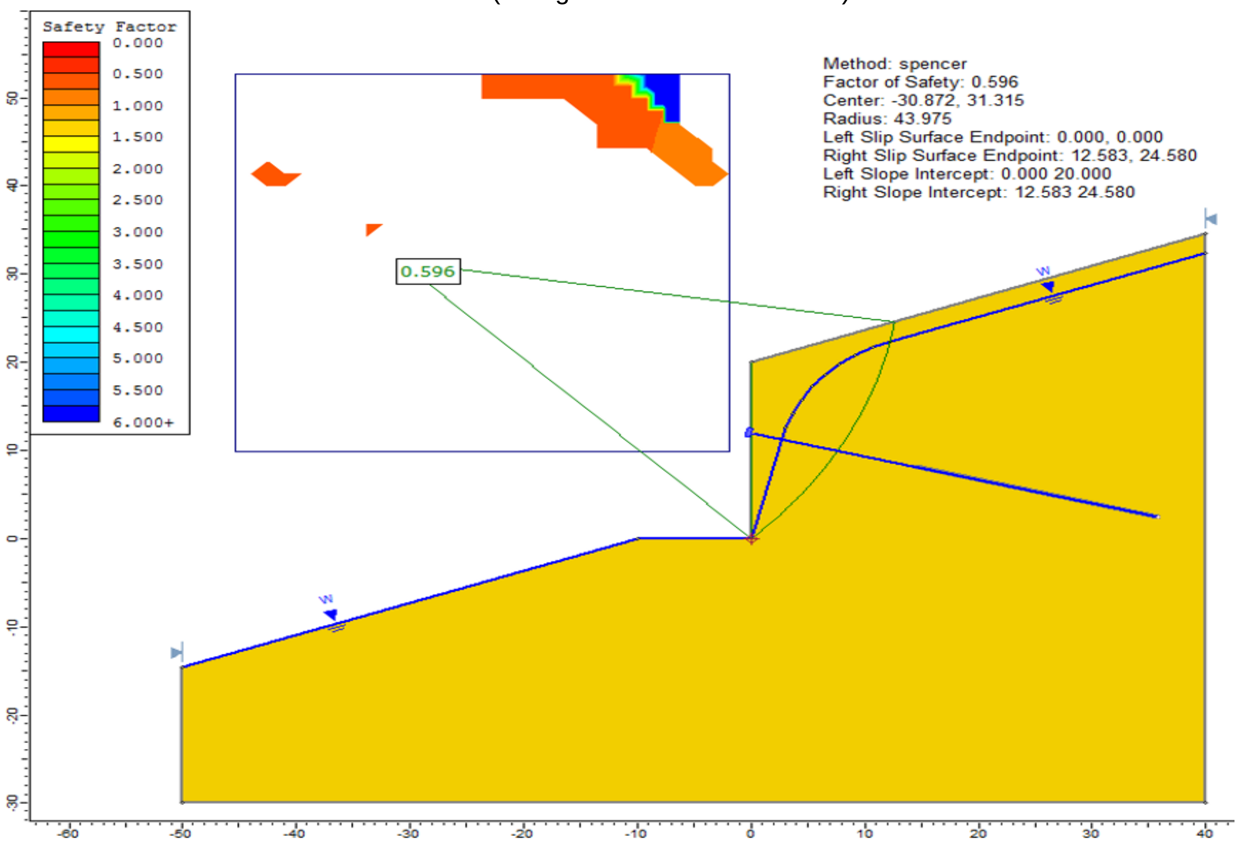


Figure 59.2: Critical failure surface, using the Spencer method

60. Slide 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

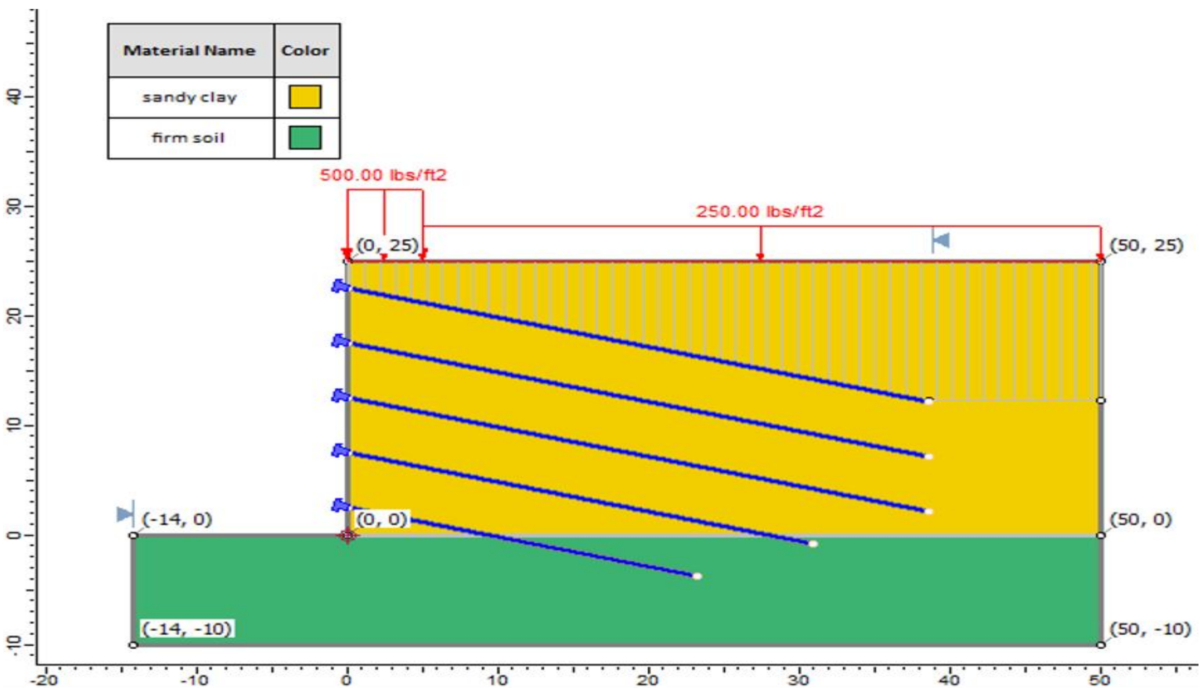


Figure 60.1: Geometry Setup in **Slide**

Table 60.1: Soil Properties

Material	c´ (psf)	ϕ´ (deg.)	γ (pcf)
Sand	800	0	120

Table 60.2: Soil Nail Properties

Tensile Cap. (lbs)	Plate Cap. (lbs)	Bond Strength (lb/ft)	Out-of-Plane spacing (ft)
25918.14	25918.14	1508	5

60.4. Results

Table 60.3: Circular failure surface

Method	Slide	UTEXAS4	SLOPE/W	WINSTABL
Spencer	1.009	1.02	1.02	0.99
Bishop simplified	0.997	1.00	1.01	1.06
Janbu simplified	1.041	1.08	1.07	1.10
Lowe-Karafiath	1.021	1.00	--	--
Ordinary	0.997	--	1.00	--

Note: GOLD-NAIL FS = 0.91 (Circular method)
RSS only allows horizontal reinforcement
XSTABL does not allow for reinforcement
SNAIL FS = 0.84 (Wedge method – noncircular)

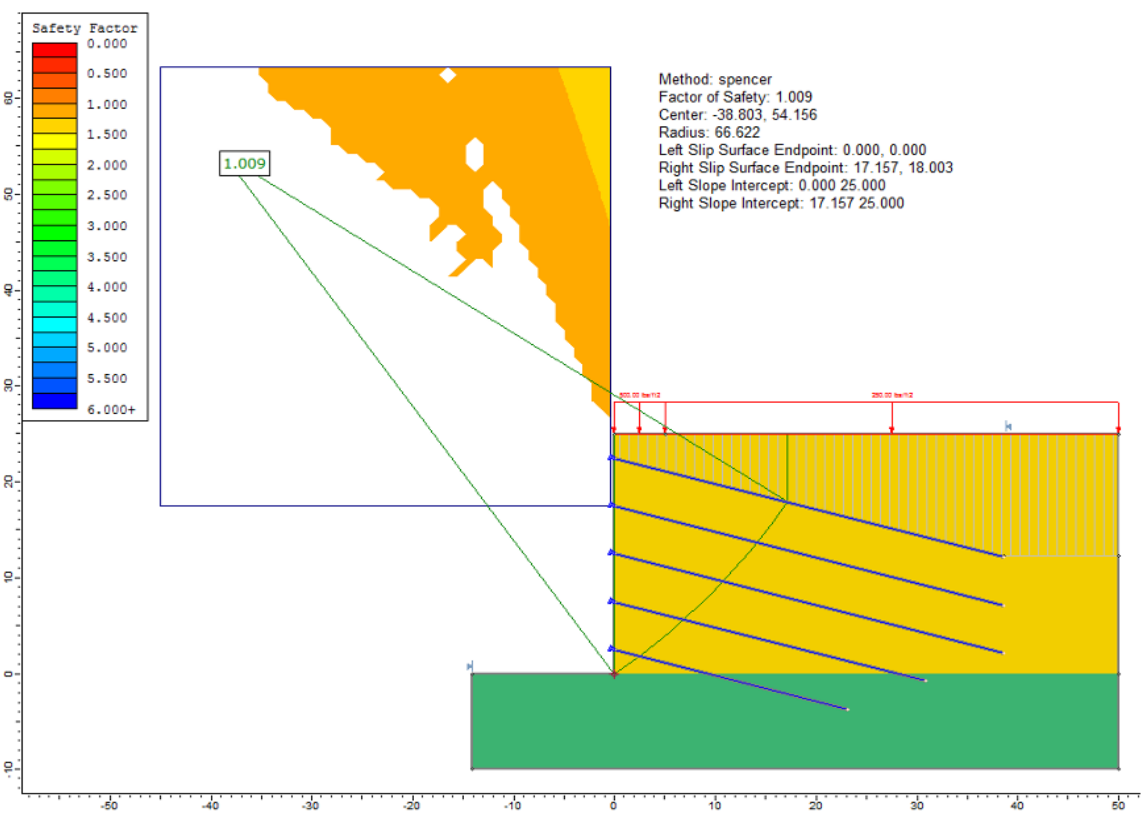


Figure 60.2: Critical failure surface, using Spencer method

61. Slide Verification Problem #61

Slope, homogenous, 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 criterio and Power Curve criterion. The power curve criterion was derived from Baker's own non-linear function:

$$\tau = P_a A \left(\frac{\sigma}{P_a} + T \right)^n$$ … 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

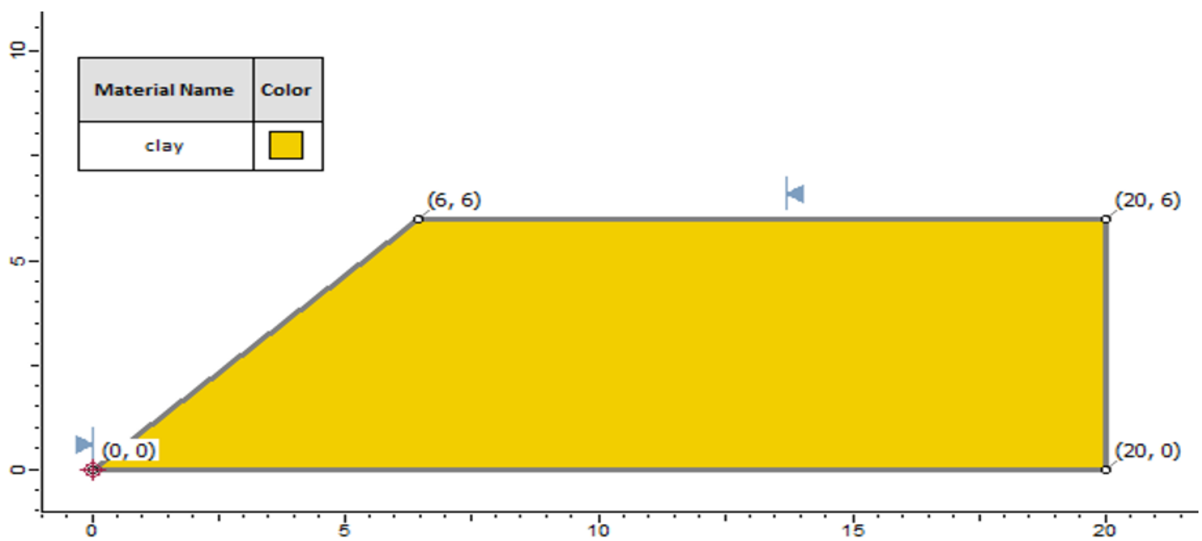


Figure 61.1: Geometry Setup in **Slide**

Table 61.1: Soil Properties – Power Curve criterion

	Baker's Parameters			Slide Paramaters			
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

Material	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Clay	6.0	32	18

61.4. Results

Table 61.3

Strength Type	Method	Factor of Safety	Maximum effective normal stress (kPa)
Power Curve	Janbu Simplified	1.348	36.33
	Spencer	1.468	31.21
Mohr-Coulomb	Janbu Simplifed	1.291	30.05
	Spencer	1.366	26.44

Note: Baker (2003) non-linear results: FS = 1.48, σ_{max} = 21.4

Baker (2003) M-C results: FS = 1.35, σ_{max} = 27.5

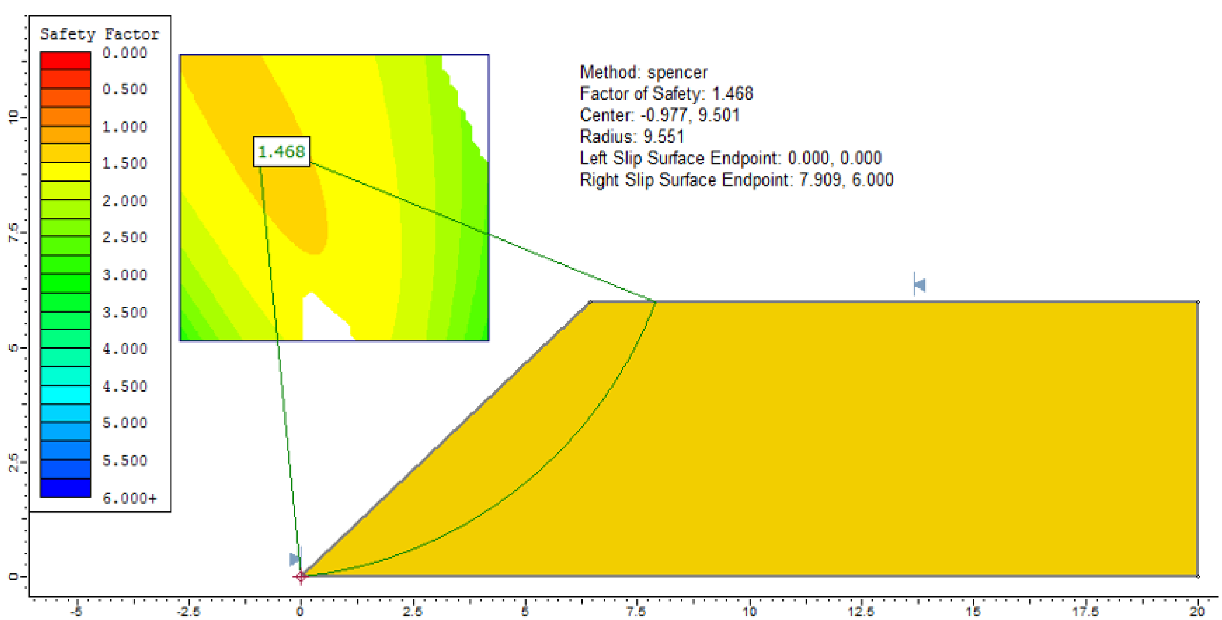


Figure 61.2: Circular critical surface with power curve criteria, Spencer method

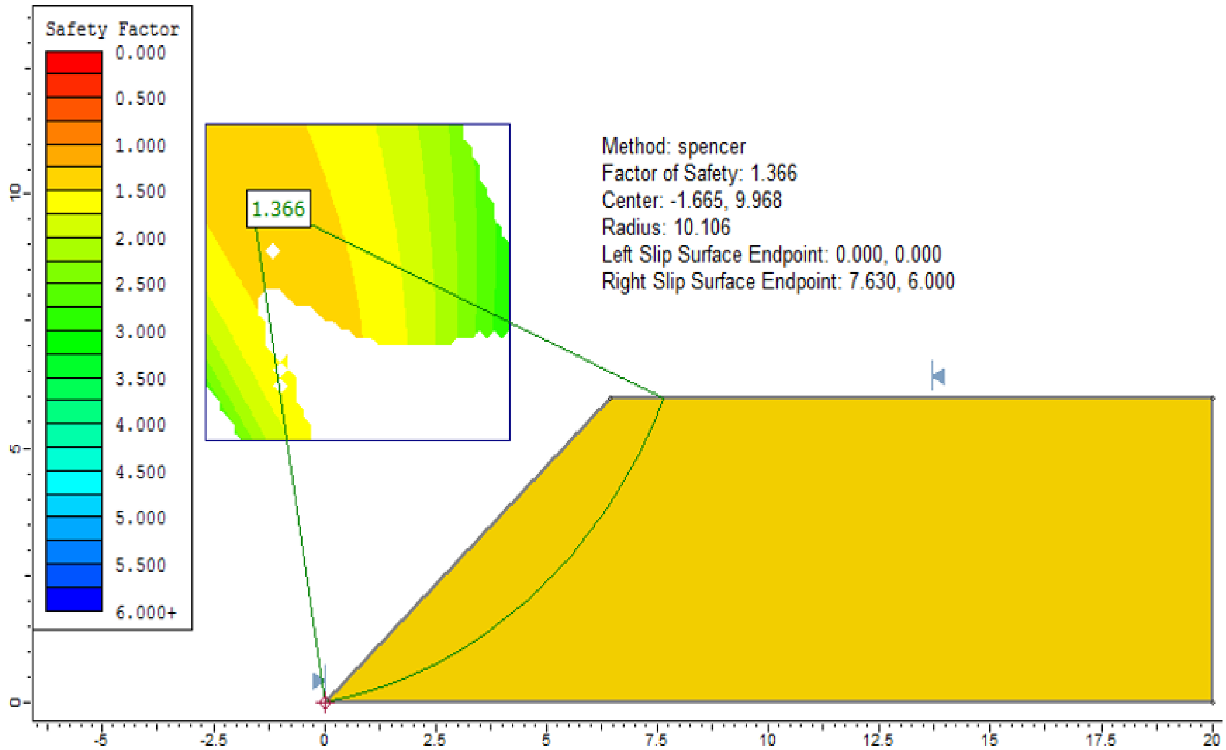


Figure 61.3: Circular critical surface with Mohr-Coulomb criteria, Spencer method

62. Slide Verification Problem #62

Slope, homogenous, 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 R_u = 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. In order to model this type of noncircular surface with **Slide**, a path search with Monte-Carlo optimization was performed.

62.3. Geometry and Material Properties

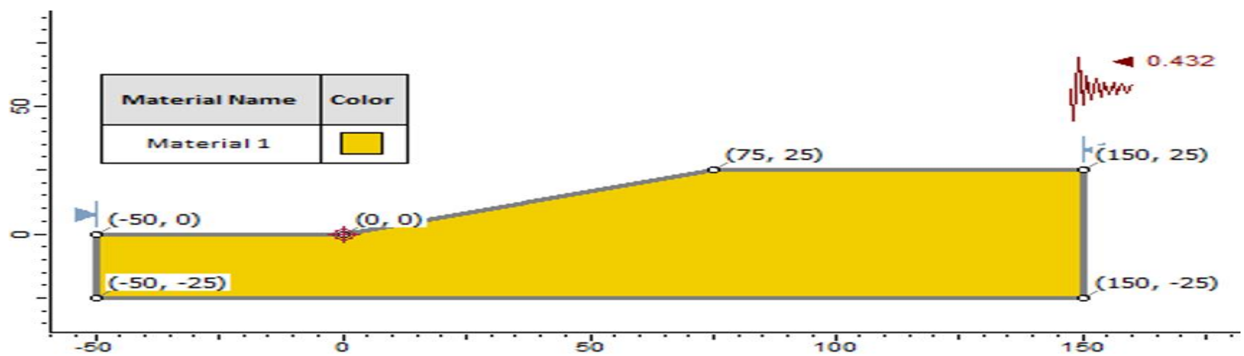


Figure 62.1: Geometry Setup in **Slide**

Table 62.1: Seismic Coefficients

Dry Slope	0.432
R_u = 0.5	0.132

Table 62.2: Soil Properties

Material	c´ (kPa)	ϕ´ (deg.)	γ (kN/m^3)
Clay	25	30	20

62.4. Results

Table 62.3: Dry slope (k_c = 0.432)

Type	Spencer	Bishop Simplified
Circular (Grid search)	1.001	0.991
Noncircular (Path search with optimization)	0.999	0.989

Note: Loukidis factor of safety (Spencer) = 1.000

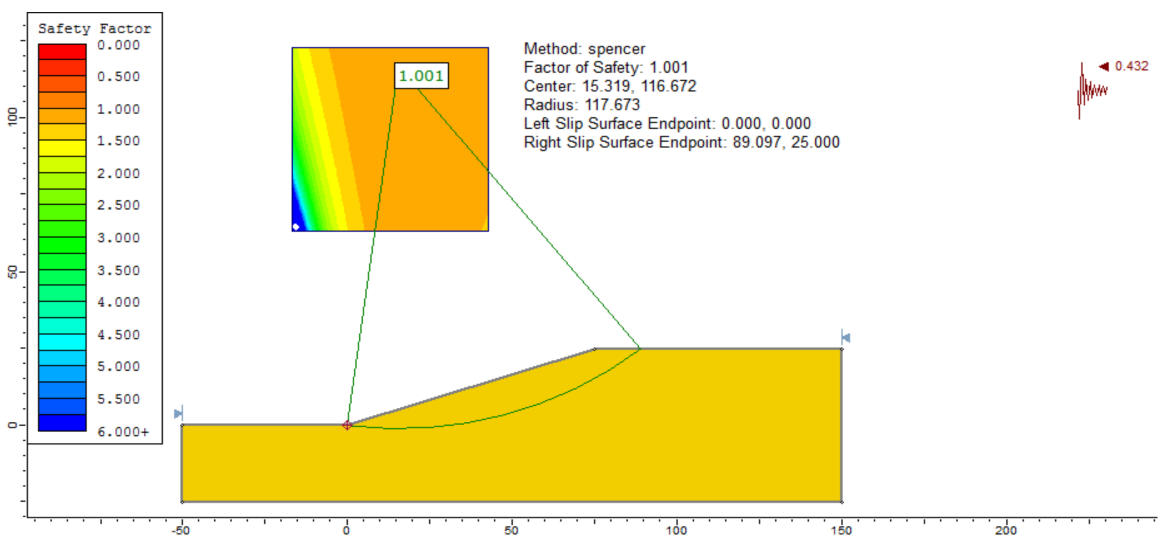


Figure 62.2: Circular slip surface, using the Spencer method

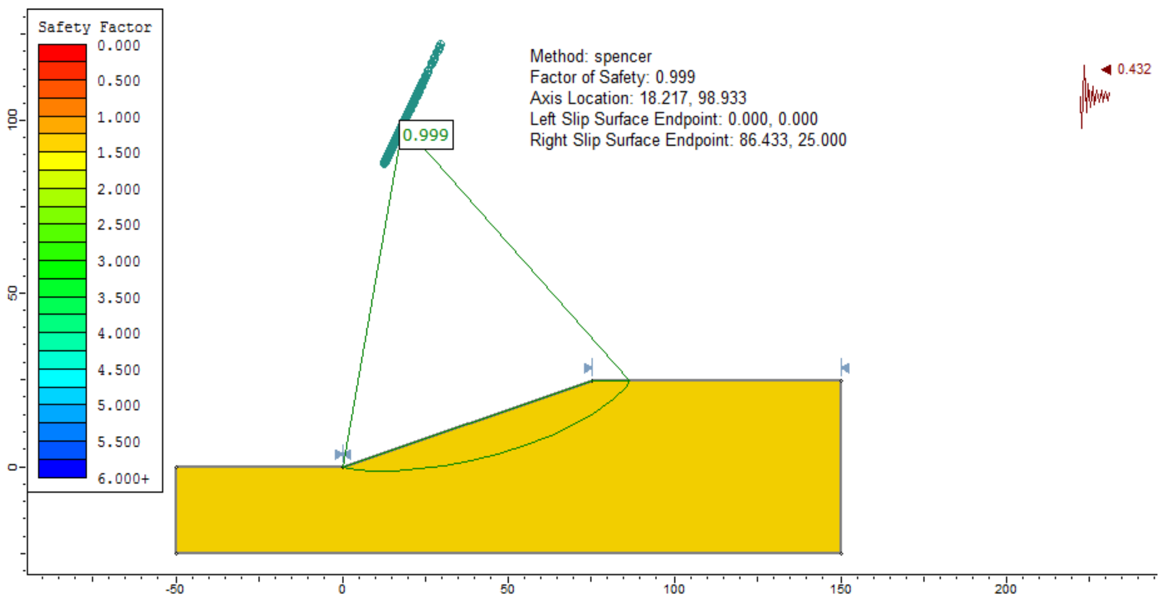


Figure 62.3: Non-circular slip surface, using the Spencer method

Table 62.4: $R_u = 0.5$ ($k_c = 0.132$)

Type	Spencer	Bishop Simplified
Circular (Grid search)	1.001	0.987
Noncircular (Path search with optimization)	0.997	0.966

Note: Loukidis factor of safety (Spencer) = 1.000

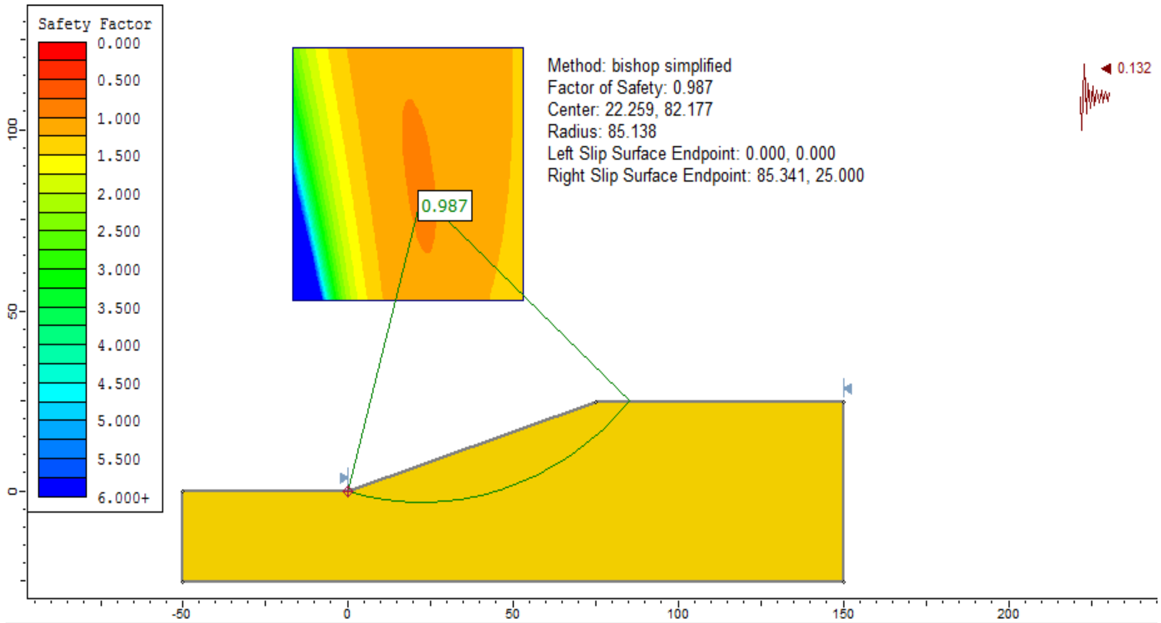


Figure 62.4: Circular slip surface, using the Bishop simplified method

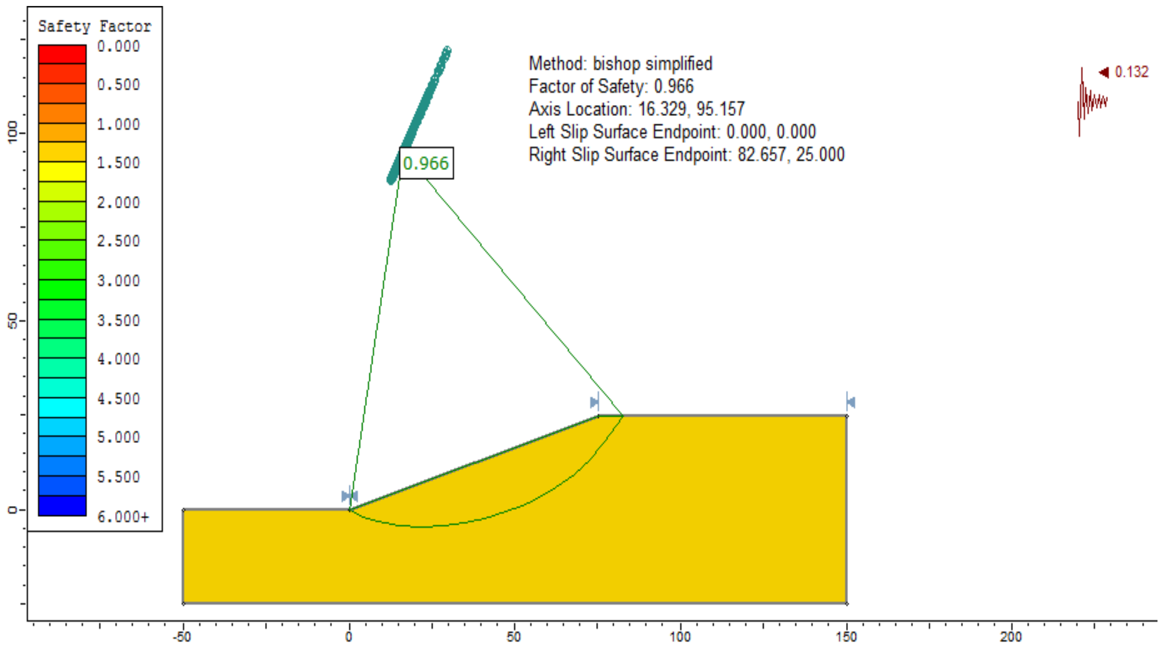


Figure 62.5: Non-circular slip surface, using the Bishop simplified method

63. Slide 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 **Slide** 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

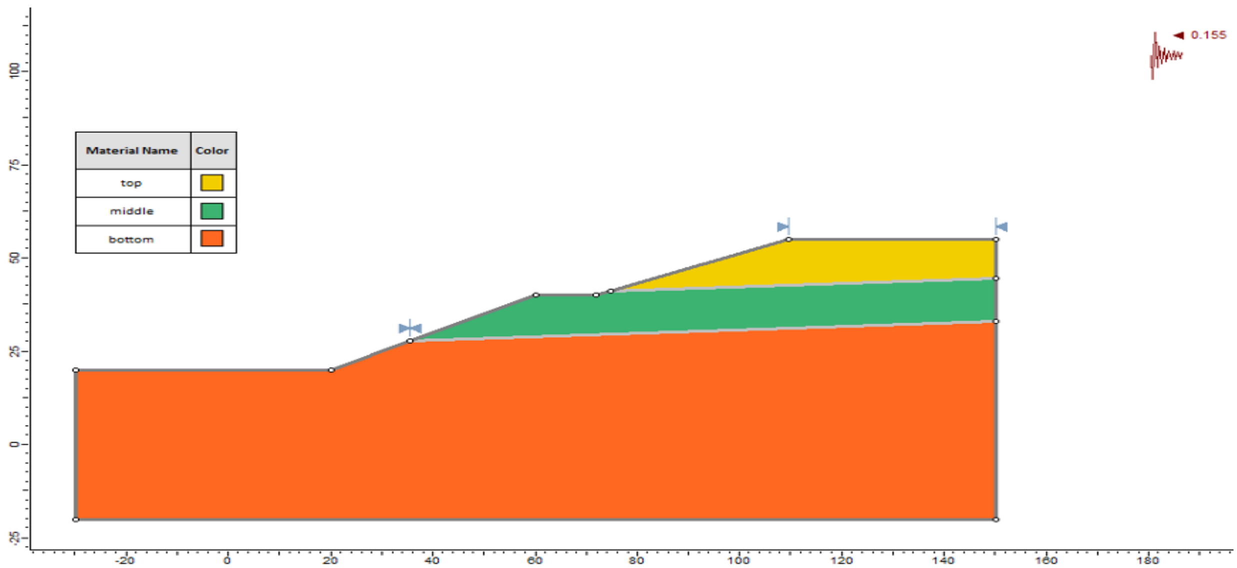


Figure 63.1: Geometry Setup in **Slide**

Table 63.1: Soil Properties

Layer	c (kN/m^2)	ϕ (deg.)	γ (kN/m^3)
Top	4	30	17
Middle	25	15	19
Bottom	15	45	19

63.4. Results

Table 63.2

Method	Factor of Safety
Spencer	0.991

Note: Loukidis factor of safety (Spencer) = 1.000

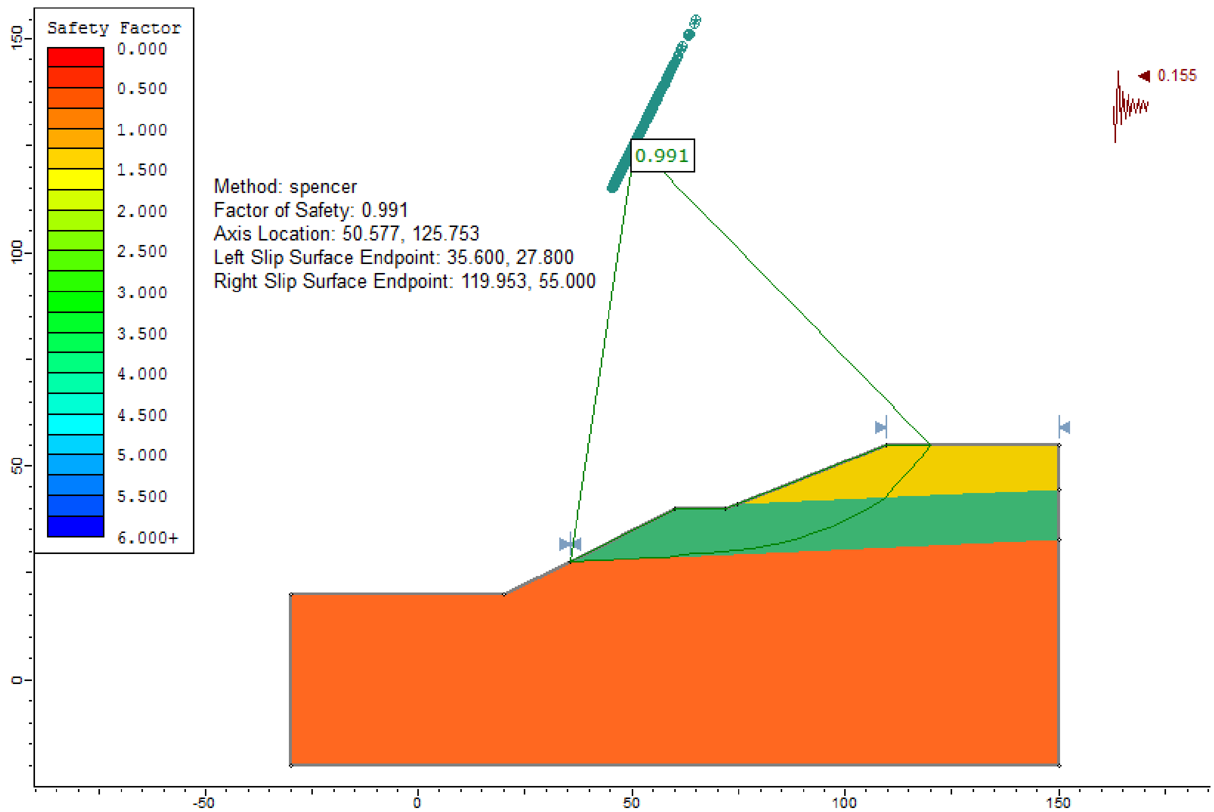


Figure 63.2: Critical slip surface, using the Spencer method

64. Slide 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

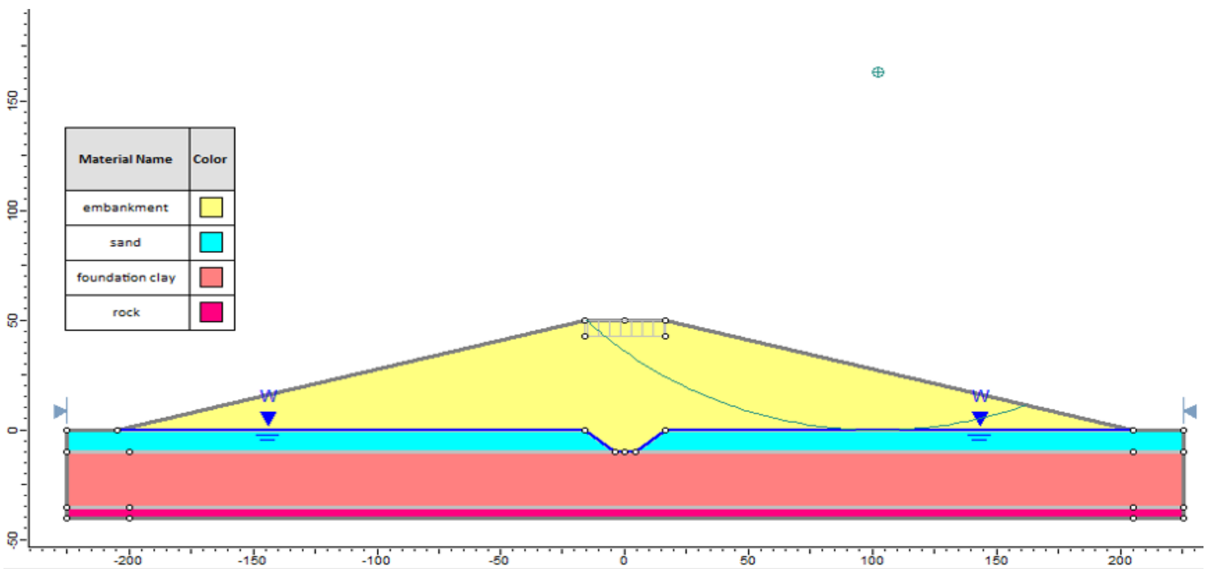


Figure 64.1: Geometry Setup in **Slide**

Table 64.1: Soil Properties

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

64.4. Results

Table 64.2

Method	Factor of Safety
Bishop	2.447
Spencer	2.445
GLE	2.447
Janbu Corrected	2.430

Note: Reference factor of safety (Spencer) = 2.44 [USACE]

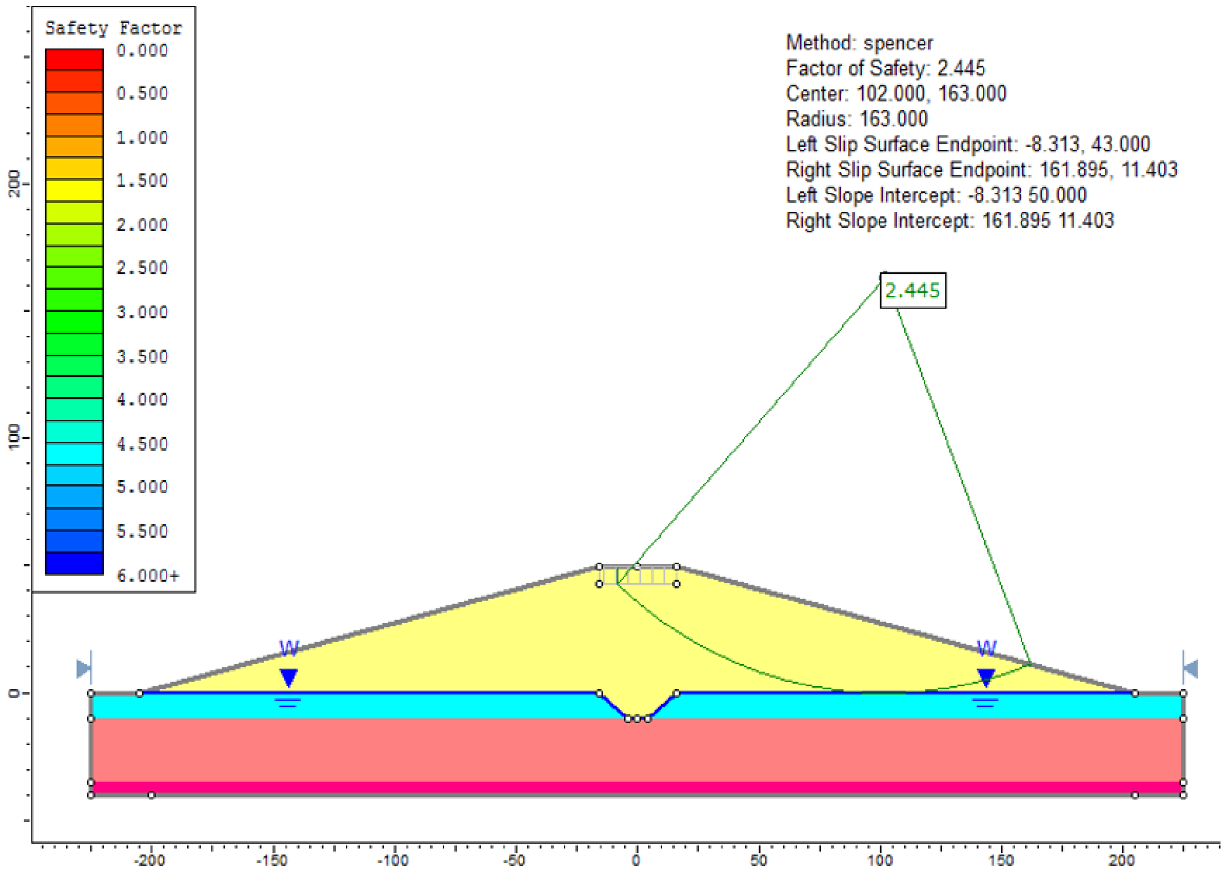


Figure 64.2: Solution, using the Spencer method

65. Slide Verification Problem #65

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

65.1. Introduction

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

65.2. 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.

65.3. Geometry and Material Properties

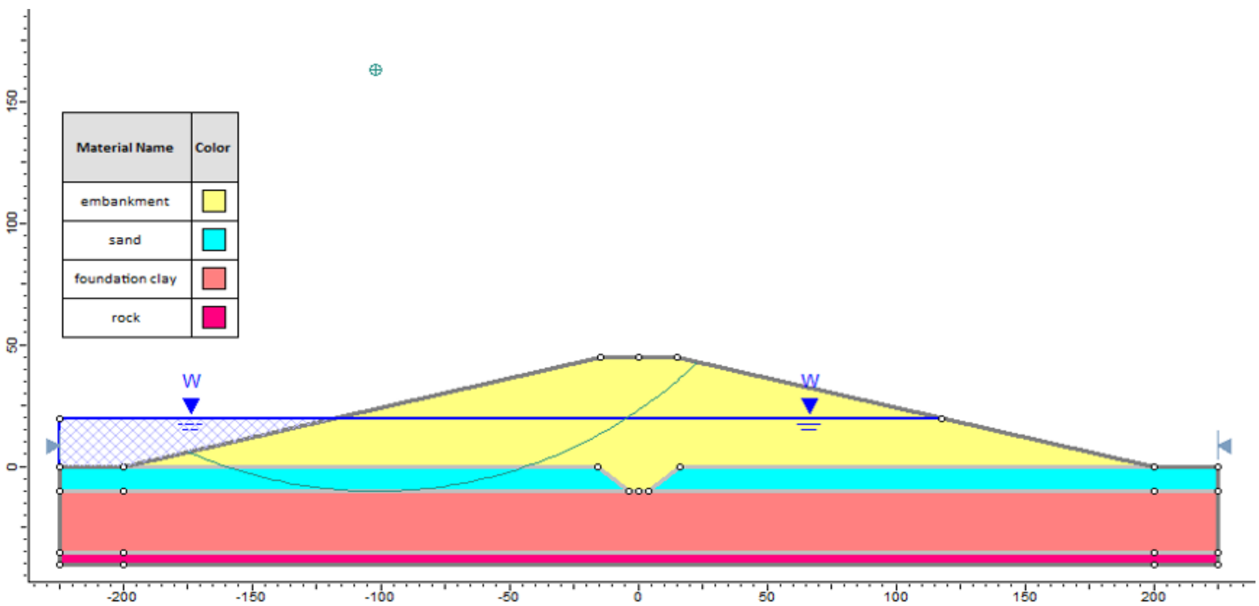


Figure 65.1: Geometry Setup in **Slide**

Table 65.1: Soil Properties

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

65.4. Results

Table 65.2

Method	Factor of Safety
Bishop	2.716
Spencer	2.736
GLE	2.744
Janbu Corrected	2.650

Note: Reference factor of safety (Bishop) = 2.71 [USACE]

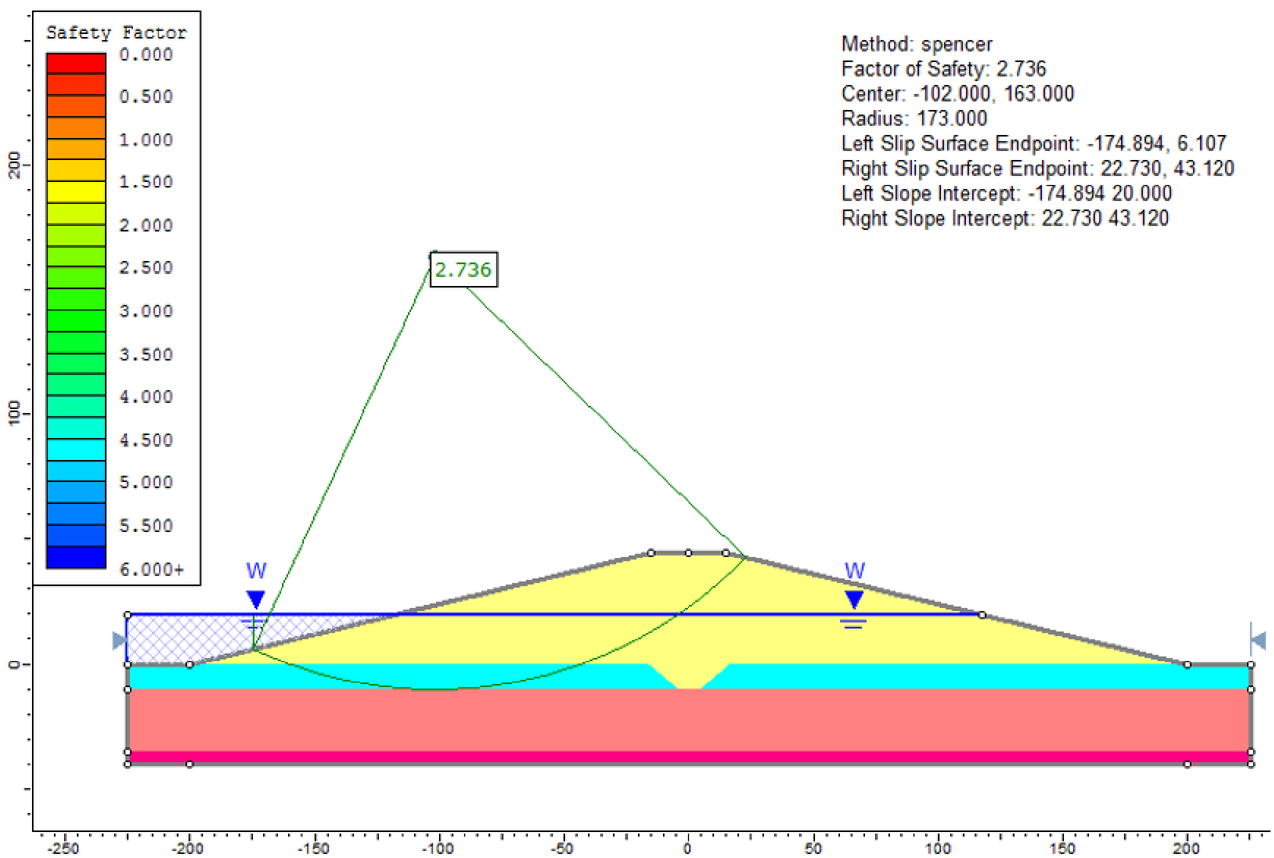


Figure 65.2: Solution, using the Spencer method

66. Slide 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

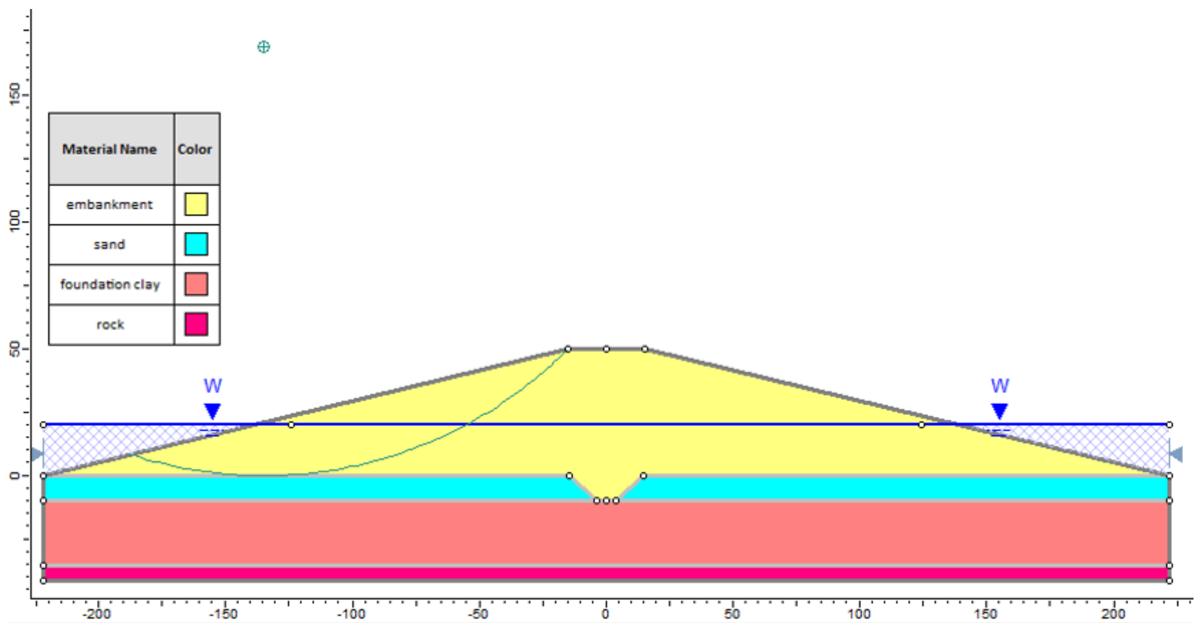


Figure 66.1: Geometry Setup in **Slide**

Table 66.1: Soil Properties

Soil	γ (pcf)	c´ (psf)	ϕ´ (deg.)
Embankment	115	200	25
Foundation Sand	130	0	35
Foundation Clay	115	0	27

66.4. Results

Table 66.2

Method	Factor of Safety
Bishop	2.307
Spencer	2.307
GLE	2.309
Janbu Corrected	2.290

Note: Reference factor of safety = 2.30 [USACE]

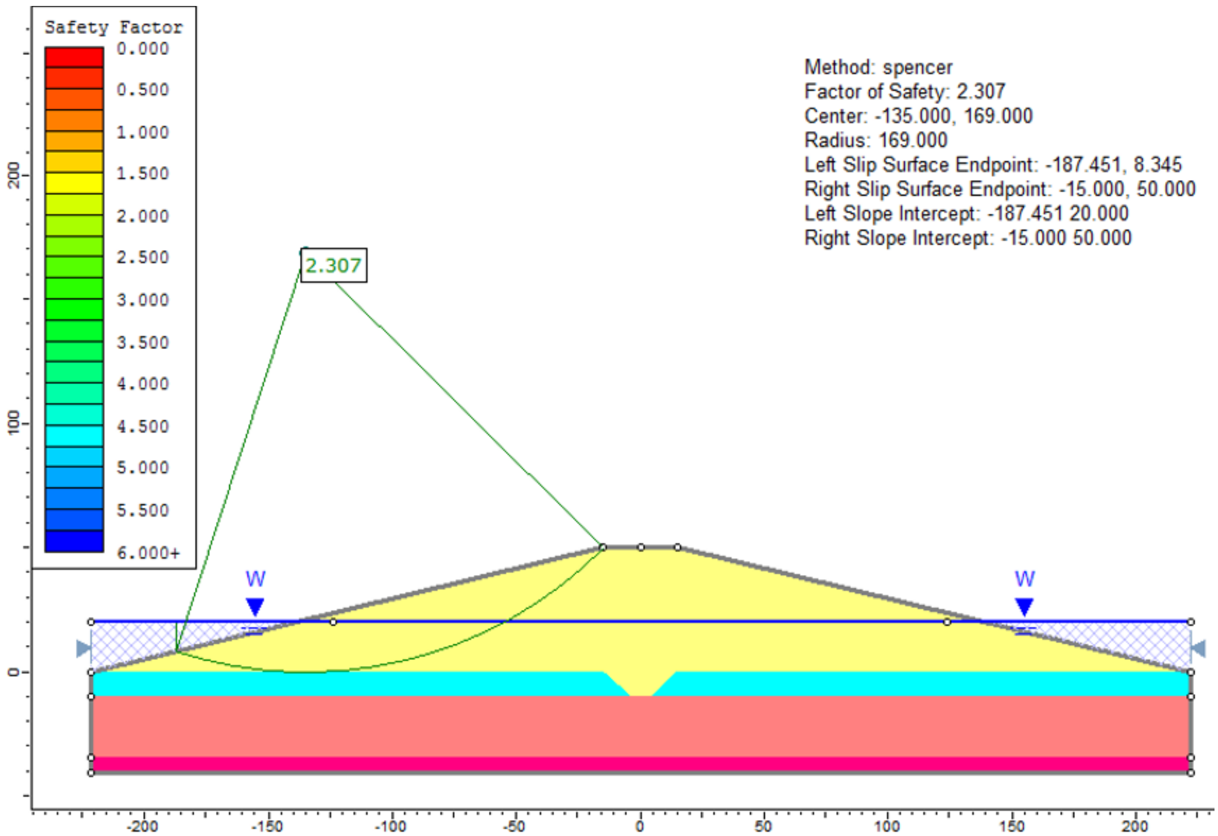


Figure 66.2: Solution, using the Spencer method

67. Slide 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

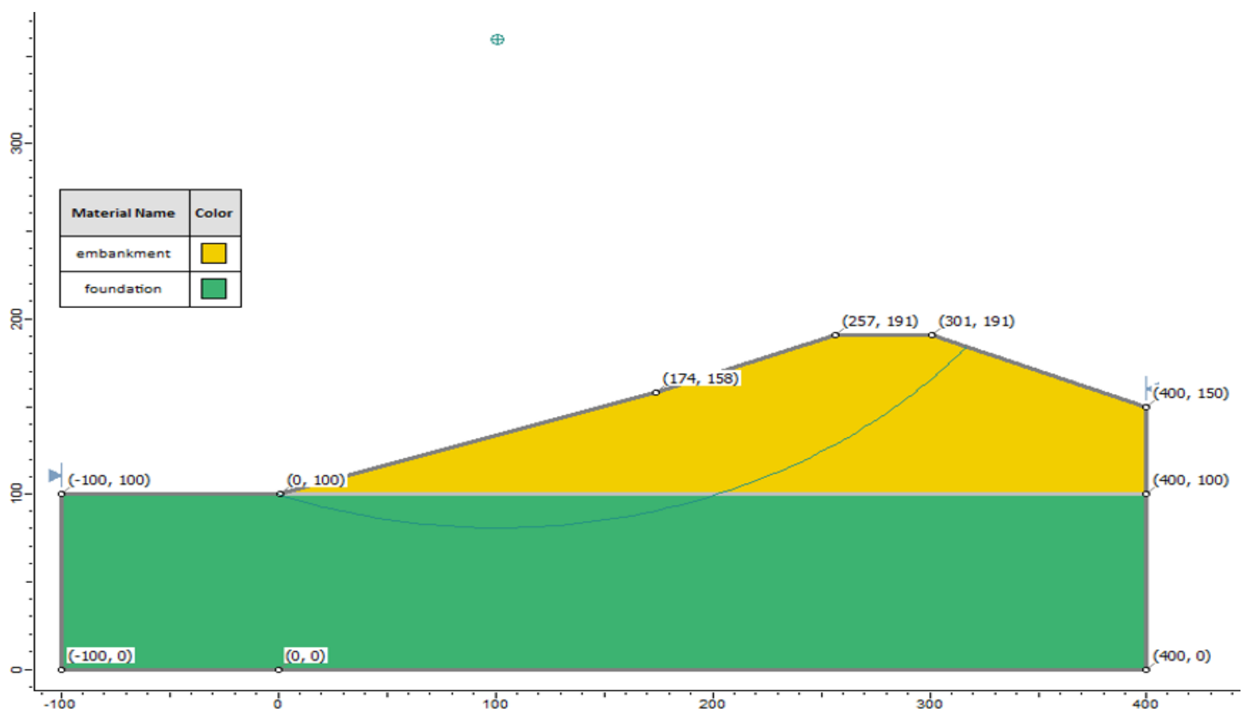


Figure 67.1: Geometry Setup in **Slide**

Table 67.1: Soil Properties

Soil	γ (pcf)	c´ (psf)	ϕ´ (deg.)
Embankment	135	1780	5
Foundation	127	1600	2

67.4. Results

Table 67.2

Method	Factor of Safety
Bishop	1.332
Spencer	1.328
GLE	1.327
Janbu Corrected	1.345

Note: Reference factor of safety = 1.33 [USACE]

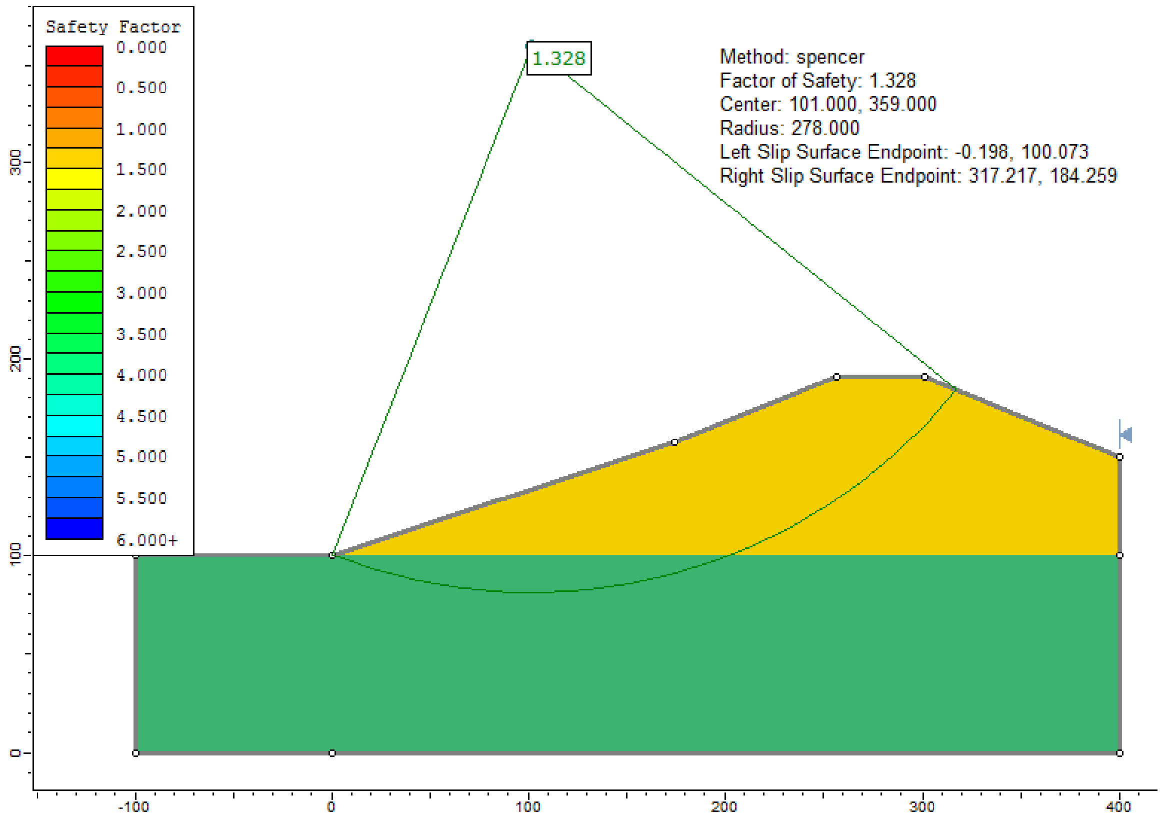


Figure 67.2: Solution, using the Spencer method

68. Slide Verification Problem #68

Embankment, (3) materials, ponded water

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 (ϕ = 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

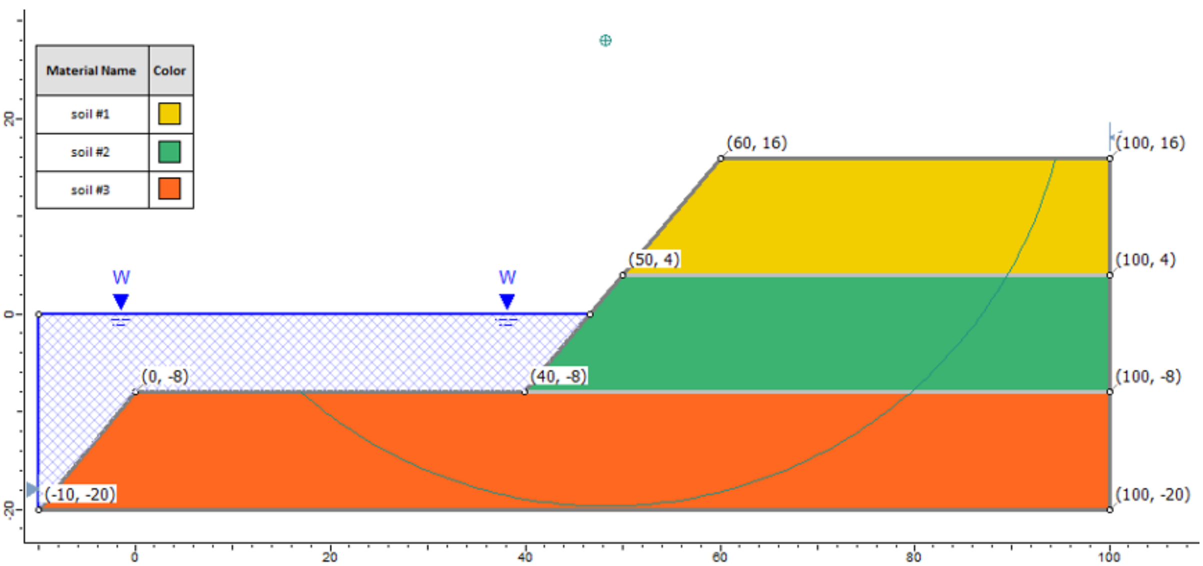


Figure 68.1: Geometry Setup in **Slide**

Table 68.1: Soil Properties

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

68.4. Results

Table 68.2

Method	Factor of Safety
Bishop	1.241
Spencer	1.241
GLE	1.244
Janbu Corrected	1.385

Note: Reference Factor of Safety = 1.33 [USACE]

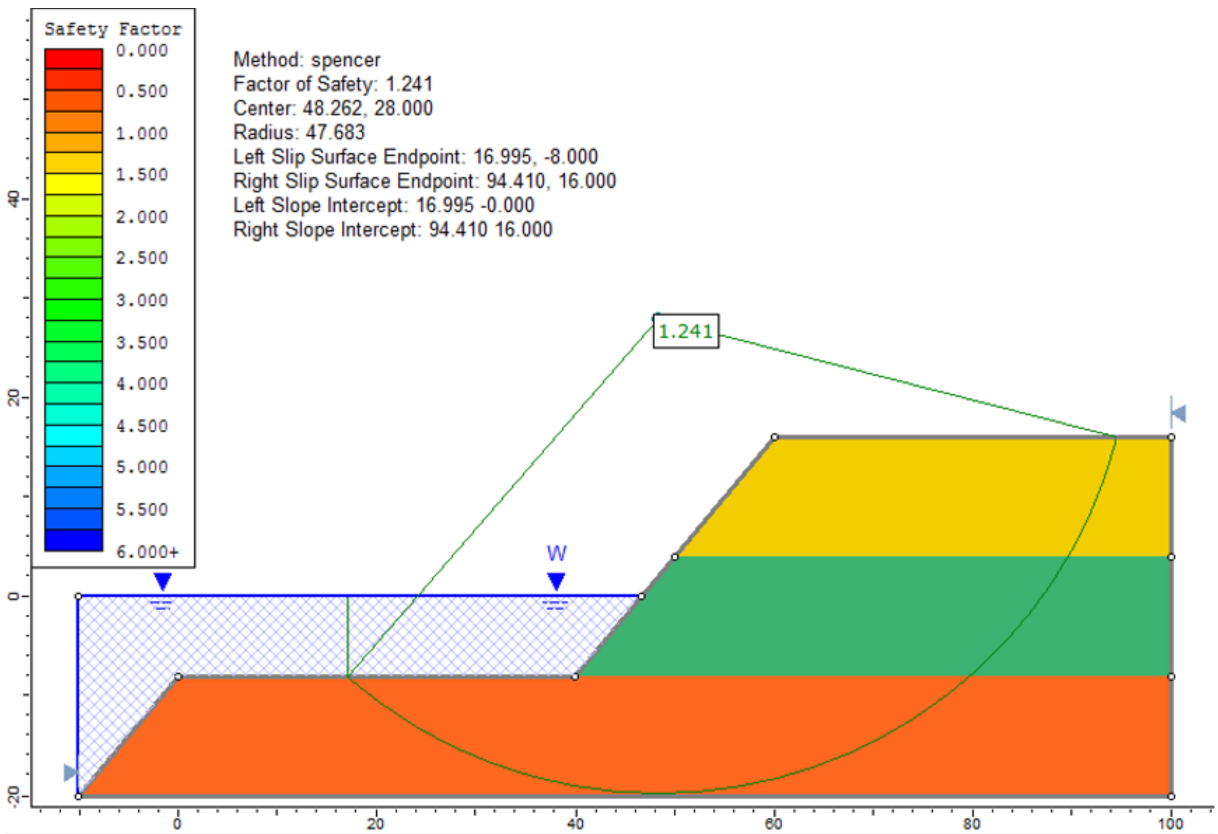


Figure 68.2: Solution, using the Spencer method

69. Slide 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

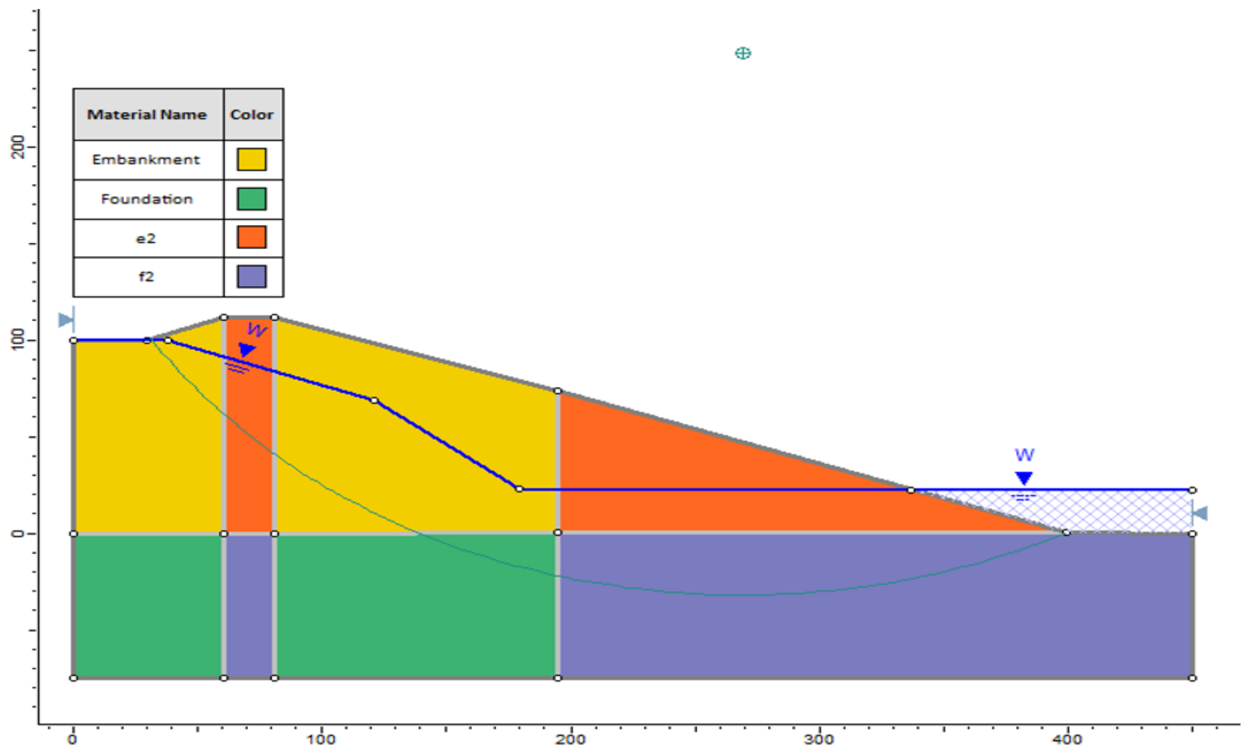


Figure 69.1: Geometry Setup in **Slide**

Table 69.1: Soil Properties

Soil	γ (pcf)	c´ (psf)	ϕ´ (deg.)
Embankment	130	0	34
Foundation	125	0	35

69.4. Results

Table 69.2

Method	Factor of Safety
Bishop	2.011
Spencer	2.026
GLE	2.027
Janbu Corrected	1.830

Note: Reference factor of safety = 2.01 [USACE]

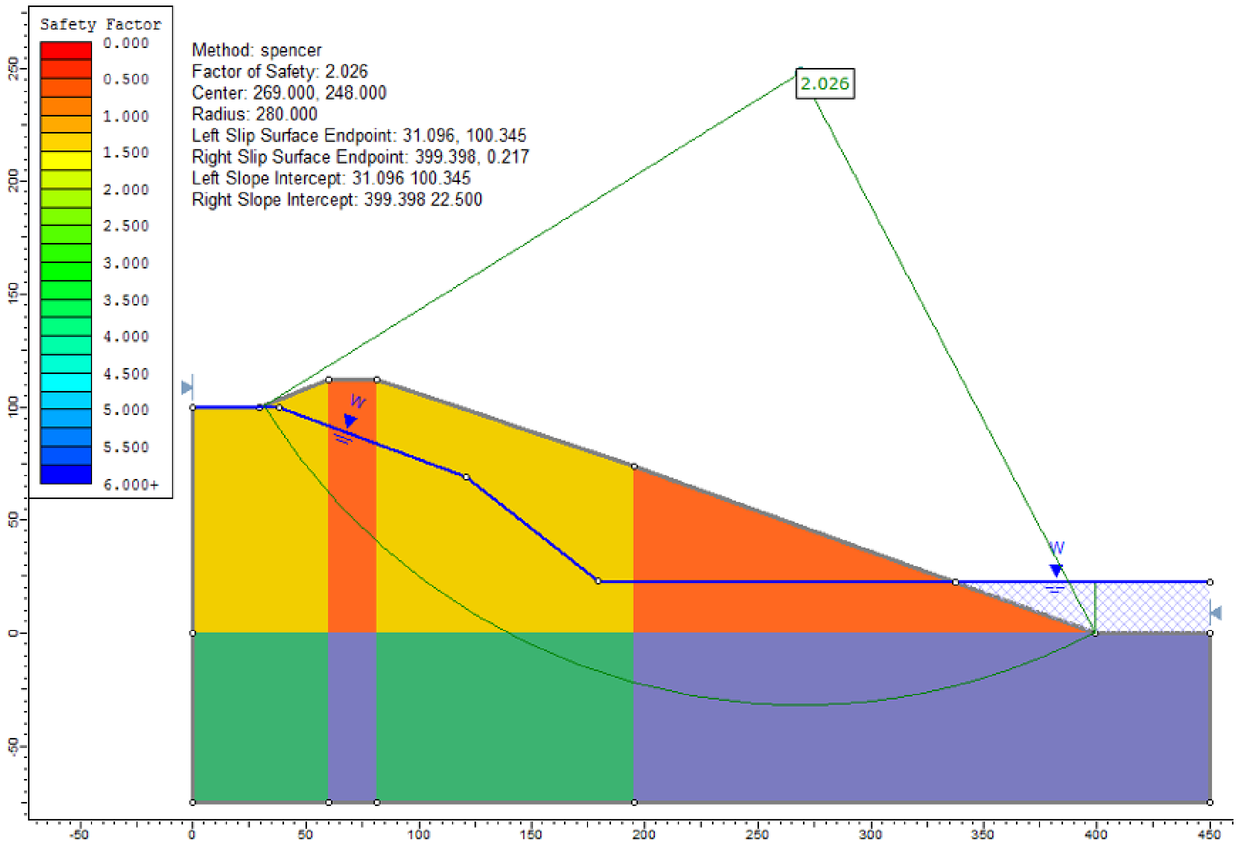


Figure 69.2: Solution, using the Spencer method

70. Slide Verification Problem #70

Submerged slope, homogenous, 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

Figure 70.1 and Figure 70.2 show a submerged slope with different water levels above the slope. The slope is homogeneous. The critical slip surface is assumed to be circular and located using auto refine search.

70.3. Geometry and Material Properties

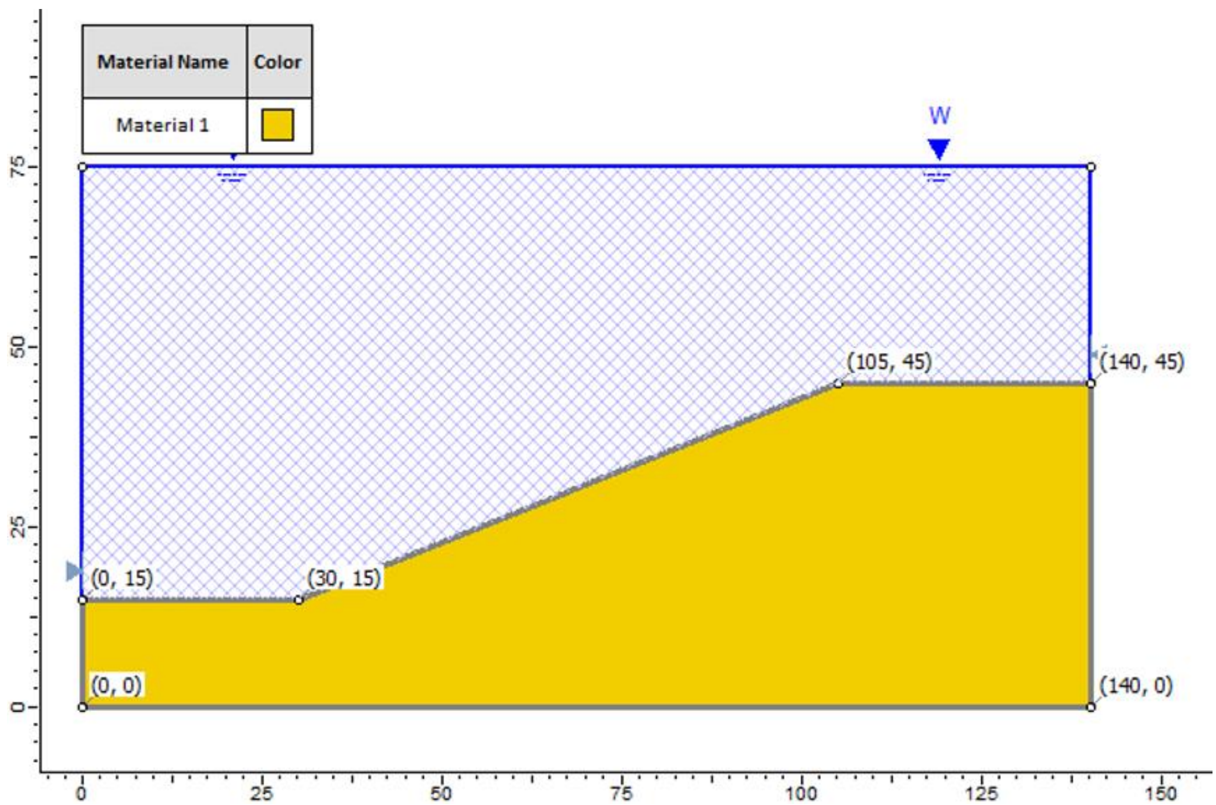


Figure 70.1: Water Table at 30' above the Crest (Case 1)

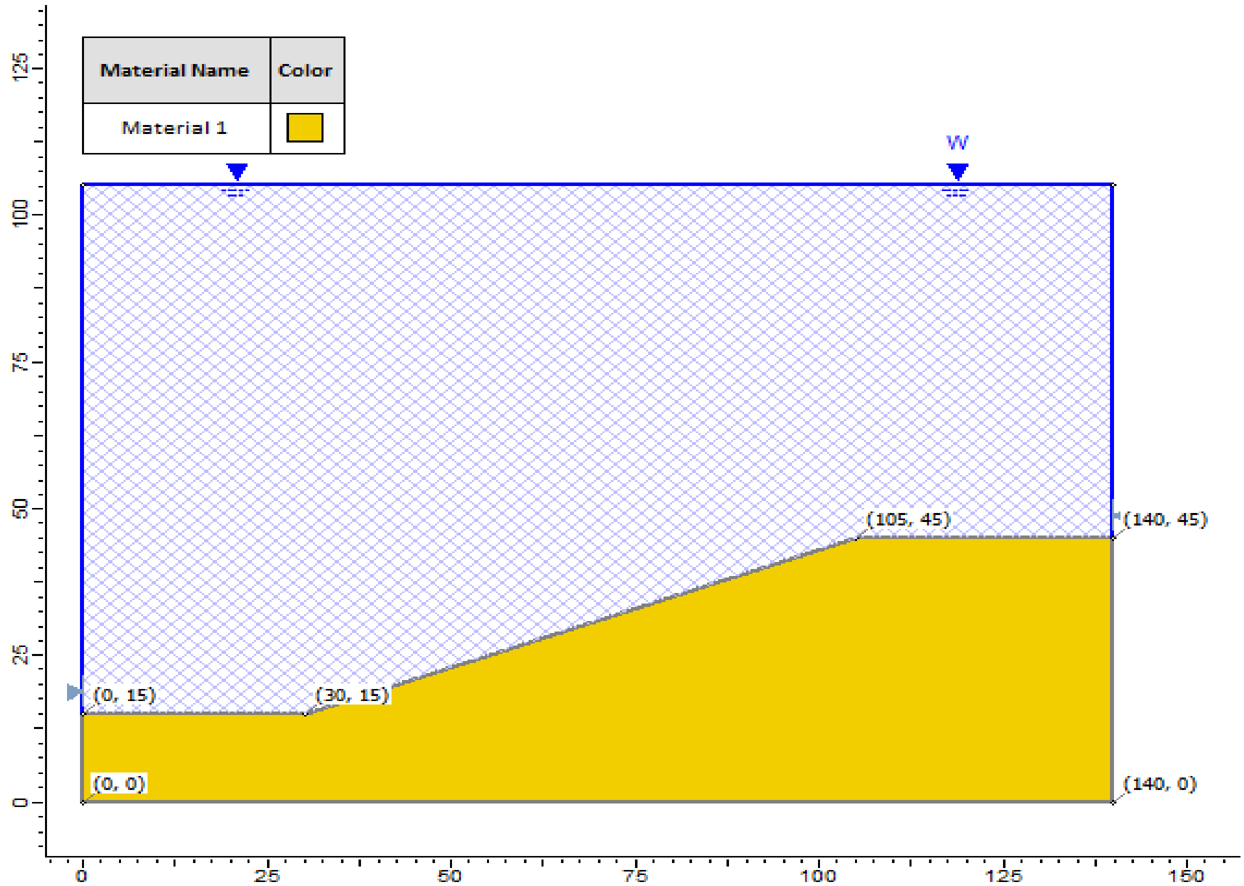


Figure 70.2: Water Table at 60’ above the Crest (Case 2)

Table 70.1: Soil Properties

γ (pcf)	c´ (psf)	ϕ´ (deg.)
128	100	20

70.4. Results

Table 70.2: Case 1 – Water table at 30 feet above the crest

Method	Factor of Safety (Circular)	Factor of Safety (Non-Circular)
Bishop	1.603	1.560
Spencer	1.599	1.592
GLE	1.599	1.592

Note: Reference factor of safety = 1.60 [Duncan and Wright]

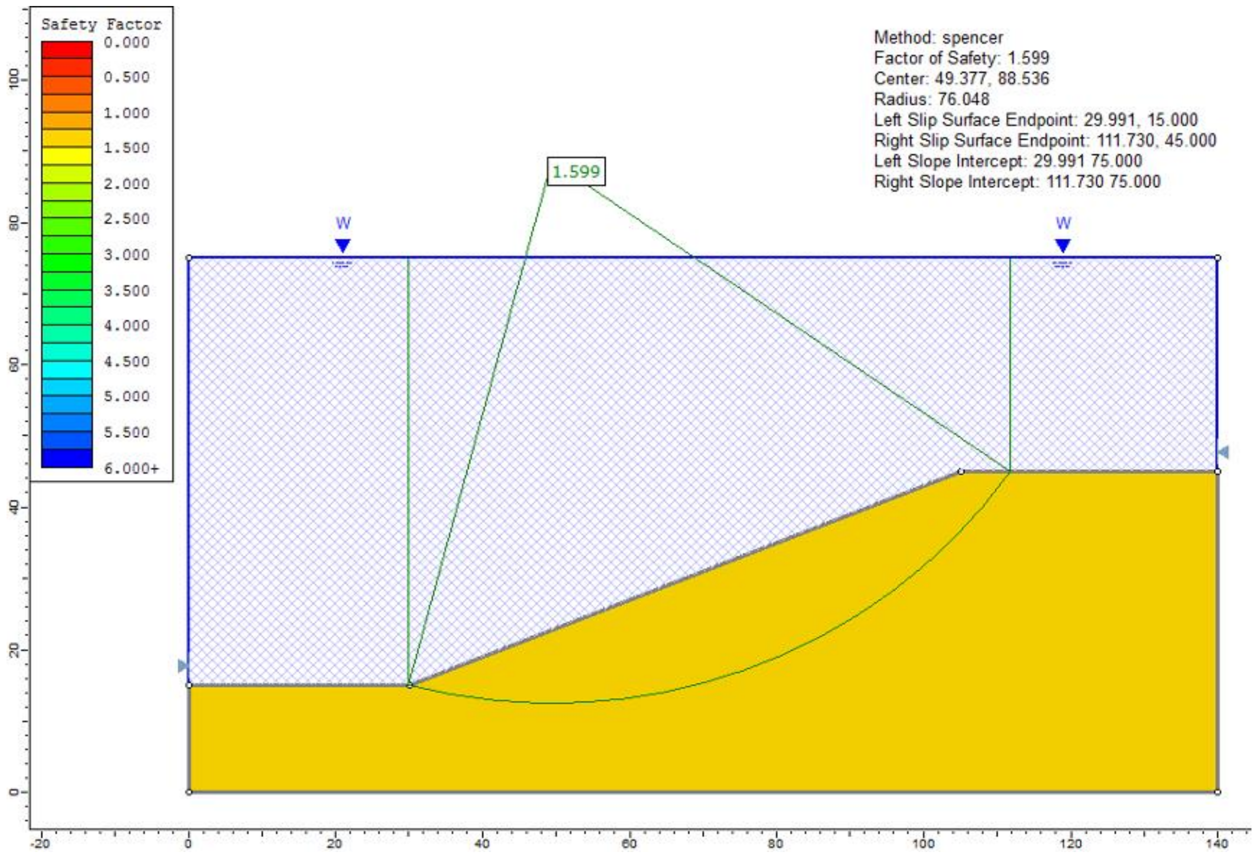


Figure 70.3: Solution to case 1 (circular), using the Spencer Method

Table 70.3: Case 2 – Water table at 60 feet above the crest

Method	Factor of Safety (Circular)	Factor of Safety (Non-Circular)
Bishop	1.603	1.560
Spencer	1.599	1.590
GLE	1.599	1.579

Note: Reference factor of safety = 1.60 [Duncan and Wright]

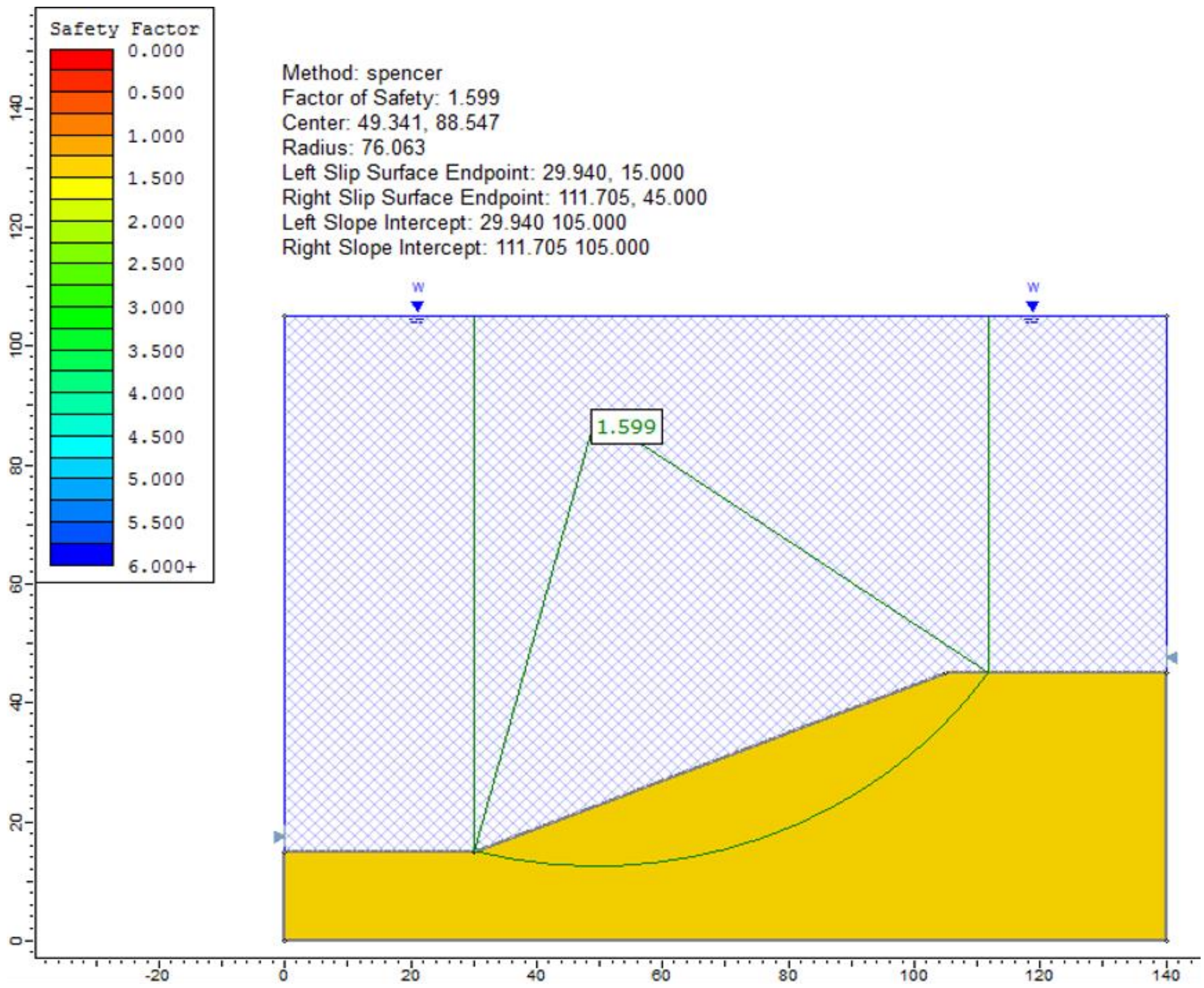


Figure 70.4: Solution to case 2 (circular), using the Spencer method

71. Slide Verification Problem #71

Slope, homogenous, 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

A homogeneous slope with water level located at 75 ft at the right end (Figure 71.1). The pore water pressure is modelled using finite element seepage analysis in case 1 (Figure 71.1) and using piezometric line approximation in case 2 (Figure 71.2). The critical slip surface is assumed to be circular and located using auto refine search for both cases.

71.3. Geometry and Material Properties

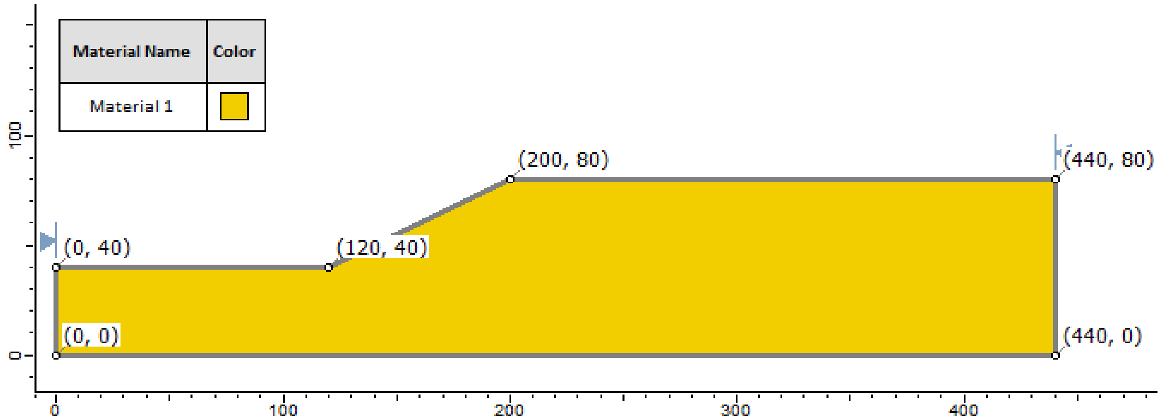


Figure 71.1: Finite Element Seepage Analysis (Case 1)

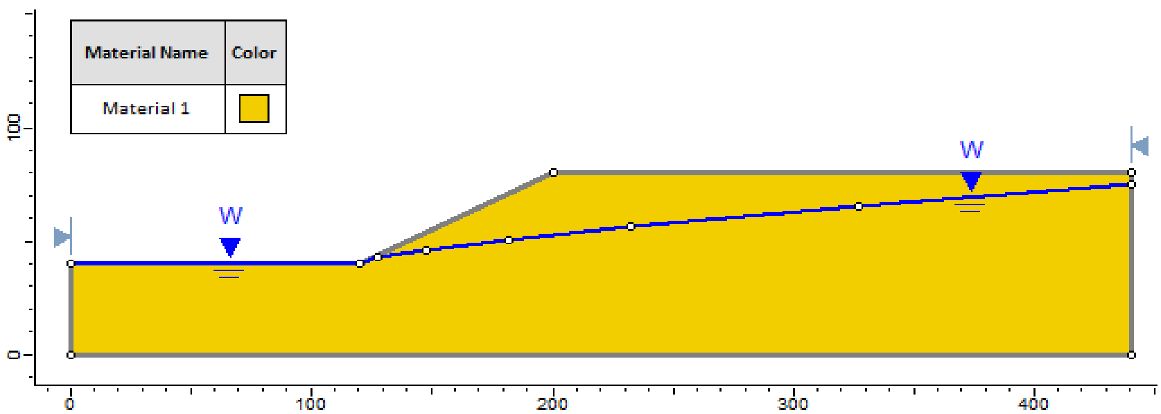


Figure 71.2: Piezometric Line Approximation (Case 2)

Table 71.1: Soil Properties

c´ (psf)	ϕ´ (º)	γ (pcf)
200	20	125

71.4. Results

Table 71.2: Case 1 – Finite Element seepage analysis

Method	Factor of Safety (Circular)	Factor of Safety (Non-Circular)
Bishop	1.141	1.081
Spencer	1.141	1.146
GLE	1.141	1.157

Note: Reference factor of safety = 1.138 [Duncan and Wright]

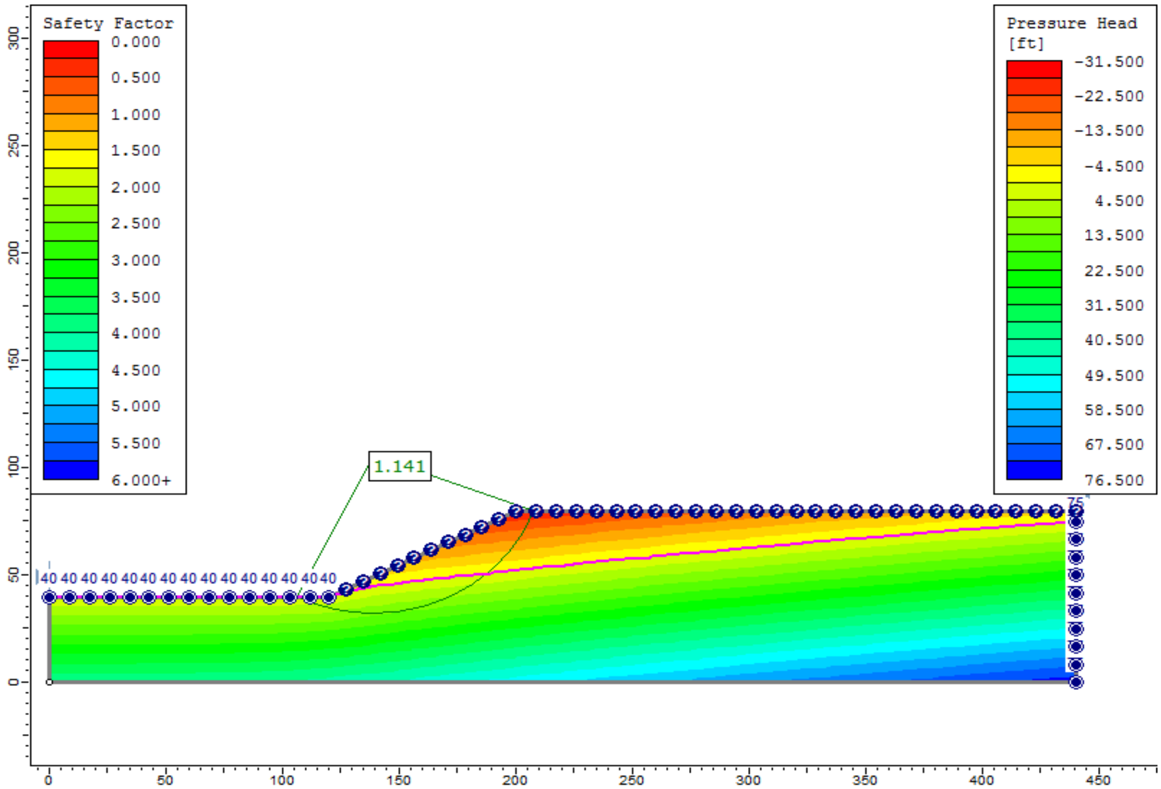


Figure 71.3: Solution to Case 1, using the Spencer method

Table 71.3: Case 2 – Piezometric Line approximation

Method	Factor of Safety (Circular)	Factor of Safety (Non-Circular)
Bishop	1.142	1.081
Spencer	1.142	1.146
GLE	1.141	1.157

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

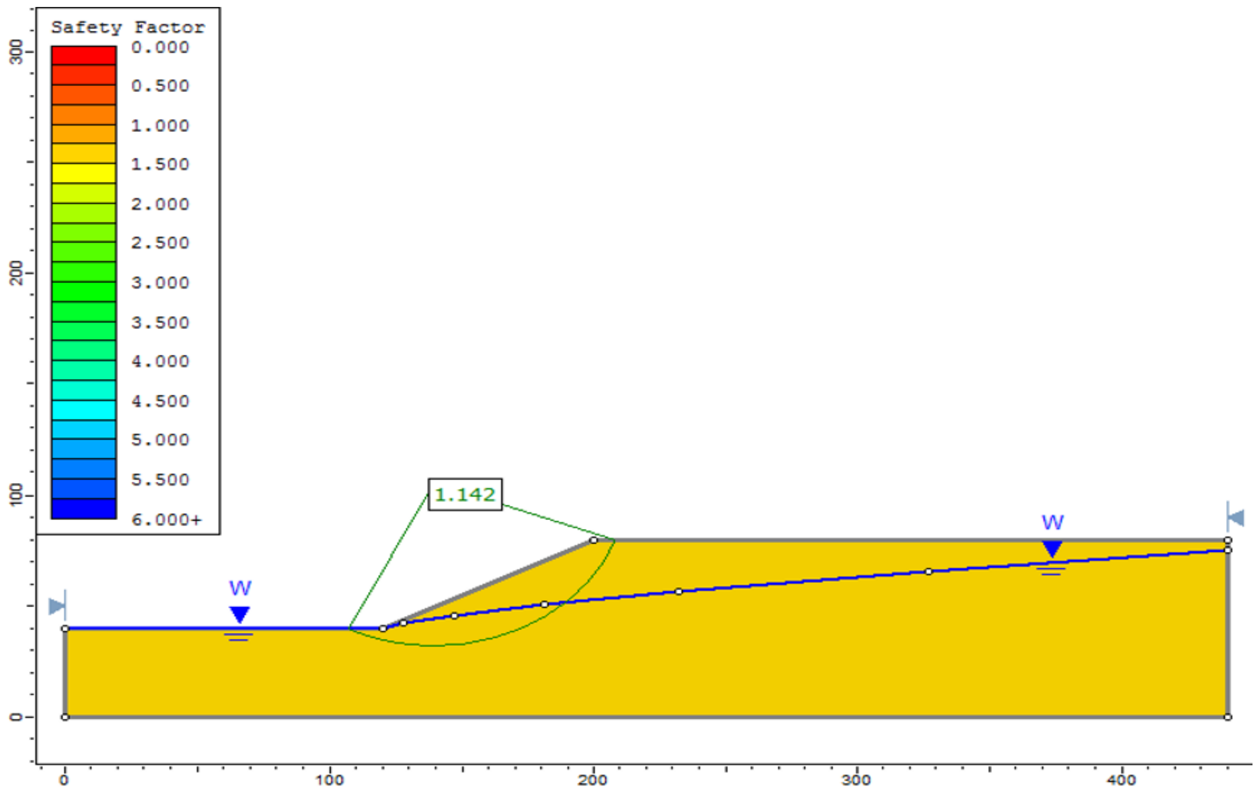


Figure 71.4: Solution to Case 2, using the Spencer method

72. Slide 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 and Figure 6.40 on page 101 of Duncan and Wright (2005).

72.2. Problem Description

A symmetric earth embankment dam resting on a layered soil foundation with ponded water of elevation 302 feet on the left side is shown in Figure 72.1 and 72.2. The left face and right face of the dam is constructed using shell material. The pore water pressure is modelled using two approaches. They are finite element seepage analysis and piezometric line approximation. 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 is of interest in case 2. Both circular and non-circular critical slip surfaces were studied in case 1 and only circular critical slip surface was studied in case 2.

72.3. Geometry and Material Properties

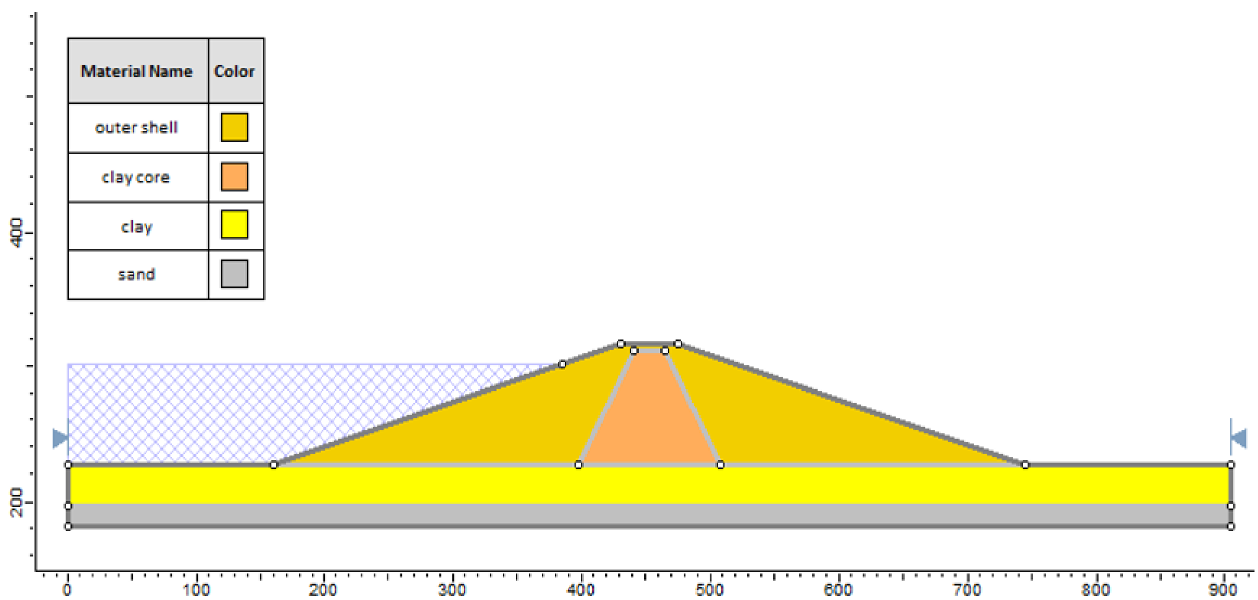


Figure 72.1: Finite Element Seepage Analysis

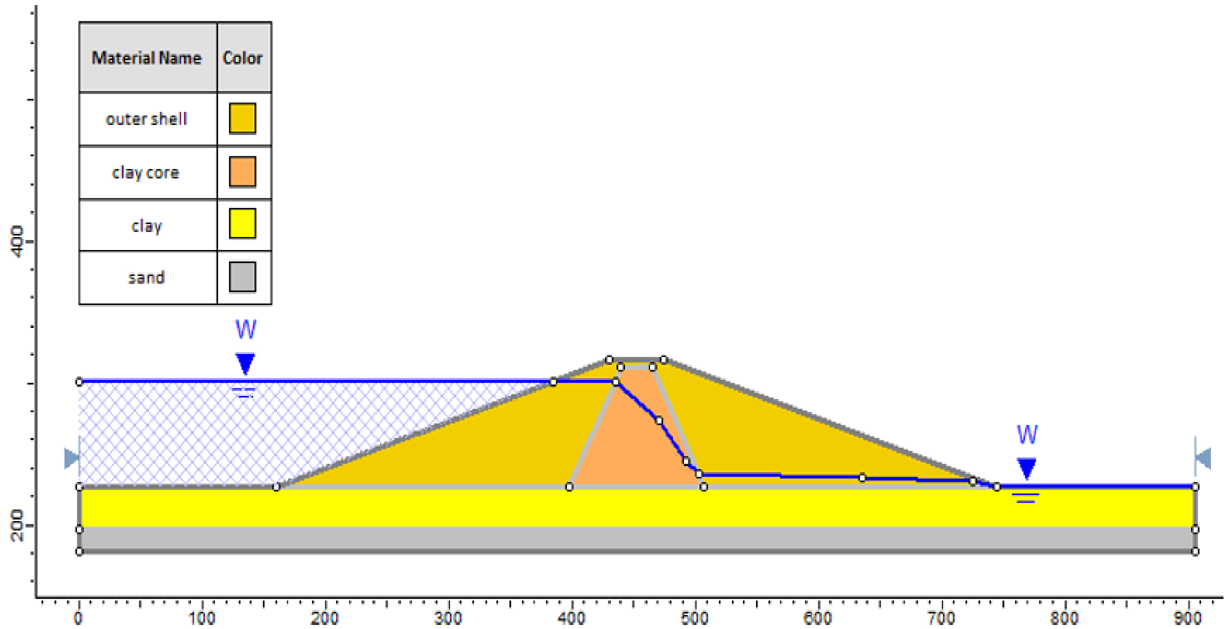


Figure 72.2: Piezometric Line Approximation

Table 72.1: Soil Properties

Material	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

72.4. Results

Table 72.2: Case 1(a) – Global critical slip surface - finite element seepage analysis

Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Bishop	1.149	0.988
Spencer	1.158	1.085
GLE	1.161	1.096

Note: Reference factor of safety = 1.11 [Duncan and Wright]

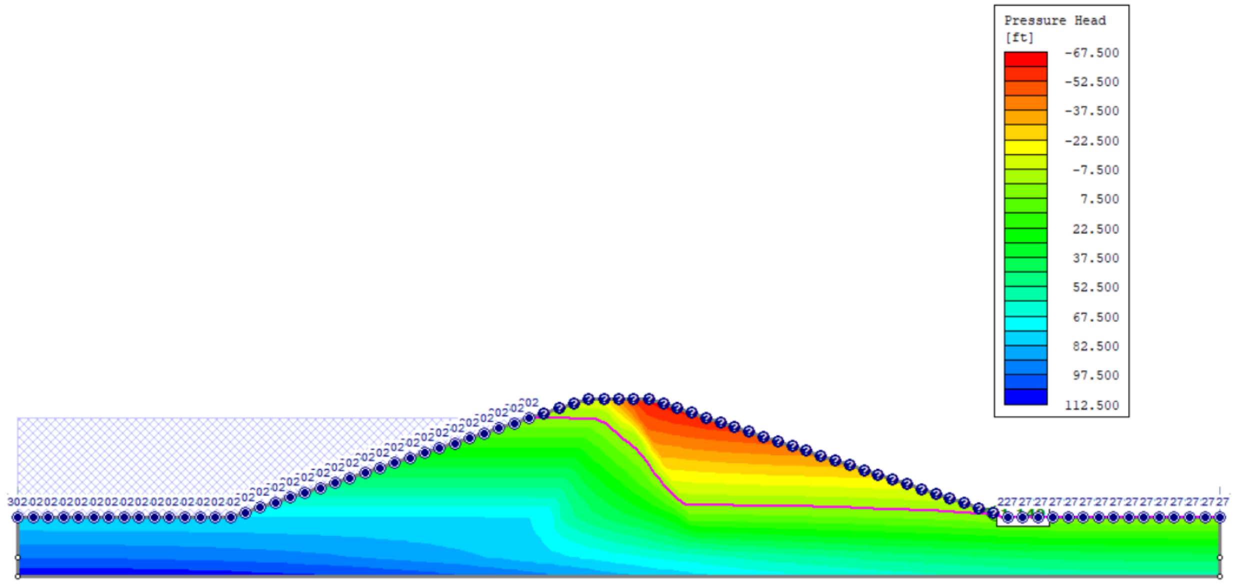


Figure 72.3: Solution to Case 1(a) (Circular), using the Bishop method

Table 72.3: Case 1(b) – Global critical slip surface - piezometric line approximation

Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Bishop	1.306	1.196
Spencer	1.301	1.241
GLE	1.303	1.232

Note: Reference factor of safety = 1.30 [Duncan and Wright]

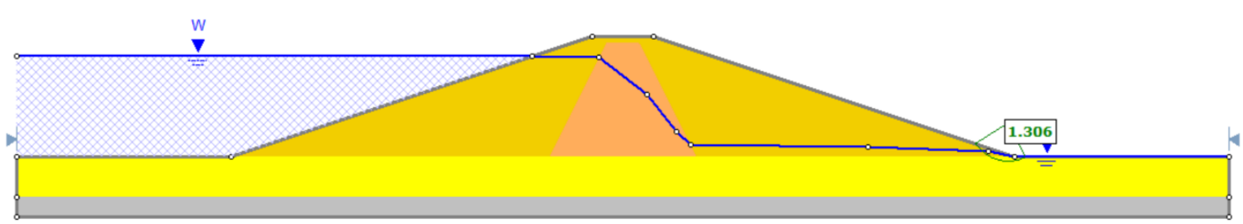


Figure 72.4: Solution to Case 1(b) (Circular), using the Bishop method

Table 72.4: Case 2(a) – Critical slip surface tangent to El. 197 – finite element seepage analysis

Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Bishop	1.312	1.236
Spencer	1.312	1.382
GLE	1.319	1.395

Note: Reference factor of safety = 1.37 [Duncan and Wright]

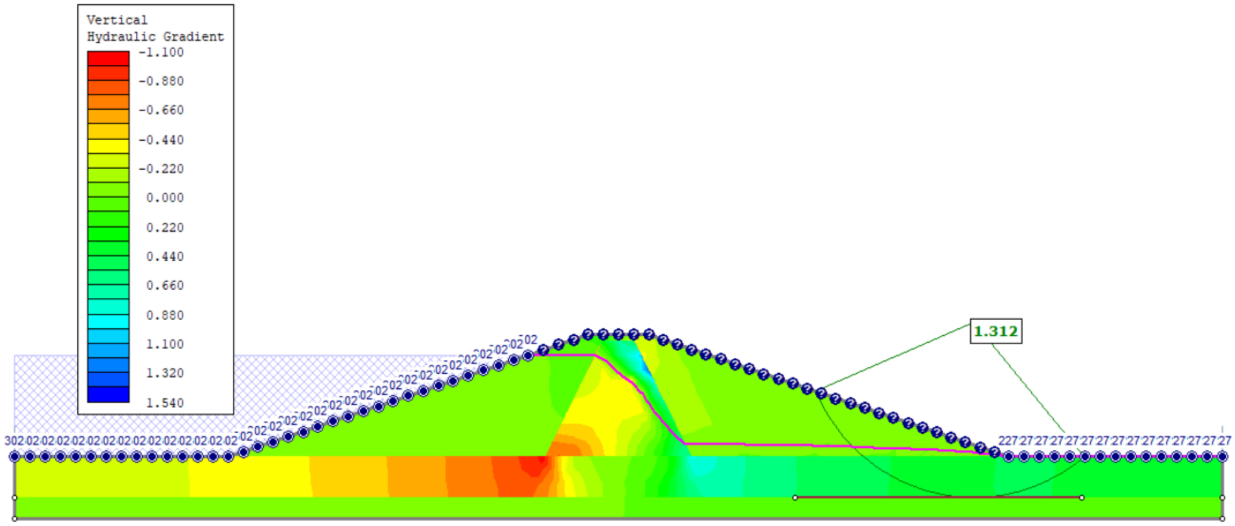


Figure 72.5: Solution to Case 2(a), using the Spencer method

Table 72.5: Case 2(b) – Critical slip surface tangent to El. 197 – piezometric line approximation

Method	Factor of Safety (circular)	Factor of Safety (non-circular)
Bishop	1.563	1.489
Spencer	1.557	1.632
GLE	1.556	1.630

Note: Reference factor of safety = 1.57 [Duncan and Wright]

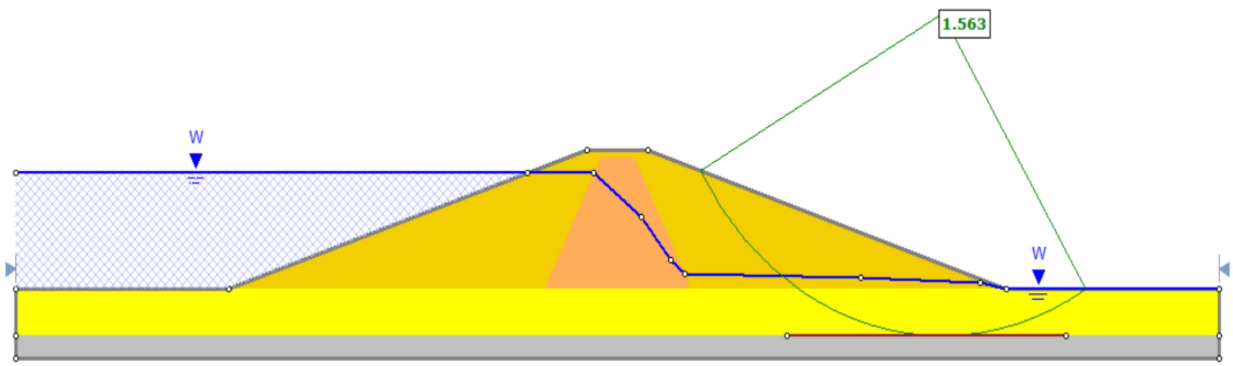


Figure 72.6: Solution to Case 2(b), using the Bishop method

73. Slide Verification Problem #73

Excavated slope, (4) materials, tension crack

73.1. Introduction

This problem is an analysis of the excavated slope for reactor 1 at Bradwell (Duncan and Wright, 2005 and Skempton and LaRochelle, 1965).

73.2. Problem Description

Figure 73.2 shows the cross section of the excavated slope. The lower part of the excavation is in the London Clay and is inclined at ½: 1 (H:V). The London Clay is overlain by Marsh Clay. The clay fill from the excavation is placed on top of the Marsh clay. The Marsh Clay and the clay fill are both inclined at 1:1 (H:V). The clay fill is modelled to crack to the full depth of the fill (11.4). The critical slip surface is assumed to be circular for all cases.

73.3. Geometry and Material Properties

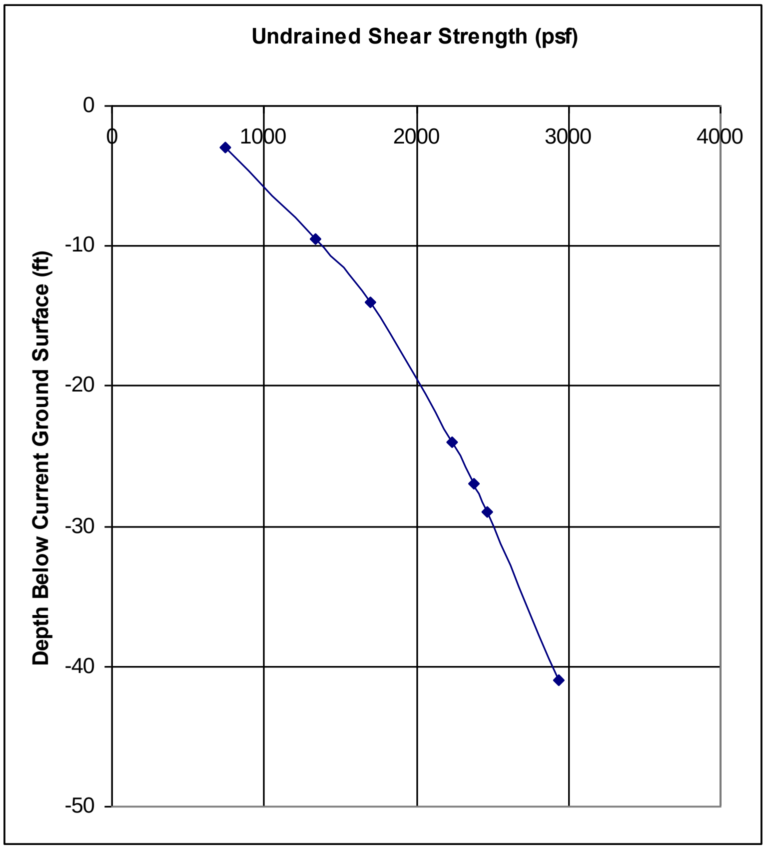


Figure 73.1: Approximation of Undrained Shear Strength Profile Based on Undrained Shear Strength Profile from Skempton and LaRochelle (1965)

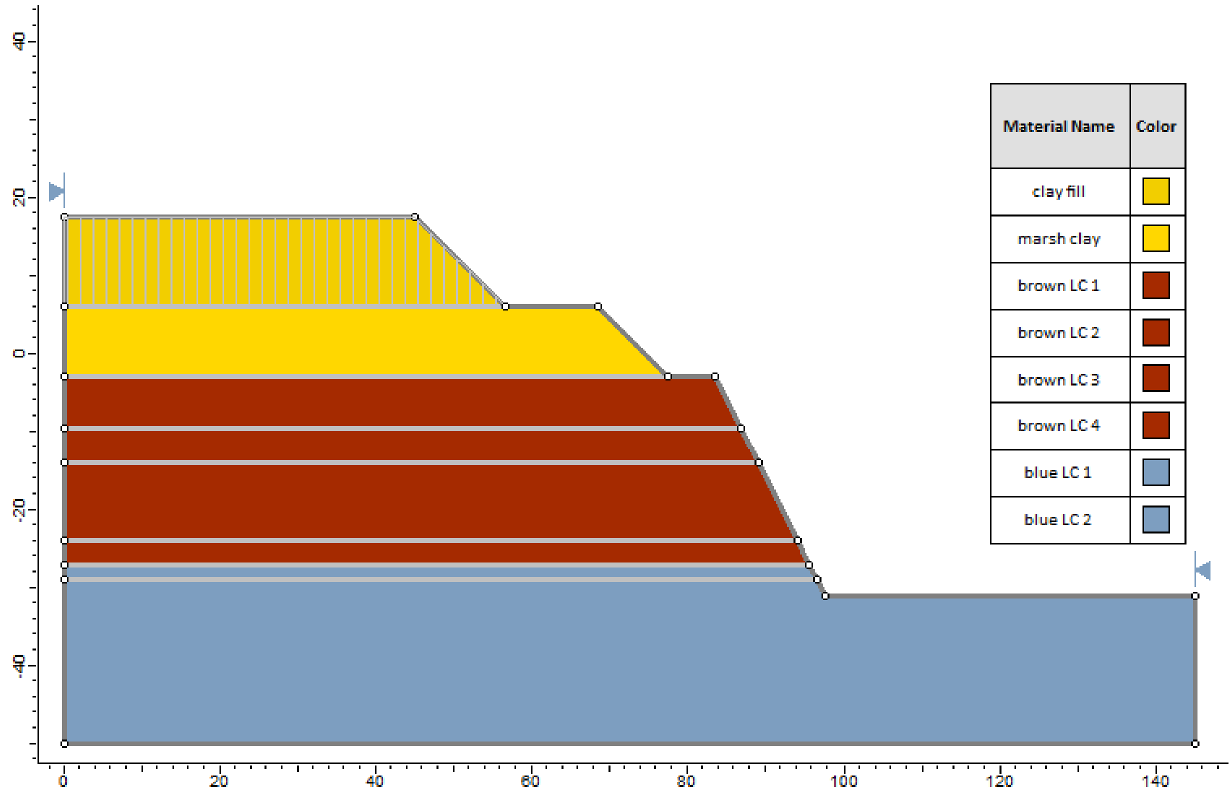


Figure 73.2: Excavated Slope Geometry in **Slide**

Table 73.1: Soil Properties

Material	c (psf)	ϕ (°)	γ (pcf)
Clay Fill	1	35	110
Marsh Clay	300	0	105
London Clay (brown and blue)	$c_z + (y_z - y)\Delta c_z$	0	120

Table 73.2: Undrained Strength Parameters for London Clay

c_z (psf)	Depth, y_z (ft)	y (ft)	Δc_z (psf/ft)
750	- 3 to -9.5	-3	90
1335	-9.5 to -14	-9.5	82
1704	-14 to -24	-14	53
2234	-24 to -27	-24	47
2375	-27 to -29	-27	47
2469	< -29	-29	39

73.4. Results

Table 73.2

Method	Reference Factor of Safety [Duncan and Wright]	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.76	1.762	1.696
Janbu Simplified	1.63	1.628	1.589
Janbu Corrected	1.74	1.736	1.676
Spencer	1.76	1.758	1.712

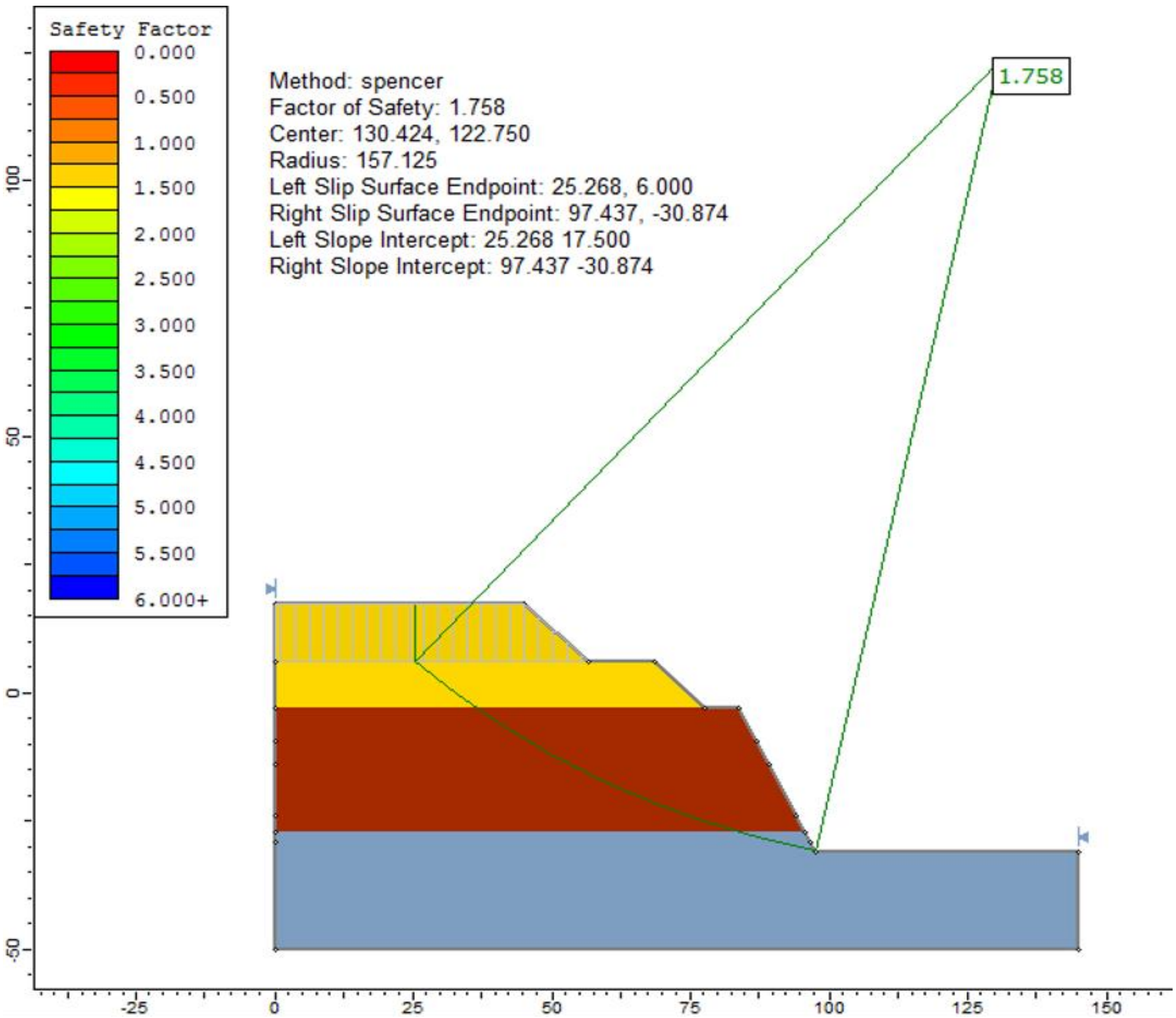


Figure 73.3: Solution, using the Spencer method (Circular)

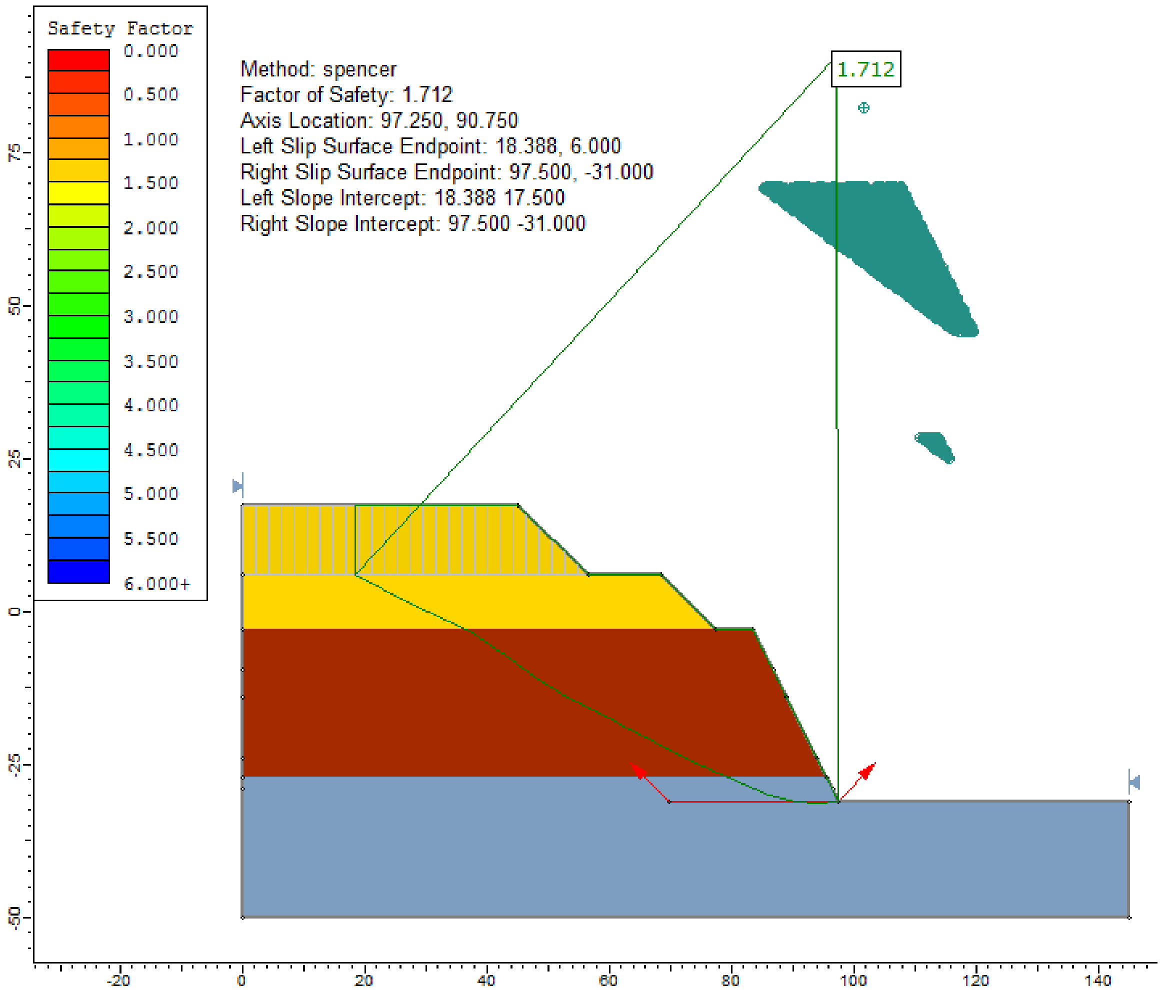


Figure 73.4: Solution, using the Spencer method (Non-circular)

74. Slide 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

Figure 74.1 shows an embankment constructed of cohesionless material resting on saturated clay foundation. The critical slip surface is assumed to be circular and located using auto refine search.

74.3. Geometry and Material Properties

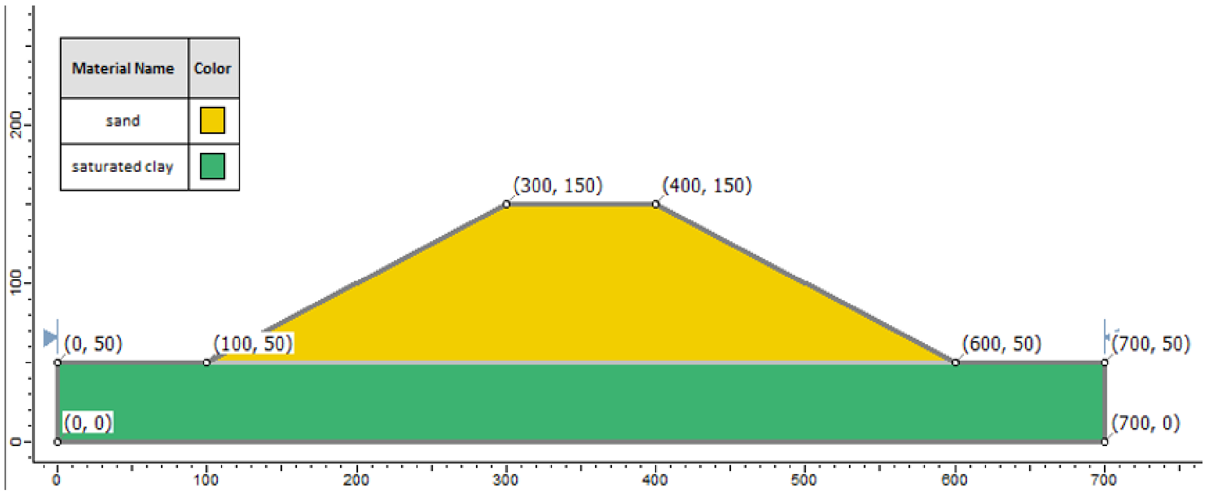


Figure 74.1: Sand Embankment on Saturated Clay Foundation

Table 74.1: Soil Properties

Material	c (psf)	ϕ (^{0})	γ (pcf)
Embankment (Sand)	0	40	140
Foundation (Saturated Clay)	2500	0	140

74.4. Results

Table 74.2

Method	Reference Factor of Safety [Duncan and Wright]	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.22	1.228	1.087
Janbu Simplified	1.07	1.079	1.032
Janbu Corrected	1.16	1.174	1.124
Spencer	1.19	1.201	1.190

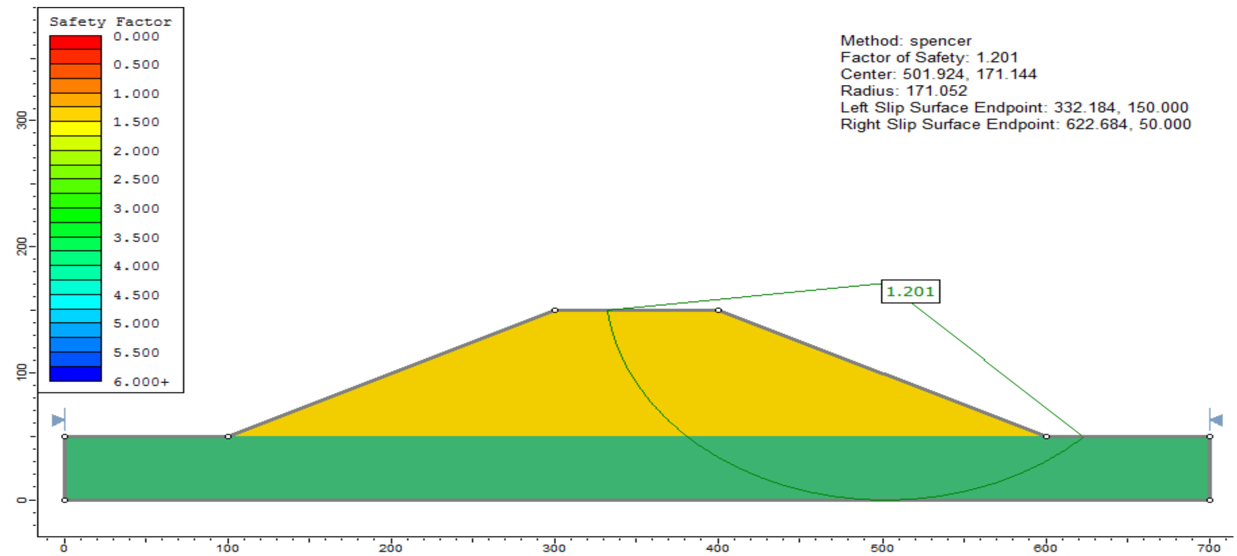


Figure 74.2: Solution, using the Spencer method (Circular)

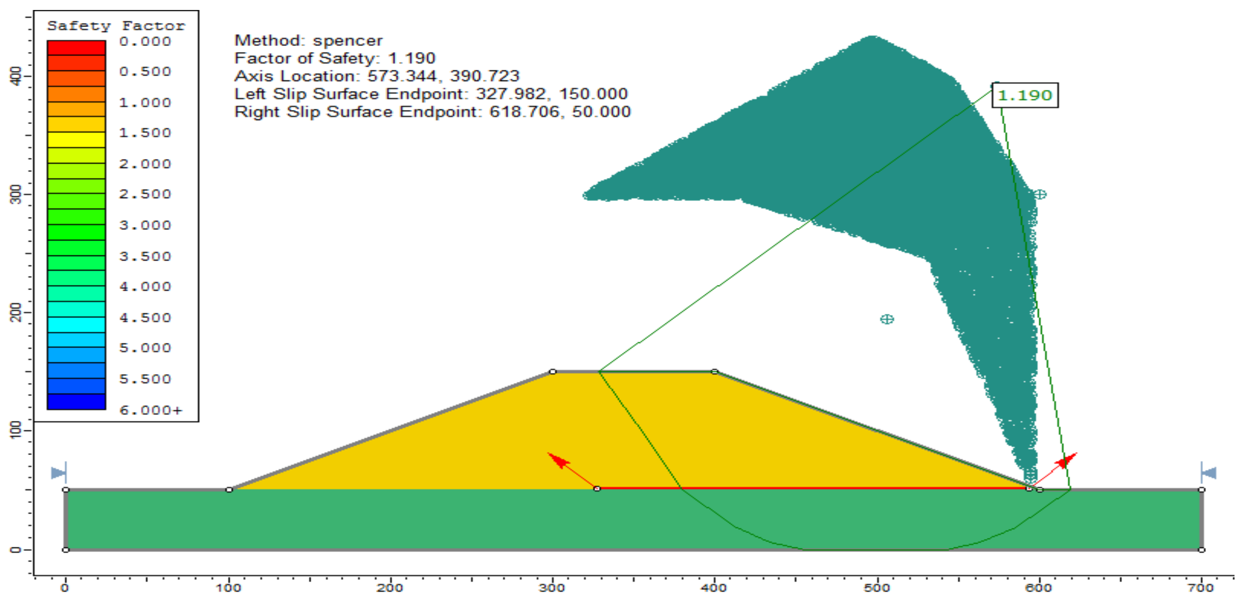


Figure 74.3: Solution, using the Spencer method (Non-circular)

75. Slide 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

Figure 75.1 shows the planned cross section of James Bay Dyke. Two cases are studied in this problem. The first case assumes that the critical slip surface is circular and the second case assumes that the critical slip surface is non-circular. The critical slip surface is located using auto refine search in case 1, and it is located using block search in case 2.

75.3. Geometry and Material Properties

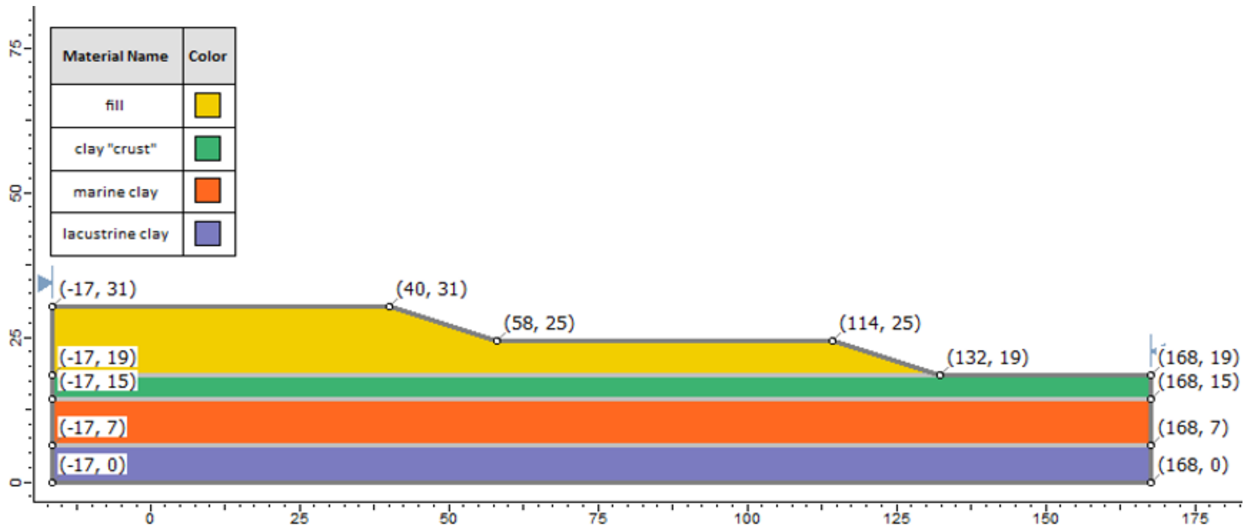


Figure 75.1: Circular Critical Slip Surface

Table 75.1: Soil Properties

Material	c´ (kN/m²)	ϕ´ (deg.)	γ (kN/m³)
Fill	0	30	20
Clay “crust”	41	0	20
Marine Clay	34.5	0	18.8
Lacustrine Clay	31.2	0	20.3

75.4. Results

Table 75.2: Case 1 – Circular critical slip surface

Method	Factor of Safety
Bishop	1.468
GLE	1.466
Spencer	1.464

Note: Reference factor of safety = 1.45 [Duncan and Wright]

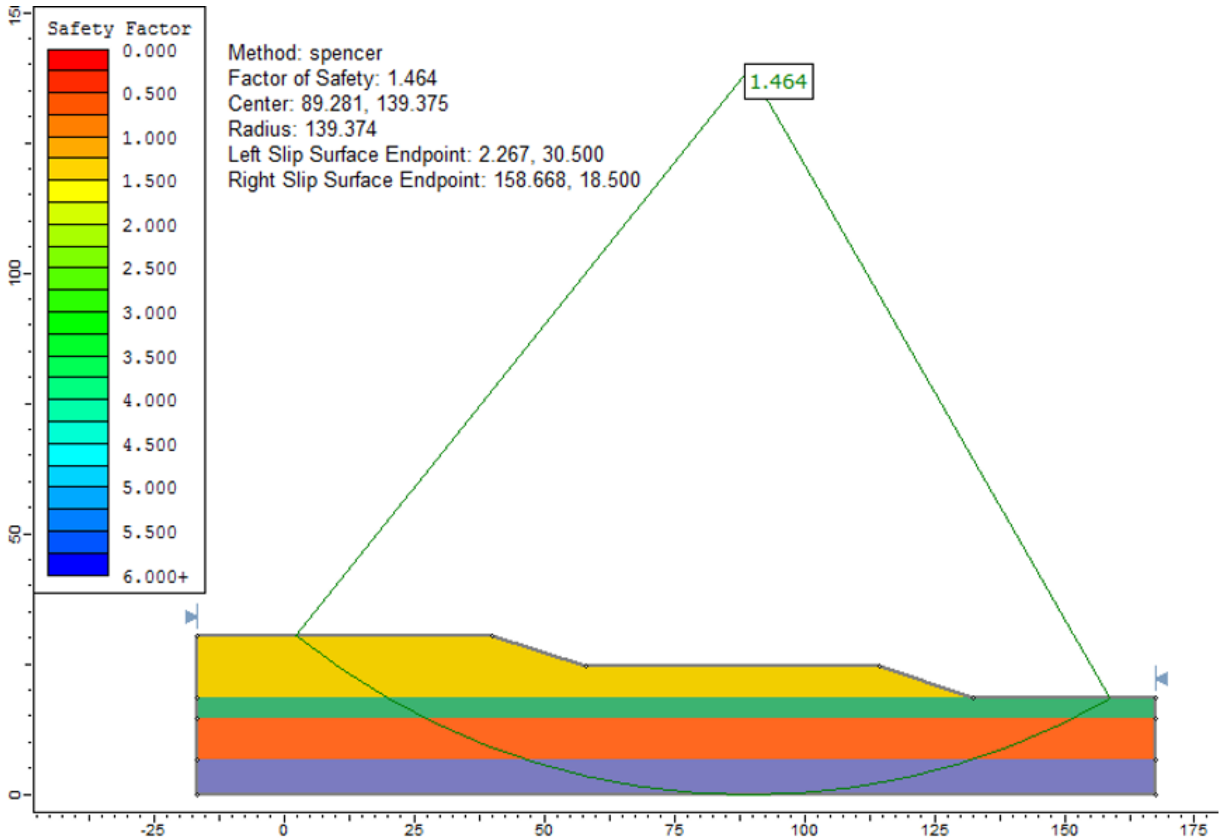


Figure 75.2: Solution to Case 1, using the Spencer method (Circular)

Table 75.3: Case 2 – Non-circular critical slip surface

Method	Factor of Safety
Bishop	1.105
Spencer	1.167
GLE	1.142

Note: Reference factor of safety = 1.17 [Duncan and Wright]

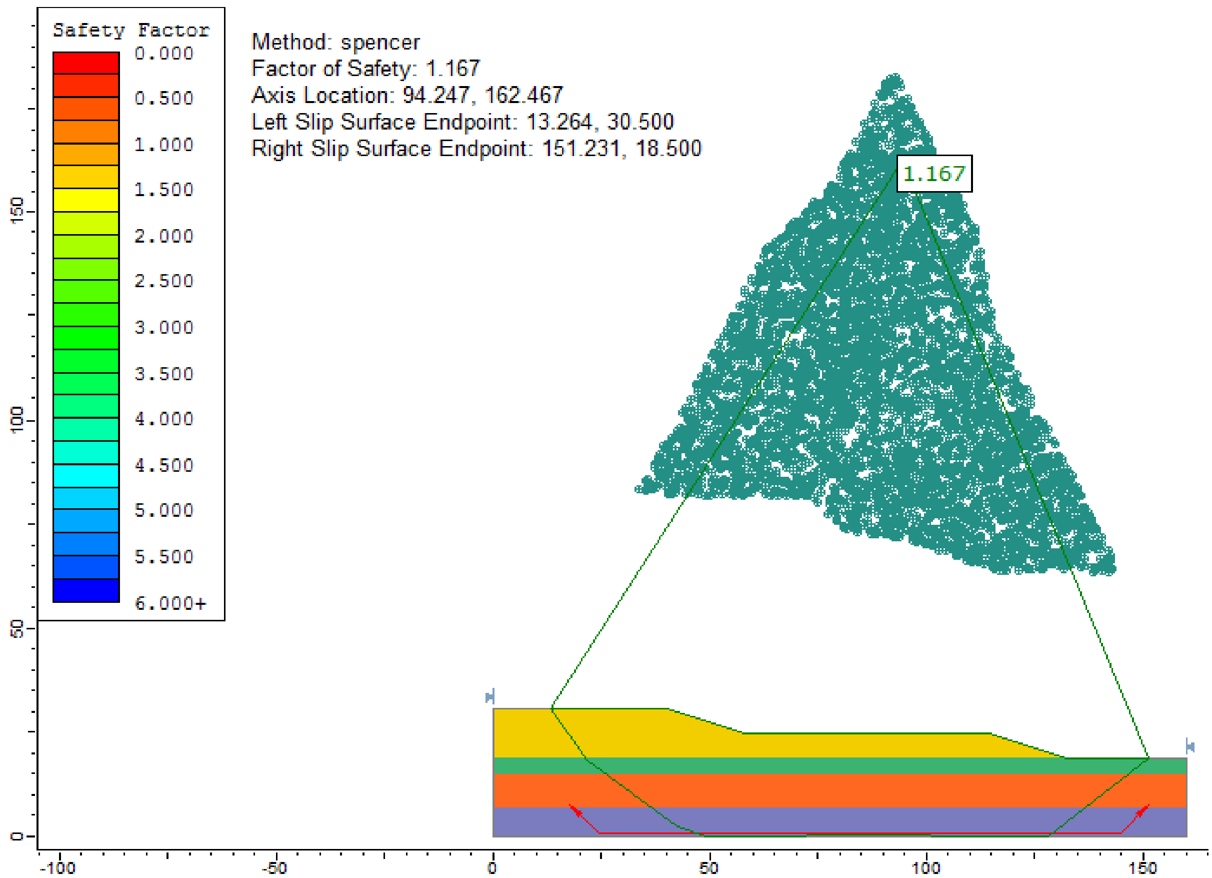


Figure 75.3: Solution to Case 2, using the Spencer method

76. Slide Verification Problem #76

Embankment dam, homogenous, 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

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 both Figure 76.1 and Figure 76.2. Seepage is assumed to have developed at a steady-state rate in this verification problem. The pore water pressure is modelled using finite element seepage analysis and piezometric line approximation. The critical slip surface is assumed to be circular and located using auto refine search for both cases.

76.3. Geometry and Material Properties

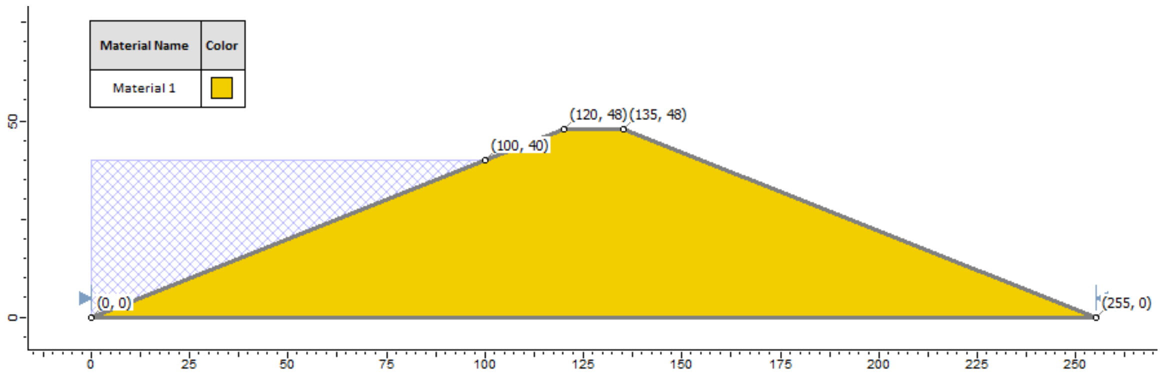


Figure 76.1: Finite Element Seepage Analysis

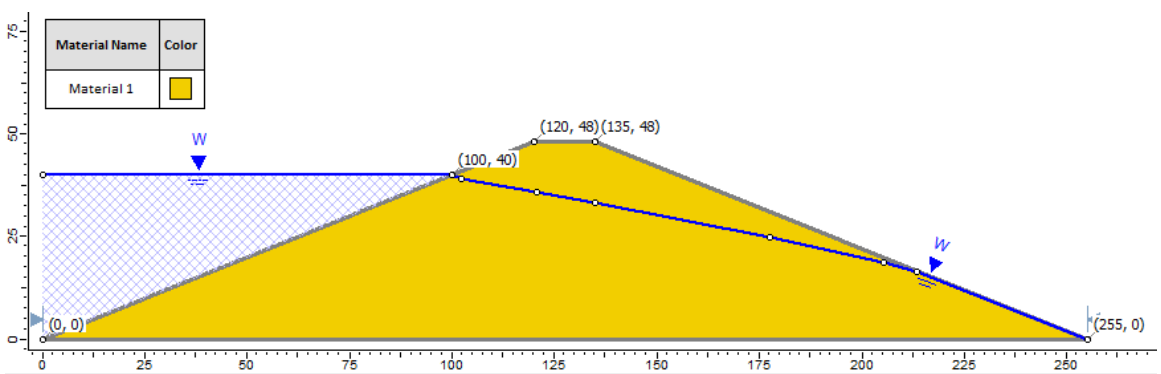


Figure 76.2: Piezometric Line Approximation

Table 76.1: Soil Properties

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

76.4. Results

Table 76.2: Case 1 – Finite Element seepage analysis

Method	Factor of Safety (Circular)
Bishop	1.068
Spencer	1.075
GLE	1.074

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

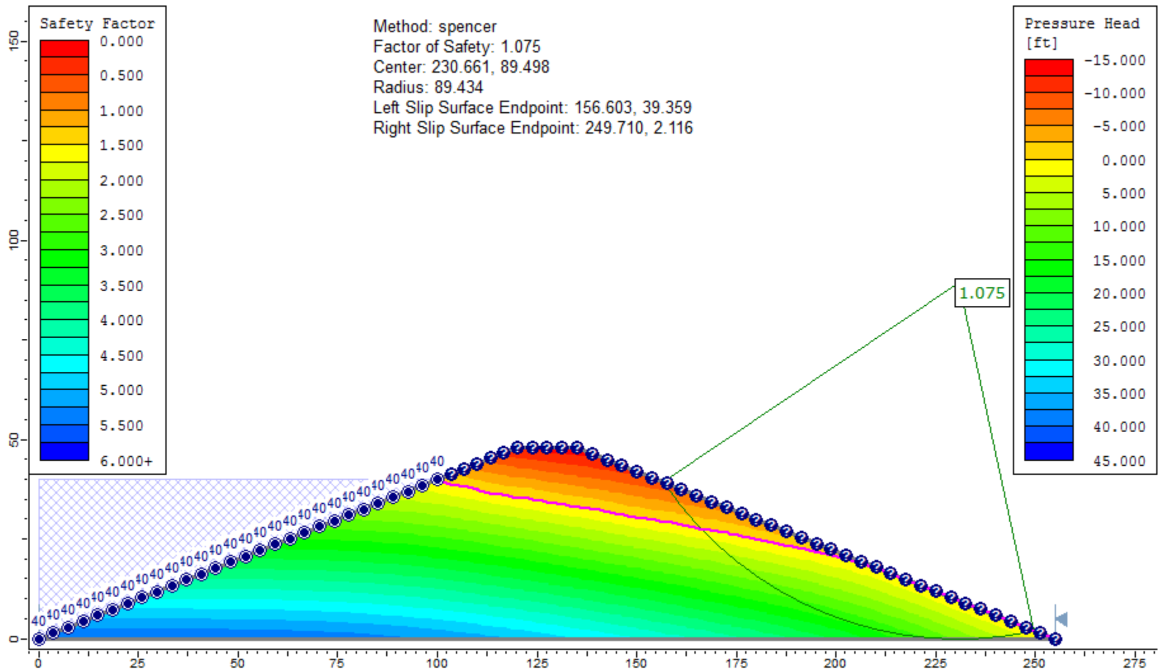


Figure 76.3: Solution to Case 1, using the Spencer method (Circular)

Table 76.3: Case 2 – Piezometric line approximation

Method	Factor of Safety (Circular)
Bishop	1.090
Spencer	1.100
GLE	1.094

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

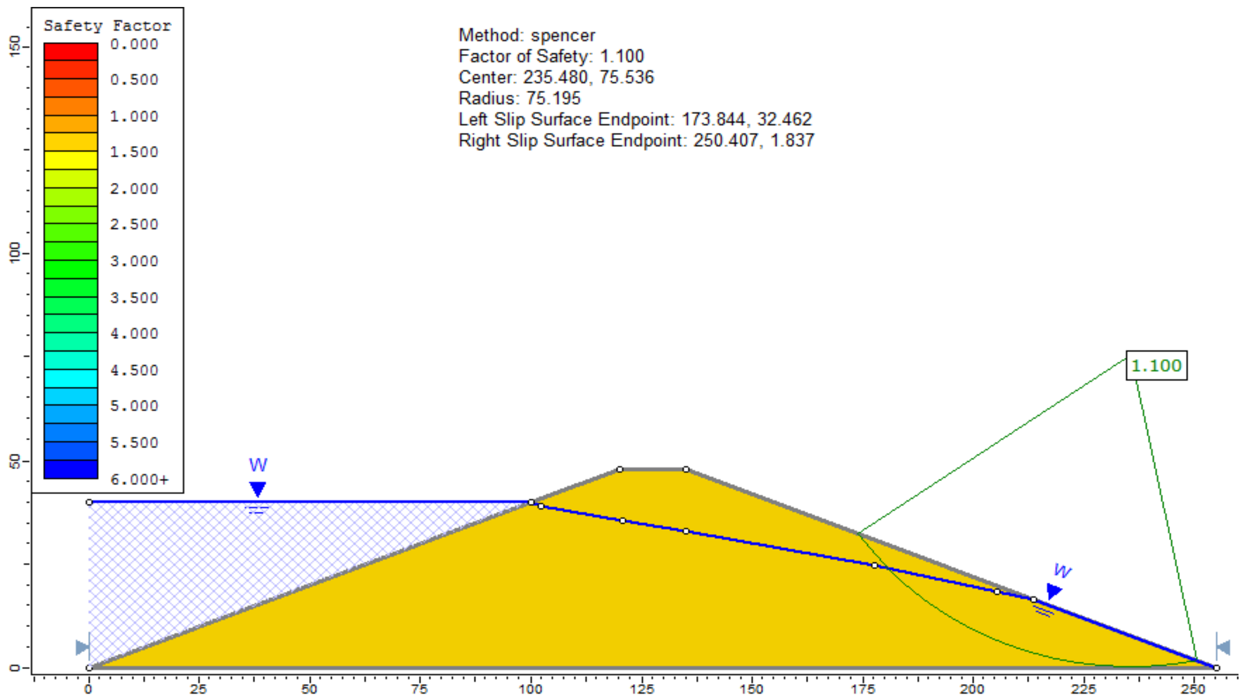


Figure 76.4: Solution to Case 2, using the Spencer method (Circular)

77. Slide Verification Problem #77

Dam, (2) materials, finite element groundwater seepage analysis, ponded water

77.1. Introduction

This problem is taken from Figure 7.24 on page 131 of Duncan and Wright (2005)

77.2. Problem Description

A symmetric earth dam with thick core and with ponded water of elevation 315 on its left side resting on an impervious foundation is shown in Figure 77.1 and Figure 77.2. Seepage is assumed to have developed at a steady-state rate. The pore water pressure is modelled using finite element seepage analysis and piezometric line approximation. The global critical slip surface occurs at shallow circles at the toe. However, in this verification problem, it is the deeper slip surface that is of interest. The deep critical slip surface is assumed to be circular and tangent to the boundary between the dam and its foundation. It is located using slope search for both cases.

77.3. Geometry and Material Properties

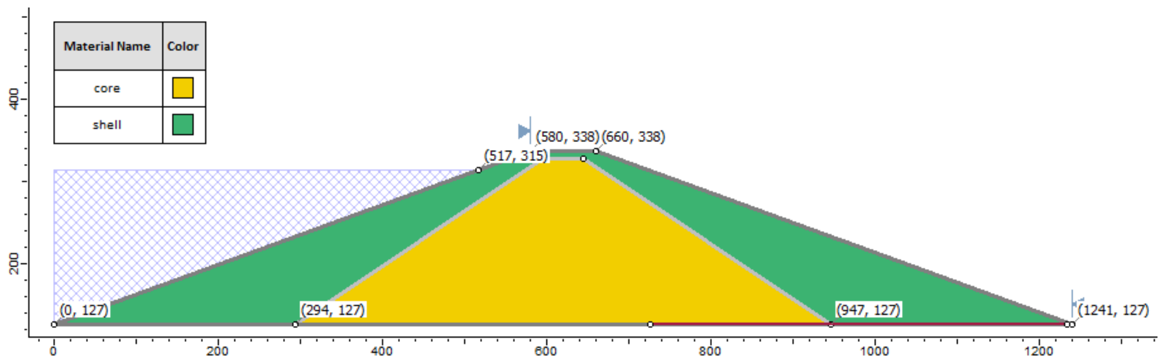


Figure 77.1: Finite Element Seepage Analysis

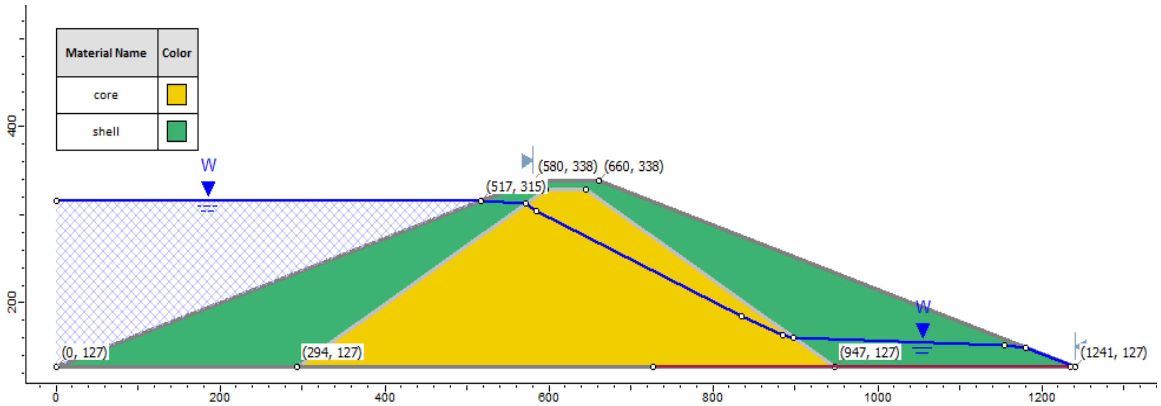


Figure 77.2: Piezometric Line Approximation

Table 77.1: Soil Properties

Zone	c' (psf)	ϕ' (⁰)	γ (pcf)	k (ft/s)
Core	0	20	120	$1.67x\ 10^{-7}$
Shell	0	38	140	$1.67x\ 10^{-5}$

77.4. Results

Table 77.2: Case 1 – Finite element seepage analysis

Method	Reference Factor of Safety [Duncan and Wright]	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.62	1.658	1.541
Spencer	1.69	1.724	1.640

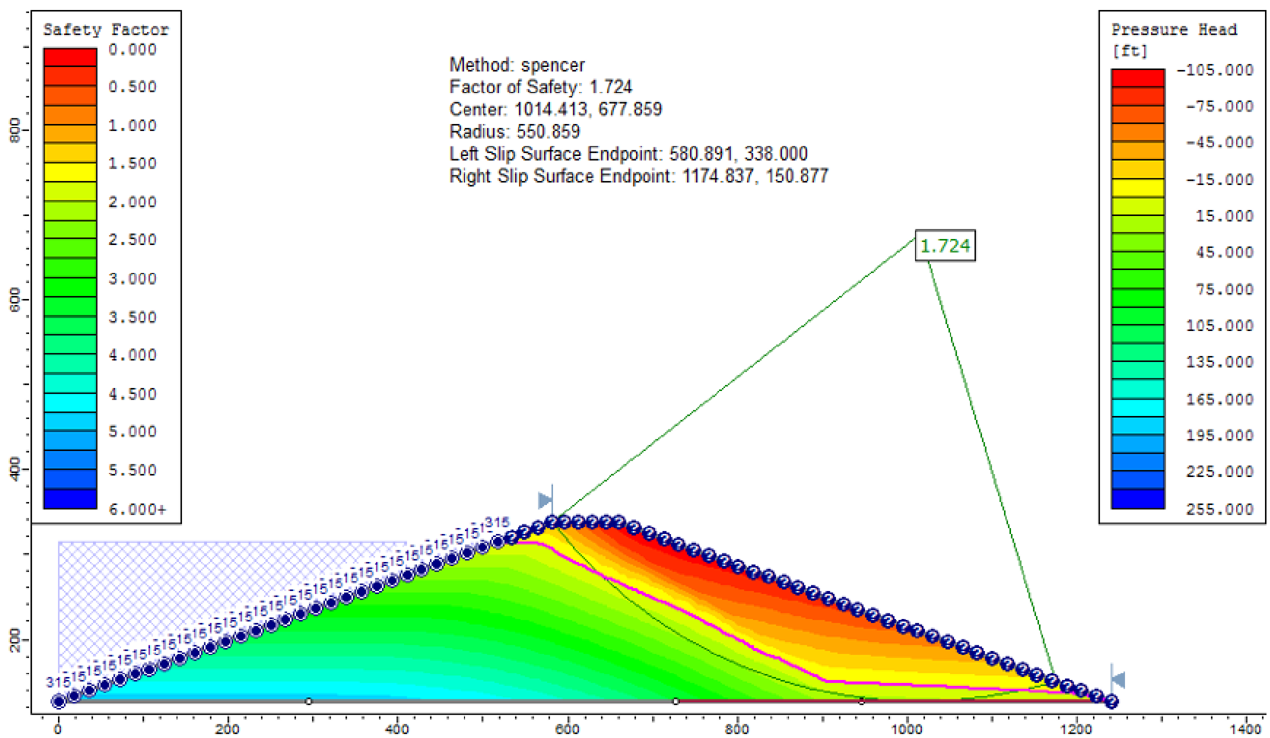


Figure 77.3: Solution to Case 1, using the Spencer method

Table 77.3: Case 2 – Piezometric line approximation

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.584	1.478
Spencer	1.648	1.570

Note: Reference factor of safety = 1.67 [Duncan and Wright]

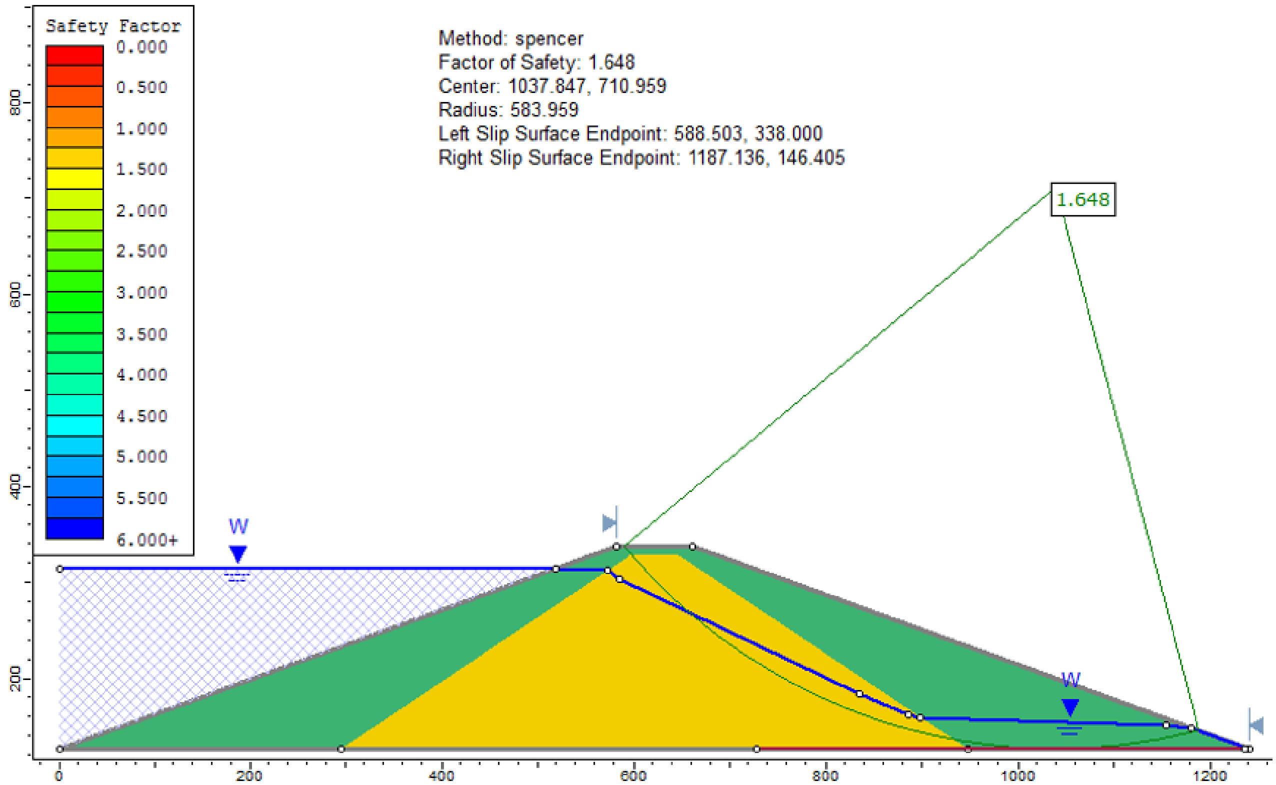


Figure 77.4: Solution to Case 2, using the Spencer method

78. Slide Verification Problem #78

Slope, homogenous

78.1. Introduction

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

78.2. Problem Description

A simple, pure cohesive slope is shown in Figure 78.1. Three different foundation thicknesses (30 feet-thick, 46.5 feet-thick and 60 feet-thick) are tested and for each case two slip surfaces are of interest in this verification problem. The first slip surface passes through the toe and the second slip surface is tangent to the bottom of the foundation. The slip surfaces are assumed to be circular.

78.3. Geometry and Material Properties

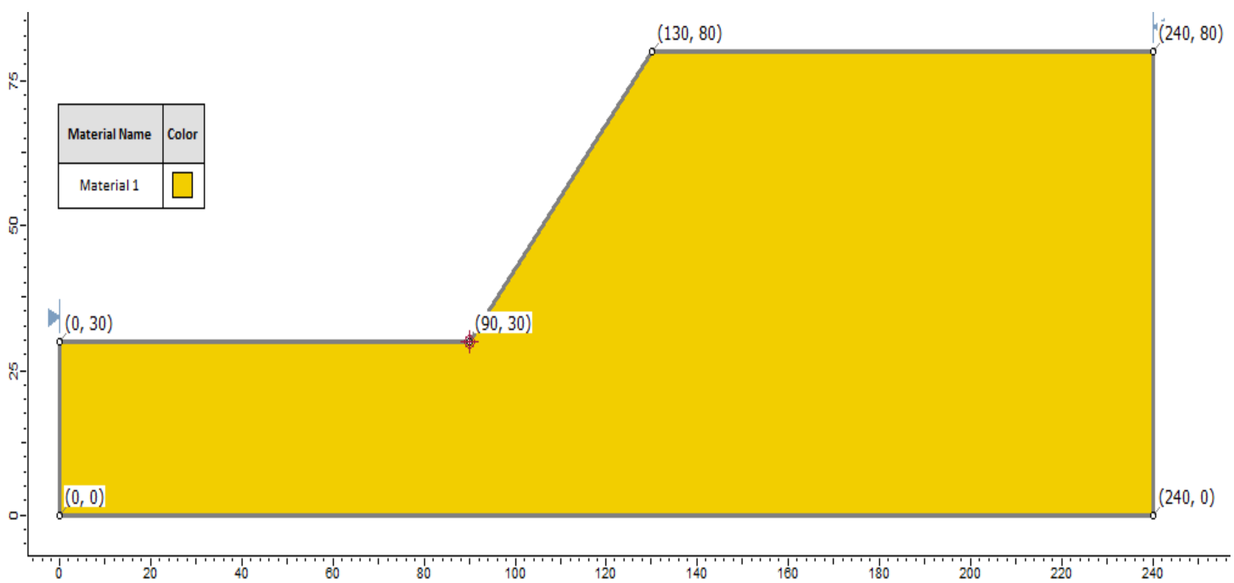


Figure 78.1: A Simple, Pure Cohesive Slope with a Foundation Thickness H

Table 78.1: Soil Properties

c (psf)	ϕ (^{0})	γ (pcf)
1000	0	100

78.4. Results

Table 78.2: Case 1(a) – 30 feet-thick foundation – slip surface passes through the toe

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.126	0.947
Spencer	1.200	0.878
GLE	1.186	0.914

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

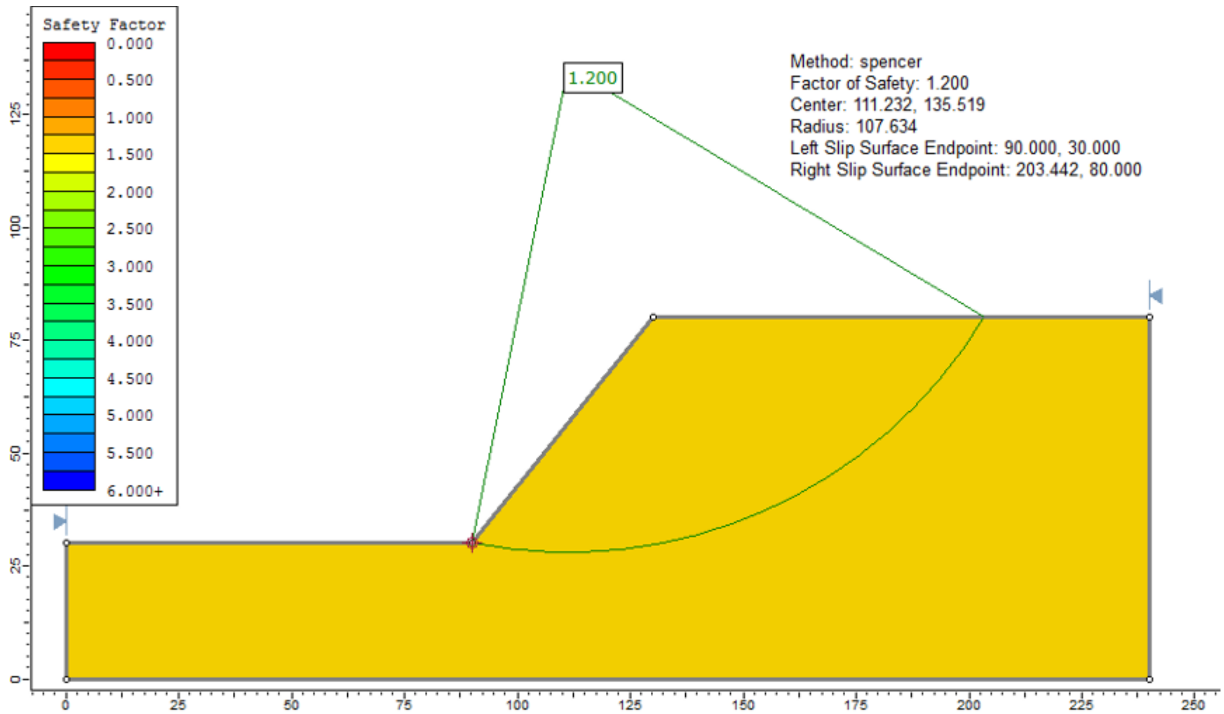


Figure 78.2: Solution to Case 1(a), using the Spencer method

Table 78.3: Case 1(b) – 30 feet-thick foundation – slip surface is tangent to the bottom of the foundation

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.141	0.915
Spencer	1.139	0.879
GLE	1.139	0.892

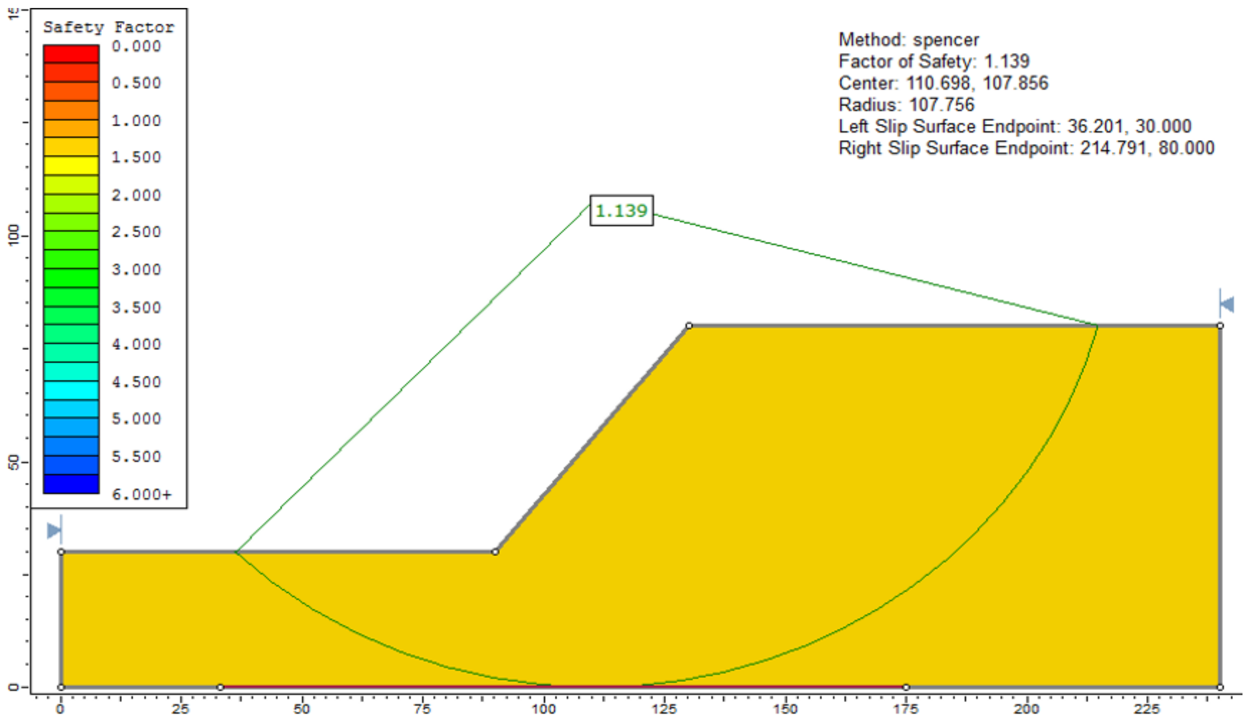


Figure 78.3: Solution to Case 1(b), using the Spencer method

Table 78.4: Case 2(a) – 46.5 feet-thick foundation – slip surface passes through the toe

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.126	0.947
Spencer	1.200	0.880
GLE	1.186	0.910

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

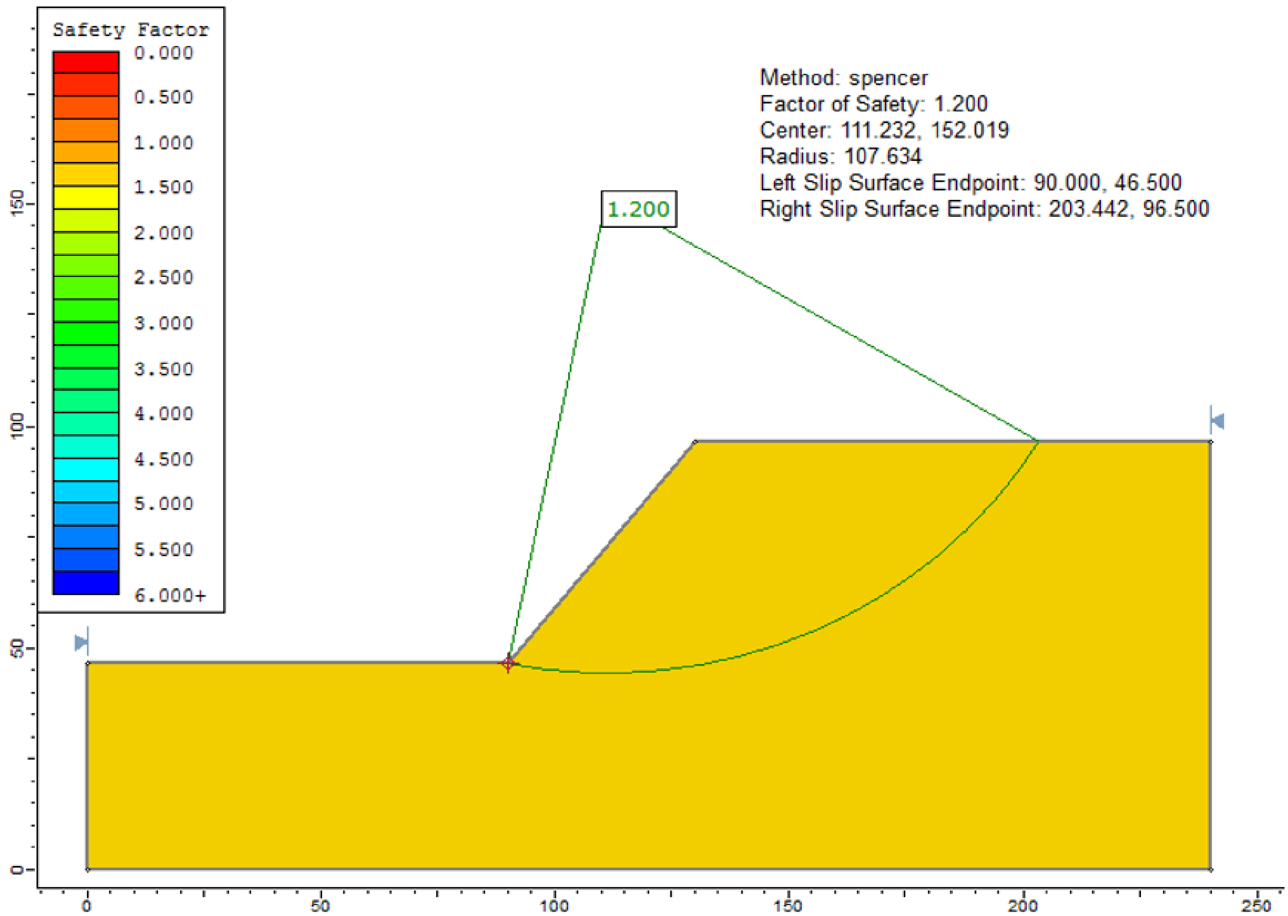


Figure 78.4: Solution to Case 2(a), using the Spencer method

Table 78.5: Case 2(b) – 46.5 feet-thick foundation – slip surface is tangent to the bottom of the foundation

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.130	0.890
Spencer	1.129	0.887
GLE	1.129	0.887

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

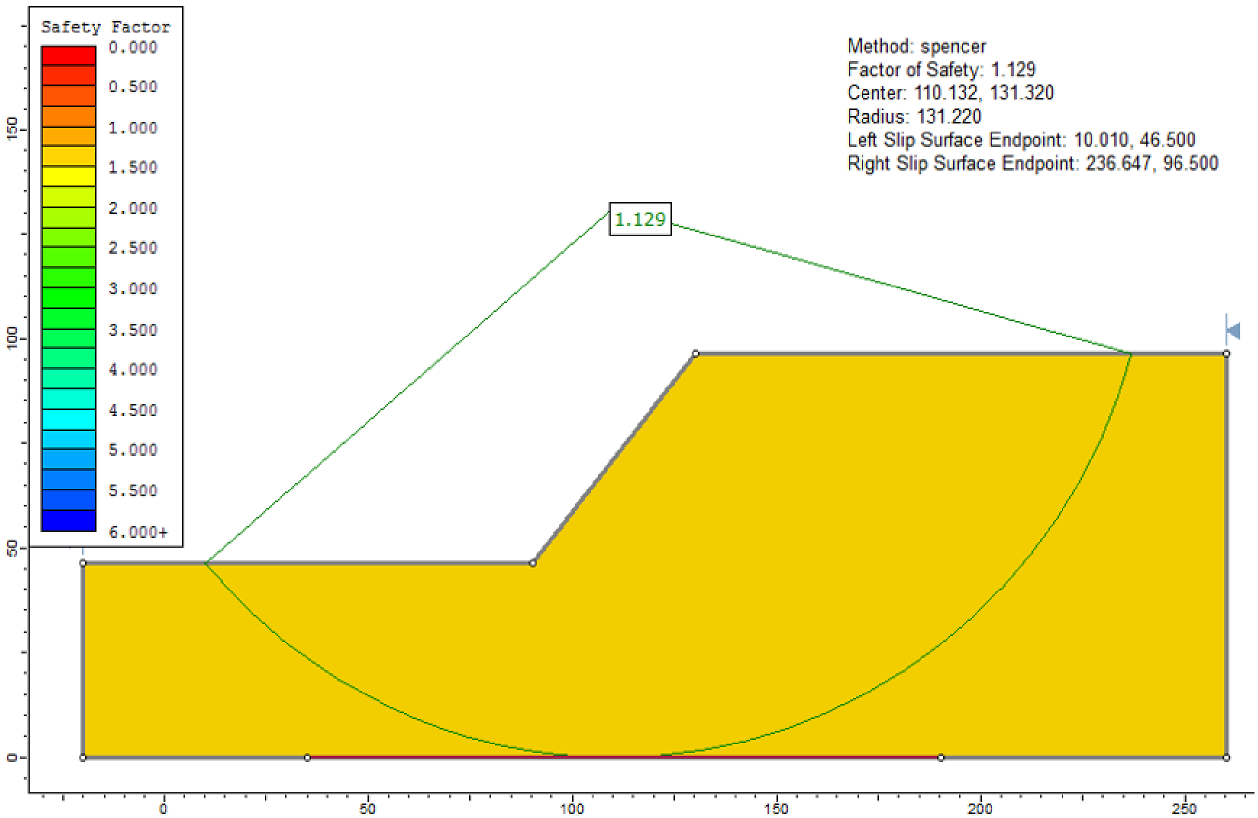


Figure 78.5: Solution to Case 2(b), using the Spencer method

Table 78.6: Case 3(a) – 60 feet-thick foundation – slip surface passes through the toe

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.125	0.947
Spencer	1.202	0.878
GLE	1.185	0.910

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

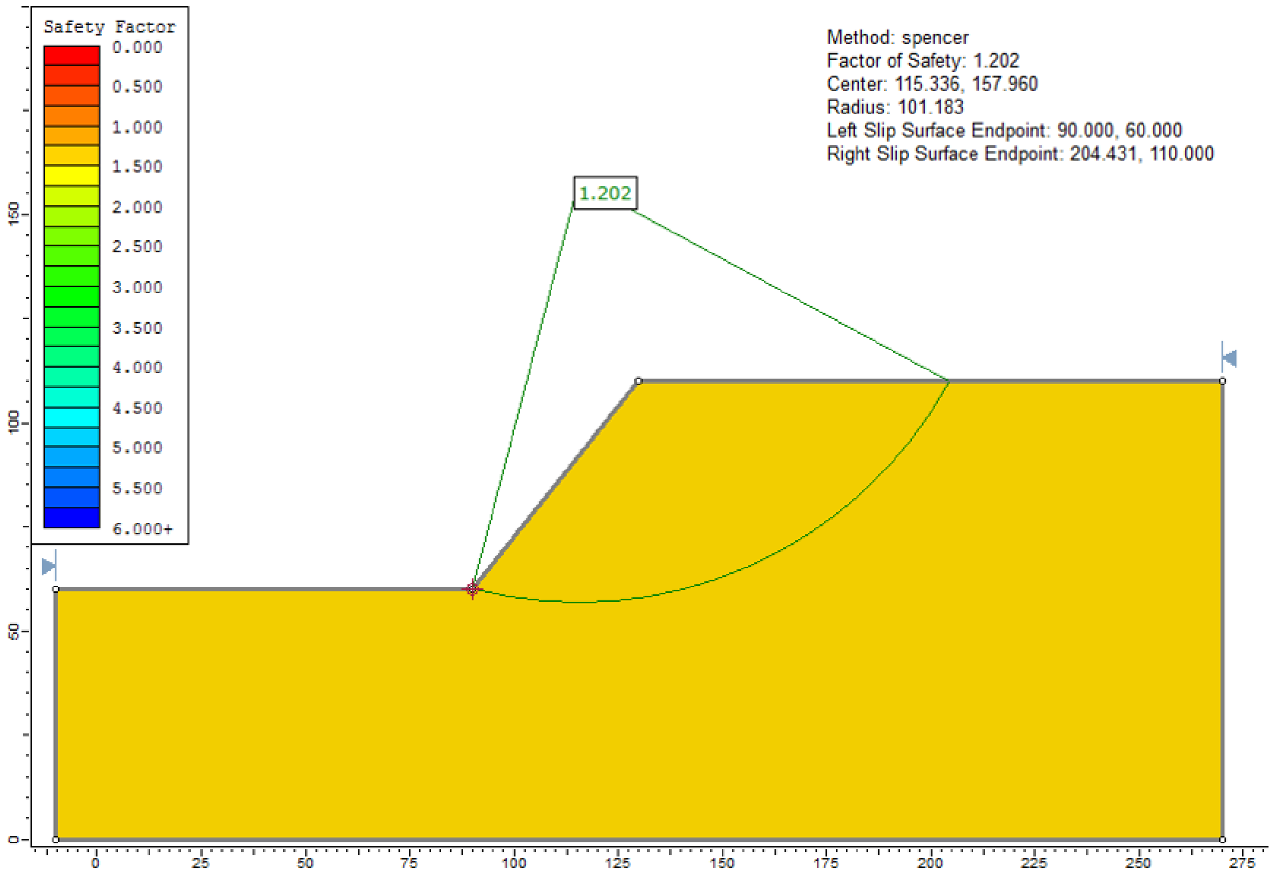


Figure 78.6: Solution to Case 3(a), using the Spencer method

Table 78.7: Case 3(b) – 60 feet-thick foundation – slip surface is tangent to the bottom of the foundation

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.125	0.873
Spencer	1.124	0.829
GLE	1.124	0.837

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

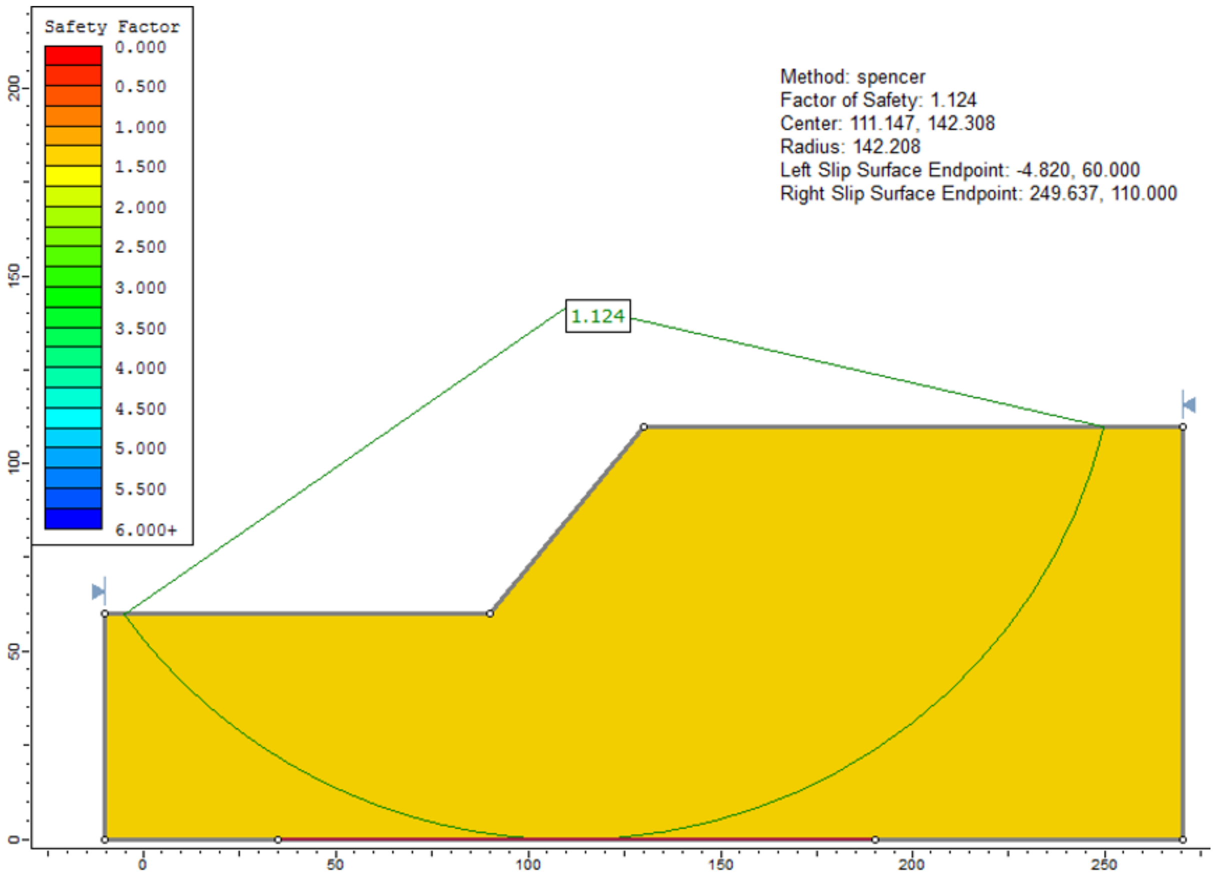


Figure 78.7: Solution to Case 3(b), using the Spencer method

79. Slide 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

Figure 79.1 shows a cohesionless slope. Two slip surfaces are of interest in this verification problem. The first is a slip surface that is very shallow (infinite slope mechanism) and the second is a deep slip surface that is tangent to the bottom of the foundation.

79.3. Geometry and Material Properties

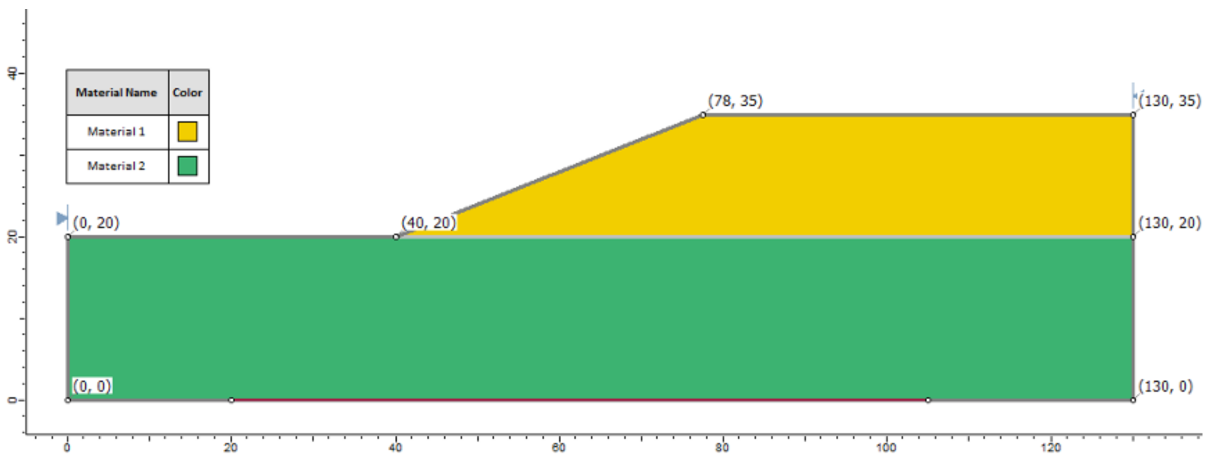


Figure 79.1: A Cohesionless Earth Embankment

Table 79.1: Soil Properties

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

79.4. Results

Table 79.2: Case 1 – Deep slip surface tangent to the bottom of the foundation

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.412	1.225
Spencer	1.400	1.361
GLE	1.404	1.373

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

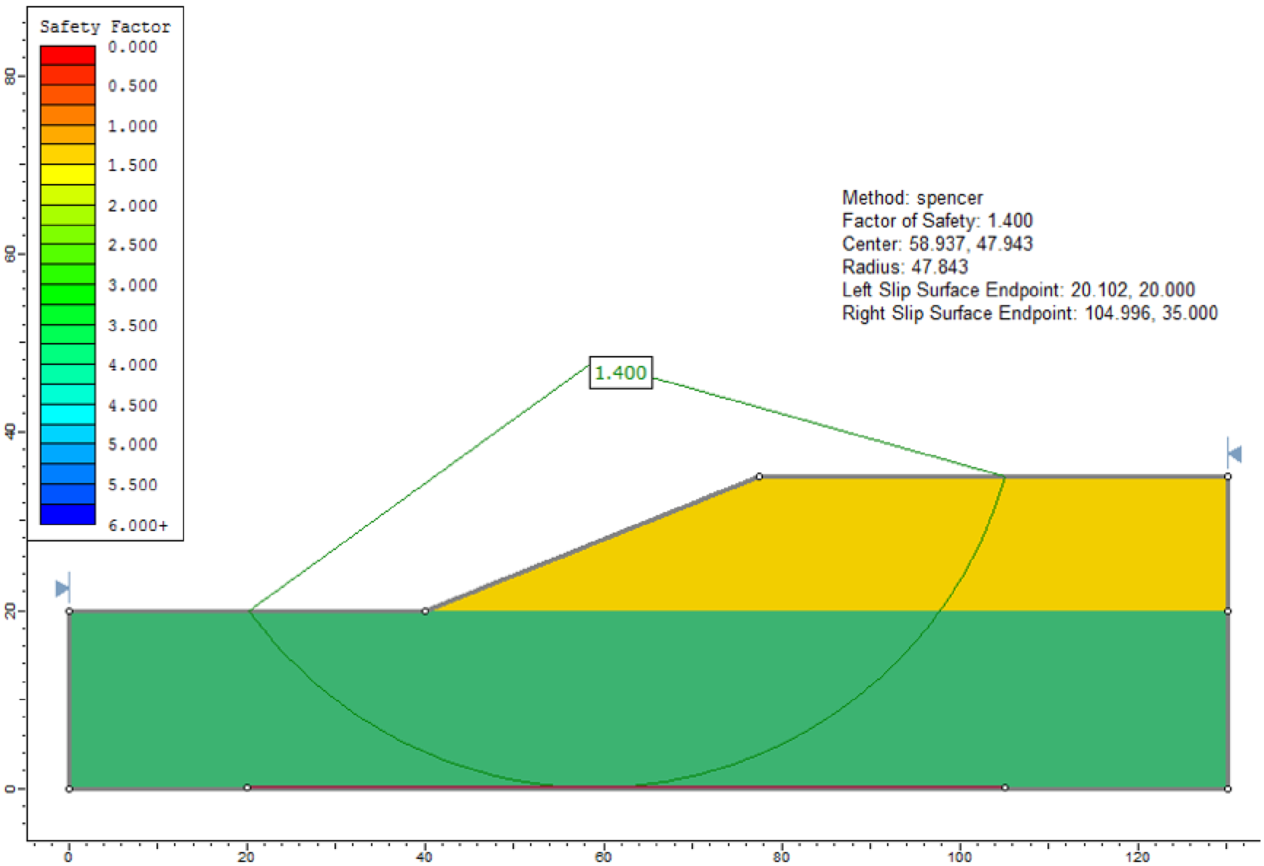


Figure 79.2: Solution to Case 1, using the Spencer method

Table 79.3: Case 2 – Very shallow slip surface (infinite slope mechanism)

Method	**Factor of Safety (Circular)**	**Factor of Safety (Non-circular)**
Bishop	1.444	1.444
Spencer	1.443	1.443
GLE	1.443	1.443

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

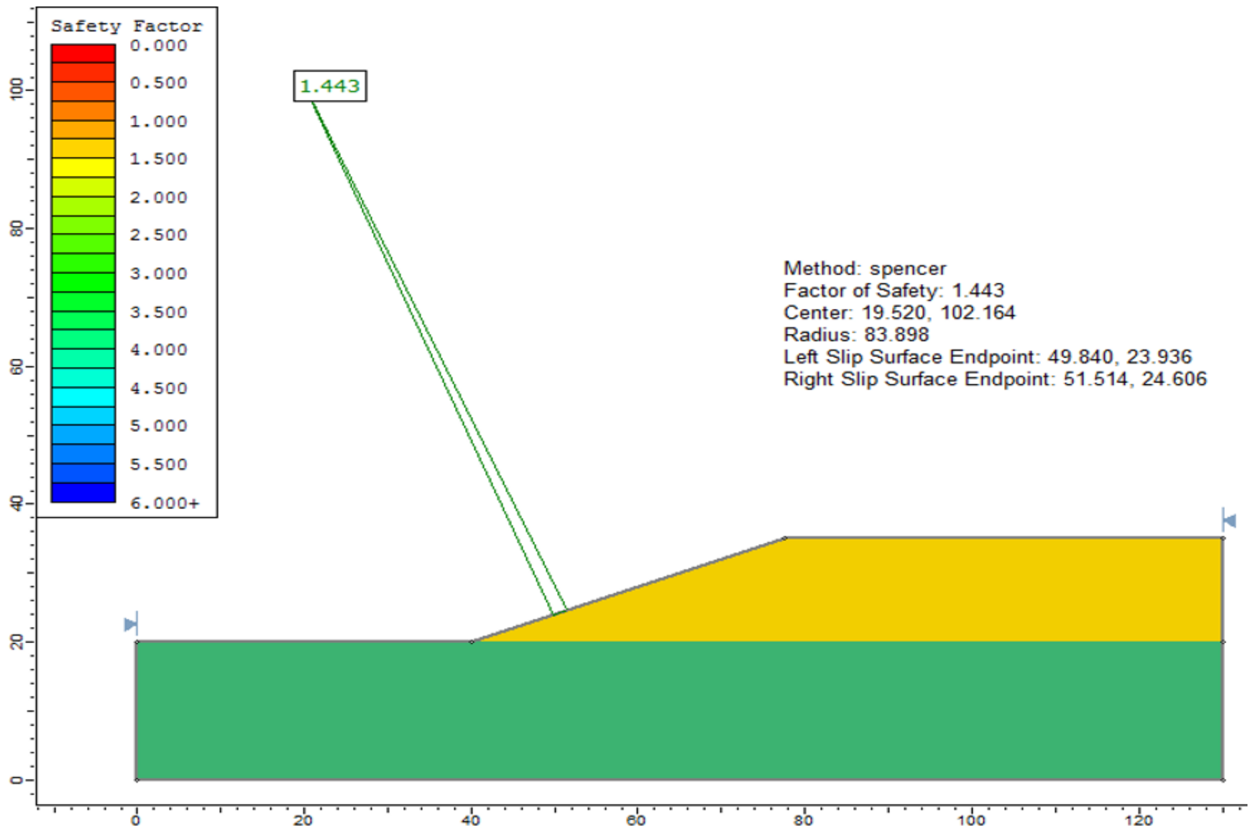


Figure 79.3: Solution to Case 2, using the Spencer method

80. Slide Verification Problem #80

Embankment, (6) materials

80.1. Introduction

This problem is taken from Figure 14.5 on page 218 of Duncan and Wright (2005).

80.2. Problem Description

An embankment wall resting on a stratified soil foundation is shown in Figure 80.1. The center point of the critical slip surface is approximated to be at (142, 147). For the given center point, several slip surfaces are located by varying the radius. In this verification problem, two slip surfaces are analyzed. The first is tangent to 0 feet-depth line and the second is tangent to 15 feet-depth line.

80.3. Geometry and Material Properties

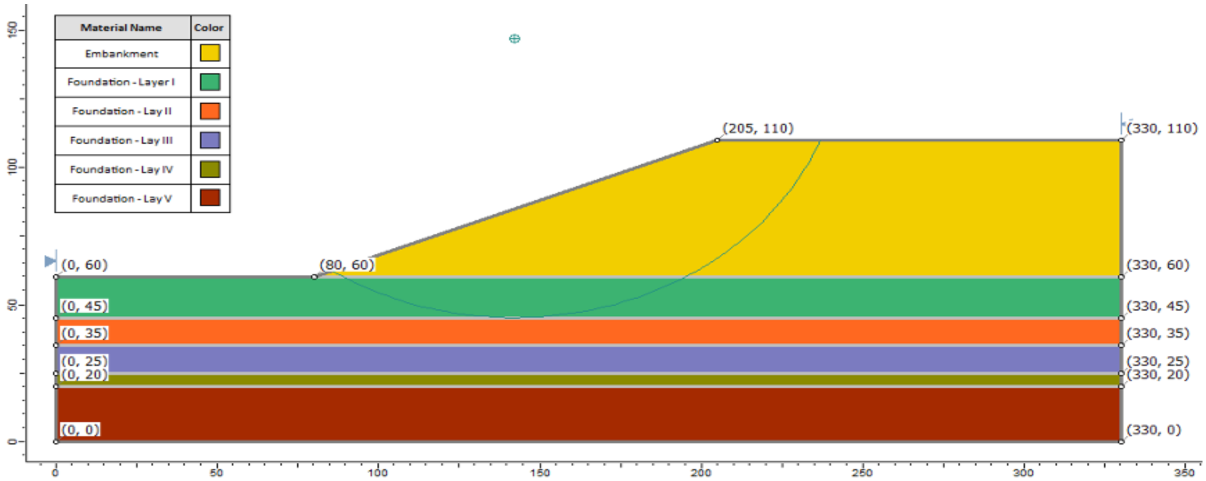


Figure 80.1: An Embankment Resting on A Stratified Soil Foundation

Table 80.1: Soil Properties

Material	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Embankment	1	35	120
Foundation – Layer I	950	0	110
Foundation – Layer II	1	32	122
Foundation – Layer III	500	0	98
Foundation – Layer IV	1	37	131
Foundation – Layer V	600	0	103

80.4. Results

Table 80.2: Case 1 – Slip surface is tangent to 0 feet-depth line

Method	Factor of Safety
Bishop	2.549
Spencer	2.545
GLE	2.550

Note: Reference factor of safety = 2.56 [Duncan and Wright]

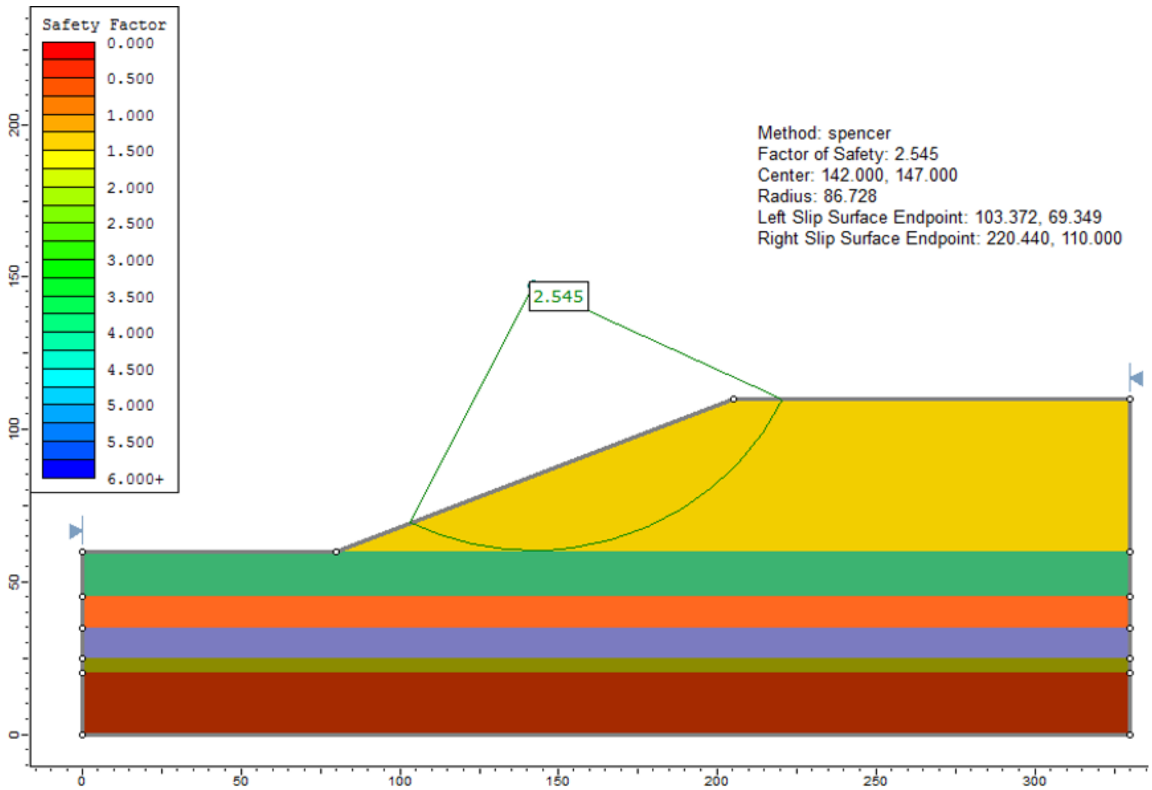


Figure 80.2: Solution to Case 1, using the Spencer method

Table 80.3: Case 2 – Slip surface is tangent to 15 feet-depth line

Method	Factor of Safety
Bishop	1.398
Spencer	1.359
GLE	1.358

Note: Reference factor of safety = 1.35 [Duncan and Wright]

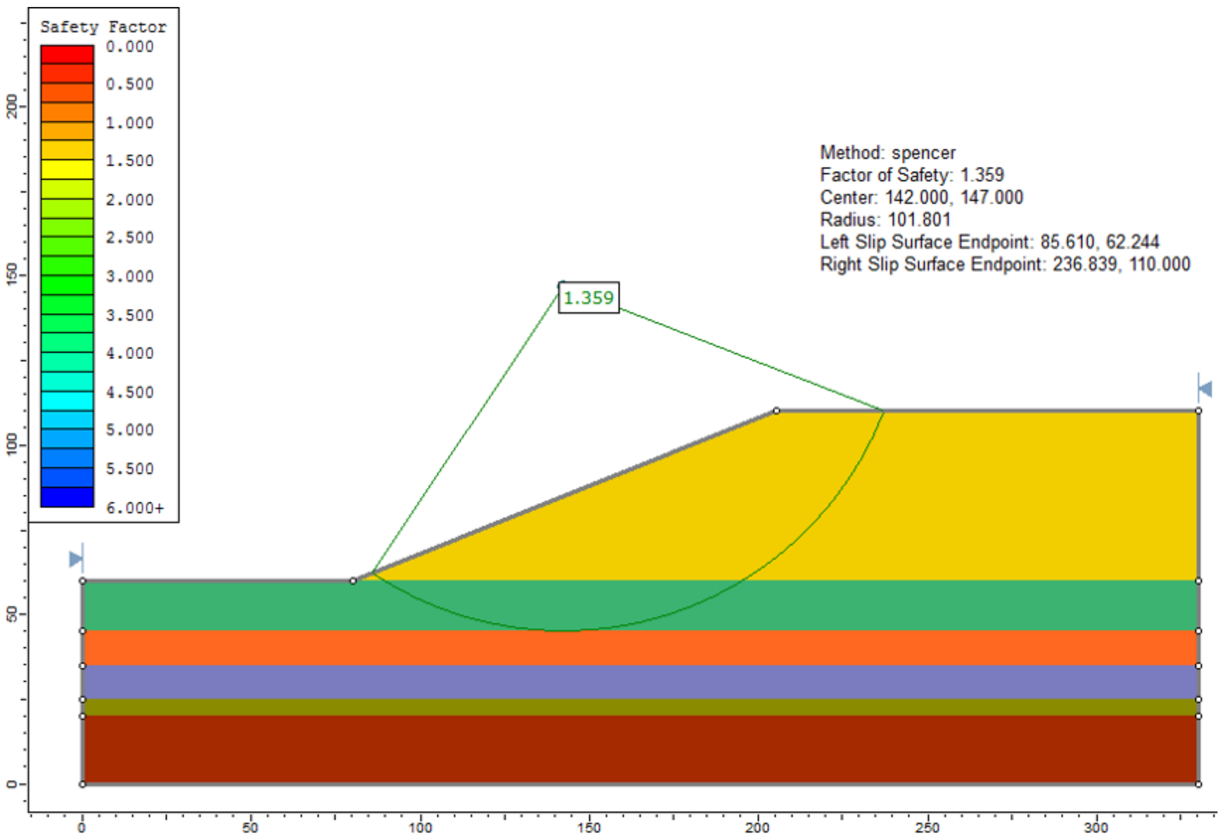


Figure 80.3: Solution to Case 2, using the Spencer method

81. Slide 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

Figure 81.1 shows an earth embankment. Two critical slip surfaces are of interest in this verification problem. The first is a deep slip surface tangent to the bottom of the foundation and the second is a very shallow (infinite slope mechanism) slip surface.

81.3. Geometry and Material Properties

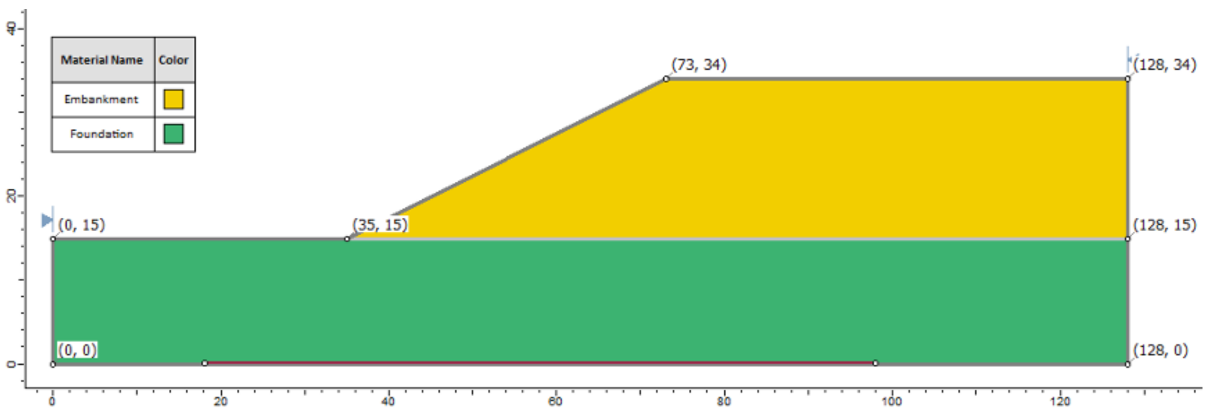


Figure 81.1: Geometry Setup in **Slide**

Table 81.1: Soil Properties

Zone	c' (psf)	ϕ' (^{0})	γ (pcf)
Embankment	0	30	124
Foundation	500	0	98

81.4. Results

Table 81.2: Case 1 – Deep slip surface tangent to the bottom of the foundation

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.230	1.081
Spencer	1.209	1.183
GLE	1.217	1.174

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

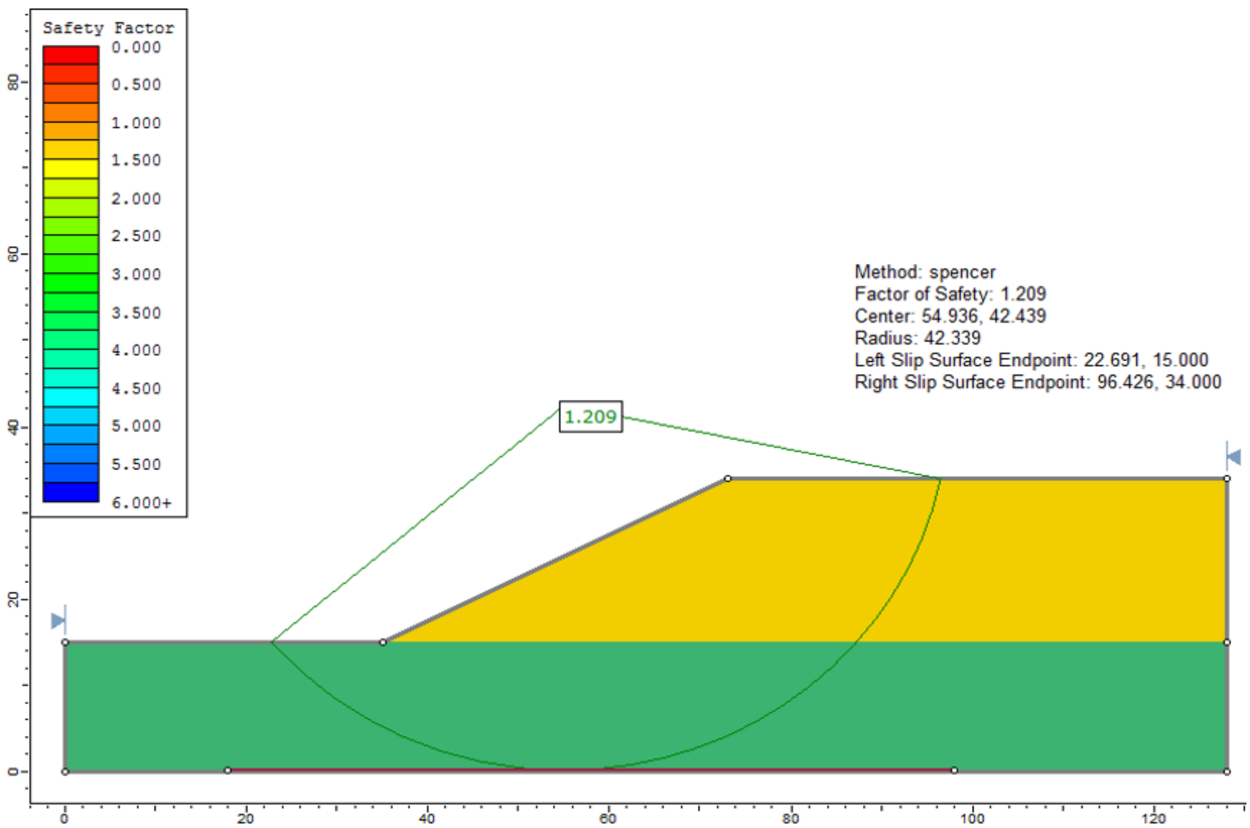


Figure 81.2: Solution for Case 1, using the Spencer method

Table 81.3: Case 2 – Very shallow (infinite slope mechanism) slip surface

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.155	1.155
Spencer	1.155	1.155
GLE	1.155	1.155

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

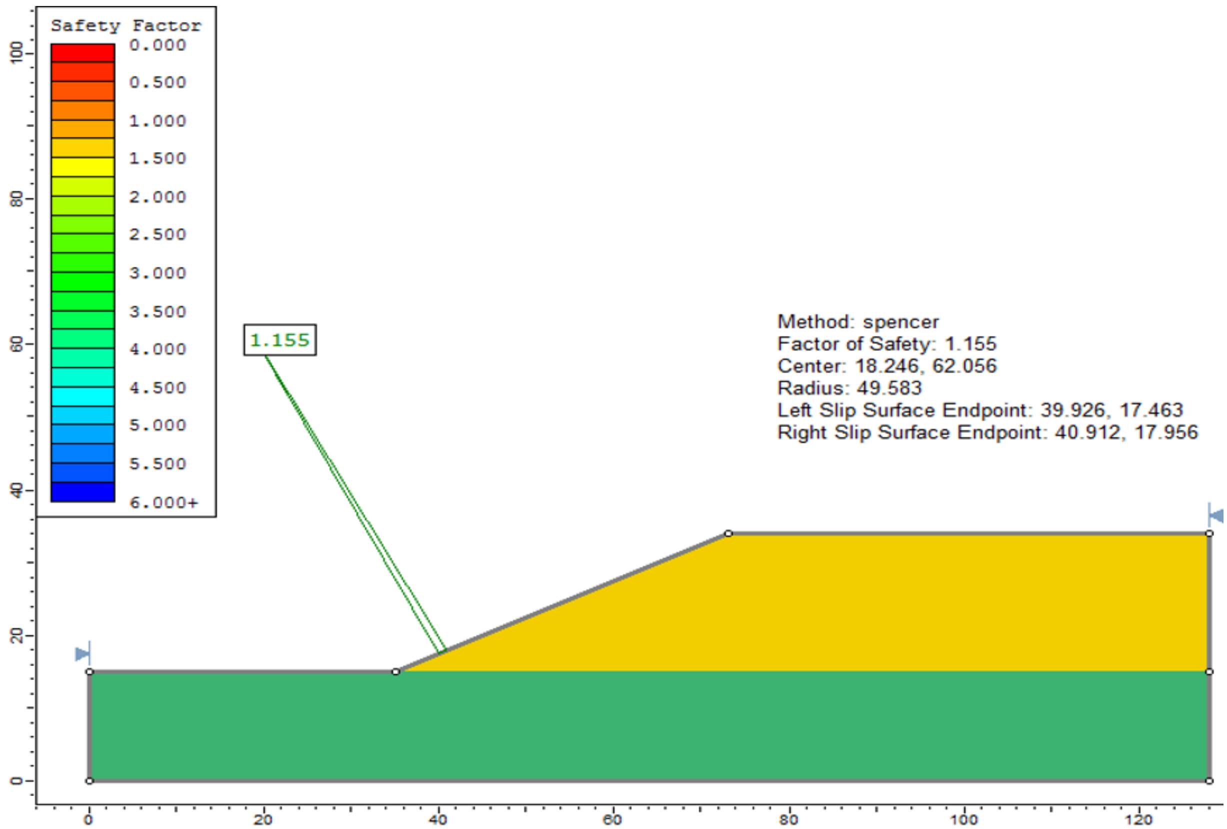


Figure 81.3: Solution for Case 2, using the Spencer method

82. Slide Verification Problem #82

Embankment, (2) materials, water table

82.1. Introduction

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

82.2. Problem Description

Figure 82.1 shows an earth embankment. 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.

82.3. Geometry and Material Properties

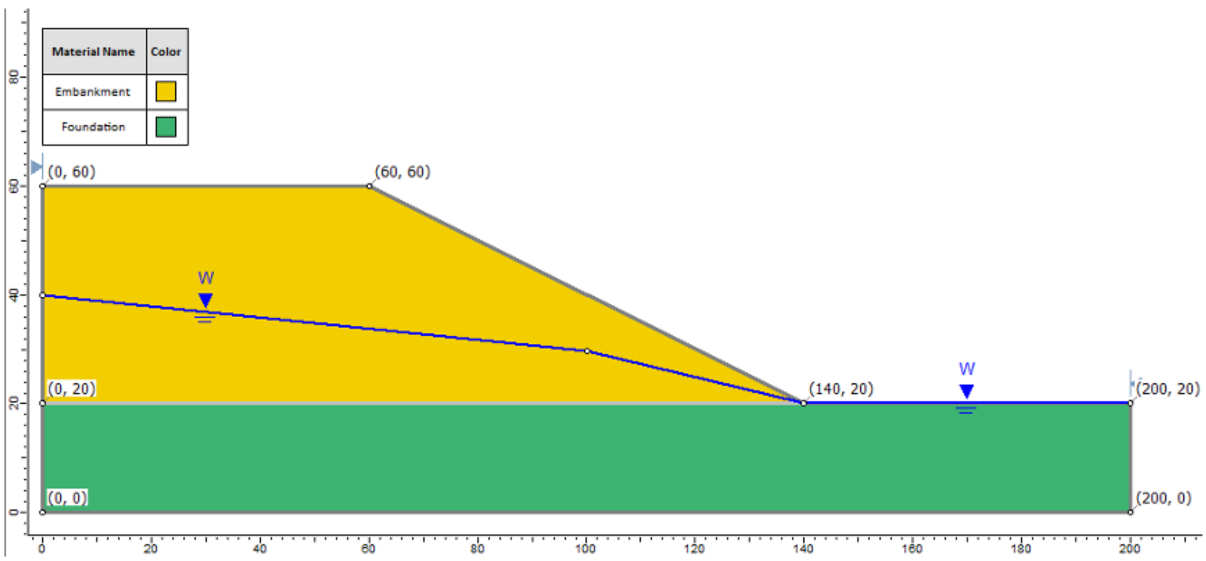


Figure 82.1: Geometry Setup in **Slide**

Table 82.1: Soil Properties

Zone	c' (psf)	ϕ' (^{0})	γ (pcf)
Embankment	600	25	125
Foundation	0	30	132

82.4. Results

Table 82.2

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.533	1.444
Spencer	1.540	1.534
GLE	1.540	1.527

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]

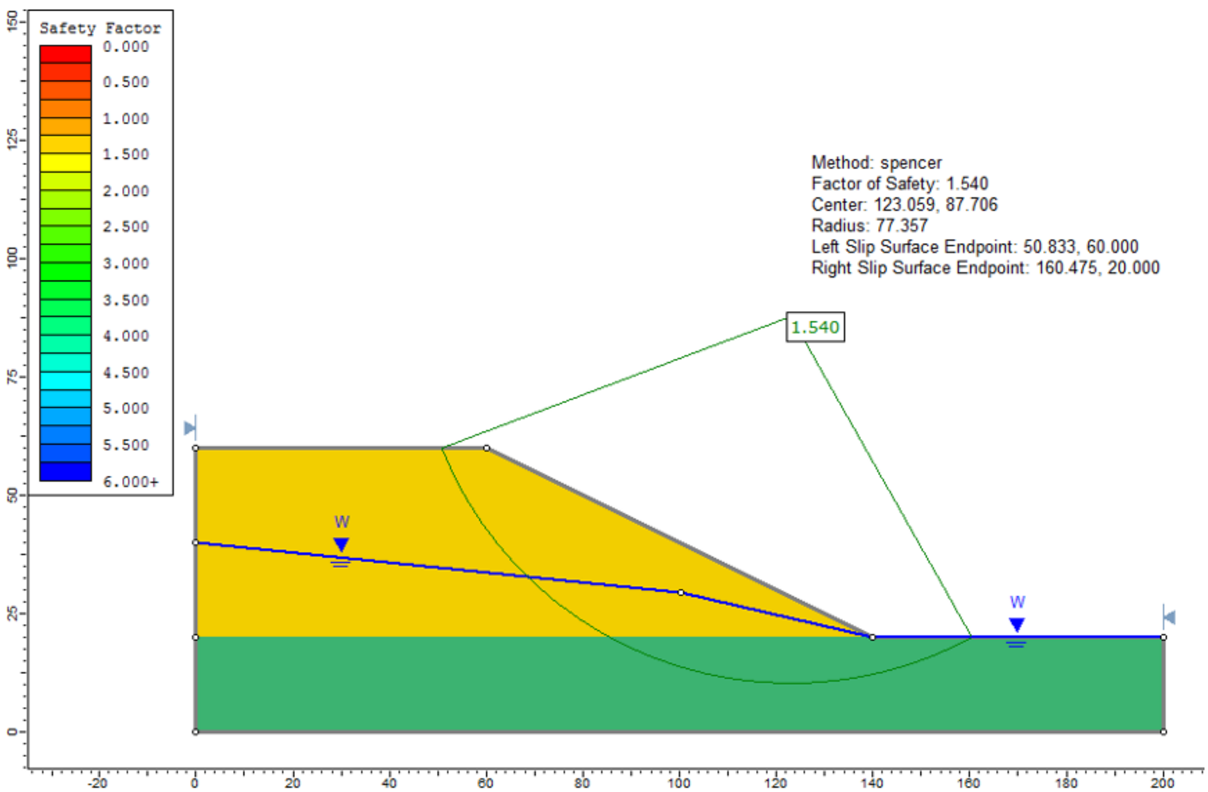


Figure 82.2: Solution, using the Spencer method

83. Slide 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

An embankment wall is shown in Figure 83.2. Two undrained shear strength profiles for its foundation are tested. The foundation's undrained shear strength profiles are shown in Figure 83.1. The slip surface that is tangent to the bottom of the foundation is of interest for the second profile. The slip surfaces in this verification problem are assumed to be circular.

83.3. Geometry and Material Properties

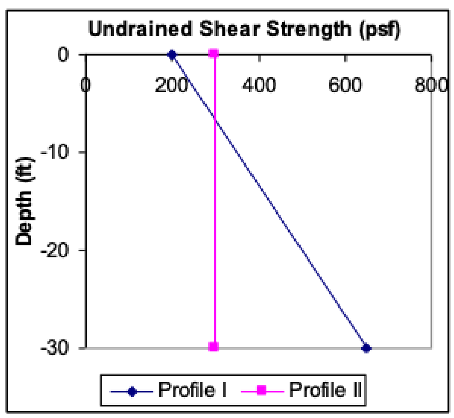


Figure 83.1: Undrained Shear Strength Profiles from Duncan and Wright (2005)

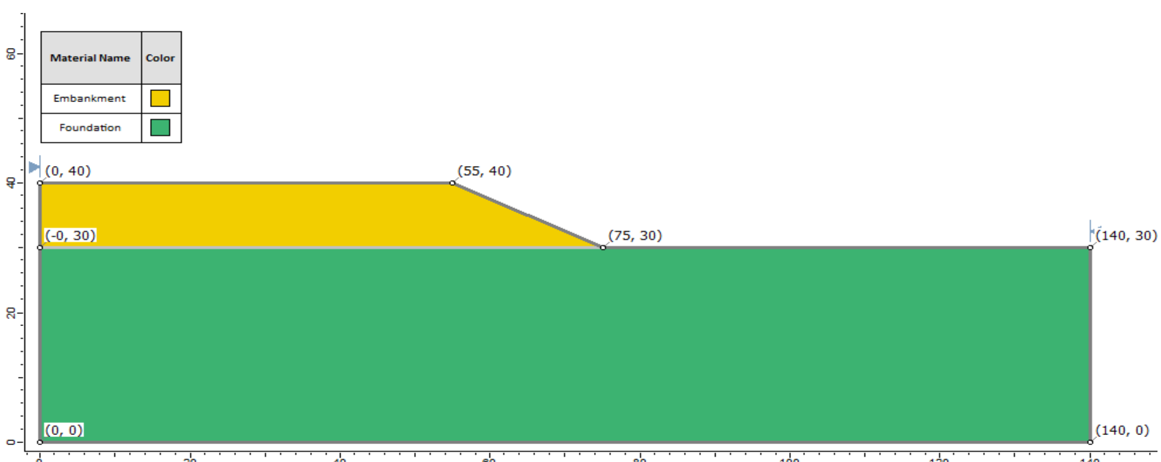


Figure 83.2: An Earth Embankment Wall in **Slide**

Table 83.1: Soil Properties

Zone	c´ (psf)		ϕ' (^{0})	γ (pcf)
Embankment	0		36	123
Foundation	Case 1	$c' = 200 + 15 \times depth$	0	97
	Case 2	$c' = 300$		

83.4. Results

Table 83.2: Case 1 – Undrained shear strength profile I

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.313	1.119
Spencer	1.285	1.262
GLE	1.294	1.229

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]

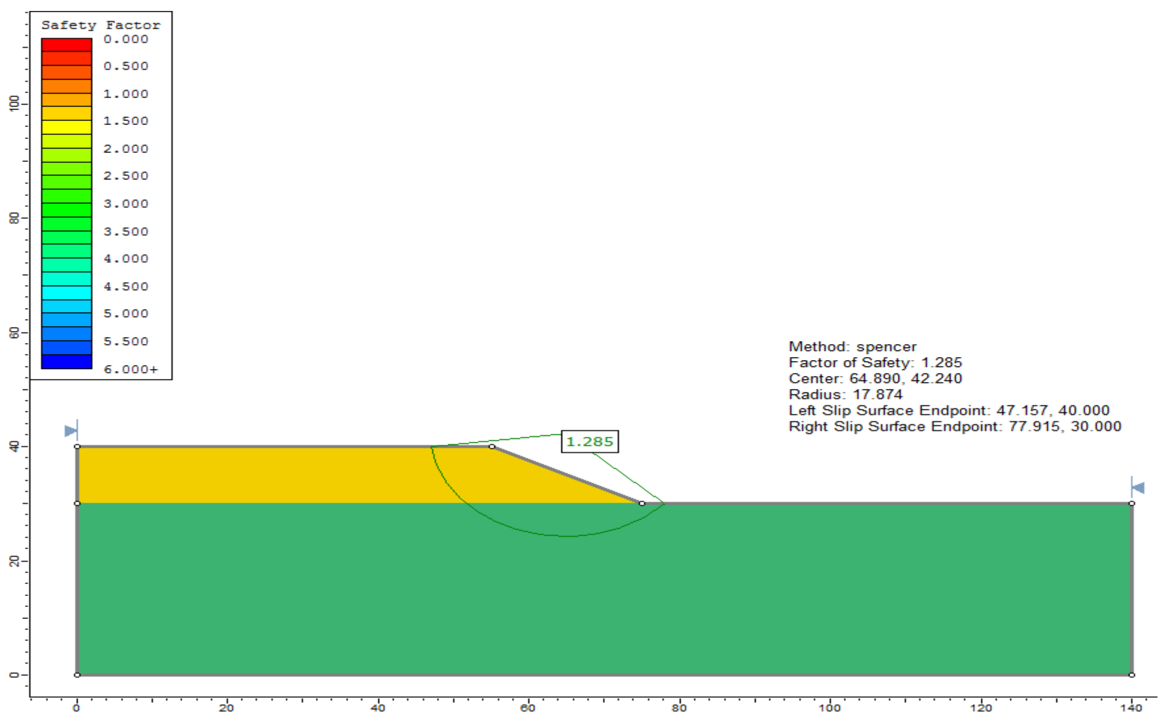


Figure 83.3: Solution to Case 1, using the Spencer method

Table 83.3: Case 2 – Undrained shear strength profile II

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.335	1.067
Spencer	1.330	1.182
GLE	1.331	1.195

Note: R 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]

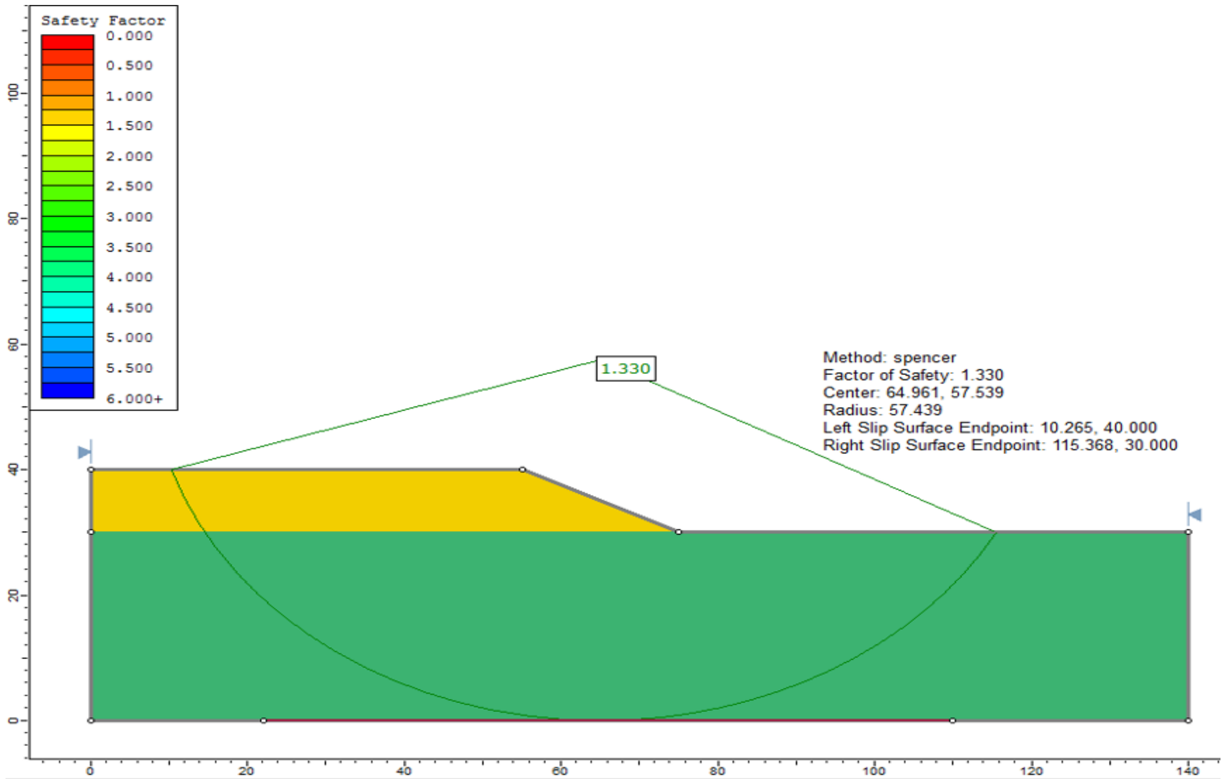


Figure 83.4: Solution to Case 2, using the Spencer method

84. Slide Verification Problem #84

Embankment, (2) materials

84.1. Introduction

This problem is taken from Figure 15.9 on page 244 of Duncan and Wright (2005).

84.2. Problem Description

An earth embankment is shown in Figure 84.1. Four undrained shear strength profiles for the foundation are analyzed. The undrained shear strength profiles can be generalized as:

$$c_u = 300 + \mathrm{c_z}\ \mathrm{z}$$

where z is depth (in feet) and c_z is the rate of increase in undrained shear strength. c_z value varies among profiles. The critical slip surfaces in this verification problem are assumed to be circular.

84.3. Geometry and Material Properties

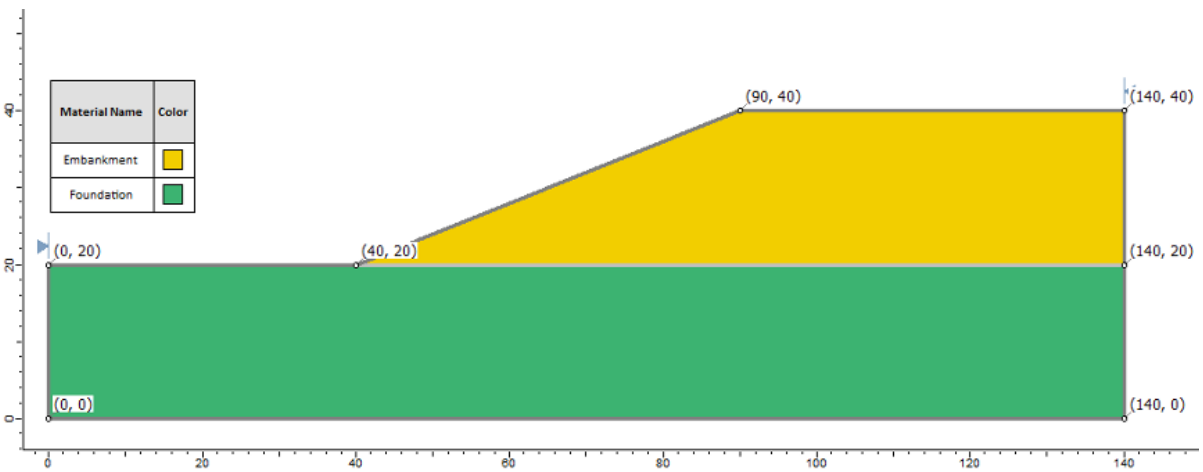


Figure 84.1: An Earth Embankment in **Slide**

Table 84.1: Soil Properties

Zone	c' (psf)	ϕ' (⁰)	γ (pcf)
Embankment	0	35	125
Foundation	$c_u = 300 + \mathrm{c_z}\ \mathrm{z}$	0	100

Table 3.2

Table 84.2: c_z values

Profile	c_z (psf/ft)
I	0
II	5
III	10
IV	15

84.4. Results

Table 84.3: Case 1 – Undrained shear strength profile I

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	0.761	0.684
Spencer	0.756	0.740
GLE	0.762	0.747

Note: Reference factor of safety = 0.75 [Duncan and Wright]

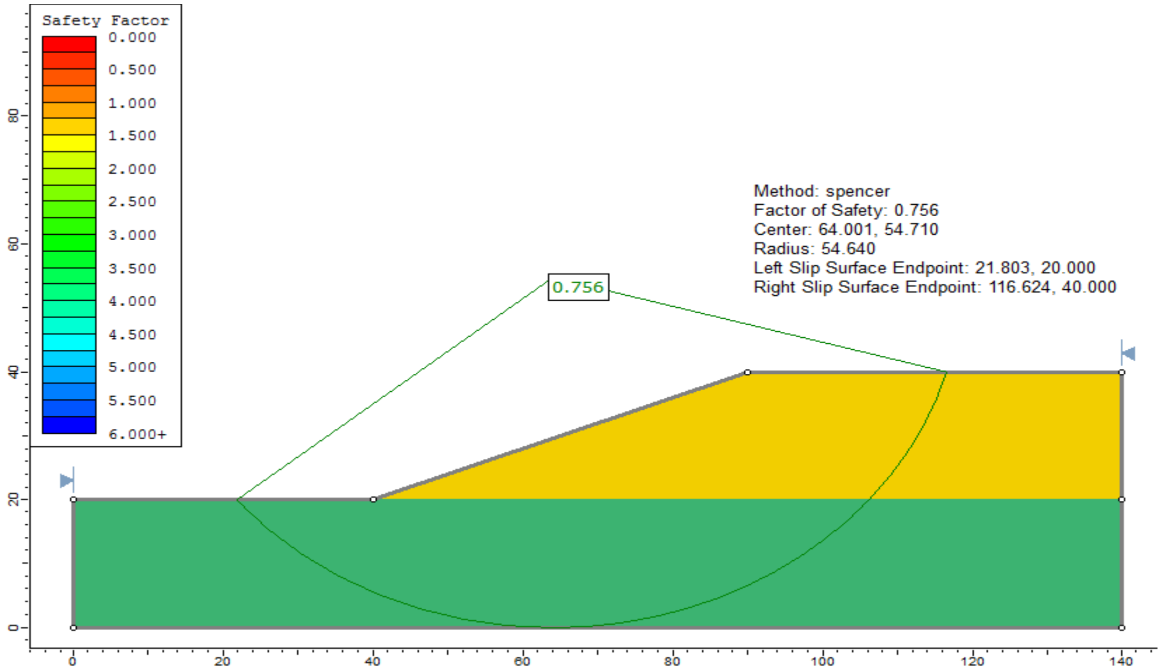


Figure 84.2: Solution to Case 1, using the Spencer method

Table 84.4: Case 2 – Undrained shear strength profile II

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	0.909	0.814
Spencer	0.898	0.903
GLE	0.908	0.908

Note: Reference factor of safety = 0.90 [Duncan and Wright]

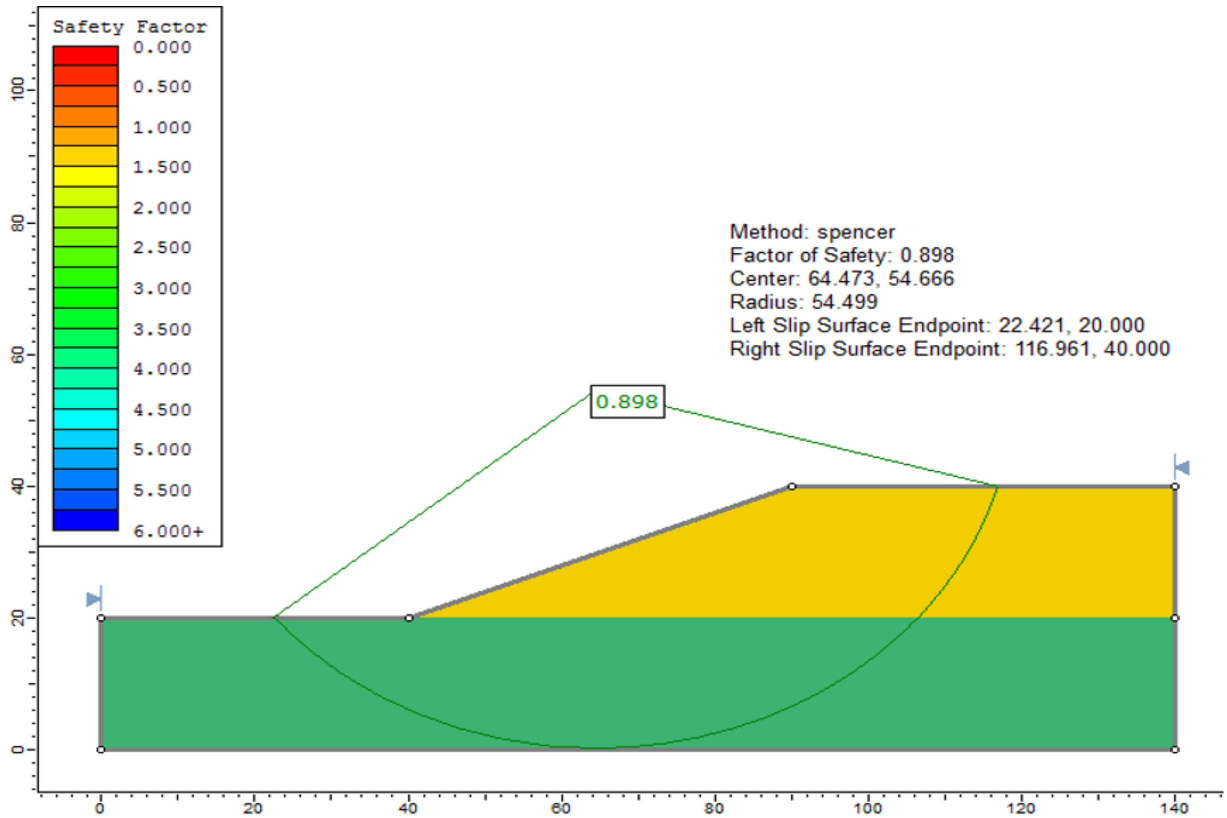


Figure 84.3: Solution to Case 2, using the Spencer method

Table 84.5: Case 3 – Undrained shear strength profile III

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.045	0.937
Spencer	1.032	1.018
GLE	1.034	1.024

Note: Reference factor of safety = 1.03 [Duncan and Wright]

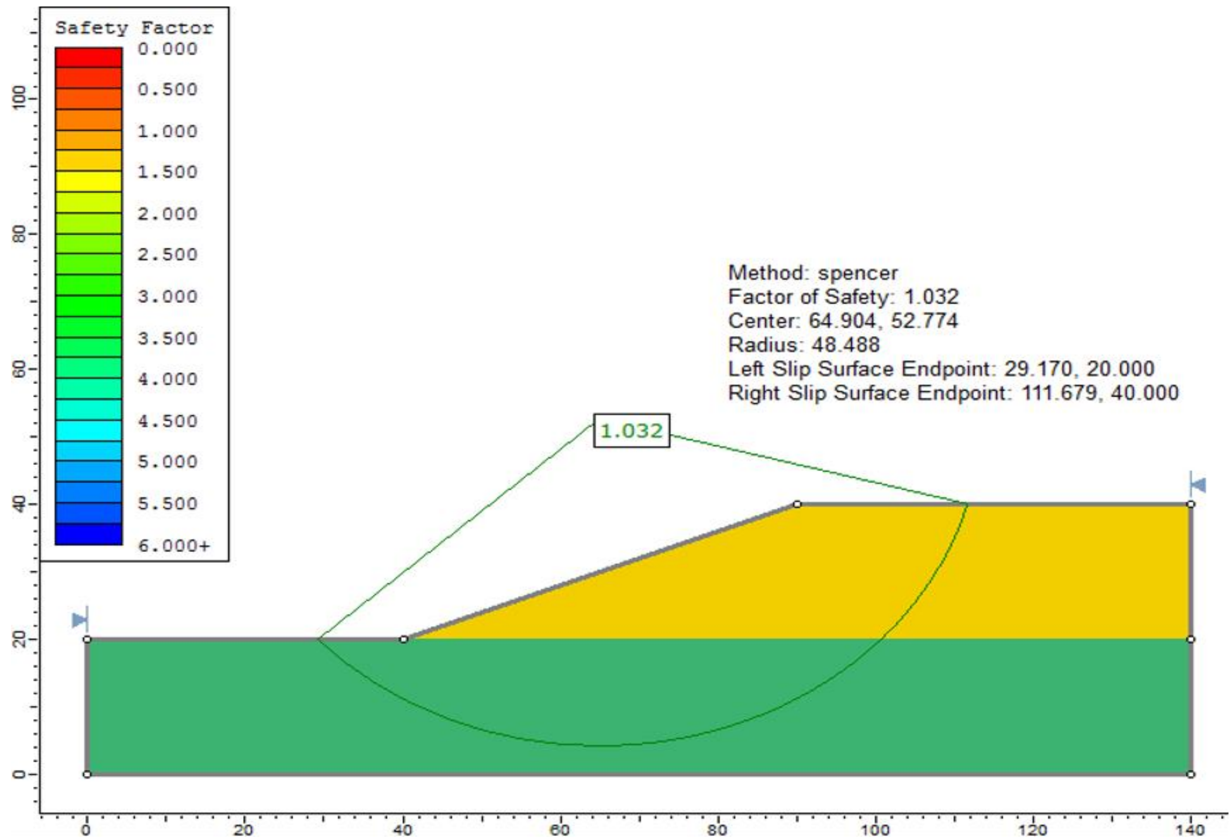


Figure 84.4: Solution to Case 3, using the Spencer method

Table 84.6: Case 4 – Undrained shear strength profile IV

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.154	1.023
Spencer	1.134	1.116
GLE	1.138	1.103

Note: Reference factor of safety = 1.13 [Duncan and Wright]

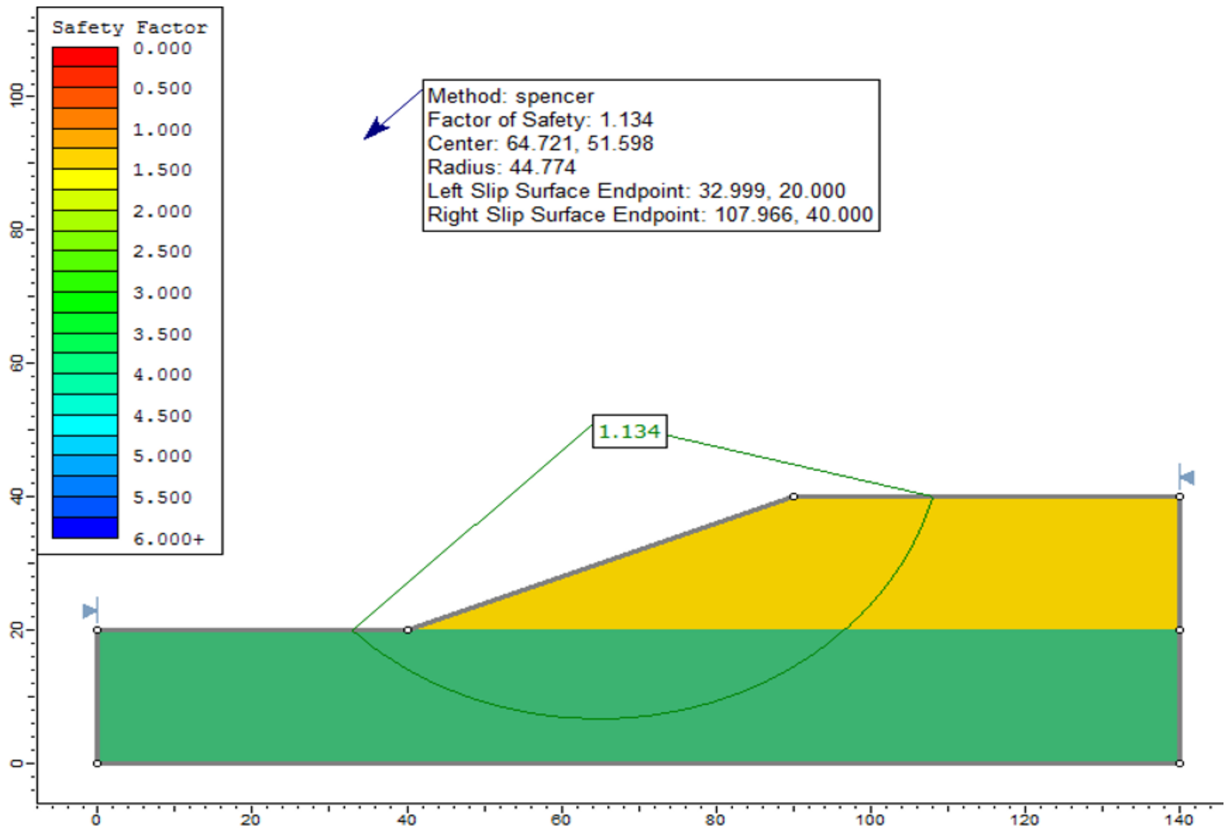


Figure 84.5: Solution to Case 4, using the Spencer method

85. Slide Verification Problem #85

Reinforced slope, homogenous, grouted tieback

85.1. Introduction

This problem is taken from Figure 6.34 on page 95 of Duncan and Wright (2005).

85.2. Problem Description

A saturated clay slope with a single support placed at its mid-height is shown in Figure 85.1. The used support has a capacity of 9,000 lb/ft. Two cases of support applications are investigated in this verification problem. The first one is active support and the second one is passive support.

85.3. Geometry and Material Properties

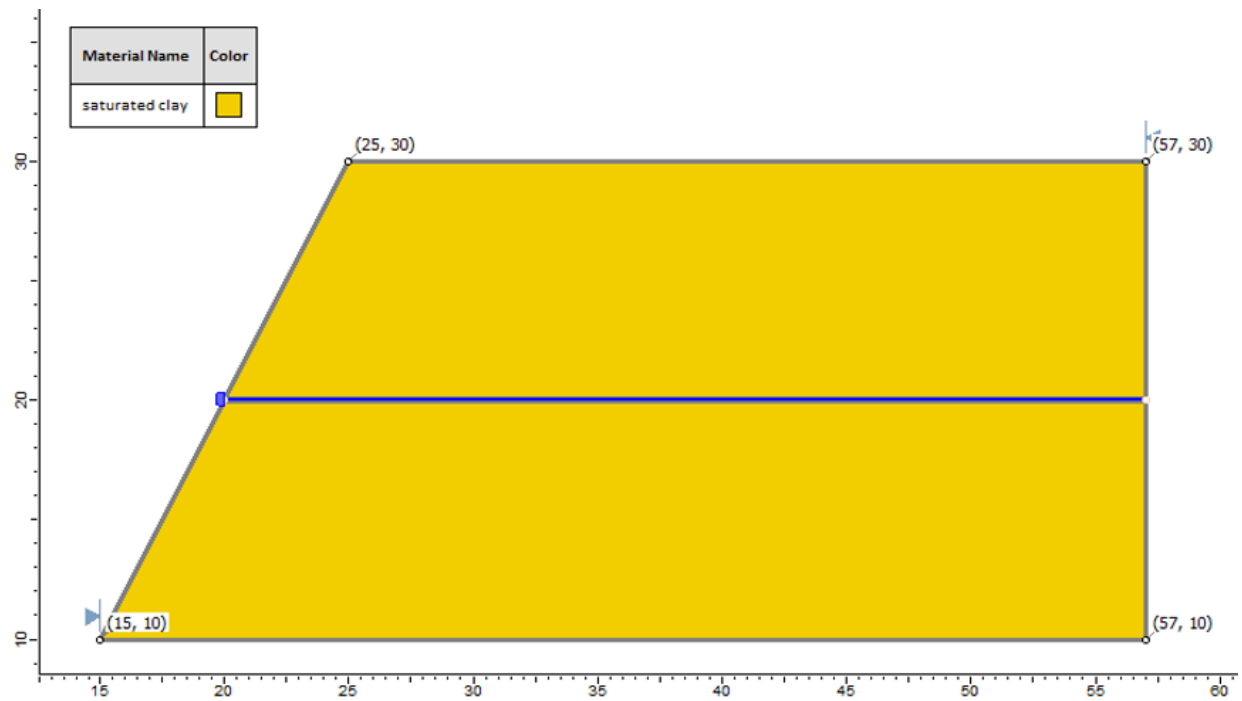


Figure 85.1: A Saturated Clay Slope in **Slide**

Table 85.1: Soil Properties

c (psf)	ϕ (^{0})	γ (pcf)
350	0	98

85.4. Results

Table 85.2: Case 1 – Active Support

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.531	1.418
Spencer	1.884	2.016
GLE	1.575	2.051

Note: Reference factor of safety = 1.51 [Duncan and Wright]

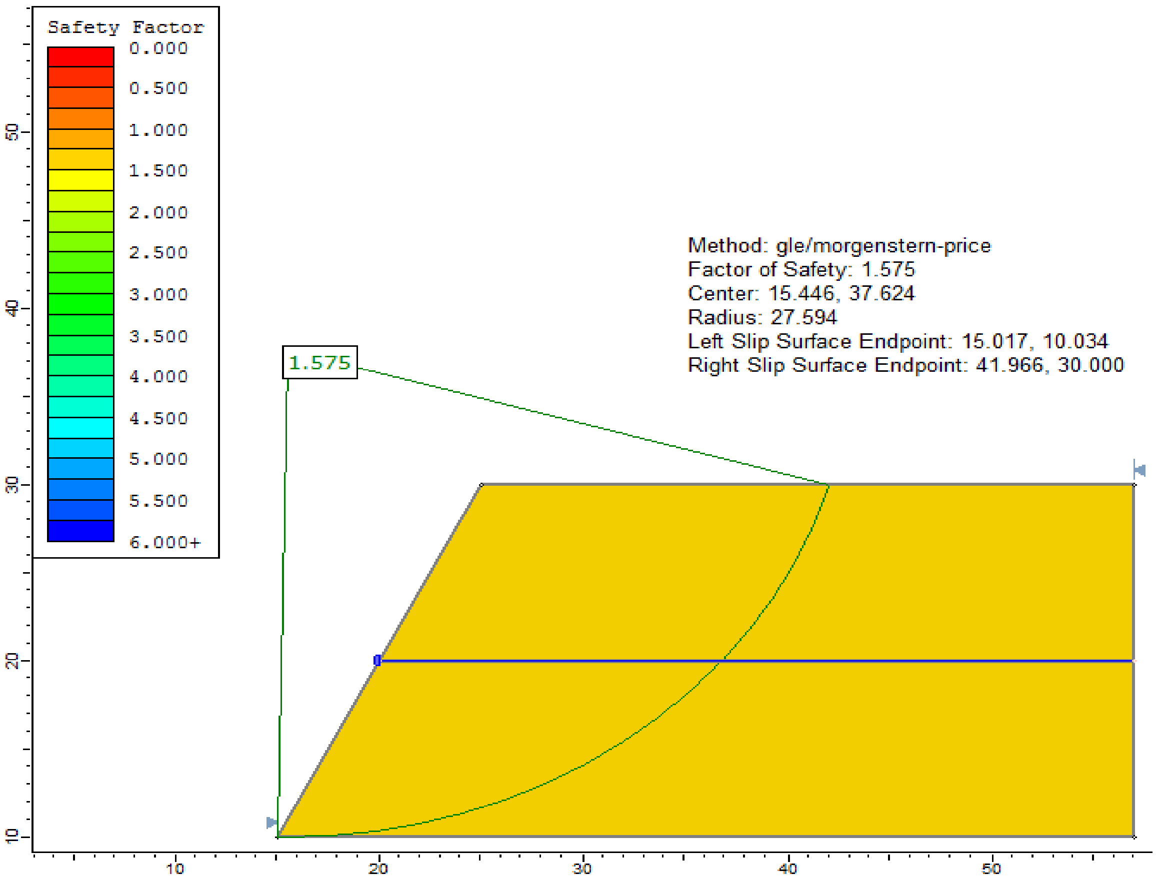


Figure 85.2: Solution to Case 1, using the GLE method

Table 85.3: Case 2 – Passive Support

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.324	1.245
Spencer	1.872	1.575
GLE	1.378	1.491

Note: Reference factor of safety = 1.32 [Duncan and Wright]

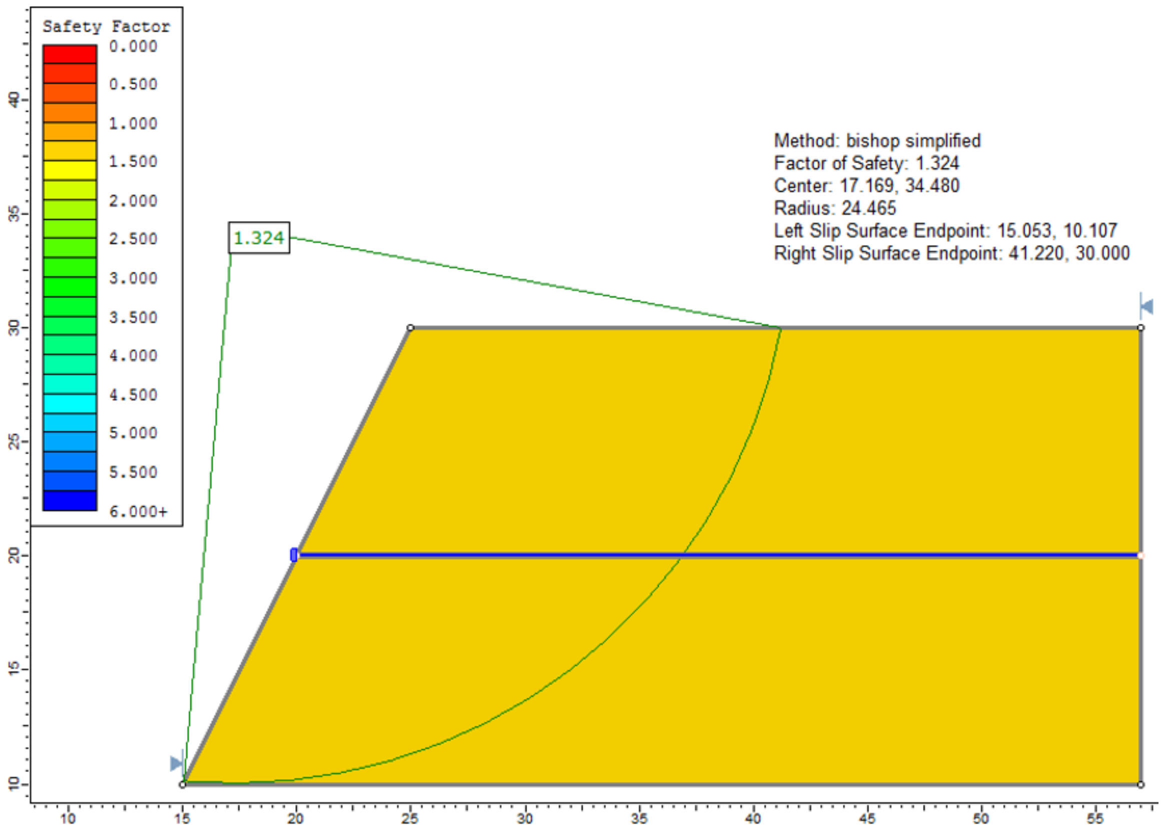


Figure 85.3: Solution to Case 2, using the GLE method

86. Slide Verification Problem #86

Reinforced slope, homogenous, grouted tieback

86.1. Introduction

This problem is taken from Figure 7.28 on page 135 of Duncan and Wright (2005) (see also the STABGM user's documentation).

86.2. Problem Description

A reinforced fill slope resting on a much stronger rock foundation is shown in Figure 86.1. Each of the used supports has a capacity of 800 lb/ft and is 20 feet long. The supports are spaced 4 feet apart vertically and the first support is located 4 feet above the foundation. The global slope failure, not the local failure between supports, is of interest.

86.3. Geometry and Material Properties

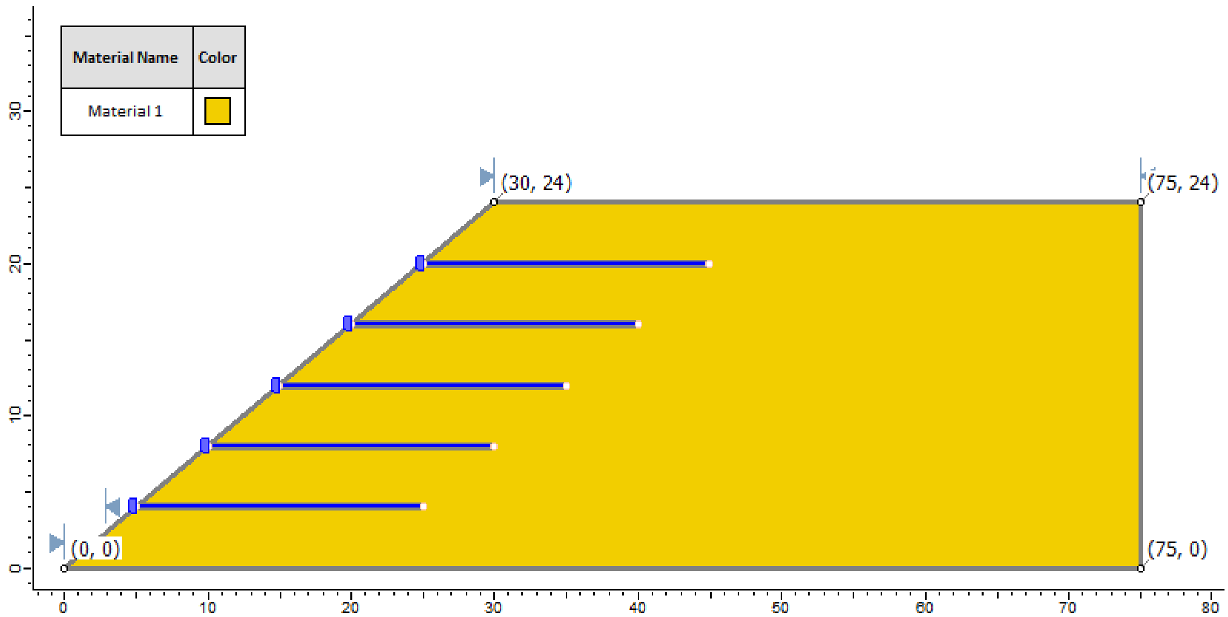


Figure 86.1: A Reinforced Fill Slope on a Strong Rock Foundation in **Slide**

Table 86.1: Soil Properties

c (psf)	ϕ' (^{0})	γ (pcf)
0	37	130

86.4. Results

Table 86.2

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.629	1.585
Spencer	1.620	1.594
GLE	1.622	1.588

Note: Reference factor of safety = 1.61 [Duncan and Wright]

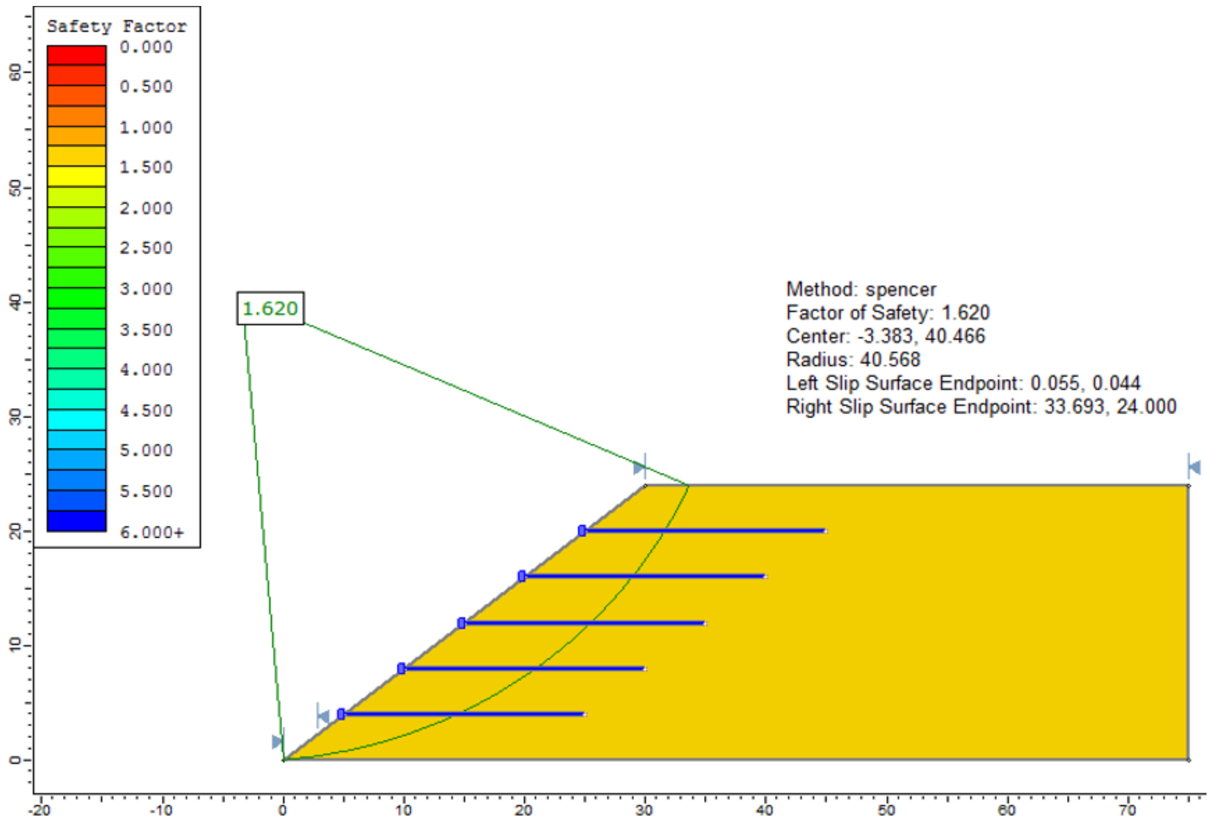


Figure 86.2: Solution, using the Spencer method

87. Slide Verification Problem #87

Retaining wall, (3) materials, geotextile

87.1. Introduction

This problem is taken from the Baseline case studied in the “Geosynthetic Reinforced Multitiered Walls”, a paper by Leshchinsky, D. and Han, J. (2004).

87.2. Problem Description

A three-tiered wall is shown in Figure 87.1. The material properties are presented in Table 87.1. The support properties are tabulated in Table 87.2. The global slope failure, not the local failure at each tier, is of interest.

87.3. Geometry and Material Properties

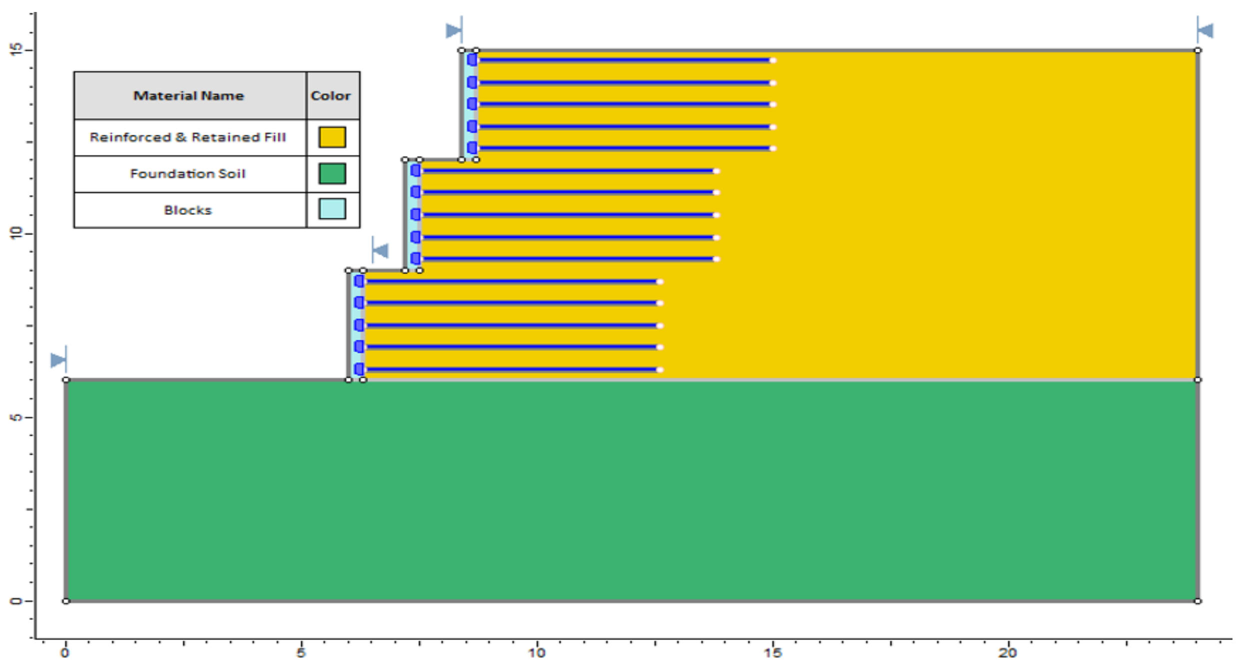


Figure 87.1: A Three-tiered Wall in **Slide**

Table 87.1: Soil Properties

Zone	c (kPa)	ϕ (^{0})	γ (kN/m^3)
Reinforced and retained fill	0	34	18
Foundation soil	10	34	18
Blocks	2.5	34	18

Table 87.2: Support Properties

Length (m)	Tensile Strength (kN/m)	Pullout Strength
6.3	10.0	80%

87.4. Results

Table 87.3

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.040	0.989
Spencer	1.097	1.103
GLE	1.168	1.118

Note: Reference factor of safety = 0.99 (using finite difference method) & 1.00 (circular slip surface using the Bishop method) [Leshchinsky and Han]

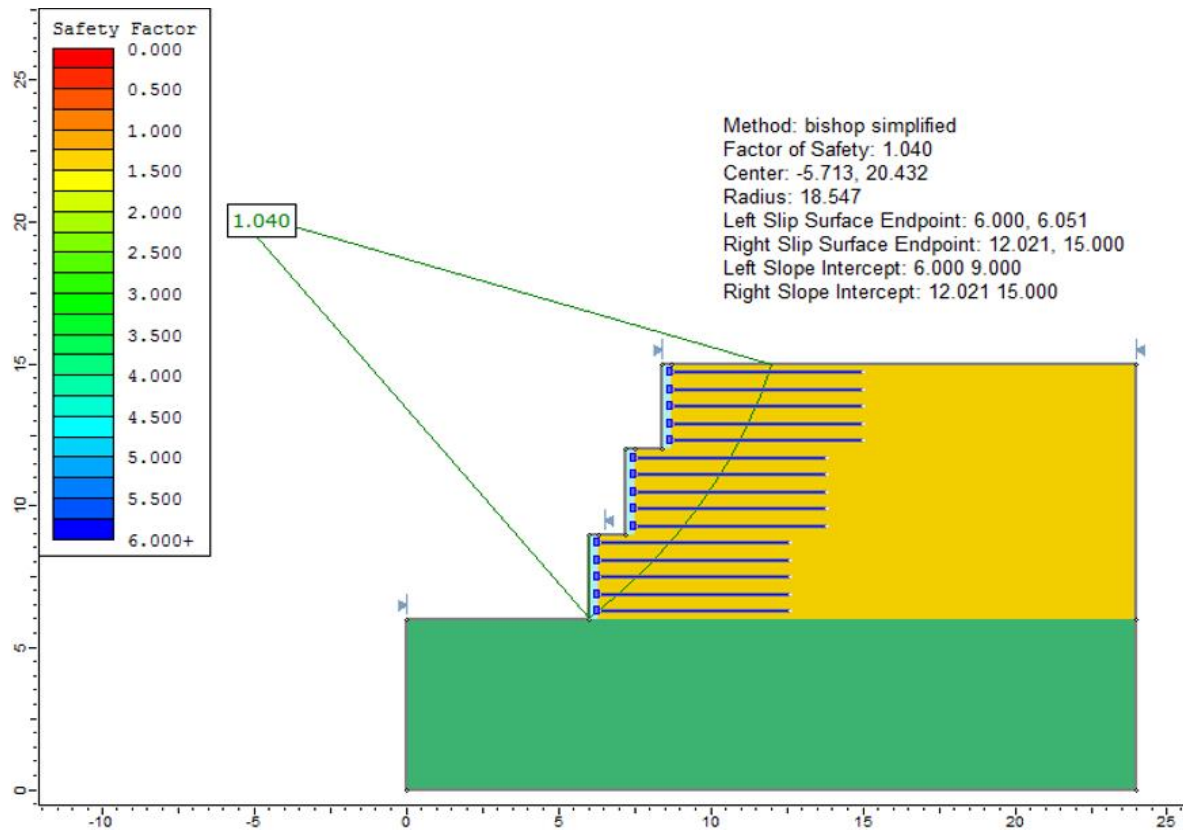


Figure 87.2: Solution, using the Bishop simplified method

88. Slide Verification Problem #88

Retaining wall, (3) materials, geotextile

88.1. Introduction

This problem is taken from the Fill Quality case studied in the "Geosynthetic Reinforced Multitiered Walls", a paper by Leshchinsky, D. and Han, J. (2004).

88.2. Problem Description

A three-tiered wall is shown in Figure 88.1. The model has the same geometry as the model in verification problem #87, but different reinforced and retained fill strength. The purpose of this model is to quantify the effect of fill quality on the stability characteristic of a multi-tiered wall. The material properties are given in Table 88.1. The support properties are shown in Table 88.2.

88.3. Geometry and Material Properties

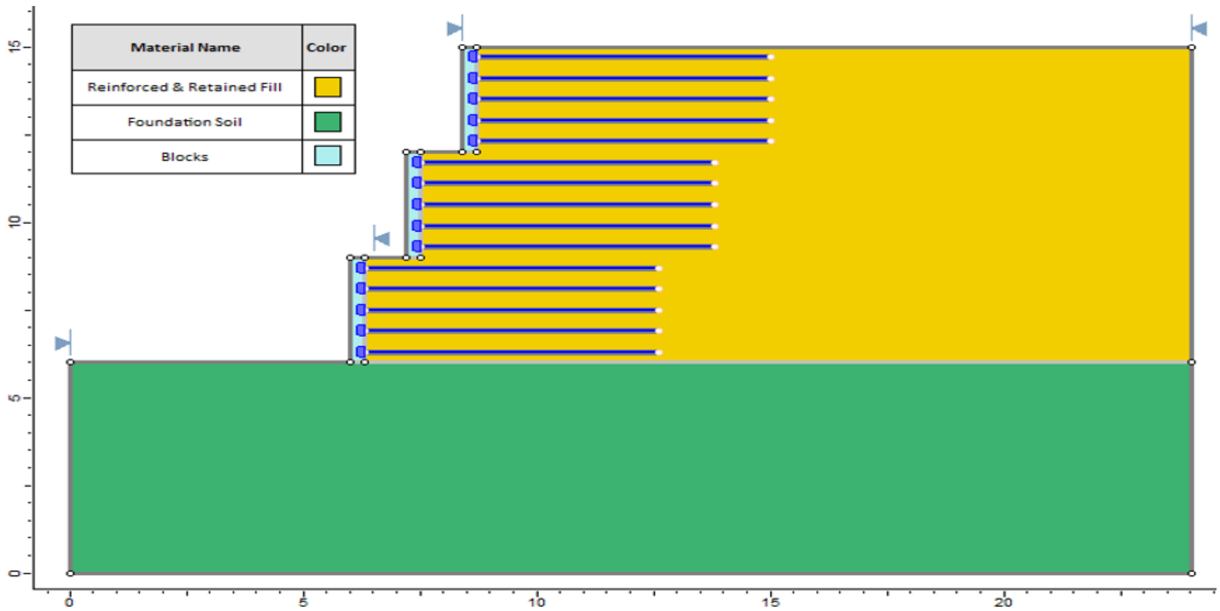


Figure 88.1: A Three-tiered Wall in **Slide**

Table 88.1: Soil Properties

Zone	c (kPa)	ϕ (^{0})	γ (kN/m^3)
Reinforced and retained fill	0	25	18
Foundation soil	10	34	18
Blocks	2.5	34	18

Table 88.2: Support Properties

Length (m)	Tensile Strength (kN/m)	Pullout Strength
6.3	22.0	80%

88.4. Results

Table 88.3

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.045	1.040
Spencer	1.043	1.037
GLE	1.043	1.033

Note: Reference factor of safety = 0.99 (using finite difference method) & 1.00 (circular slip surface using the Bishop method) [Leshchinsky and Han]

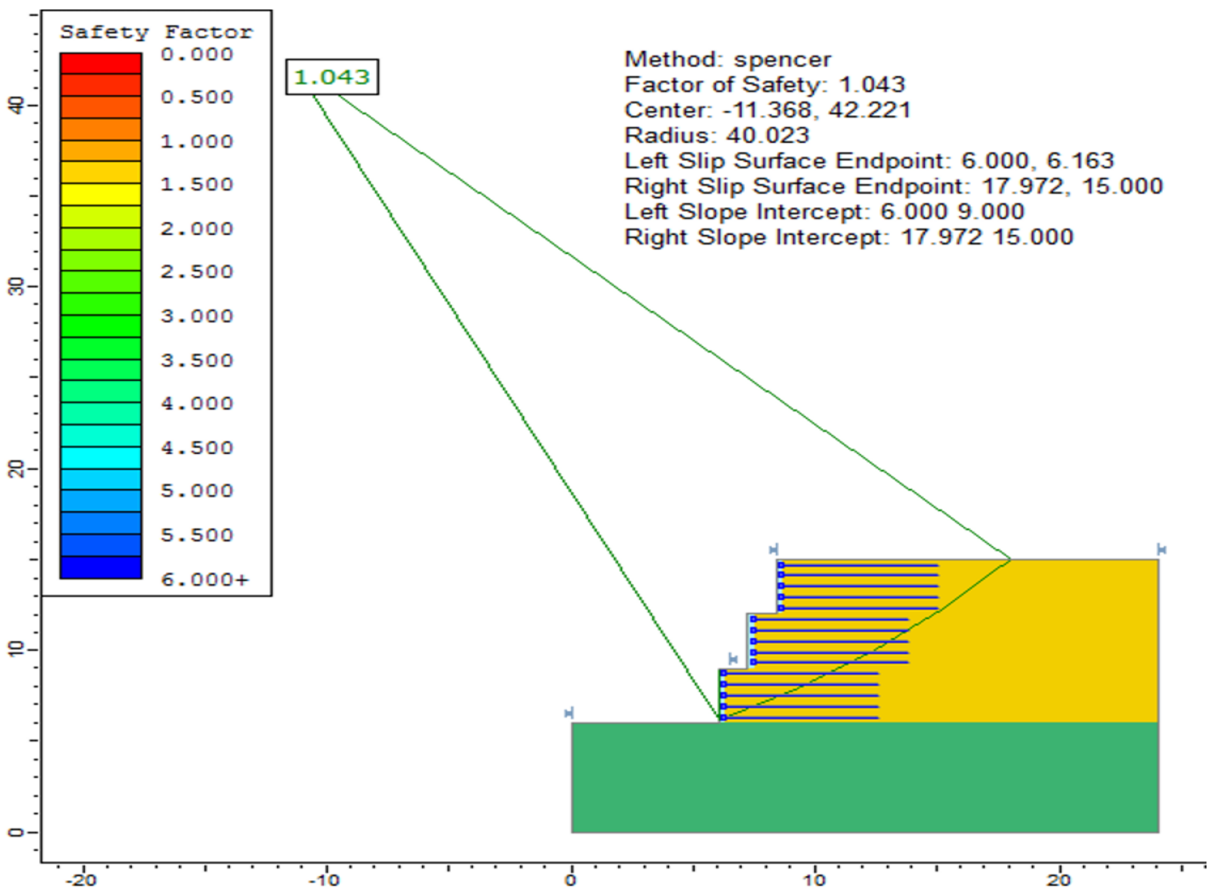


Figure 88.2: Solution, using the Spencer method

89. Slide Verification Problem #89

Retaining wall, (3) materials, geotextile

89.1. Introduction

This problem is taken from the Reinforcement Length case studied in the “Geosynthetic Reinforced Multitiered Walls”, a paper by Leshchinsky, D. and Han, J. (2004).

89.2. Problem Description

A three-tiered wall is shown in Figure 89.1. The support used in this model has a shorter length than that of verification model #87. The purpose of this model is to quantify the effect of reinforcement length on the stability characteristic of a multi-tiered wall. The material properties are given in Table 89.1. The support properties are presented in Table 89.2.

89.3. Geometry and Material Properties

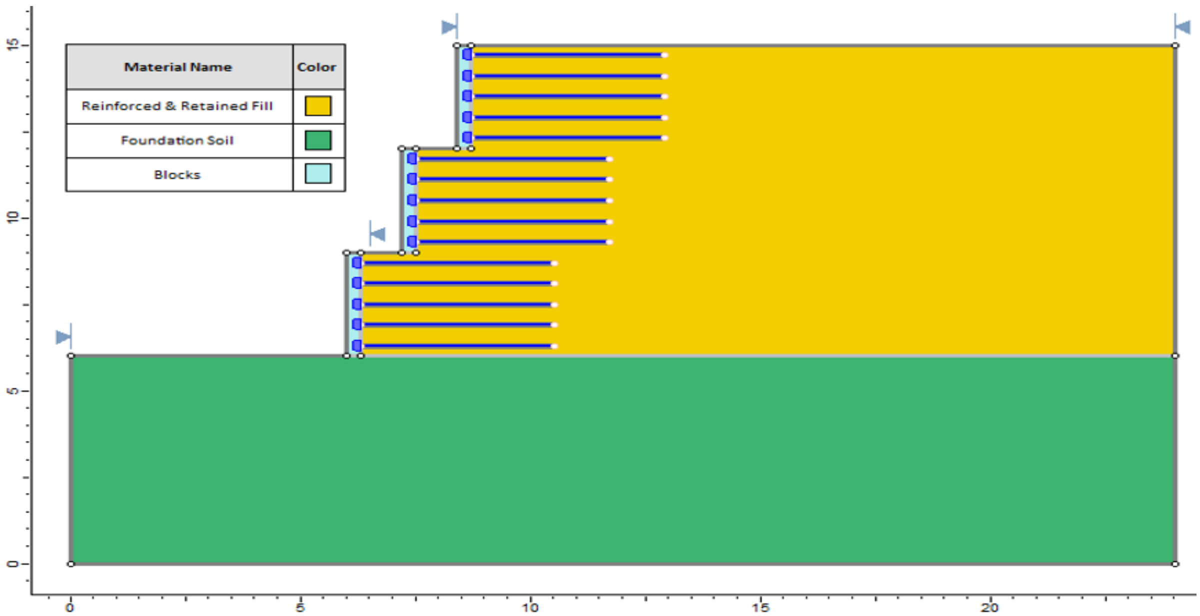


Figure 89.1: A Three-tiered Wall in **Slide**

Table 89.1: Soil Properties

Zone	c (kPa)	ϕ (^{0})	γ (kN/m^3)
Reinforced and retained fill	0	34	18
Foundation soil	10	34	18
Blocks	2.5	34	18

Table 89.2: Support Properties

Length (m)	Tensile Strength (kN/m)	Pullout Strength
4.2	11.4	80%

89.4. Results

Table 89.3

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	0.976	0.988
Spencer	0.971	0.966
GLE	0.971	0.962

Note: Reference factor of safety = 0.98 (using finite difference method) & 1.00 (circular slip surface using the Bishop method) [Leshchinsky and Han]

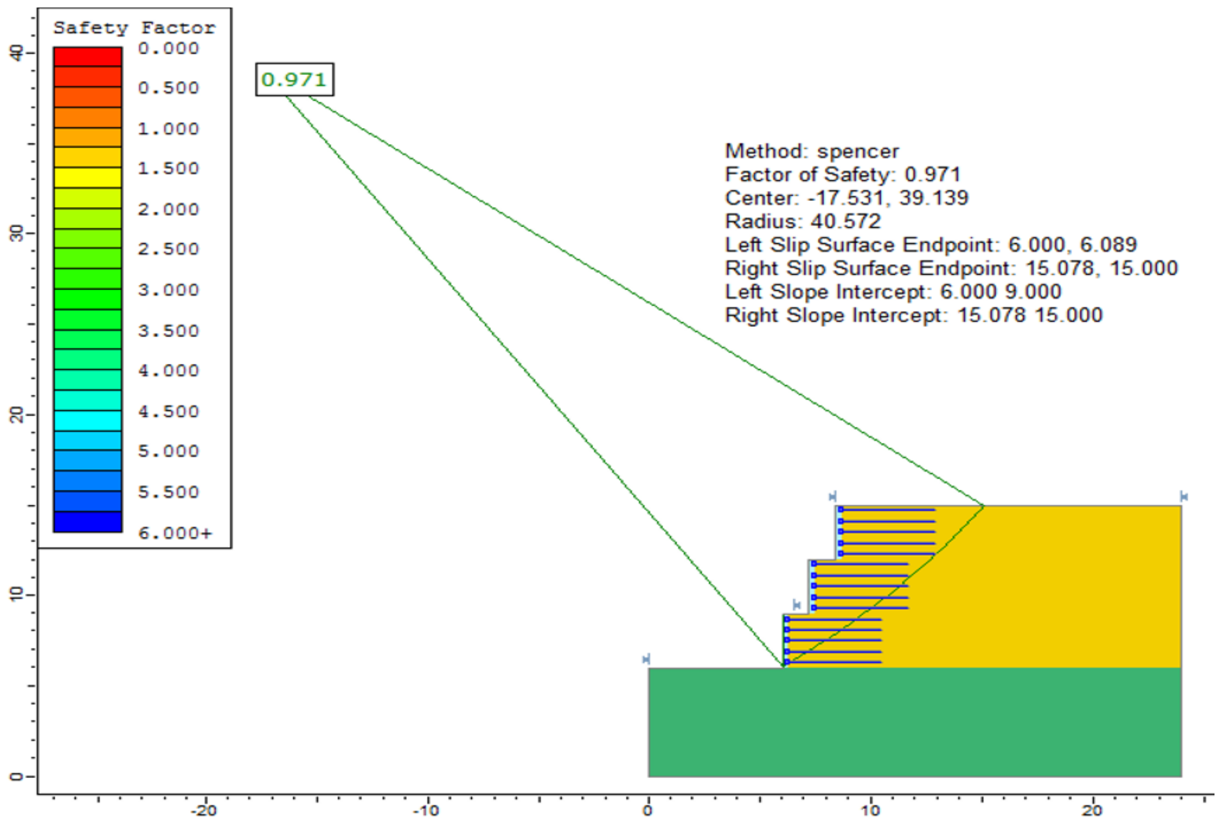


Figure 89.2: Solution, using the Spencer method

90. Slide Verification Problem #90

Retaining wall, (3) materials, geotextile

90.1. Introduction

This problem is taken from the Reinforcement Type case studied in the "Geosynthetic Reinforced Multitiered Walls", a paper by Leshchinsky, D. and Han, J. (2004).

90.2. Problem Description

A three-tiered wall is shown in Figure 90.1. This model uses two support types. The purpose of this model is to quantify the effect of reinforcement type on the stability characteristic of a multi-tiered wall. The material properties are given in Table 90.1. The support properties are presented in Table 90.2.

90.3. Geometry and Material Properties

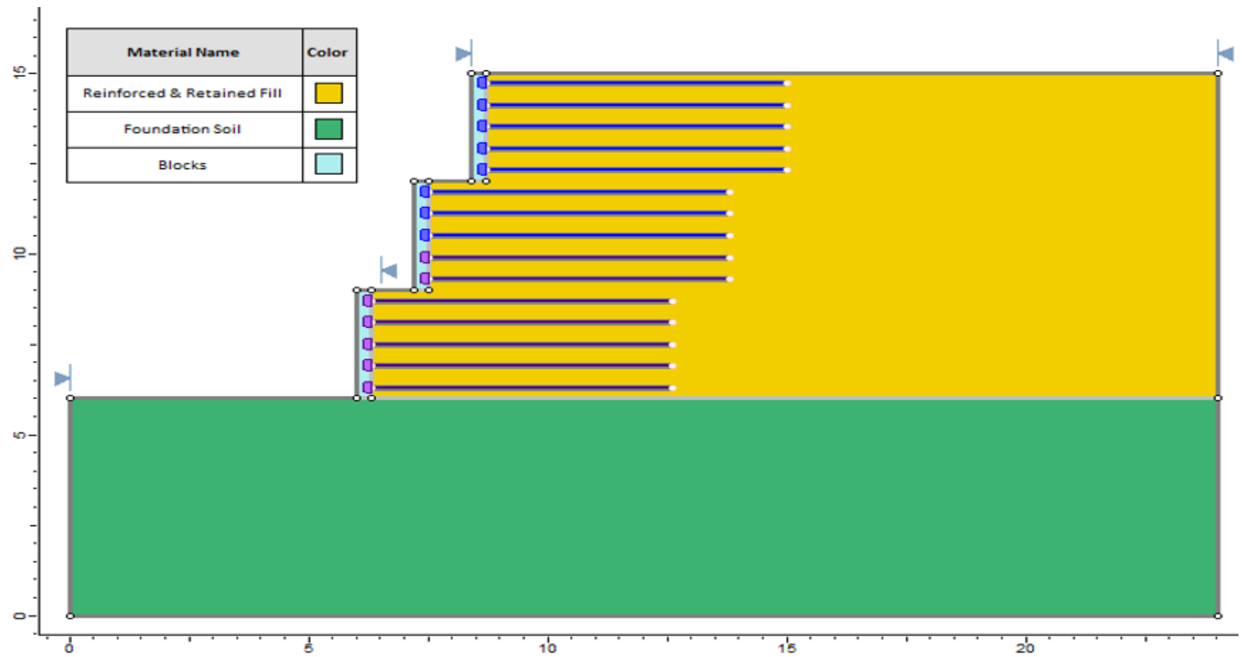


Figure 90.1: A Three-tiered Wall in **Slide**

Table 90.1: Soil Properties

Zone	c (kPa)	ϕ (^{0})	γ (kN/m^3)
Reinforced and retained fill	0	34	18
Foundation soil	10	34	18
Blocks	2.5	34	18

Table 90.2: Support Properties

Type	Length (m)	Tensile Strength (kN/m)	Pullout Strength
#1 (upper 8 layers)	6.3	7.5	80%
#2 (lower 7 layers)	6.3	11.0	80%

90.4. Results

Table 90.3

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.004	0.978
Spencer	1.002	1.146
GLE	1.004	1.158

Note: Reference factor of safety = 1.01 (using finite difference method) & 1.00 (circular slip surface using the Bishop method) [Leshchinsky and Han]

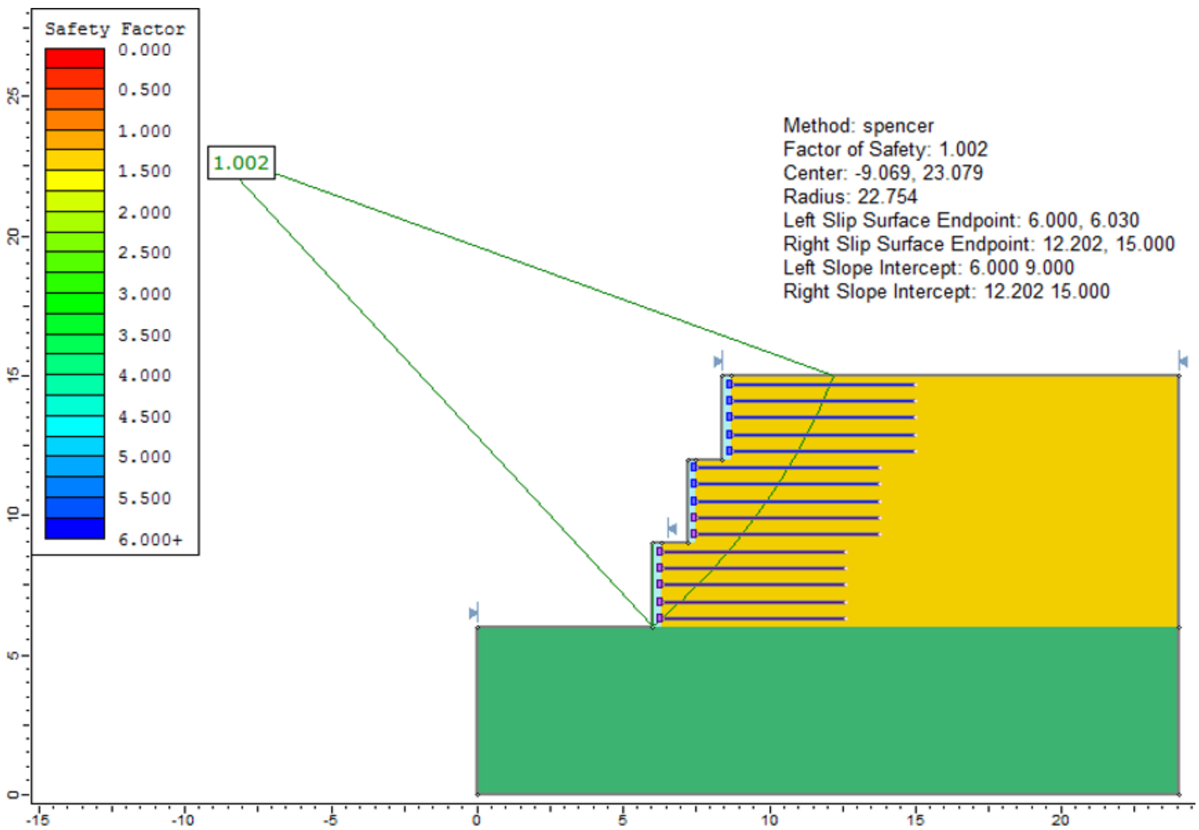


Figure 90.2: Solution, using the Spencer method

91. Slide Verification Problem #91

Retaining wall, (3) materials, geotextile

91.1. Introduction

This problem is taken from the Foundation Soil case studied in the “Geosynthetic Reinforced Multitiered Walls”, a paper by Leshchinsky, D. and Han, J. (2004).

91.2. Problem Description

A three-tiered wall is shown in Figure 91.1. The model has the same geometry as the model in verification problem #87, but different foundation soil strength. The purpose of this model is to quantify the effect of foundation soil strength on the stability characteristic of a multi-tiered wall. The material properties are shown in Table 91.1. The support properties are given in Table 91.2.

91.3. Geometry and Material Properties

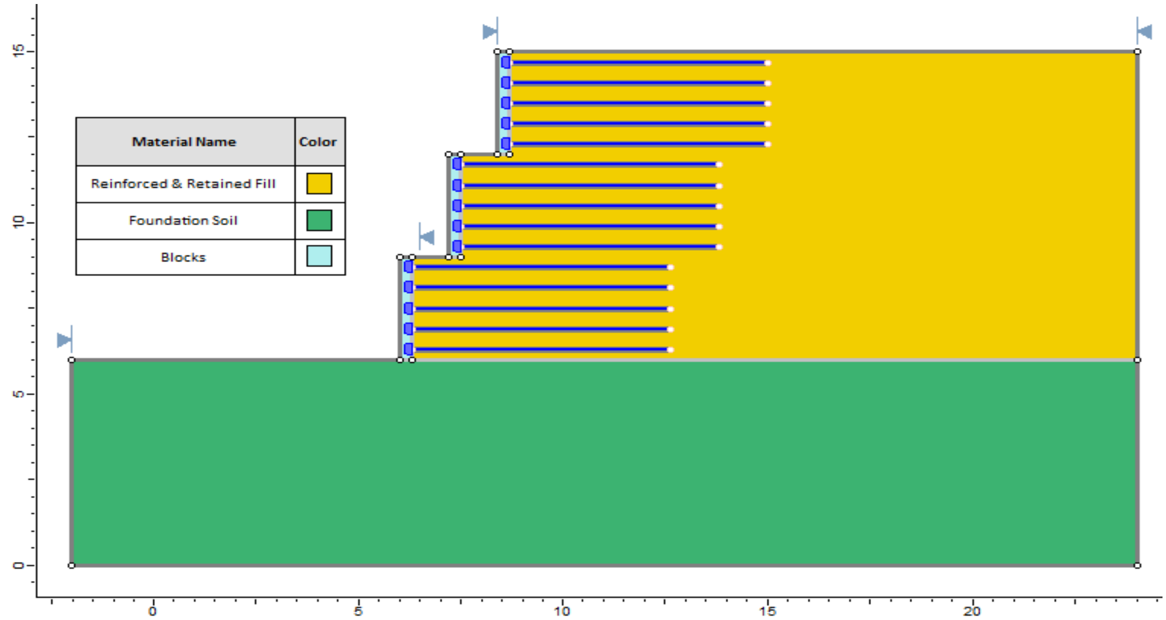


Figure 91.1: A Three-Tiered Wall in **Slide**

Table 91.1: Soil Properties

Zone	c (kPa)	ϕ (^{0})	γ (kN/m^3)
Reinforced and retained fill	0	34	18
Foundation soil	0	18	18
Blocks	2.5	34	18

Table 91.2: Support Properties

Length (m)	Tensile Strength (kN/m)	Pullout Strength
6.3	10.0	80%

91.4. Results

Table 91.3

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	0.985	0.783
Spencer	0.964	0.829
GLE	0.963	1.007

Note: Reference factor of safety = 0.86 (using finite difference method) & 1.00 (circular slip surface using the Bishop method) [Leshchinsky and Han]

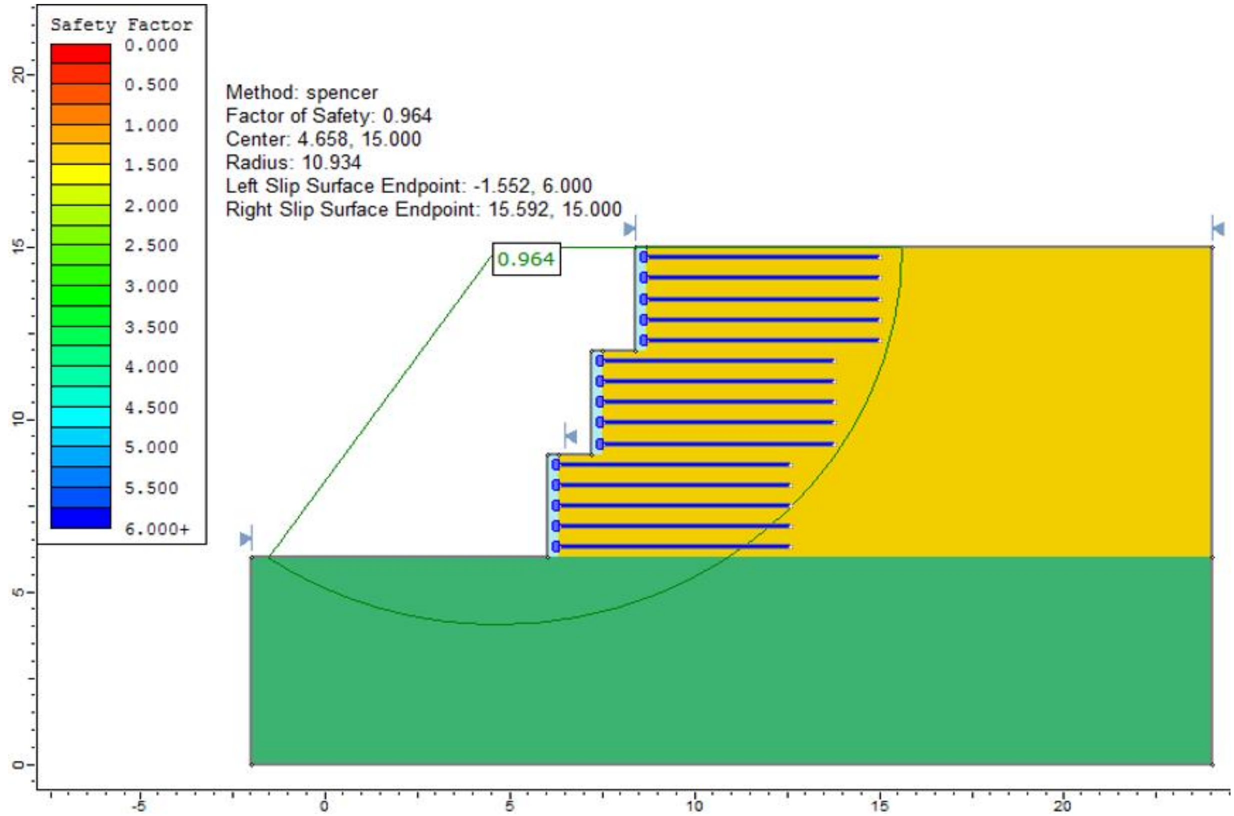


Figure 91.2: Solution, using the Spencer method

92. Slide Verification Problem #92

Retaining wall, (3) materials, geotextile

92.1. Introduction

This problem is taken from the Water case studied in the “Geosynthetic Reinforced Multitiered Walls”, a paper by Leshchinsky, D. and Han, J. (2004).

92.2. Problem Description

A three-tiered wall is shown in Figure 92.1. The model has the same geometry as the model in verification problem #87 with an addition of water seepage. The purpose of this model is to quantify the effect of water seepage on the stability characteristic of a multi-tiered wall. The material properties are shown in Table 92.1. The support properties are given in Table 92.2.

92.3. Geometry and Material Properties

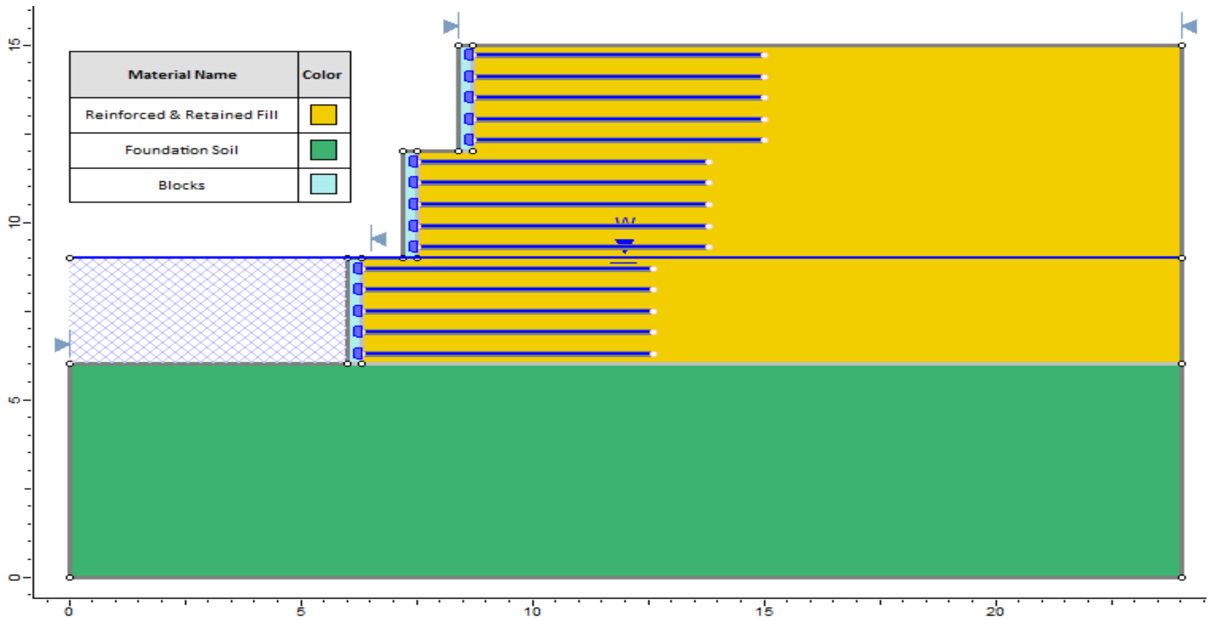


Figure 92.1: A Three-Tiered Wall in **Slide**

Table 92.1: Soil Properties

Zone	c (kPa)	ϕ (^{0})	γ (kN/m^3)
Reinforced and retained fill	0	34	18
Foundation soil	10	34	18
Blocks	2.5	34	18

Table 92.2: Support Properties

Length (m)	Tensile Strength (kN/m)	Pullout Strength
6.3	9.25	80%

92.4. Results

Table 92.3

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.037	1.040
Spencer	1.111	1.131
GLE	1.111	1.132

Note: Reference factor of safety = 1.01 (using finite difference method) & 1.00 (circular slip surface using the Bishop method) [Leshchinsky and Han]

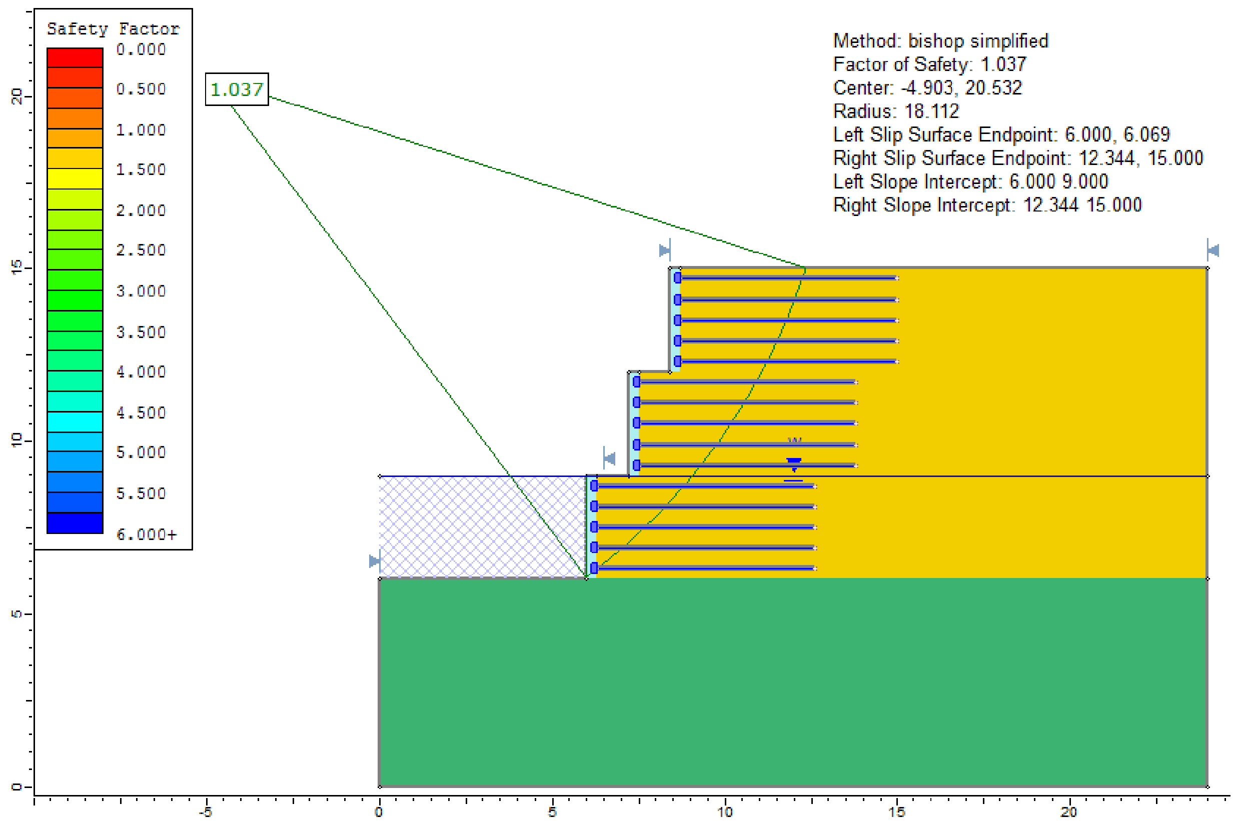


Figure 92.2: Solution, using the Bishop simplified method

93. Slide Verification Problem #93

Retaining wall, (3) materials, distributed load, geotextile

93.1. Introduction

This problem is taken from the Surcharge case studied in the “Geosynthetic Reinforced Multitiered Walls”, a paper by Leshchinsky, D. and Han, J. (2004).

93.2. Problem Description

A three-tiered wall is shown in Figure 93.1. The model has the same geometry as the model in verification problem #87 with an addition of surcharge on the uppermost tier. The purpose of this model is to quantify the effect of surcharge on the stability characteristic of a multi-tiered wall. The material properties are shown in table 93.1. The support properties are given in table 93.2.

93.3. Geometry and Material Properties

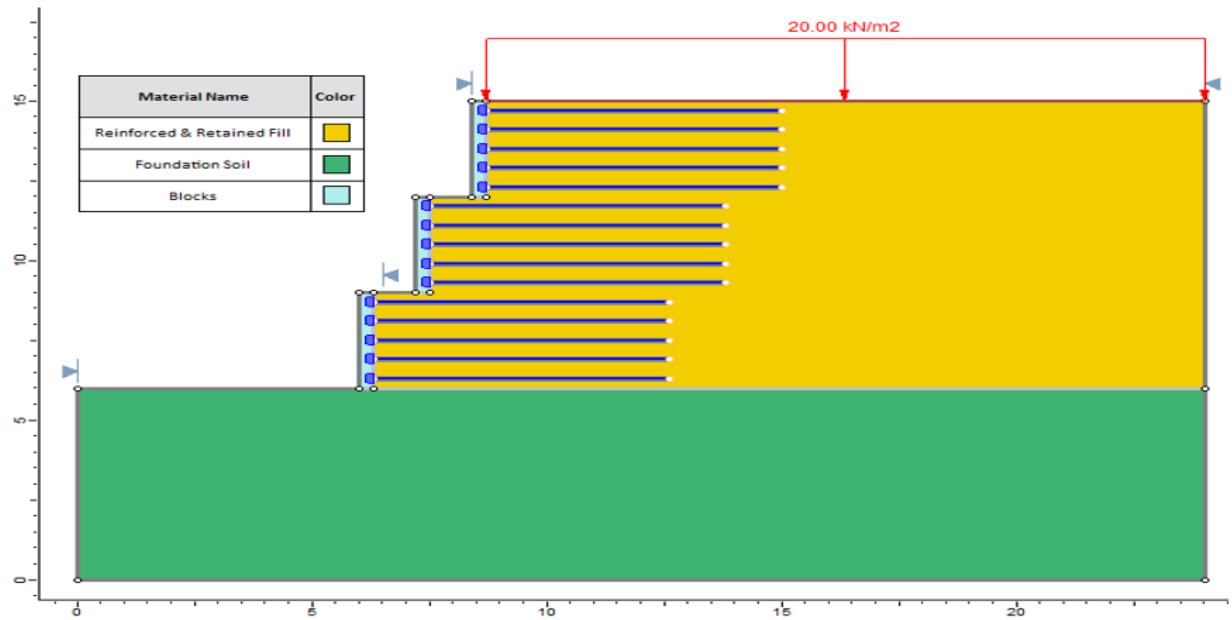


Figure 93.1: A Three-tiered Wall in **Slide**

Table 93.1: Soil Properties

Zone	c (kPa)	ϕ (^{0})	γ (kN/m^3)
Reinforced and retained fill	0	34	18
Foundation soil	10	34	18
Blocks	2.5	34	18

Table 93.2: Support Properties

Length (m)	Tensile Strength (kN/m)	Pullout Strength
6.3	11.6	80%

93.4. Results

Table 93.3

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	0.958	0.981
Spencer	0.957	0.995
GLE	0.956	1.050

Note: Reference factor of safety = 1.02 (using finite difference method) & 1.00 (circular slip surface using the Bishop method) [Leshchinsky and Han]

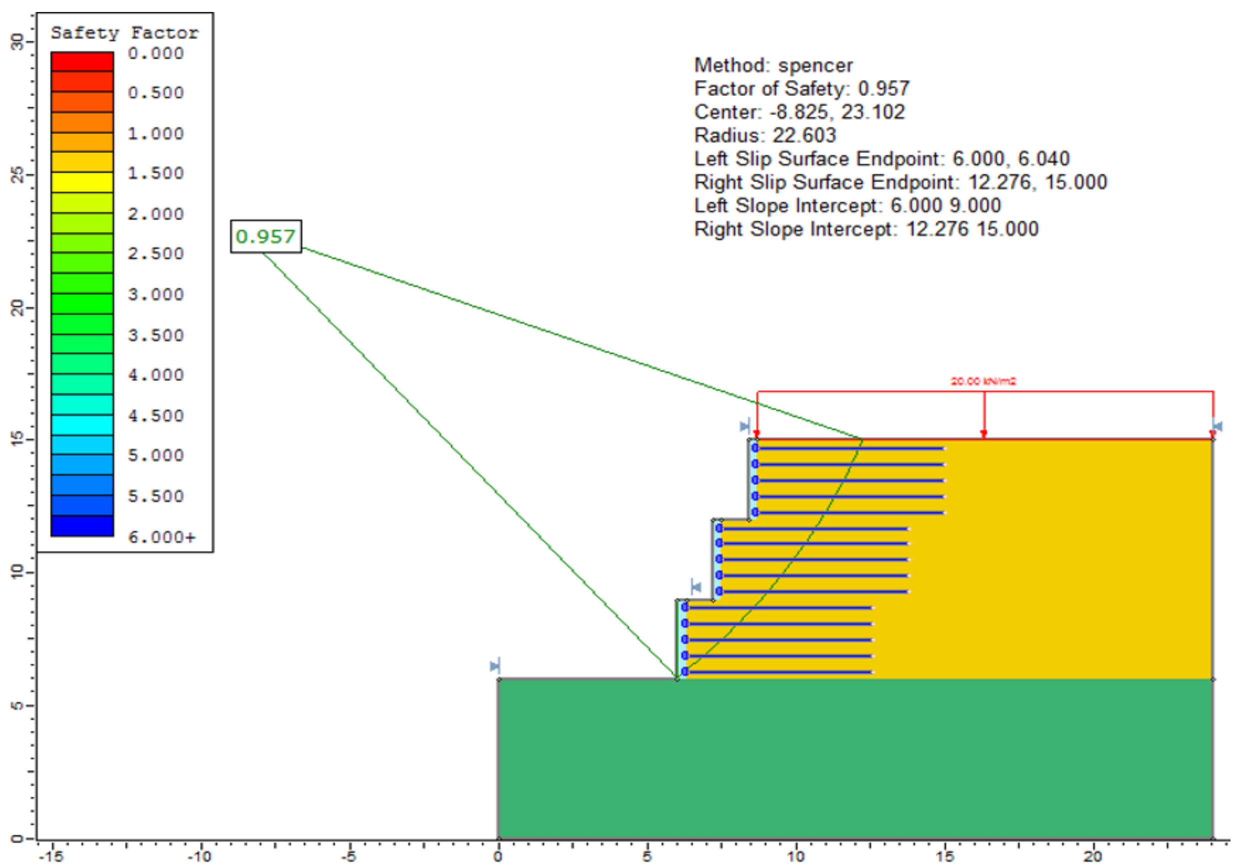


Figure 93.2: Solution, using the Spencer method

94. Slide Verification Problem #94

Retaining wall, (3) materials, geotextile

94.1. Introduction

This problem is taken from the Number of Tiers case studied in the “Geosynthetic Reinforced Multitiered Walls”, a paper by Leshchinsky, D. and Han, J. (2004).

94.2. Problem Description

A five-tiered wall is shown in Figure 94.1. The purpose of this model is to quantify the effect of number of tiers on the stability characteristic of a multi-tiered wall. The material properties are given in table 94.1. The support properties are presented in table 94.2.

94.3. Geometry and Material Properties

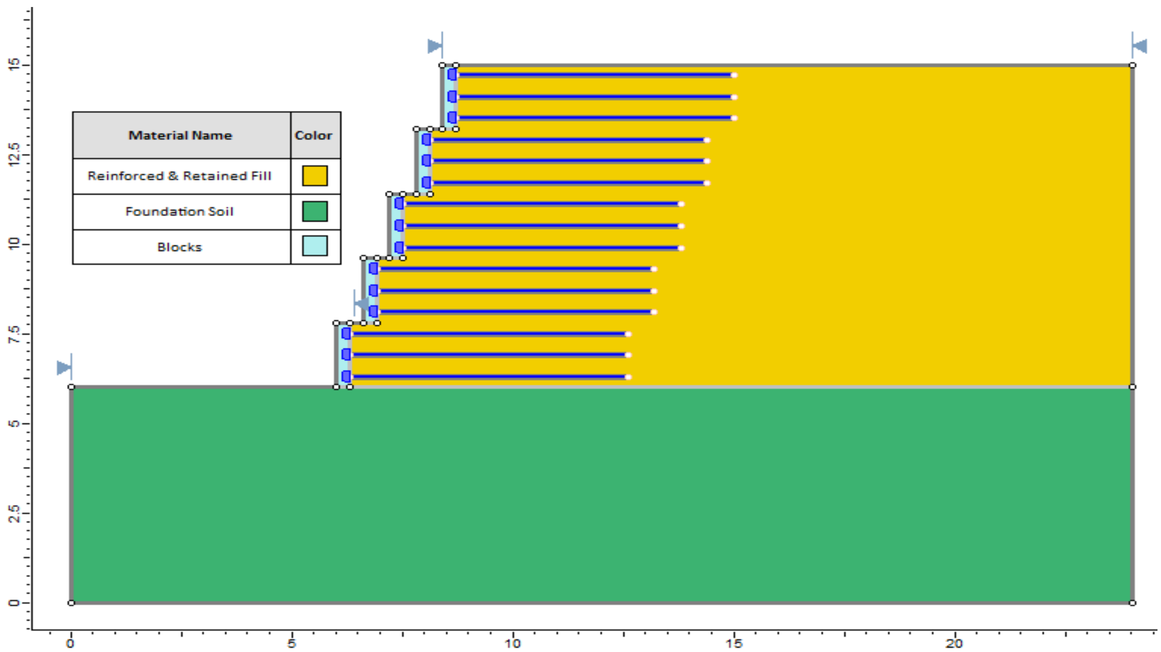


Figure 94.1: A Three-Tiered Wall in **Slide**

Table 94.1: Soil Properties

Zone	c (kPa)	ϕ (^{0})	γ (kN/m^3)
Reinforced and retained fill	0	34	18
Foundation soil	10	34	18
Blocks	2.5	34	18

Table 93.2: Support Properties

Length (m)	Tensile Strength (kN/m)	Pullout Strength
6.3	10.1	80%

94.4. Results

Table 94.3

Method	Factor of Safety (Circular)	Factor of Safety (Non-circular)
Bishop	1.040	0.990
Spencer	1.129	1.075
GLE	1.194	1.074

Note: Reference factor of safety = 1.00 (using finite difference method & circular slip surface using the Bishop method) [Leshchinsky and Han]

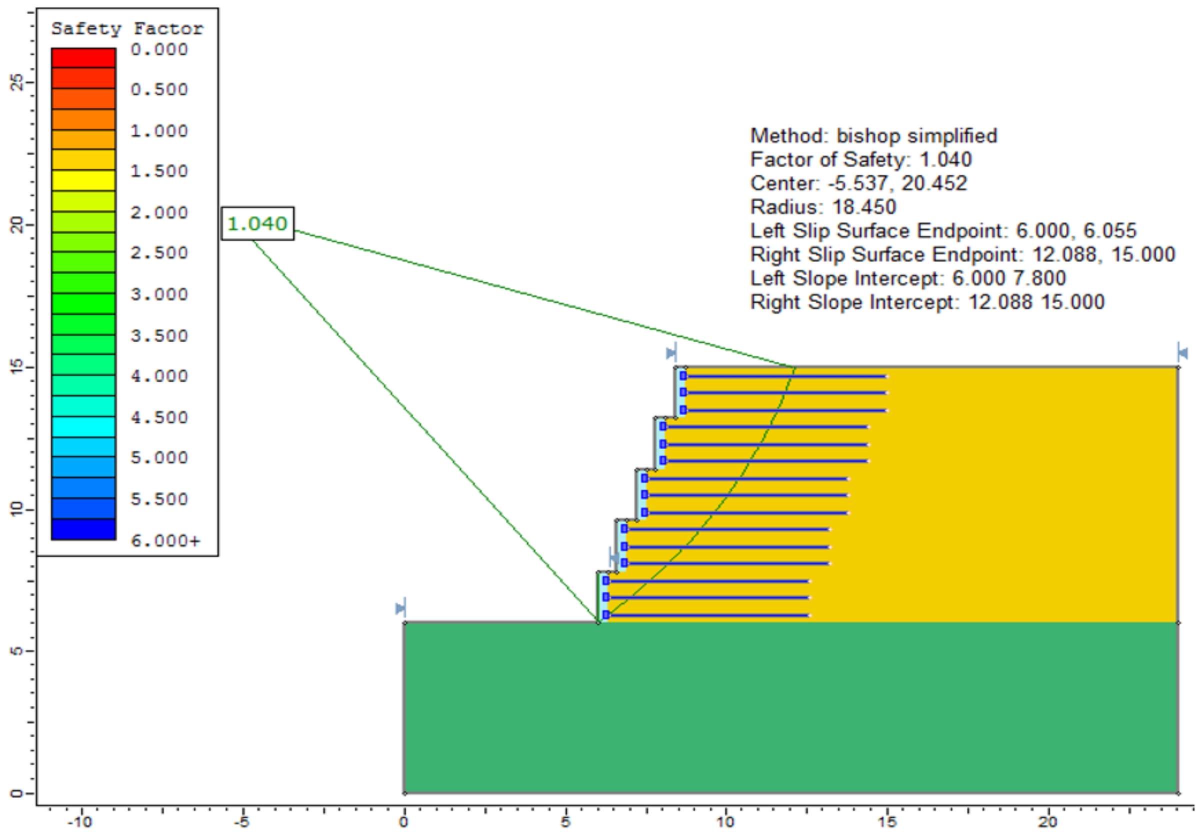


Figure 94.2: Solution, using the Bishop simplified method

95. Slide Verification Problem #95

Embankment dam, homogenous, rapid drawdown, water table

95.1. Introduction

This rapid drawdown problem is taken from Appendix G of the Engineering Manual EM 1110-2-1902, "Engineering and Design – Stability of Earth and Rock-Fill Dams," by Corps of Engineers (1970).

95.2. Problem Description

The slope in Figure 95.1 is analyzed for slope stability. An initial water level is assumed at elevation 110 ft. Rapid drawdown brings the water level down to an elevation of 24 ft. Material properties of the slope are given in Table 95.1. One circular slip surface is considered. This slip surface is centered at coordinates (169.5, 210) and has a radius of 210 ft. The Army Corps of Engineers 2-stage rapid drawdown method is used.

95.3. Geometry and Material Properties

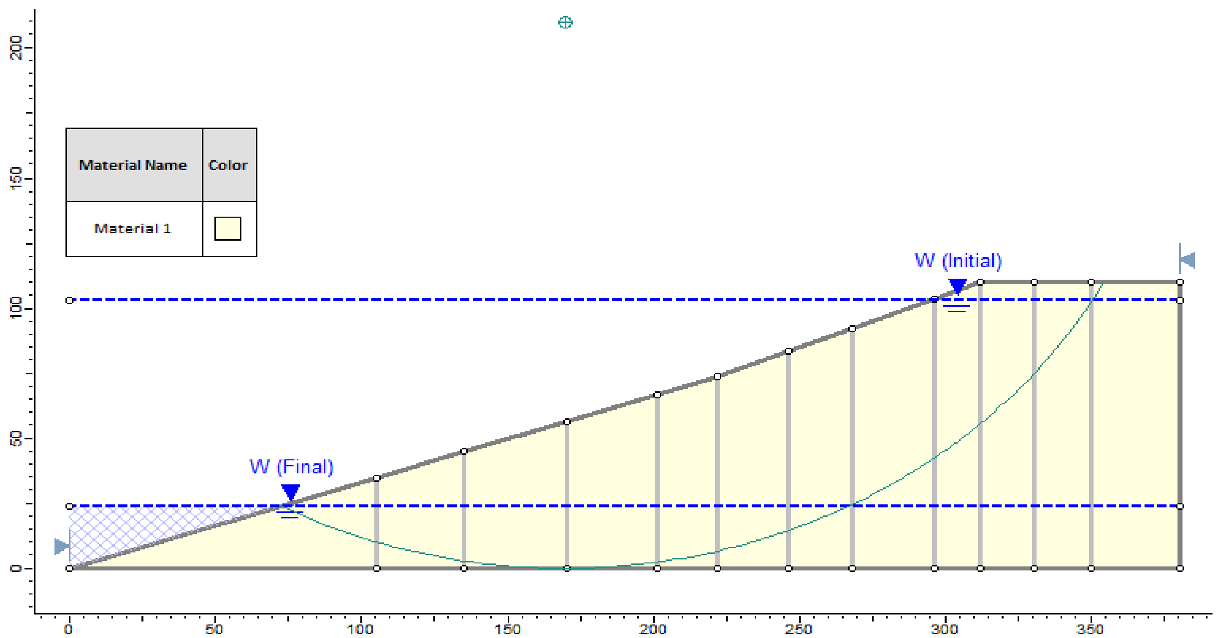


Figure 95.1: Slope Subjected to Rapid Drawdown in **Slide**

Table 95.1: Slope Material Properties

Unit Weight	Effective Stress Envelope		R-Envelope	
	Intercept, c'	Slope, Φ'	Intercept, c_R	Slope, Φ_R
135 pcf	0	30°	1200 psf	16°

95.4. Results

Table 95.2

Rapid Drawdown Method	Factor of Safety
Army Corp. Eng. 2 Stage	1.347

Note: Reference factor of safety = 1.35 (using Army Corp. Eng. 2 Stage method) [Corps of Engineers]

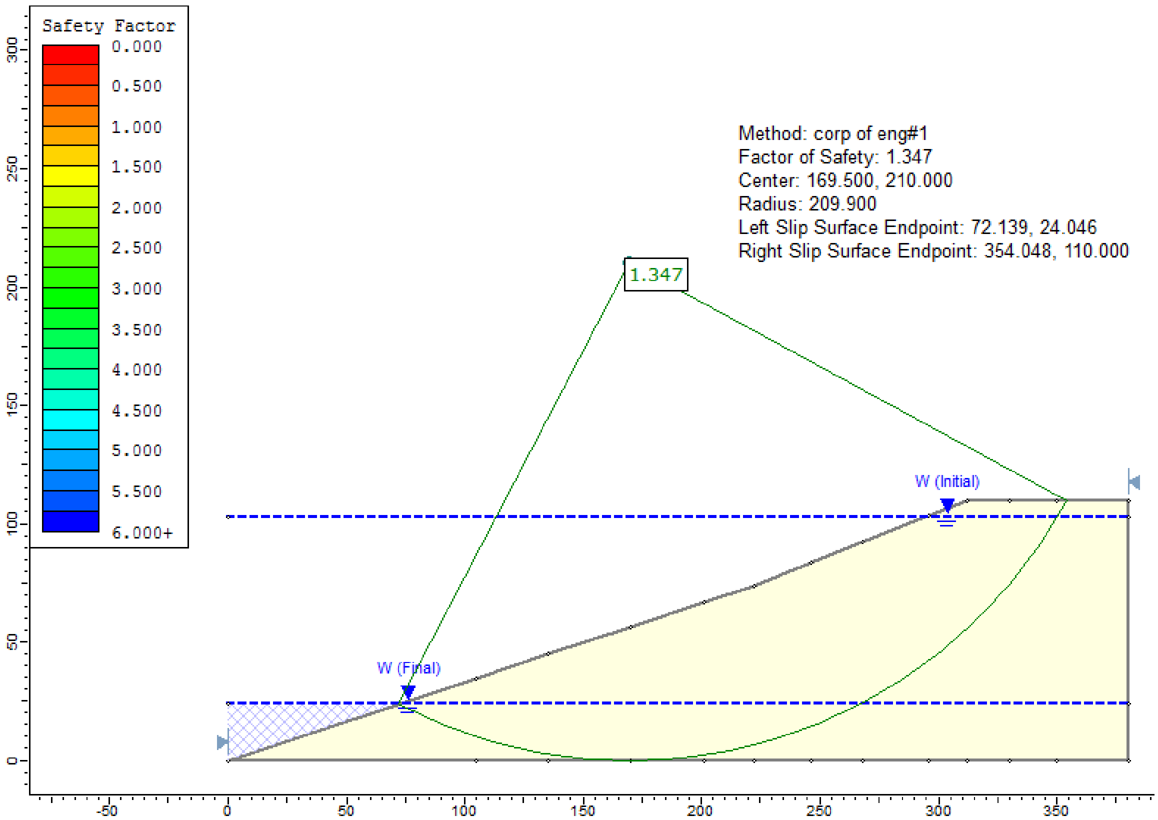


Figure 95.2: Solution, using the Army Corp. Eng. 2-stage rapid drawdown method

96. Slide Verification Problem #96

Embankment dam, homogenous, rapid drawdown, water table

96.1. Introduction

This rapid drawdown problem is similar to Verification Problem #95, also taken from Appendix G of the Engineering Manual EM 1110-2-1902, “Engineering and Design – Stability of Earth and Rock-Fill Dams,” by Corps of Engineers (1970).

96.2. Problem Description

The slope in Figure 96.1 is analyzed for slope stability. An initial water level is assumed at elevation 110 ft. Rapid drawdown brings the water level down to an elevation of 24 ft. Material properties of the slope are given in Table 96.1. One circular slip surface is considered. This slip surface is centered at coordinates (169.5, 210) and has a radius of 210 ft. The Duncan, Wright and Wong 3-stage rapid drawdown method is used.

96.3. Geometry and Material Properties

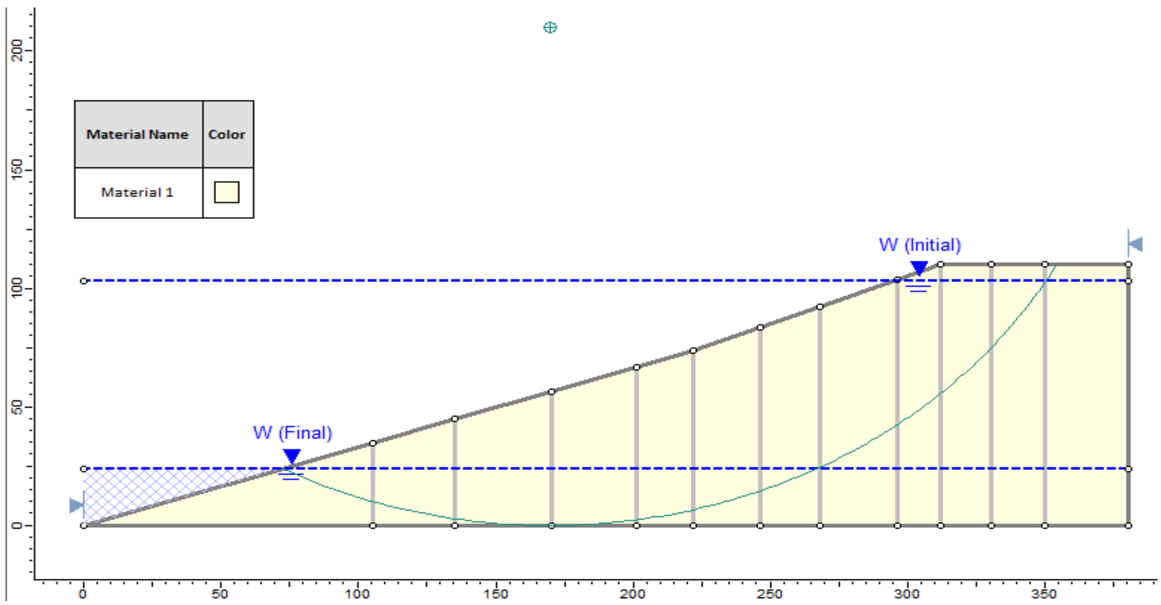


Figure 96.1: Slope Subjected to Rapid Drawdown

Table 96.1: Slope Soil Properties

Unit Weight	Effective Stress Envelope		R-Envelope	
	Intercept, c’	Slope, Φ’	Intercept, c_R	Slope, Φ_R
135 pcf	0	30°	1200 psf	16°

96.4. Results

Table 96.2

Rapid Drawdown Method	Factor of Safety
Duncan, Wright and Wong 3-stage	1.443

Note: Reference factor of safety = 1.44 (using Duncan, Wright and Wong 3 stage method) [Corps of Engineers]

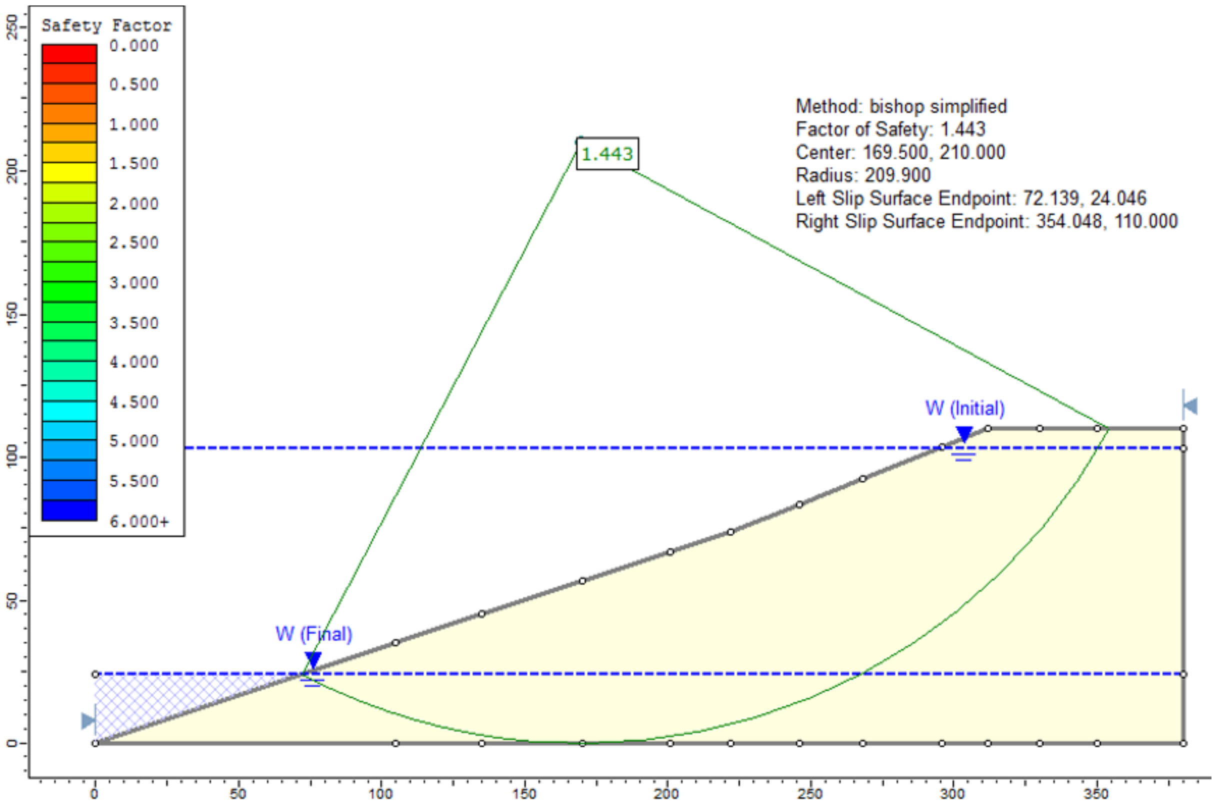


Figure 96.2: Solution, using the Duncan, Wright and Wong 3-stage rapid drawdown method

97. Slide Verification Problem #97

Embankment dam, homogenous, rapid drawdown, water table

97.1. Introduction

This rapid drawdown problem is taken from the "Slope Stability during Rapid Drawdown" paper by Duncan, Wright and Wong (1990). It is based on the Pilarcitos Dam in California.

97.2. Problem Description

The slope in Figure 97.1 is analyzed for slope stability. An initial water level is assumed at a height of 72 ft. Rapid drawdown brings the water level down to a height of 37 ft. Material properties of the slope are given in Table 97.1. Various slip surfaces are considered to find the minimum factor of safety.

97.3. Geometry and Material Properties

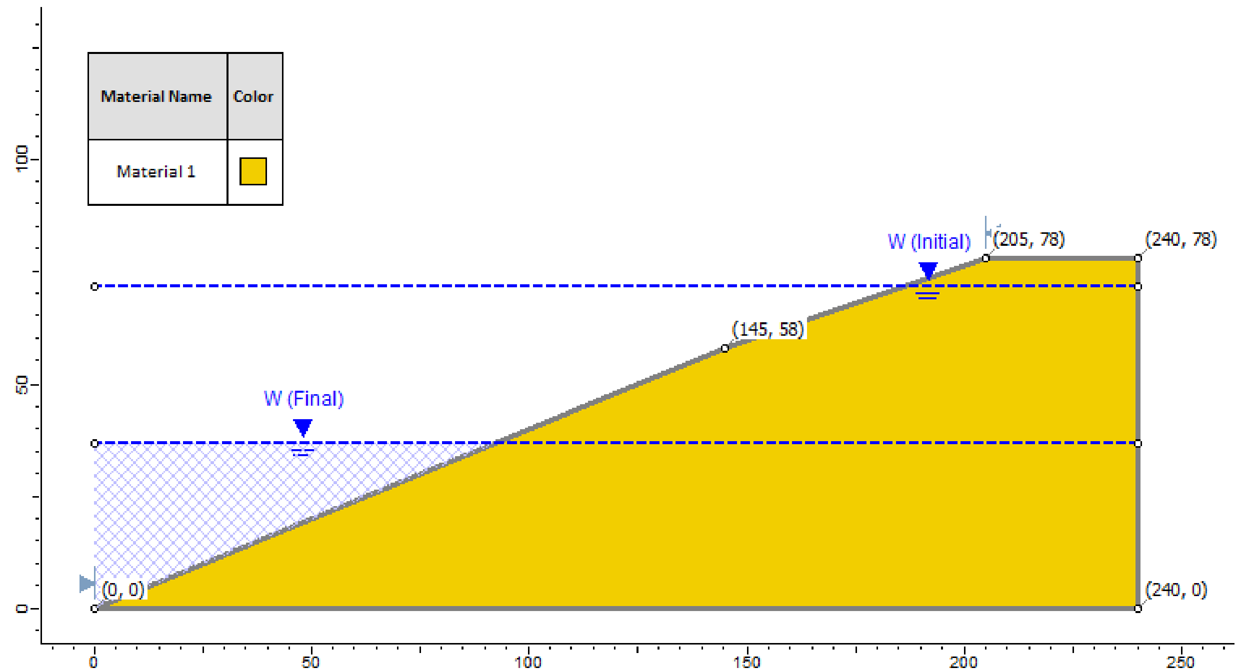


Figure 97.1: Pilarcitos Dam Model in **Slide**

Table 97.1: Dam Soil Properties

Unit Weight	Effective Stress Envelope		R-Envelope	
	Intercept, c'	Slope, Φ'	Intercept, c_R	Slope, Φ_R
135 pcf	0	45°	60 psf	23°

97.4. Results

Table 97.2

Rapid Drawdown Method	Factor of Safety (from Slide)	Factor of Safety (from Duncan, Wright and Wong, 1990)
Army Corp. Eng. 2 Stage	0.823	0.82
Lowe and Karafiath	1.047	1.05
Duncan, Wright, Wong 3 Stage	1.043	1.05

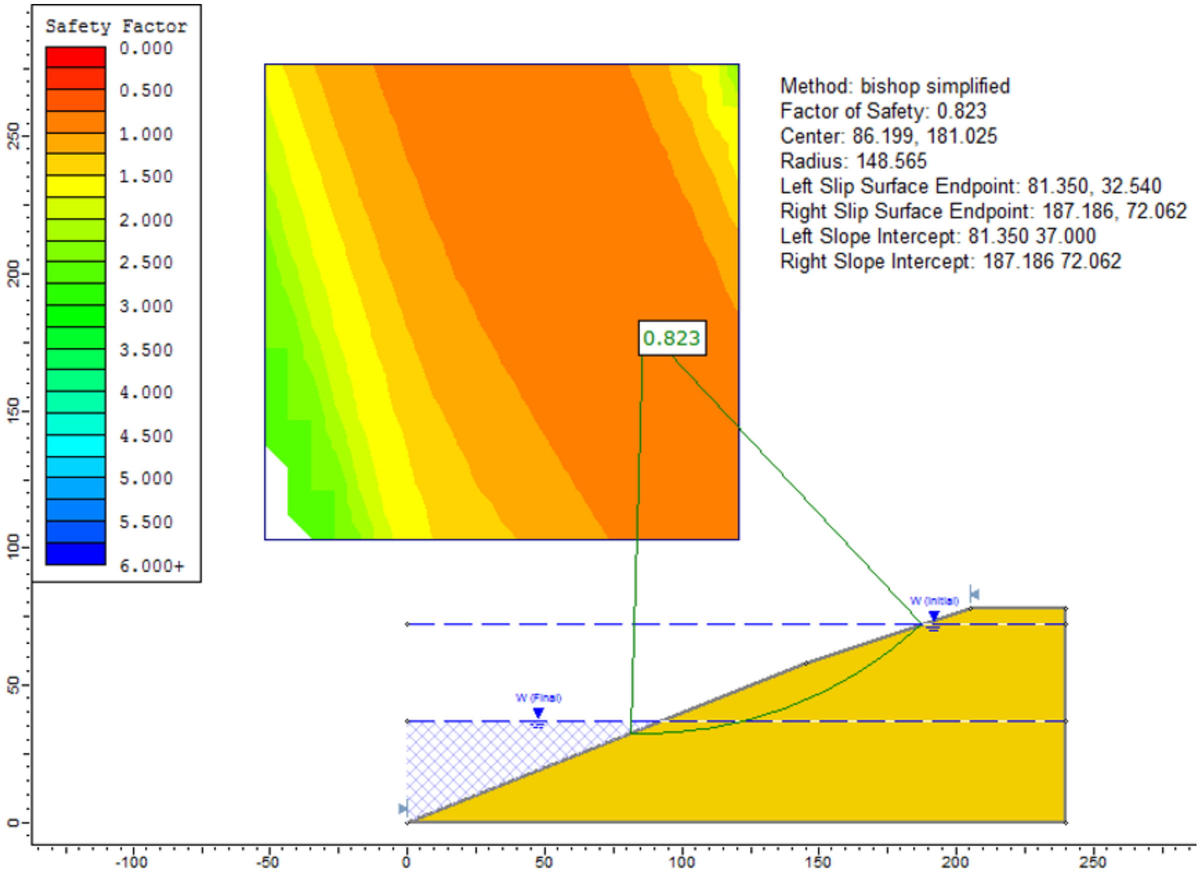


Figure 97.2: Solution, using the Army Corp. Eng. 2-stage rapid drawdown method

98. Slide Verification Problem #98

Embankment dam, (5) materials, rapid drawdown, water table

98.1. Introduction

This rapid drawdown problem is taken from the “Slope Stability during Rapid Drawdown” paper by Duncan, Wright, and Wong (1990). It is based on the Walter Bouldin Dam in Alabama.

98.2. Problem Description

The slope in Figure 98.1 is analyzed for slope stability. An initial water level is assumed at a height of 47 ft. Rapid drawdown brings the water level down to a height of 15 ft. Material properties of the slope are given in Table 98.1. Various slip surfaces are considered to find the minimum factor of safety.

98.3. Geometry and Material Properties

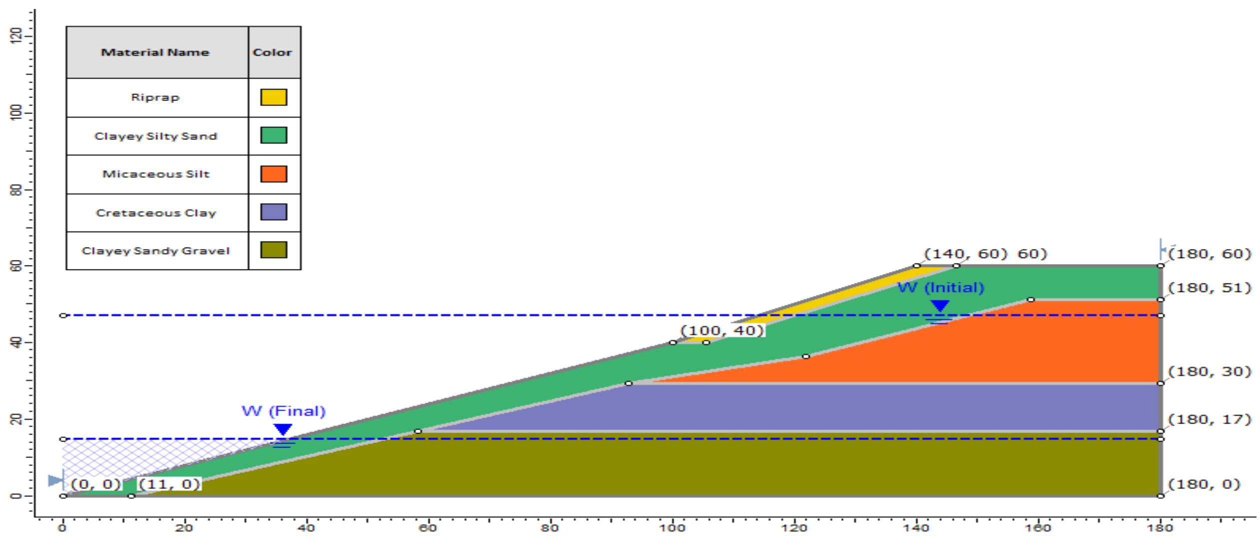


Figure 98.1: Walter Bouldin Dam Model

Table 98.1: Dam Material Properties

Material	Unit Weight	Effective Stress Envelope		R-Envelope	
		Intercept, c’	Slope, Φ’	Intercept, c_R	Slope, Φ_R
Riprap	125 pcf	0	40.0°	--	--
Clayey Silty Sand	128 pcf	240	32.7°	650 psf	13.0°
Micaceous Sand	123 pcf	220	22.5°	450 psf	11.0°
Cretaceous Clay	124 pcf	180	19.0°	180 psf	13.0°
Clayey Sandy Gravel	125 pcf	0	40.0°	--	--

98.4. Results

Table 98.2

Rapid Drawdown Method	Factor of Safety (from Slide)	Factor of Safety (from Duncan, Wright and Wong, 1990)
Army Corp. Eng. 2 Stage	0.931	0.93
Lowe and Karafiath	1.075	1.09
Duncan, Wright, Wong 3 Stage	1.039	1.04

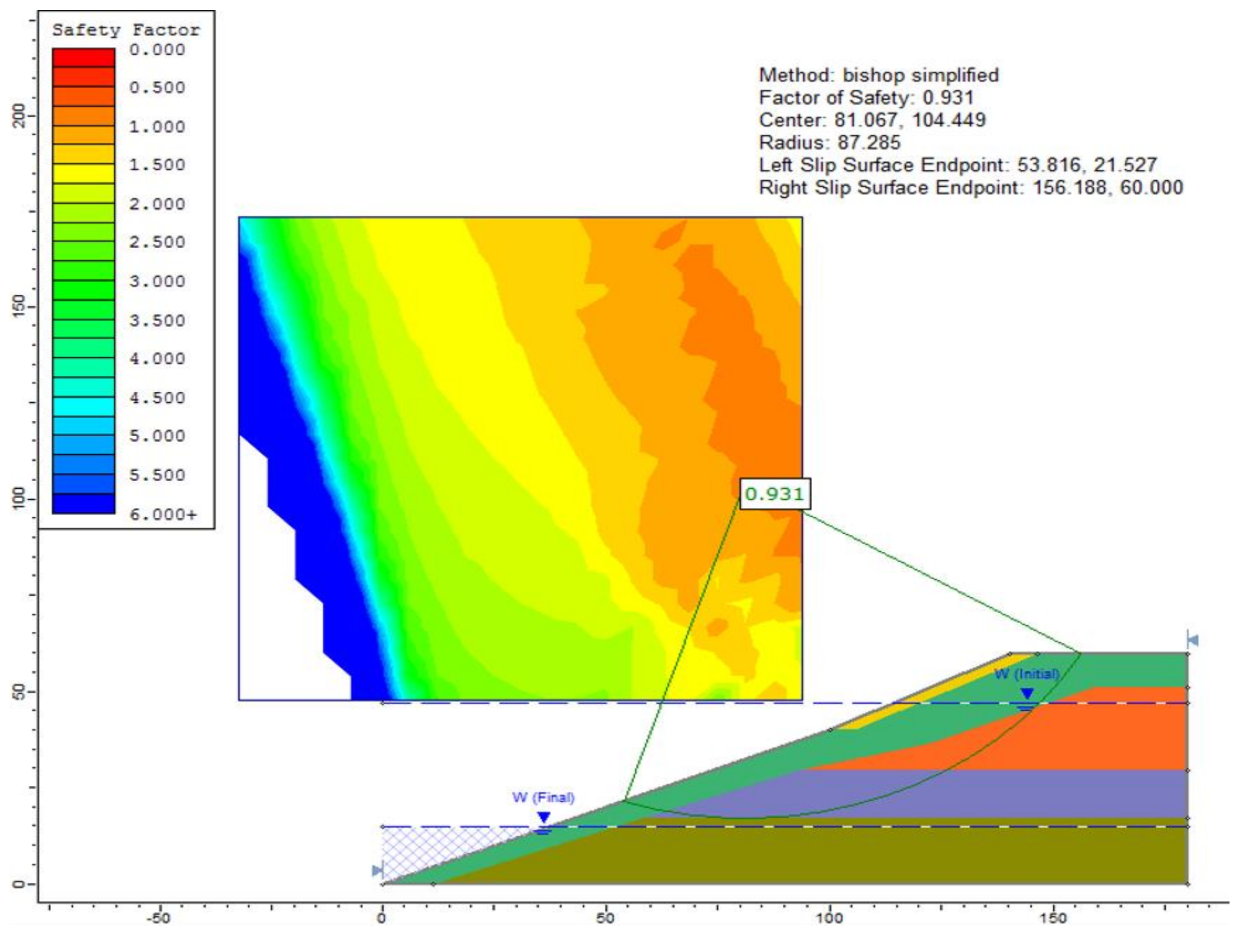


Figure 98.2: Solution, using the Army Corp. Eng. 2-stage rapid drawdown method

99. Slide Verification Problem #99

Embankment dam, (3) materials, rapid drawdown, water table

99.1. Introduction

This rapid drawdown problem is taken from the "Slope Stability during Rapid Drawdown" paper by Duncan, Wright and Wong (1990). It is a hypothetical pumped storage project dam.

99.2. Problem Description

The slope in Figure 99.1 is analyzed for slope stability. An initial water level is assumed at a height of 285 ft. Rapid drawdown brings the water level down to the height of 120 ft. Soil properties of the slope are given in Table 99.1. Various slip surfaces are considered to find the minimum factor of safety.

99.3. Geometry and Material Properties

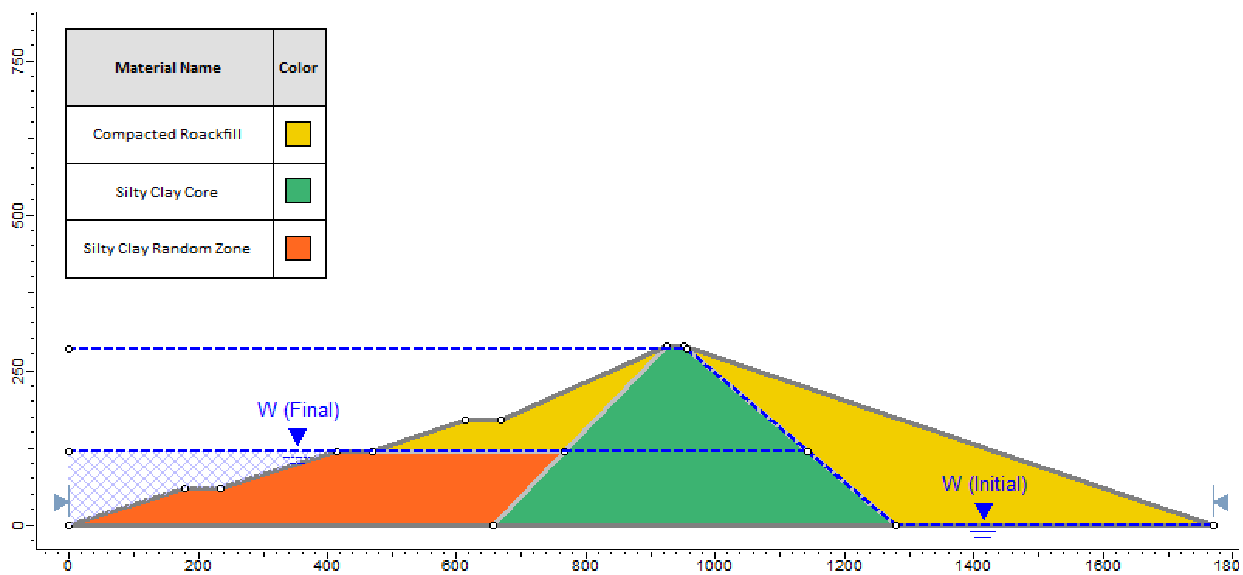


Figure 99.1: Pumped Storage Project Dam Model

Table 99.1: Dam Material Properties

Material	Unit Weight	Effective Stress Envelope		R-Envelope	
		Intercept, c'	Slope, Φ'	Intercept, c_R	Slope, Φ_R
Compacted Rockfill	142 pcf	0	37°	--	--
Silty Clay Core	140 pcf	0	36°	2000 psf	18°
Silty Clay Random Zone	140 pcf	0	36°	2000 psf	18°

99.4. Results

Table 99.2

Rapid Drawdown Method	Factor of Safety (from Slide)	Factor of Safety (from Duncan, Wright and Wong, 1990)
Army Corp. Eng. 2 Stage	1.345	1.37
Lowe and Karafiath	1.620	1.58
Duncan, Wright, Wong 3 Stage	1.534	1.56

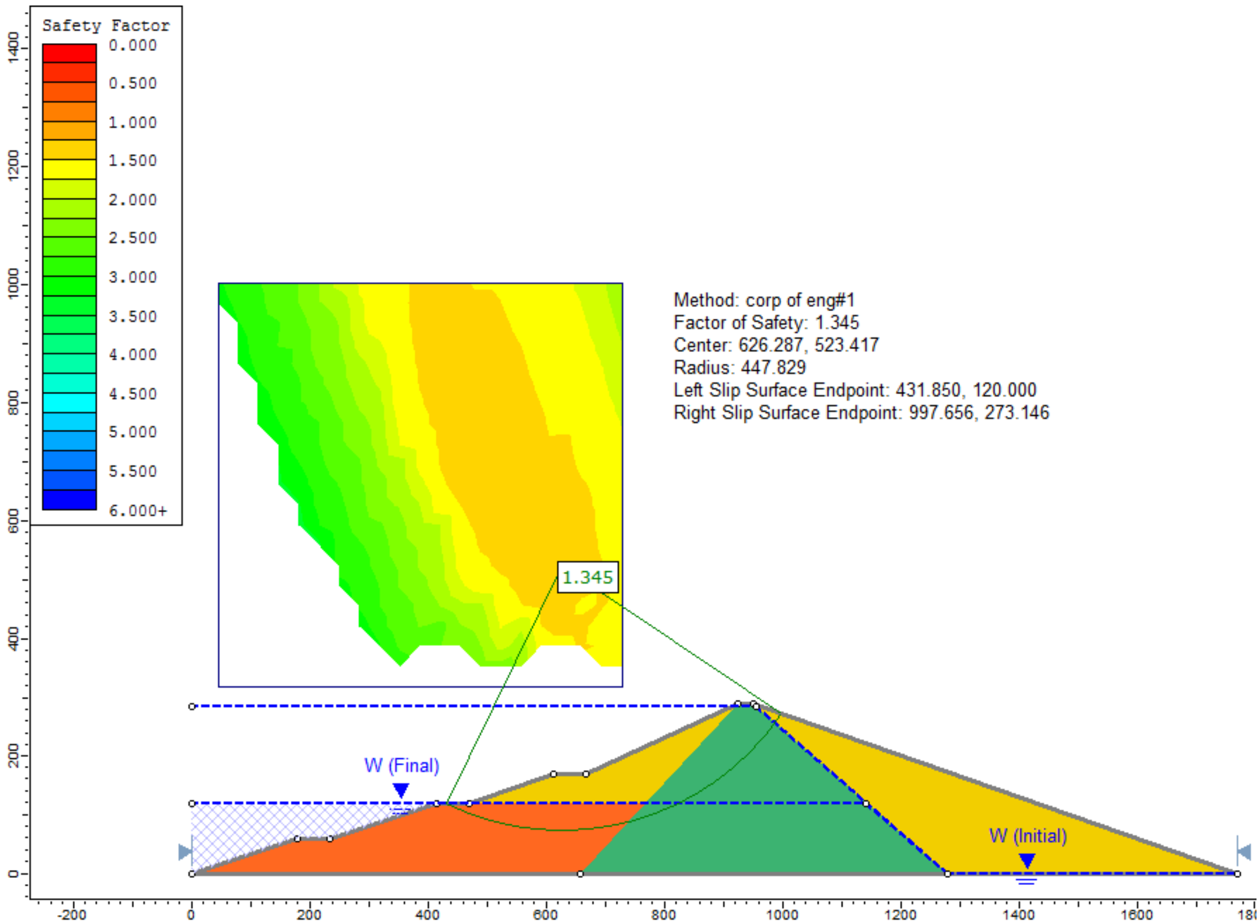


Figure 99.2: Solution Using Army Corp. Eng. 2-stage rapid drawdown method

100. Slide Verification Problem #100

Embankment dam, homogenous, rapid drawdown, water table

100.1. Introduction

This rapid drawdown problem is taken from the “Stability Charts for Earth Slopes During Rapid Drawdown” paper by Morgenstern (1963). It is a simple slope subjected to complete drawdown.

100.2. Problem Description

The slope in Figure 100.1 is analyzed for slope stability. An initial water level is assumed at a height of 100 ft. Rapid drawdown brings the water level completely down to 0 ft. Soil properties of the slope are given in Table 100.1. Various slip surfaces are considered to find the minimum factor of safety.

100.3. Geometry and Material Properties

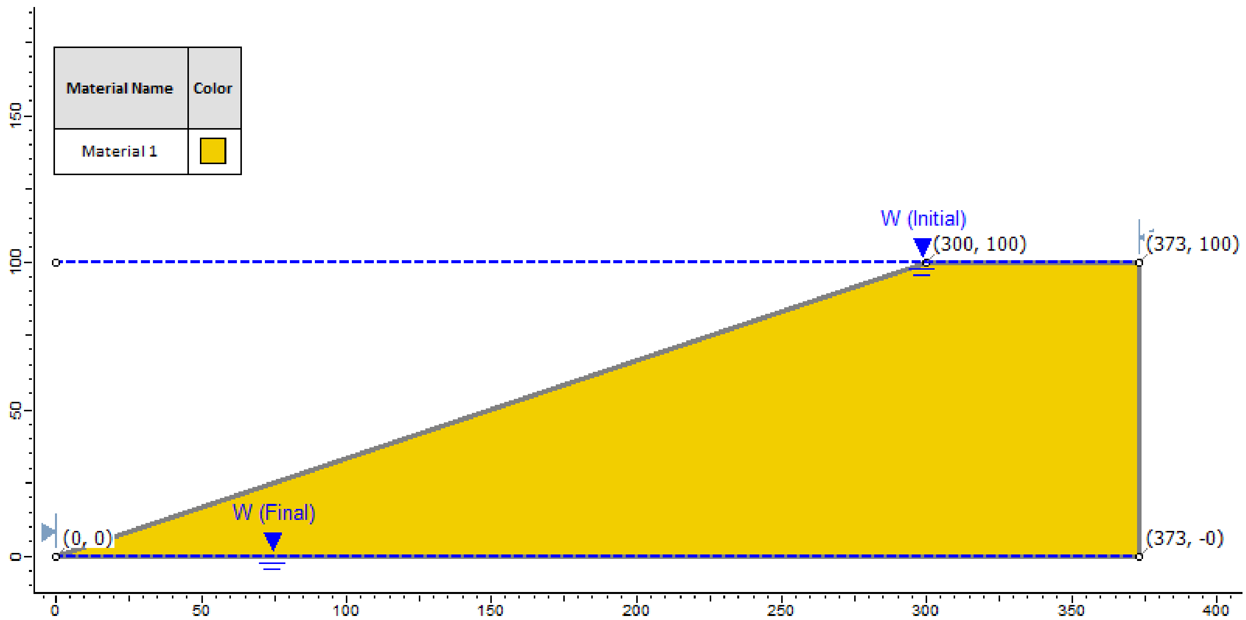


Figure 100.1: Slope Model in **Slide**

Table 100.1: Dam Soil Properties

Unit Weight	Effective Stress Envelope		B-Bar Value
	Intercept, c’	Slope, Φ’	
124.8 pcf	312 psf	30°	1

100.4. Results

Table 100.2

Rapid Drawdown Method	Factor of Safety (from Slide)	Factor of Safety (from Morgenstern, 1963)
B-Bar	1.212	1.20

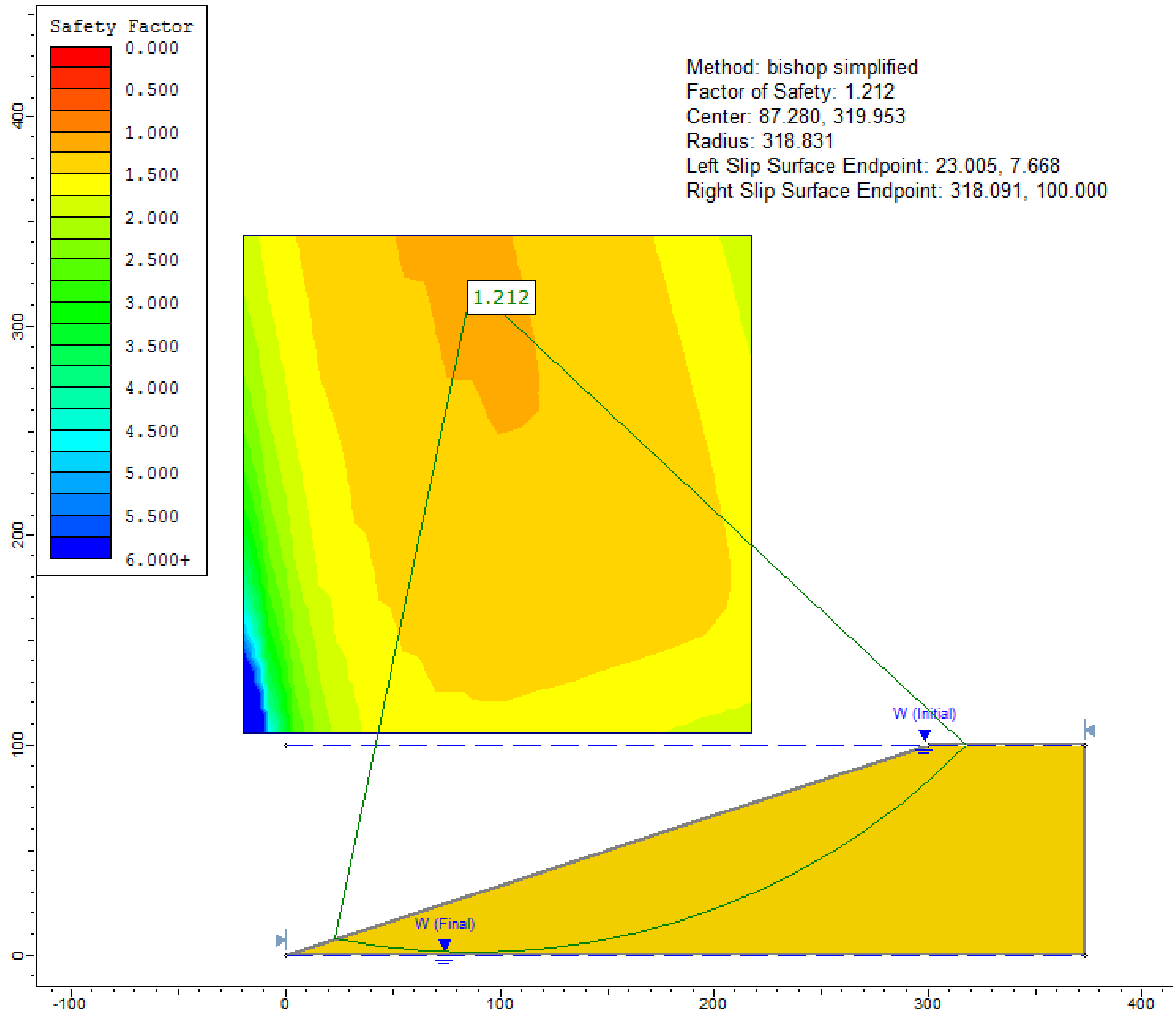


Figure 100.2: Solution, using B-Bar rapid drawdown method

101. Slide Verification Problem #101

Embankment dam, homogenous, rapid drawdown, water table

101.1. Introduction

This rapid drawdown problem is similar to verification problem #100 and is taken from the “Stability Charts for Earth Slopes During Rapid Drawdown” paper by Morgenstern (1963). It is a simple slope subjected to drawdown.

101.2. Problem Description

The slope in Figure 101.1 is analyzed for slope stability. An initial water level is assumed at a height of 100 ft. Rapid drawdown brings the water level down to 50 ft. Soil properties of the slope are given in Table 101.1. Various slip surfaces are considered to find the minimum factor of safety.

101.3. Geometry and Material Properties

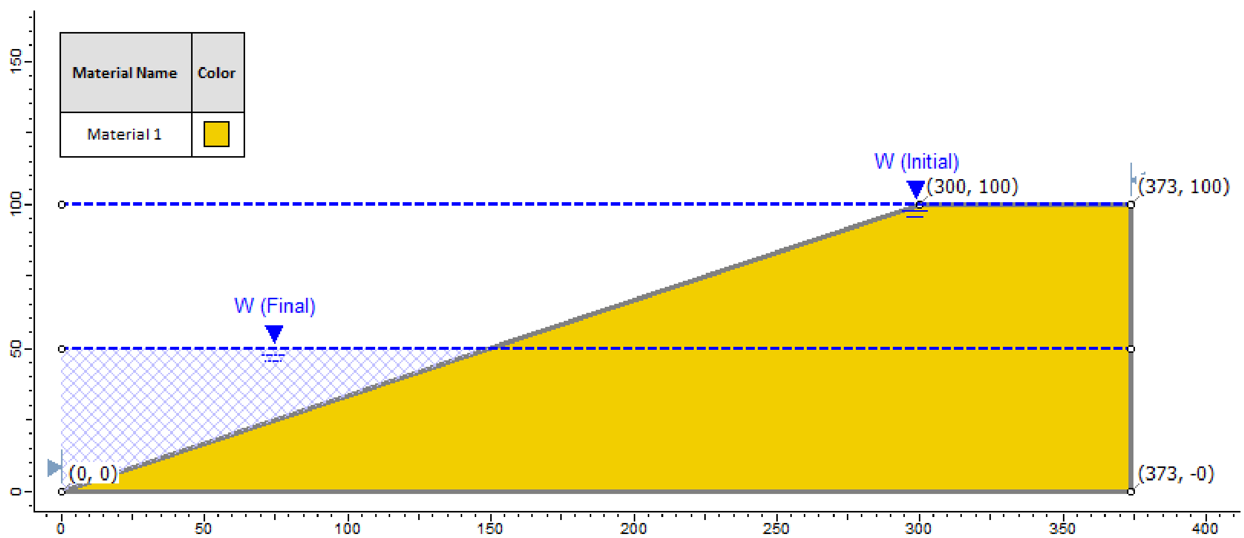


Figure 101.1: Slope Model in **Slide**

Table 101.1: Slope Material Properties

Unit Weight	Effective Stress Envelope		B-Bar Value
	Intercept, c’	Slope, Φ’	
124.8 pcf	312 psf	30°	1

101.4. Results

Table 101.2

Rapid Drawdown Method	Factor of Safety (from Slide)	Factor of Safety (from Morgenstern, 1963)
B-Bar	1.417	1.41

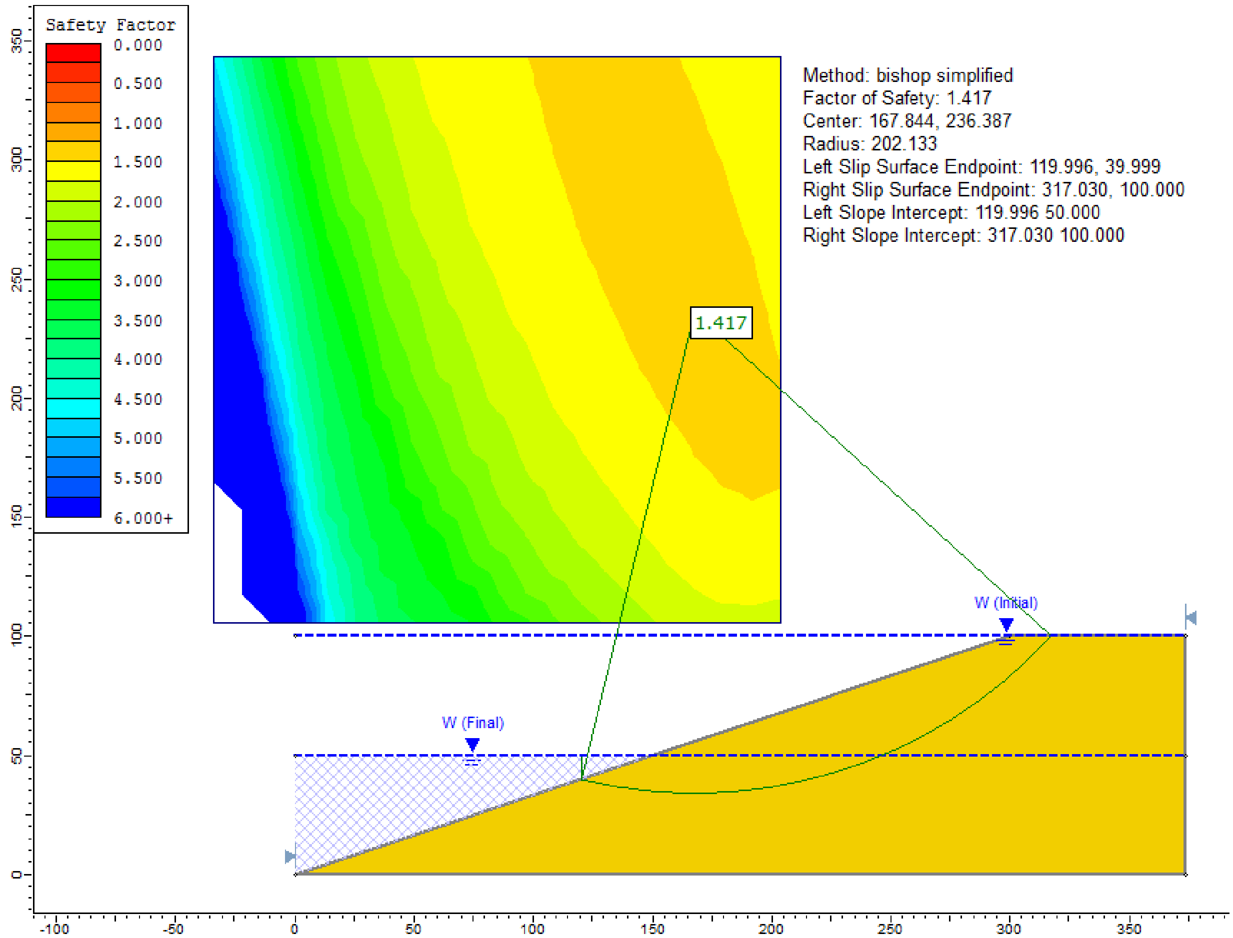


Figure 101.2: Solution, using the B-Bar rapid drawdown method

102. Slide Verification Problem #102

Embankment dam, homogenous, rapid drawdown

102.1. Problem Description

This problem investigates the stability of an earth dam subjected to rapid drawdown conditions. The dam material is a homogenous, isotropic soil with the soil properties outlined in Table 102.1.

102.2. Geometry and Material Properties

Figure 102.1 shows the **Slide** model used to perform the stability analysis.

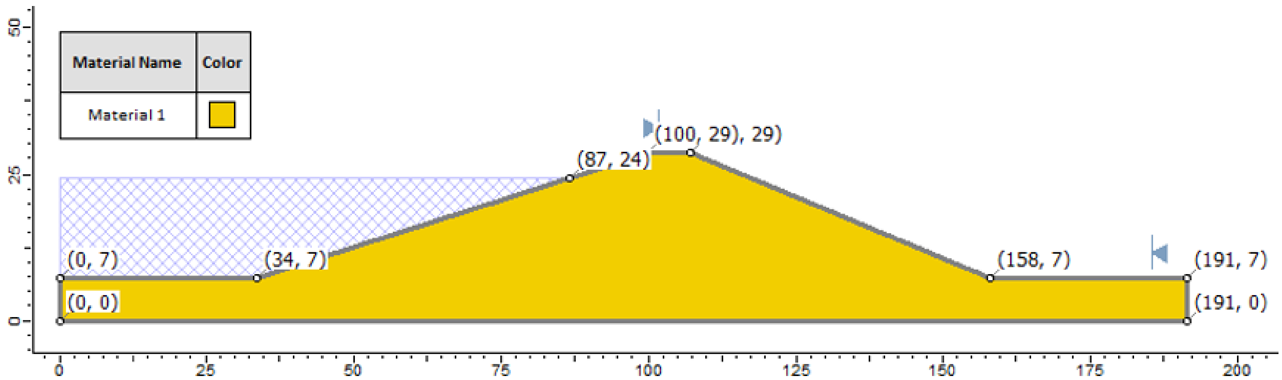


Figure 102.1: Geometry Setup in **Slide**

Table 102.1: Soil Properties

Property	Value
c'	13.8 kPa
φ'	37º
γ	18.2 kN/m^3
E	1 x 10^5 kPa
ν	0.3

102.3. Results

Figure 102.2 shows the **Slide** results for the earth dam under dry conditions. The calculated factor of safety of 2.455(Spencer method) corresponds closely with the value of 2.43 quoted in the “Strength reduction FEM in stability analysis of soil slopes subjected to transient unsaturated seepage” paper by Huang and Jia (2008).

Figure 102.3 shows the **Slide** analysis for initial steady state before rapid drawdown. Total head contours are also shown. The calculated factor of safety of 1.745 corresponds closely with the value of 1.70 quoted in Huang and Jia (2008).

Transient analysis considered a φ^b value of both 0º and 37º. **Slide** results at different times for the two cases are plotted on Figures 102.4 and Figure 102.5, along with values from Huang and Jia (2008). The Slide results correspond closely with the published ones. Figures 102.6 to Figure 102.11 show the Slide model results for both cases at various analysis times. Tables 102.2 and Table 102.3 list these values.

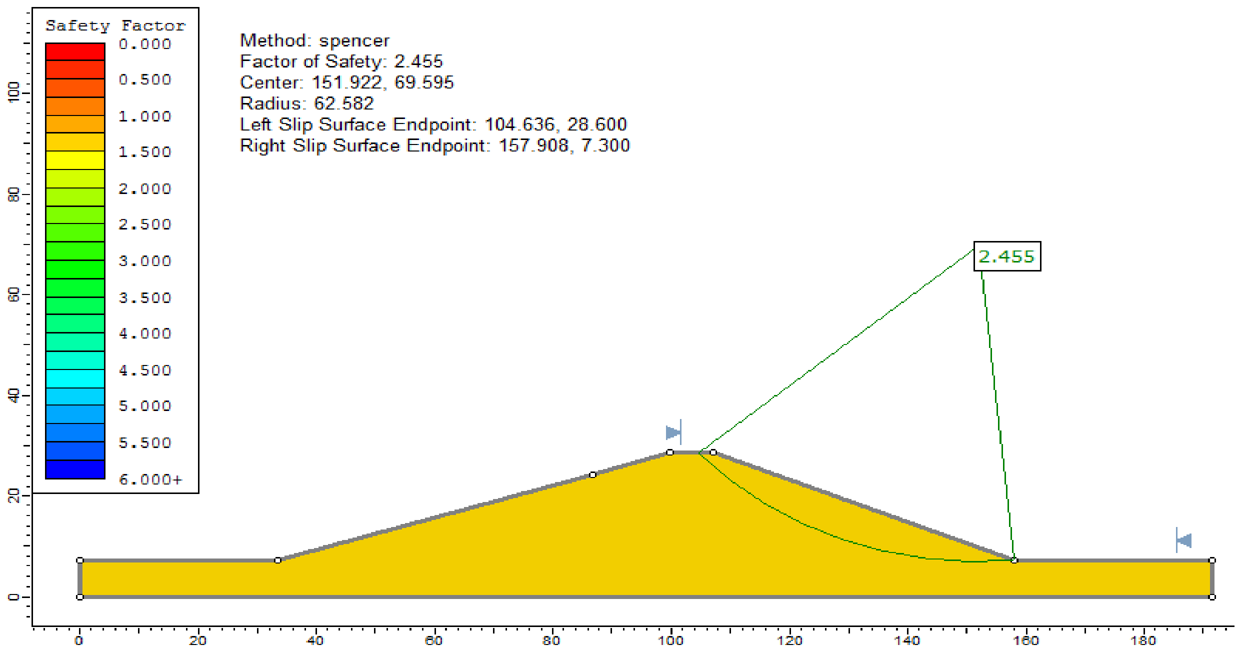


Figure 102.2: **Slide** Results for Dry Conditions, using the Spencer method

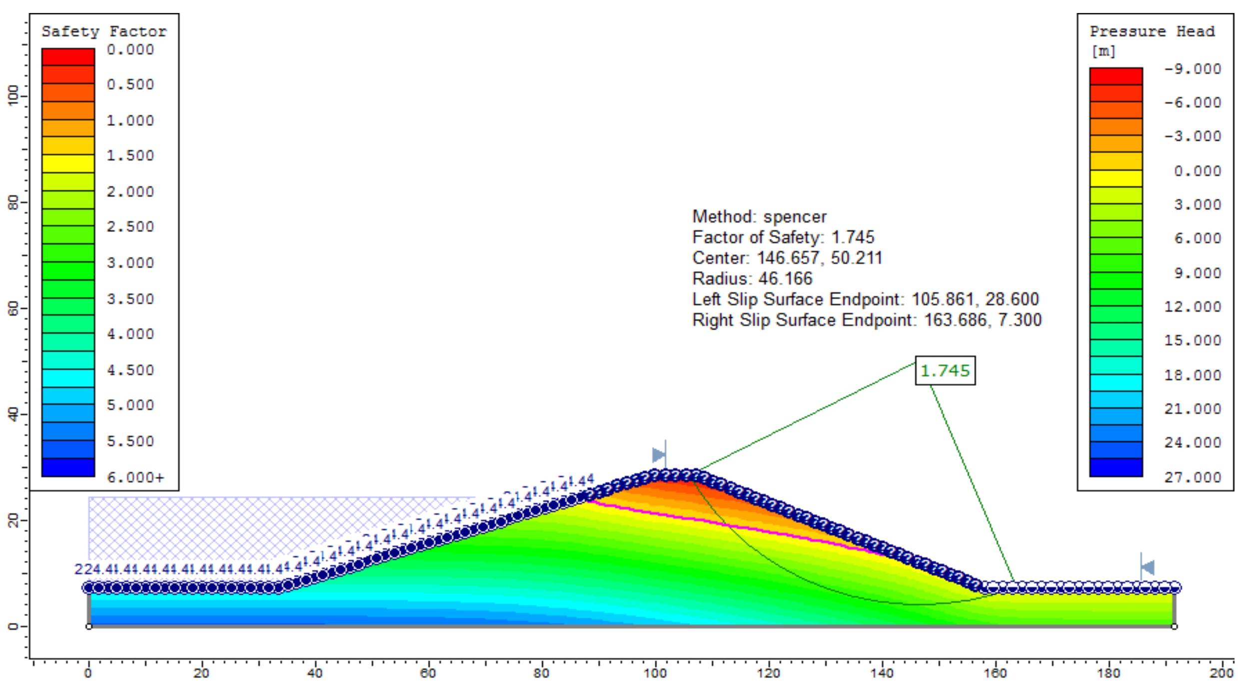


Figure 102.3: **Slide** Results for Initial Conditions, using the Spencer method

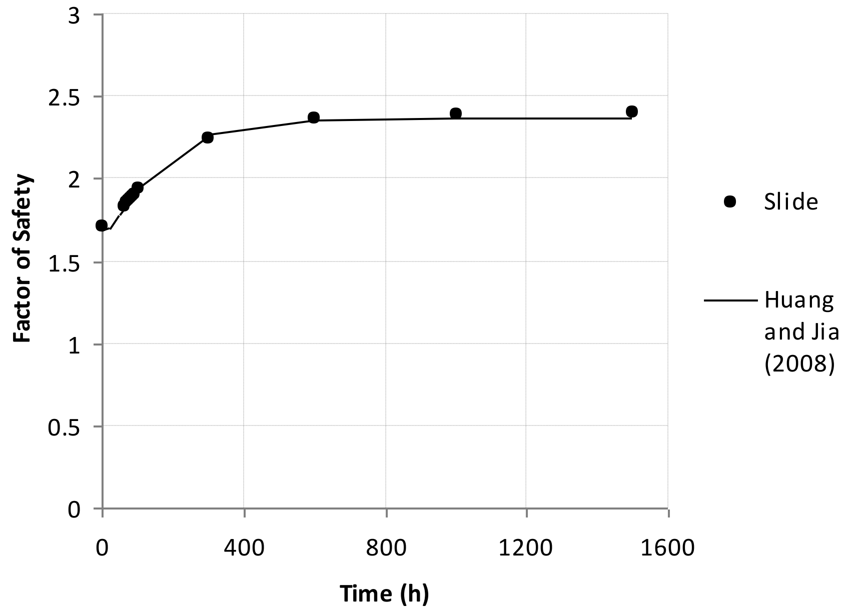


Figure 102.4: Factors of Safety Plot for $\varphi^b = 0^o$

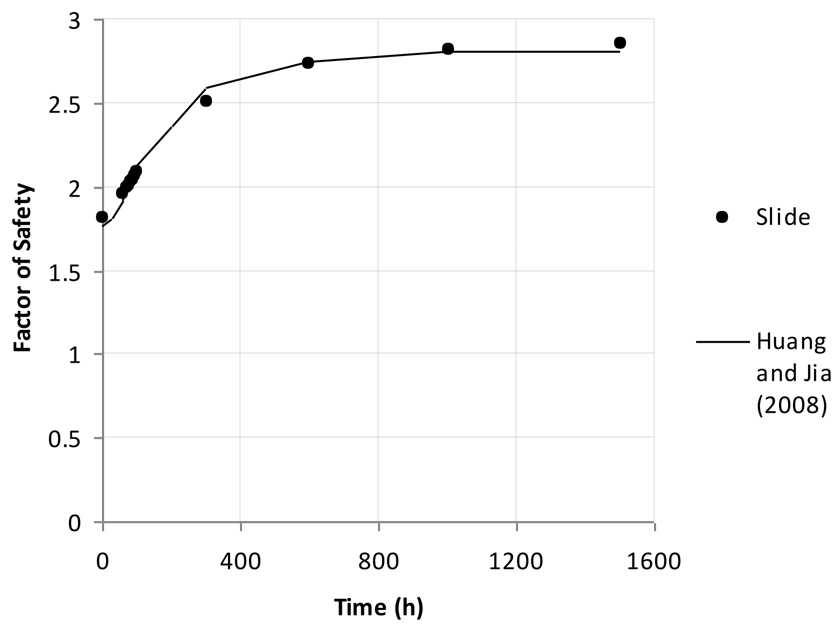


Figure 102.5: Factors of Safety Plot for $\varphi^b = 37^o$

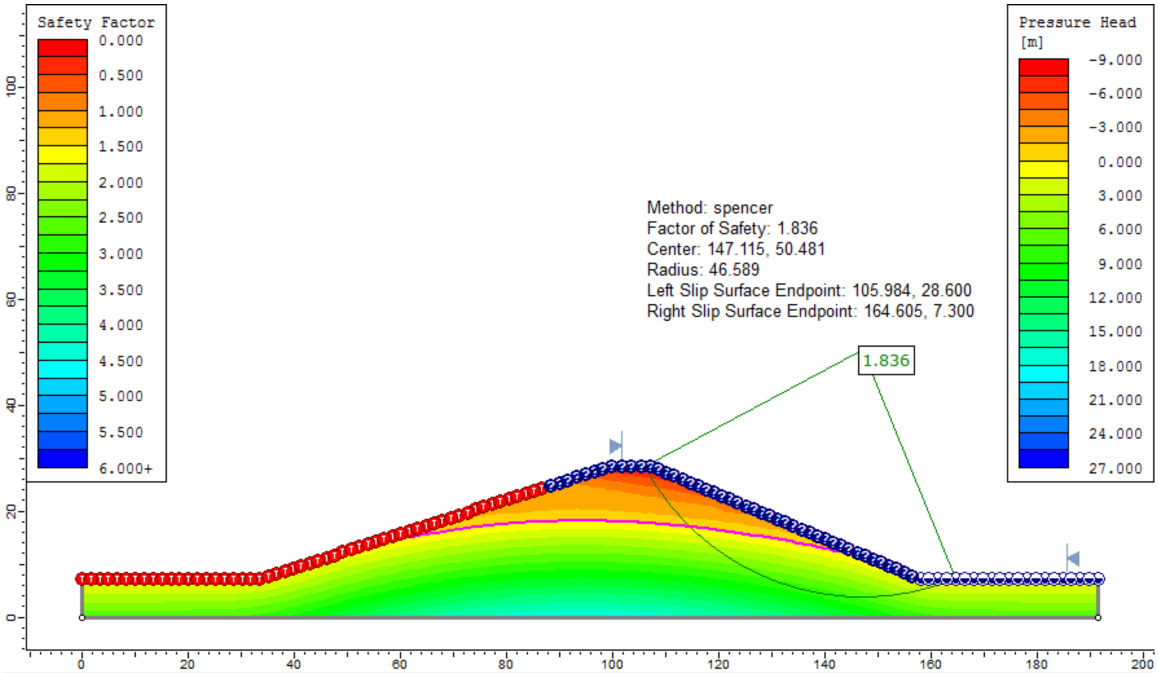


Figure 102.6: **Slide** Results for φ^b = 0º at 80 h, using the Spencer method

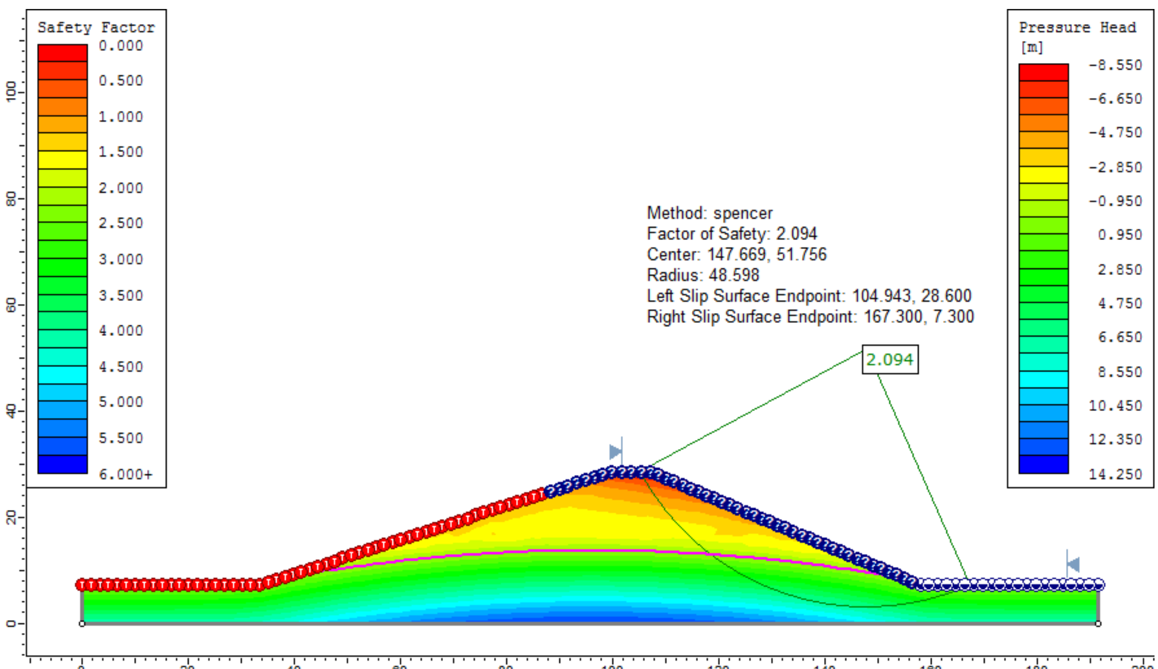


Figure 102.7: **Slide** Results for φ^b = 0º at 300 h, using the Spencer method

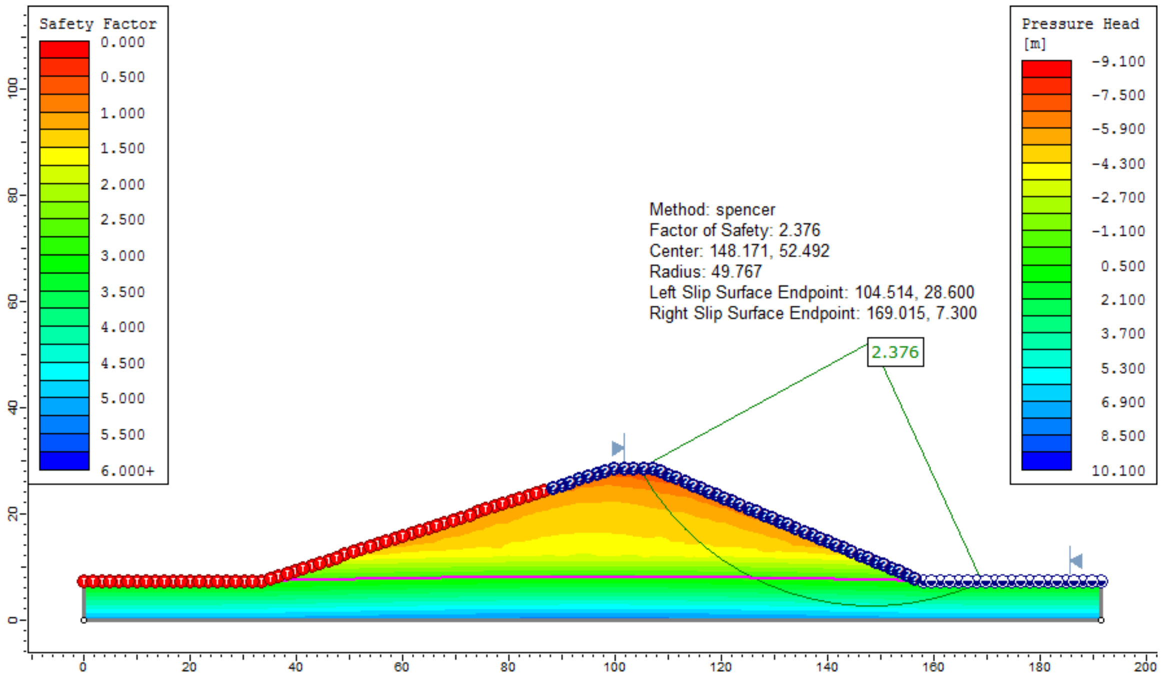


Figure 102.8: **Slide** Results for $\varphi^b = 0^o$ at 1500 h, using the Spencer method

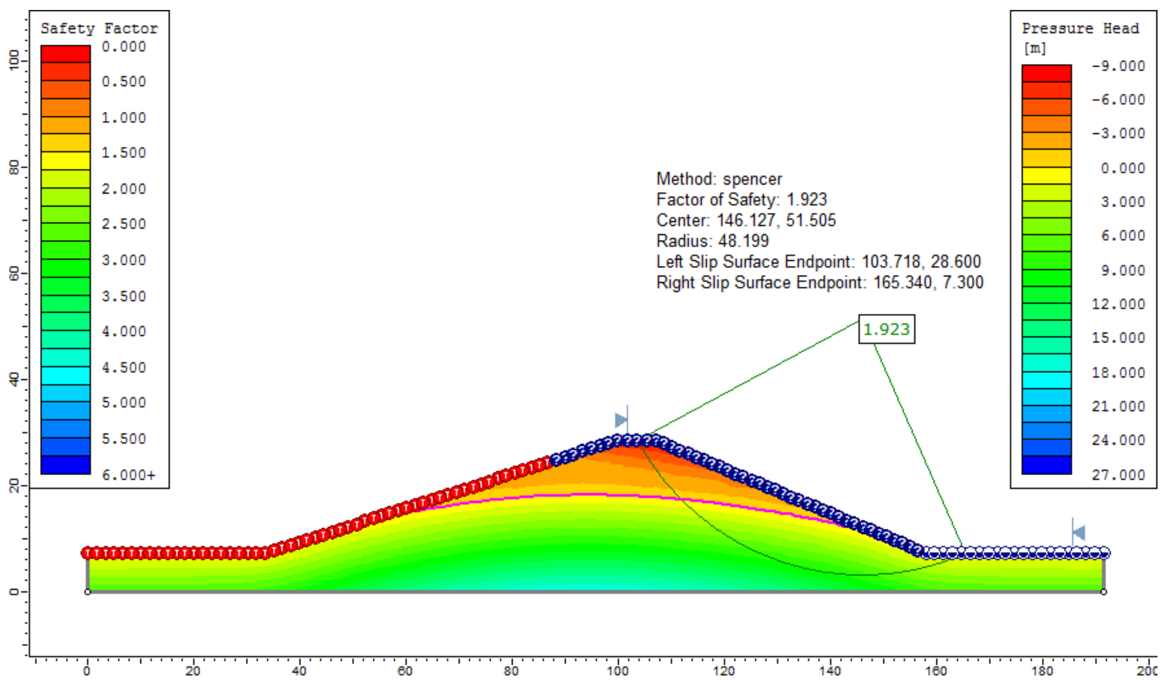


Figure 102.9: **Slide** Results for $\varphi^b = 37^o$ at 80 h, using the Spencer method

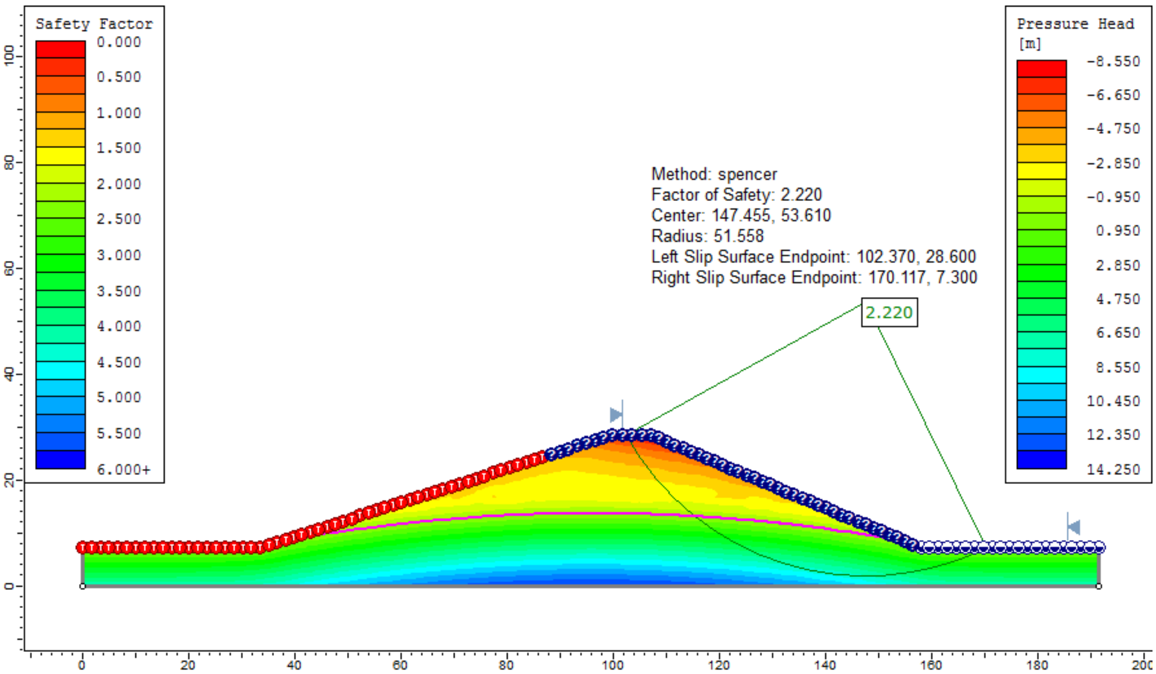


Figure 102.10: **Slide** Results for φ^b = 37º at 300 h, using the Spencer method

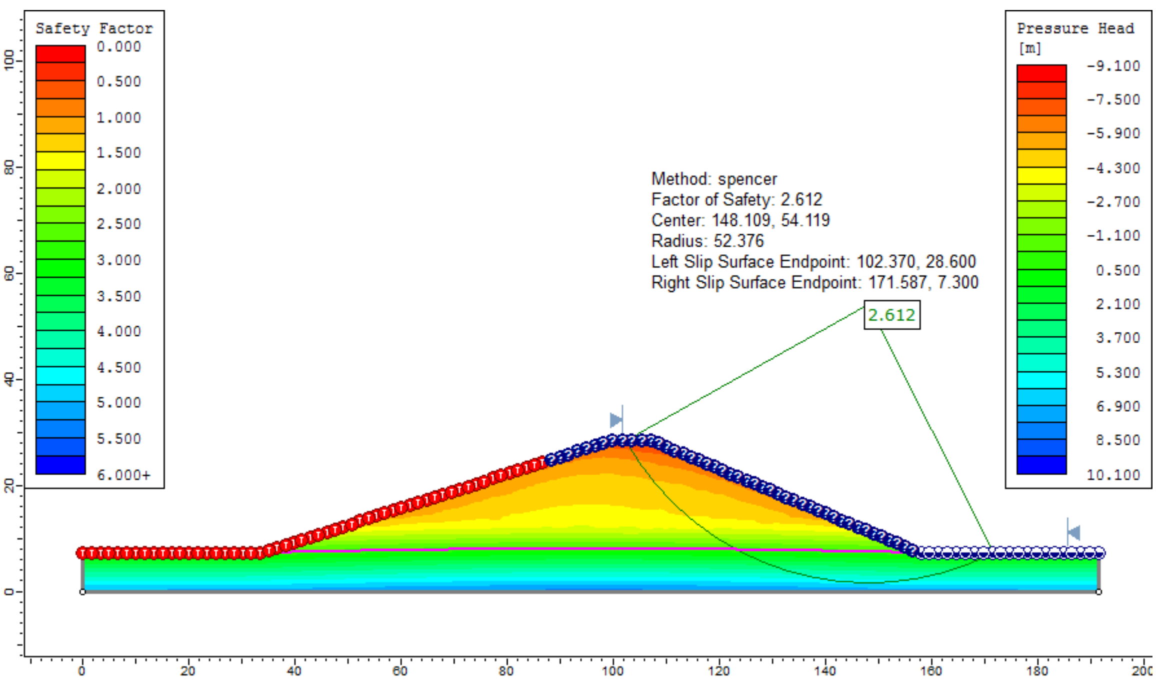


Figure 102.11: **Slide** Results for φ^b = 37º at 1500 h, using the Spencer method

Table 102.2: Factors of Safety for $\varphi^b = 0^o$

Time (h)	Factor of Safety (Slide)	Factor of Safety (Huang and Jia, 2008)
0	1.745	1.683
60	1.805	1.805
70	1.820	1.840
75	1.828	1.858
80	1.836	1.875
85	1.844	1.893
90	1.852	1.909
100	1.868	1.940
300	2.094	2.274
600	2.243	2.360
1000	2.330	2.374
1500	2.376	2.374

Table 102.3: Factors of Safety for $\varphi^b = 37^o$

Time (h)	Factor of Safety (Slide)	Factor of Safety (Huang and Jia, 2008)
0	1.815	1.764
60	1.886	1.930
70	1.904	1.982
75	1.913	2.009
80	1.923	2.035
85	1.932	2.065
90	1.942	2.098
100	1.961	2.134
300	2.220	2.595
600	2.416	2.754
1000	2.542	2.804
1500	2.612	2.813

103. Slide Verification Problem #103

Undrained slope, multi-model optimization (MMO)

103.1. Problem Description

This example comes from Guo & Griffiths (2020). In the image below, the three different cohesion ratios lead to three different modes of failure using finite element method (FEM) with Shear Strength Reduction (SSR). This slope was replicated in Slide2 and was computed with multi-modal Particle Swarm (PS) search and Surface Altering (SA) optimization.

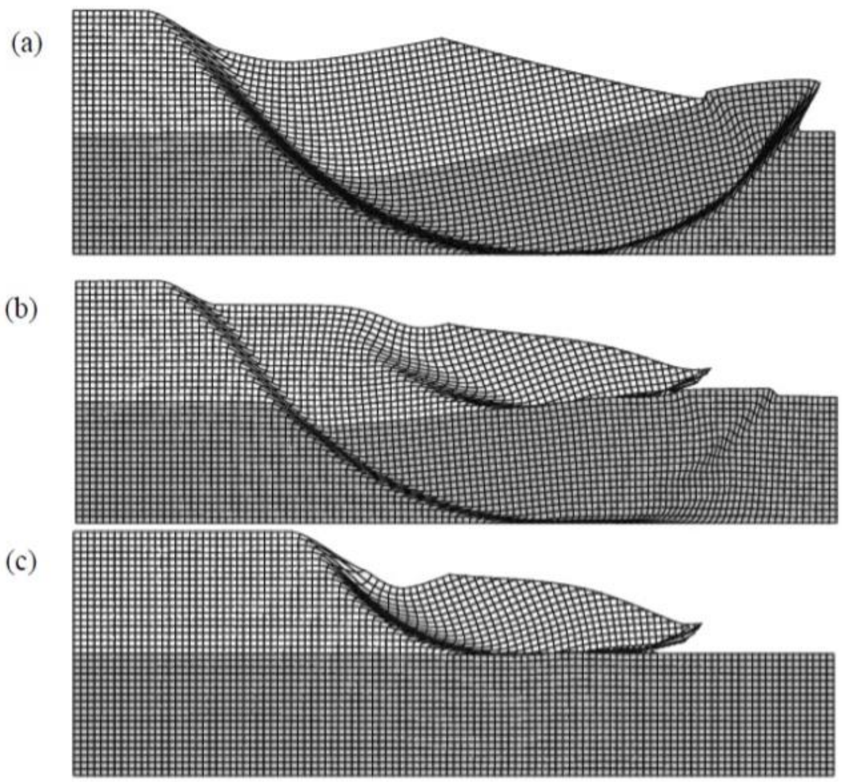


Fig. 5. Deformed meshes at failure for different strength ratios c_{u2}/c_{u1} $(D = 2.0$ and $\cot\beta = 2.0)$: (a) $c_{u2}/c_{u1} = 1.4$; (b) $c_{u2}/c_{u1} = P_{crit} = 1.5$; (c) $c_{u2}/c_{u1} = 1.6$

Figure 103.1: The three strength ratios and failure modes used in Guo and Griffiths (2020)

103.2. Results

The materials were set up as shown:

Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Cohesion Type	Water Surface	Ru
Material 1		20	Undrained	60	Constant	None	0
Base1.4		20	Undrained	84	Constant	None	0
Base1.5		20	Undrained	90	Constant	None	0
Base1.6		20	Undrained	96	Constant	None	0

Figure 103.2: The corresponding materials defined in **Slide2**

The results using Spencer method are shown below. The first row shows the MMO results with strength ratios of 1.4, 1.5, and 1.6 respectively. The second row shows the same results using regular, uni-modal, PS with SA.

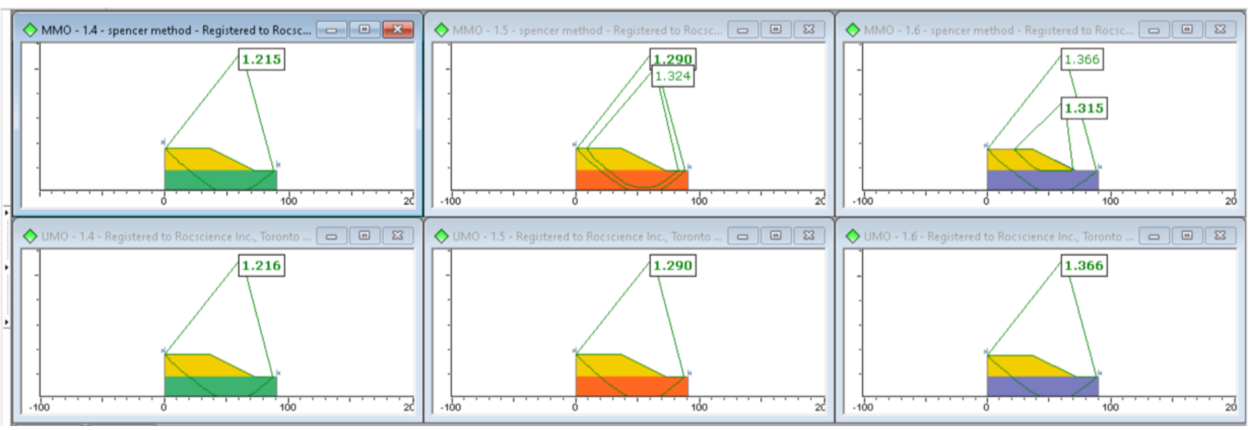


Figure 103.3: **Slide2** results for MMO (top row) and uni-modal (bottom row)

It can be seen that in the case of limit equilibrium, the split into the two failure modes must occur somewhere between the 1.5 and 1.6 ratios.

104. Slide Verification Problem #104

Newmark analysis, seismic analysis, multi-modal optimization (MMO)

104.1. Introduction

This example is based on Tutorial 28 Seismic Analysis with Newmark Method. Two groups were defined: one is the MMO PS with SA, and the other is the uni-modal PS with SA for comparison. Note that an area filter of 1 m was applied in the Surface Options dialog to eliminate some very shallow surfaces. The Spencer method is used, as it is in the tutorial.

104.2. Problem Description

The first row shows the MMO results for each seismic scenario. The second row shows the same results using regular, uni-modal, PS with SA. The four scenarios are:

- No Seismic: regular slope stability analysis
- Seismic coefficient of 0.15: seismic coefficient applied, otherwise regular slope stability analysis
- Critical acceleration: returns critical seismic coefficient such that the factor of safety (FS) is 1.
- Newmark displacement: returns associated displacement for surface, given seismic record

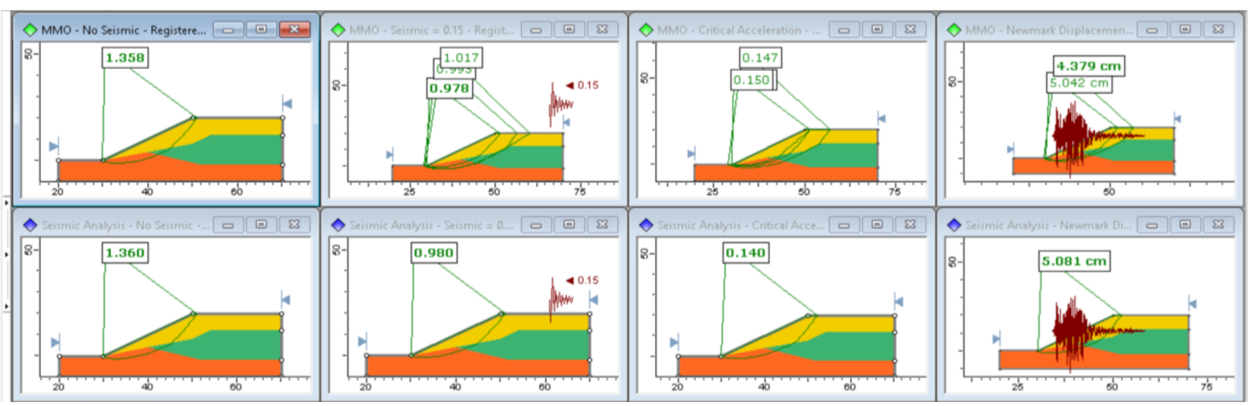


Figure 104.1: **Slide2** results for MMO (top row) and uni-modal (bottom row)

The most critical MMO result for each scenario is compared to the corresponding uni-modal result below and they are found to be in very good agreement.

Table 104.1: **Slide2** MMO vs uni-modal results for each scenario

	MMO (most critical)	**Uni-modal**
No Seismic	FS = 1.359	FS = 1.360
Seismic coefficient of 0.15	FS = 0.978	FS = 0.980
Critical acceleration	Ky = 0.139	Ky = 0.140
Newmark displacement	Disp = 5.042 cm	Disp = 5.081 cm

As an additional verification, the Ky = 0.147 surface in the third scenario, which was quite different from the critical surface, was computed with a regular slope stability analysis, and a seismic coefficient of 0.147. The results were as shown:

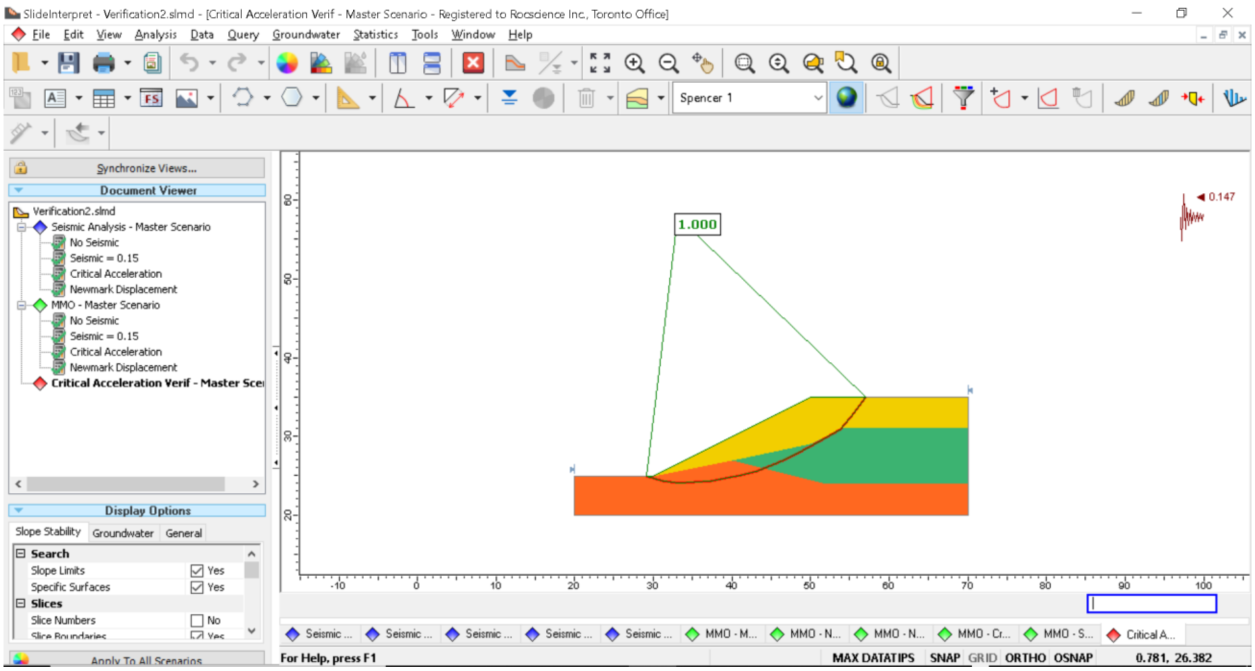


Figure 104.2: Ky = 0.147 applied to corresponding surface found using MMO

An additional view of interest is the comparison of all the surfaces between the MMO (left) and uni-modal (right) for the Newmark displacement scenario. Several distinct high displacement regions are visible with the MMO algorithm which are not clear with the uni-modal:

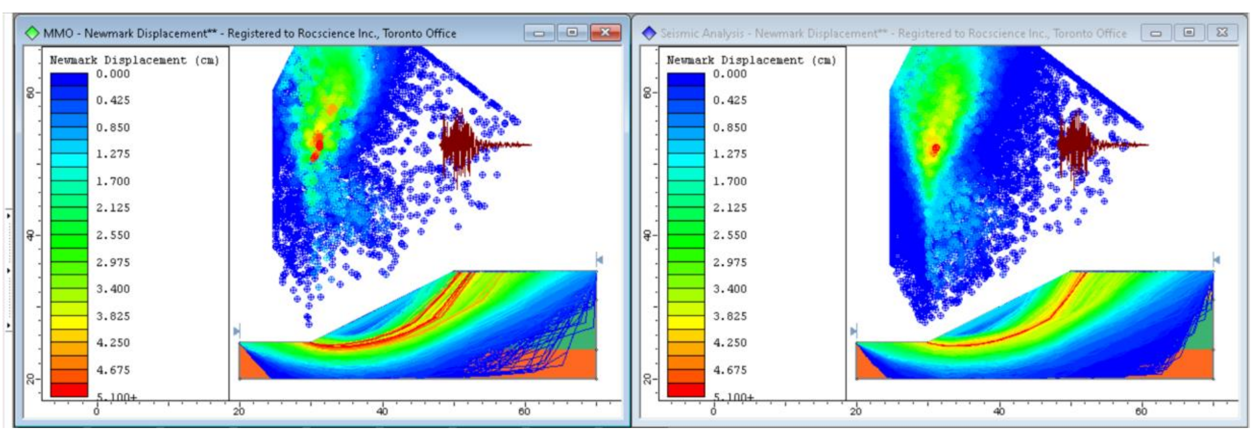


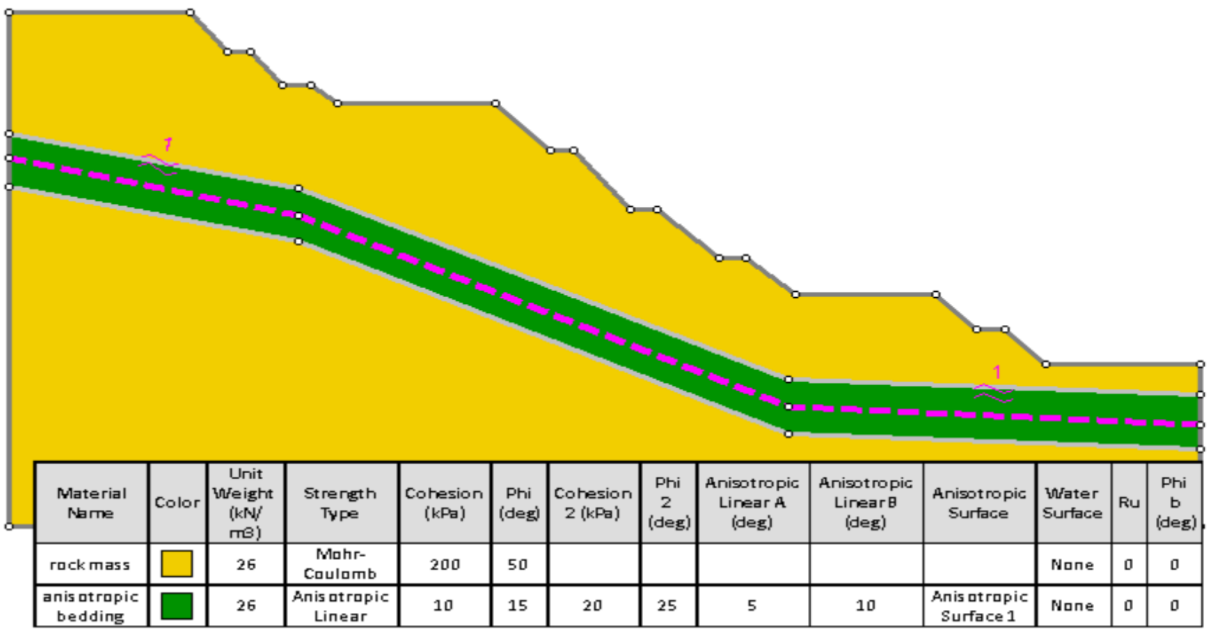
Figure 104.3: MMO vs uni-modal all surfaces view for Newmark scenario

105. Slide Verification Problem #105

Anisotropic surface, multi-modal optimization (MMO)

105.1. Problem Description

This example is based on **Slide2** Tutorial 32 Anisotropic Surface. The purpose of this example is to ensure that the most critical surface found by MMO PS with SA is in agreement with that found by uni-modal PS with SA. The methods used are Bishop, Janbu Simplified, Spencer, and GLE.



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Cohesion 2 (kPa)	Phi 2 (deg)	Anisotropic Linear A (deg)	Anisotropic Linear B (deg)	Anisotropic Surface	Water Surface	Ru	Phi b (deg)
rock mass		26	Mohr-Coulomb	200	50						None	0	0
anisotropic bedding		26	Anisotropic Linear	10	15	20	25	5	10	Anisotropic Surface 1	None	0	0

Figure 105.1: Tutorial model used in this example

105.2. Results

The most critical MMO result for each method is compared to the corresponding uni-modal result below and they are found to be in very good agreement.

Table 105.1: MMO vs uni-modal results for each method

	MMO (most critical)	Uni-modal
Bishop	0.970	0.976
Janbu Simplified	0.935	0.938
Spencer	1.086	1.084
GLE	1.017	1.015

The view below compares the MMO (left) and uni-modal (right) results for Bishop. A filter has been applied to only display surfaces with FS less than 1. This is a good way to understand the difference between the MMO and uni-modal algorithms. Note that the MMO algorithm seeks minima everywhere and hence is able to find a bigger region with surfaces that have an FS below 1. The uni-modal algorithm works to converge to the lowest FS region and hence only the region about the critical surface is found.

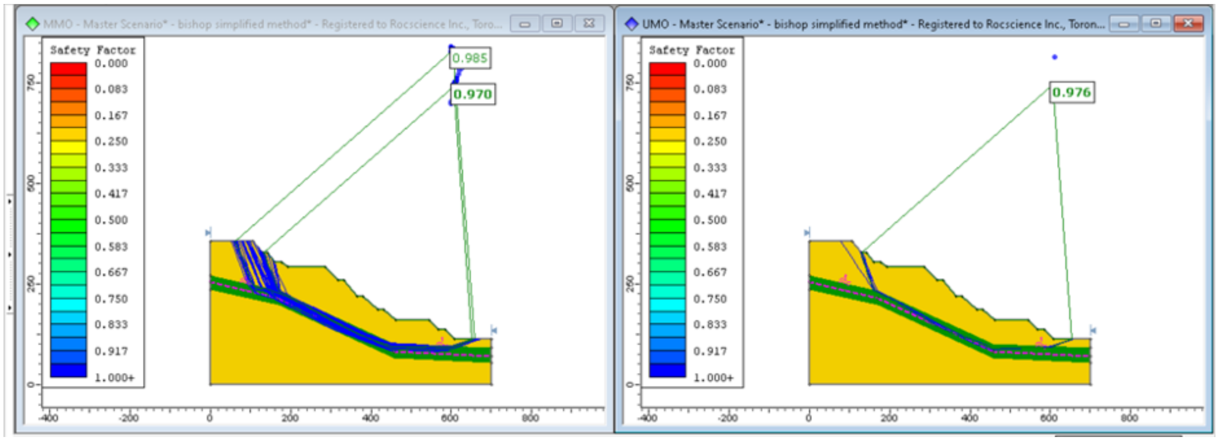


Figure 105.2: MMO vs uni-modal all surfaces with FS < 1

106. Slide Verification Problem #106

Support, Ito & Matsui pile

106.1. Problem Description

This example comes from Cai & Ugai (2000) where the Ito & Matsui pile was used in a Bishop's circular analysis in order to compare to finite element analysis. The results of their Bishop analysis are compared to Slide2 below:

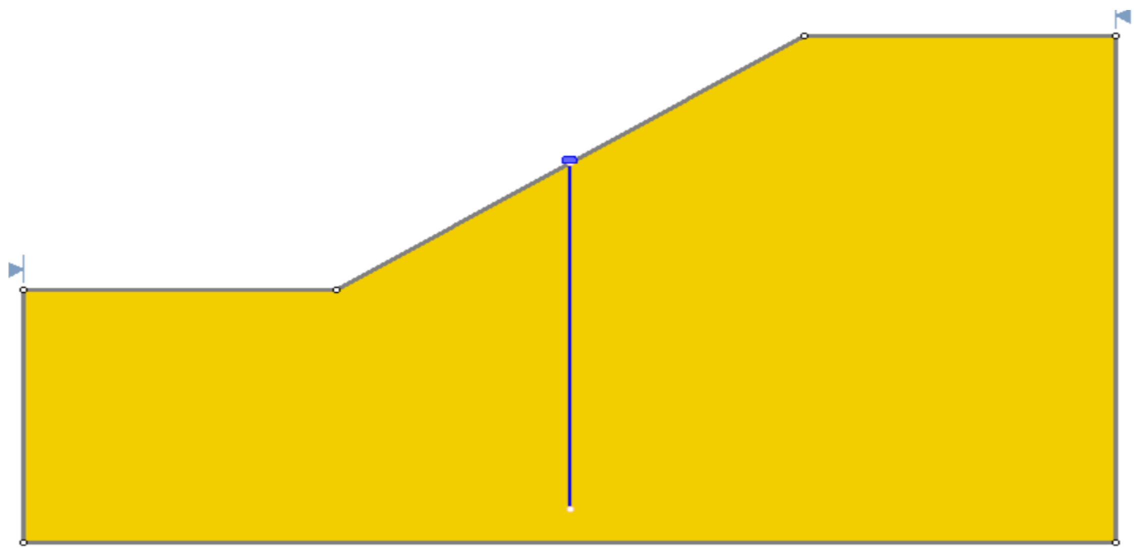


Figure 106.1: Cai & Ugai (2000) model used in this example

106.2. Results

The pile spacing was varied in each scenario following the paper, and the results from the paper and Slide2 are shown below:

Table 106.1: FS for Cai & Ugai (2000) vs Slide2 for each pile spacing

Pile (Spacing/Diameter)	Cai & Ugai (2000) FS	Slide2 FS
No Pile	1.13	1.14
2	1.54	1.54
3	1.37	1.43
4	1.31	1.33
6	1.25	1.25

It can be surmised that any differences are due to the different search methods used and hence surfaces found in the paper vs. **Slide2**.

107. Slide Verification Problem #107

Retaining walls, gabion walls, supports

107.1. Introduction

This example is from Cao L. et al. (2016) in which WSP conducted a case study of a wall failure in Vancouver, British Columbia using Slide. The purpose of this verification is to demonstrate the analysis of a gabion wall using (a) an equivalent cohesion method and (b) a mesh method.

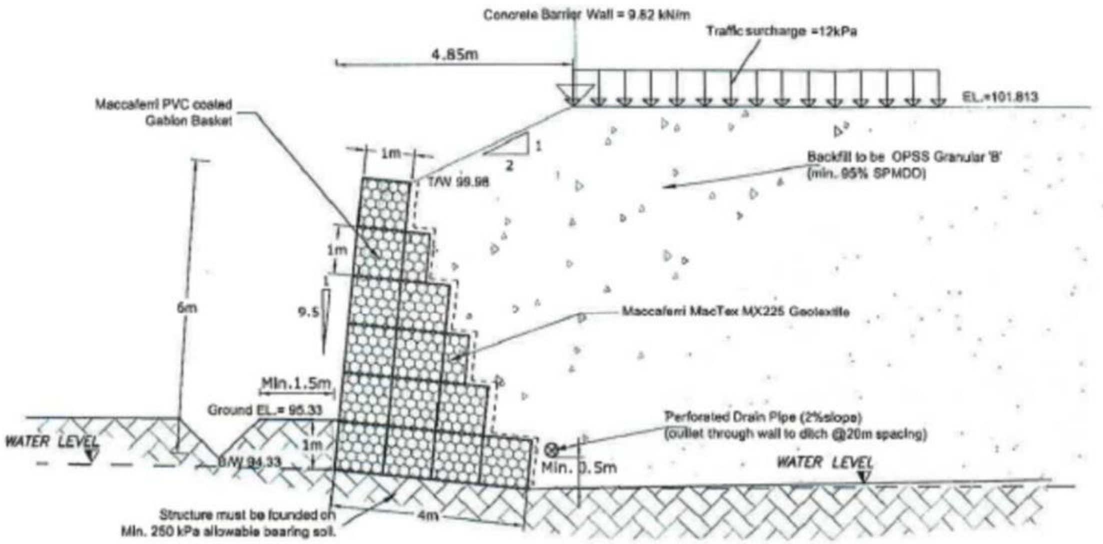


Figure 107.1: Drawing of gabion wall provided by Cao et Al. (2016)

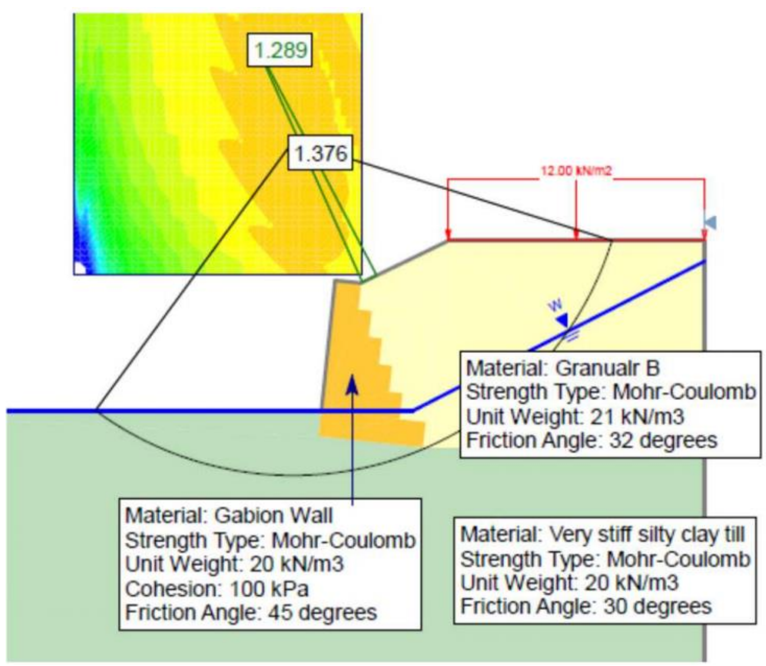
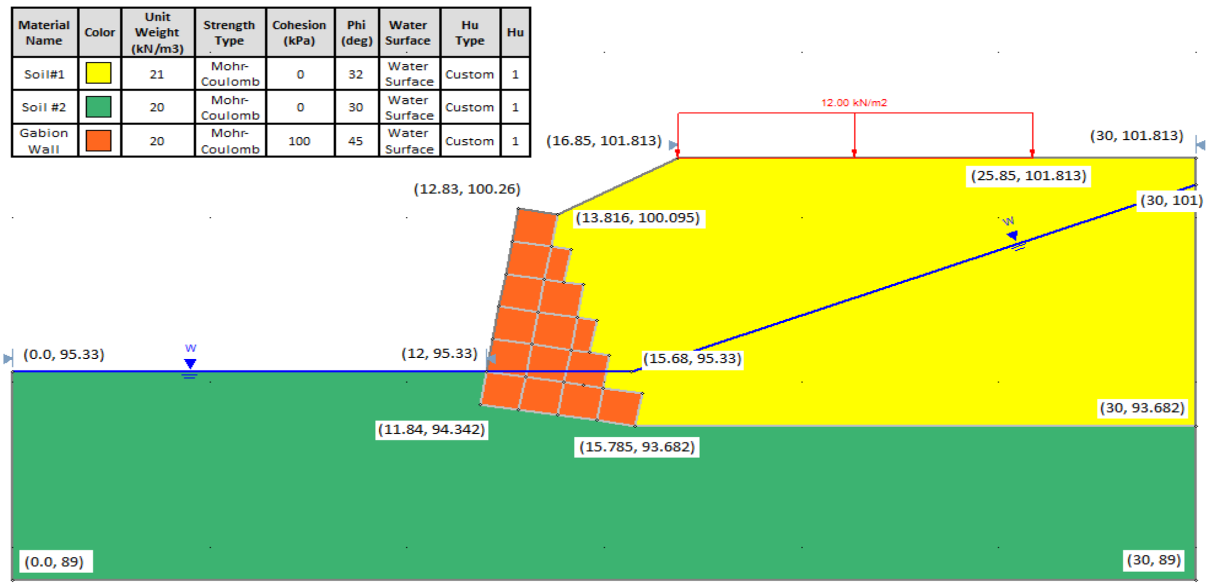


Figure 107.2: **Slide** model of gabion wall provided by Cao et Al. (2016)

107.2. Problem Description

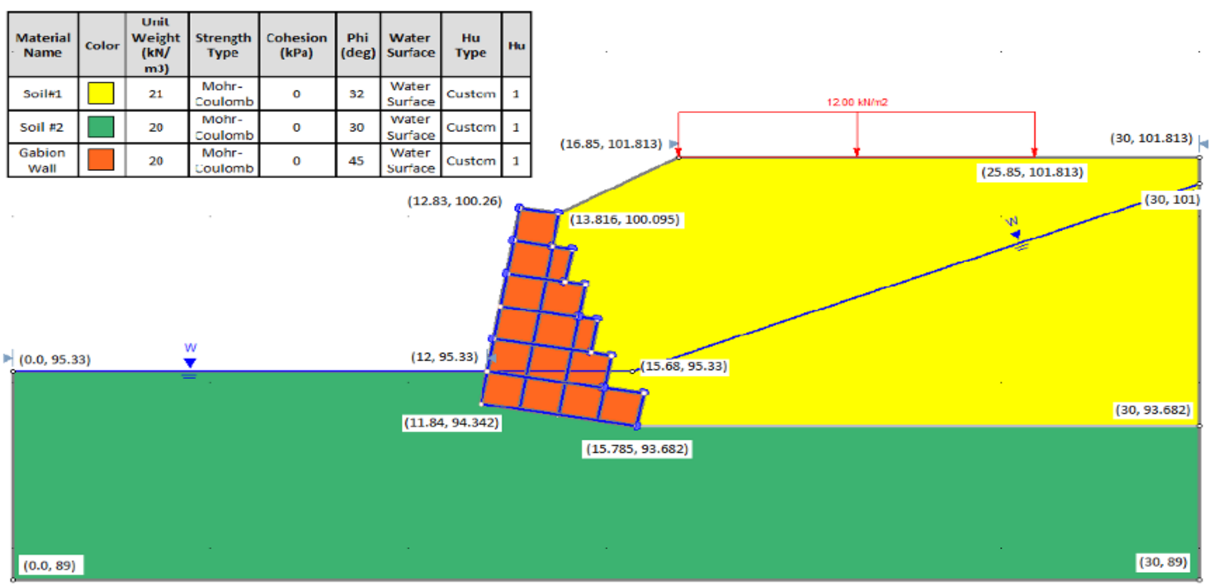
As shown in Figure 106.1, the study consists of a 6m tall gabion wall with a base width of 4m, each layer being composed of 1m tall x 1m wide x 4m long gabions. While Slide does not conduct internal stability calculations, the results of the overall slope stability are of interest. The case study assumed the material parameters of the gabion wall. The equivalent cohesion method simulates the existence of steel mesh via a non-zero value of c, while the mesh method explicitly models the steel mesh using geosynthetic supports.

107.3. Geometry and Material Properties



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface	Hu Type	Hu
Soil#1		21	Mohr-Coulomb	0	32	Water Surface	Custom	1
Soil #2		20	Mohr-Coulomb	0	30	Water Surface	Custom	1
Gabion Wall		20	Mohr-Coulomb	100	45	Water Surface	Custom	1

Figure 107.3: Gabion Wall Model in **Slide** (equivalent cohesion method)



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface	Hu Type	Hu
Soil#1		21	Mohr-Coulomb	0	32	Water Surface	Custom	1
Soil #2		20	Mohr-Coulomb	0	30	Water Surface	Custom	1
Gabion Wall		20	Mohr-Coulomb	0	45	Water Surface	Custom	1

Figure 107.4: Gabion Wall Model in **Slide** (mesh method)

A helpful feature is the ability to specify the length of any line and its angle in the prompt line from a selected point. The format is as follows:

@#<Deg

The # symbol represents the line length. Deg is a value between 0 to 360 representing the angle. Note that the angle is relative to the horizontal on the right side of a selected point. This can be used to draw the gabion wall.

A second set of limits is defined at the bottom of the wall (12, 95.33) and the top of the slope (16.85, 101.813) to filter out smaller slip surfaces.

Table 107.1: Soil Properties

	c´ (kN/m^2)	**ϕ´ (deg.)**	**γ (kN/m^3)**
Soil #1	0	32	21
Soil #2	0	30	20
Gabion Wall	**100***	45	20

*For the mesh method, cohesion = 0. For the equivalent cohesion method, the cohesion of the gabion wall can be estimated using the following equations (Grodecki, 2017):

$$c_r = \frac{\Delta\sigma_3}{2}\tan\left(45^{\circ} + \frac{\varphi}{2}\right)$$

$$\Delta\sigma_3 = \frac{2 f_t \varepsilon_c}{d\varepsilon_a(1-\varepsilon_a)}$$

$$\varepsilon_c = \frac{1-\sqrt{1-\varepsilon_a}}{1-\varepsilon_a}$$

Table 107.2: Additional Assumed Gabion Properties

$\boldsymbol{f_t}$ [kN/m]	71
d [m]	1
ε_a	0.07
c_r [kPa] (Calculated)	**100**

Table 107.3: Geosynthetic Support Properties

Force Application	Active
Force Direction	Tangent to Slip Surface
Strip Coverage	100%
Allowable Tensile Strength	71
Anchorage	Both Ends
Connection Strength Input	Constant
Connection Strength	71

107.4. Results

The critical FS for each method is shown below.

Table 107.4

Model	**Equivalent Cohesion Method**		**Mesh Method**	
Method	**FS, Grid Search (Circular)**	**FS, Cuckoo Search (Non-Circular)**	**FS, Grid Search (Circular)**	**FS, Cuckoo Search (Non-Circular)**
Bishop	1.373	1.032	1.378	1.034
Janbu	1.156	0.962	1.156	0.966
Spencer	1.386	1.25	1.392	1.26
GLE	1.387	1.29	1.394	1.291

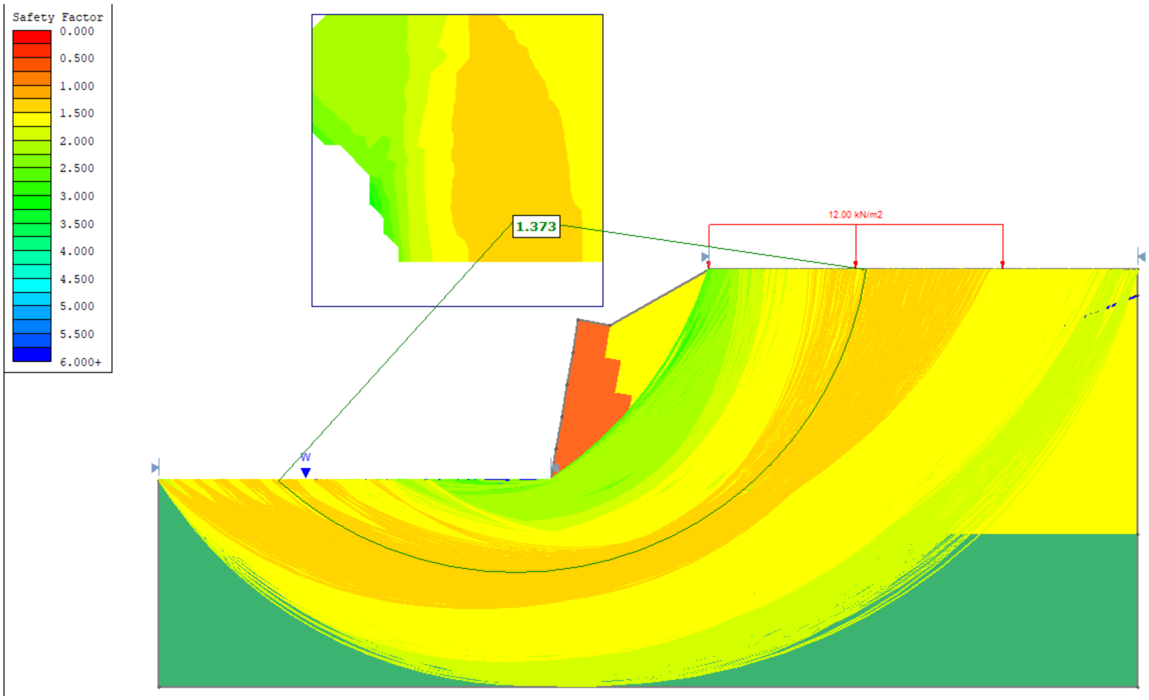


Figure 107.5: Solution for Equivalent Cohesion Method Using Circular Search and Bishop Method

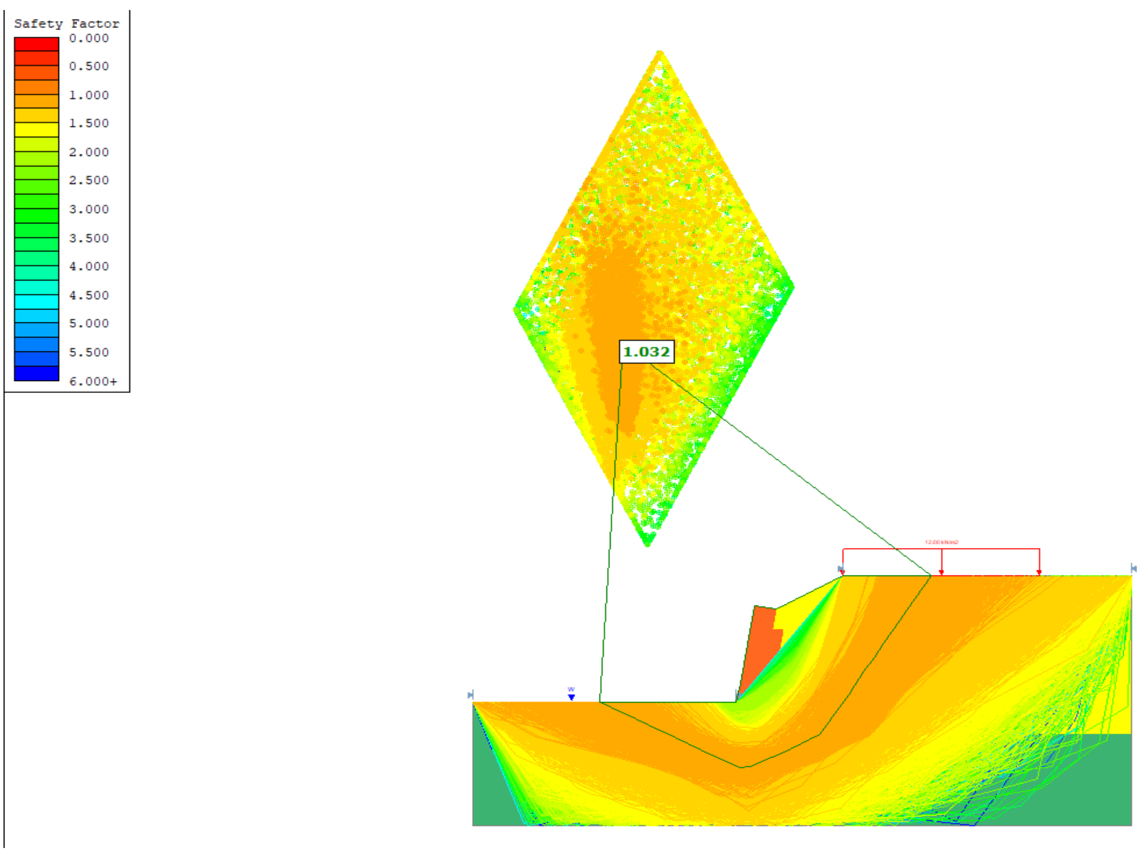


Figure 107.6: Solution for Equivalent Cohesion Method Using Cuckoo Search and Bishop Method

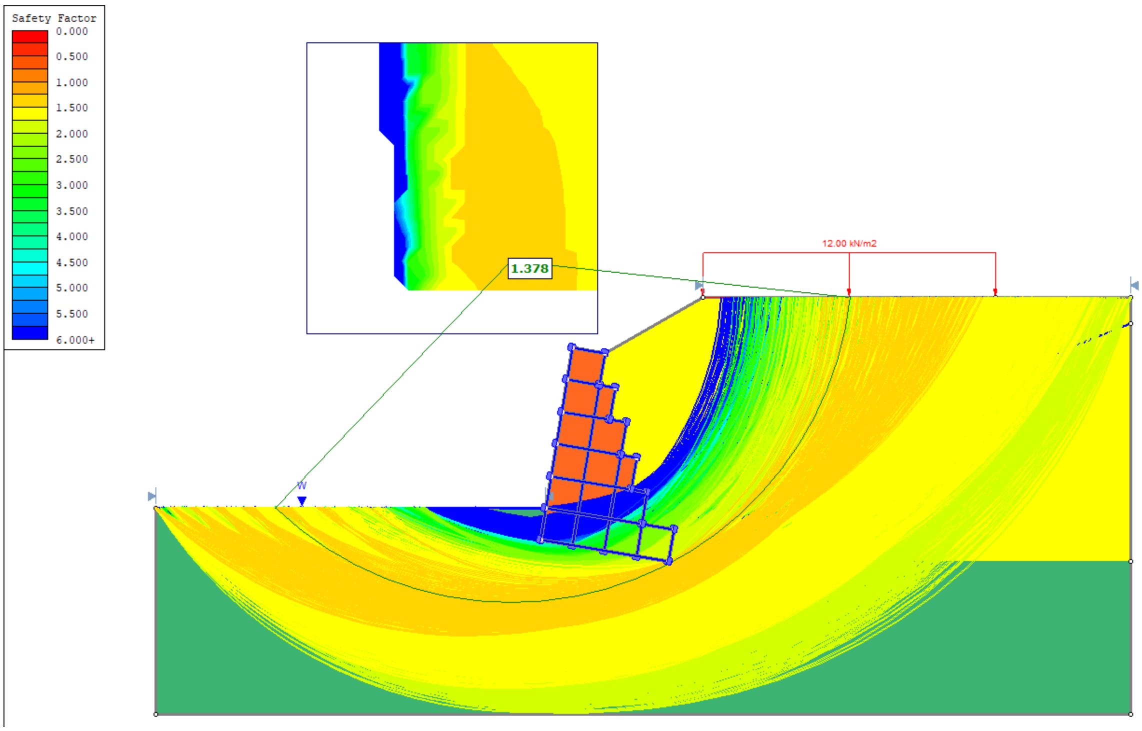


Figure 107.7: Solution for Mesh Method Using Circular Search and Bishop Method

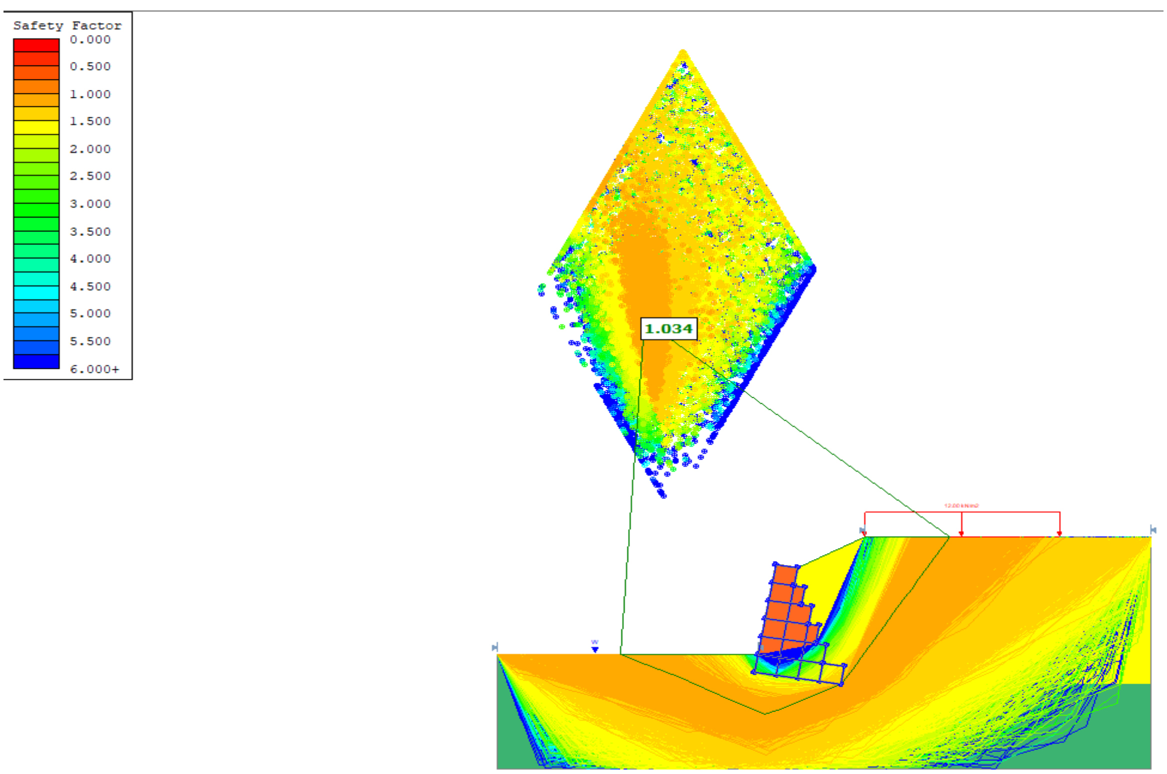


Figure 107.8: Solution for Mesh Method Using Cuckoo Search and Bishop Method

108. Slide Verification Problem #108

Retaining walls, gabion walls, supports

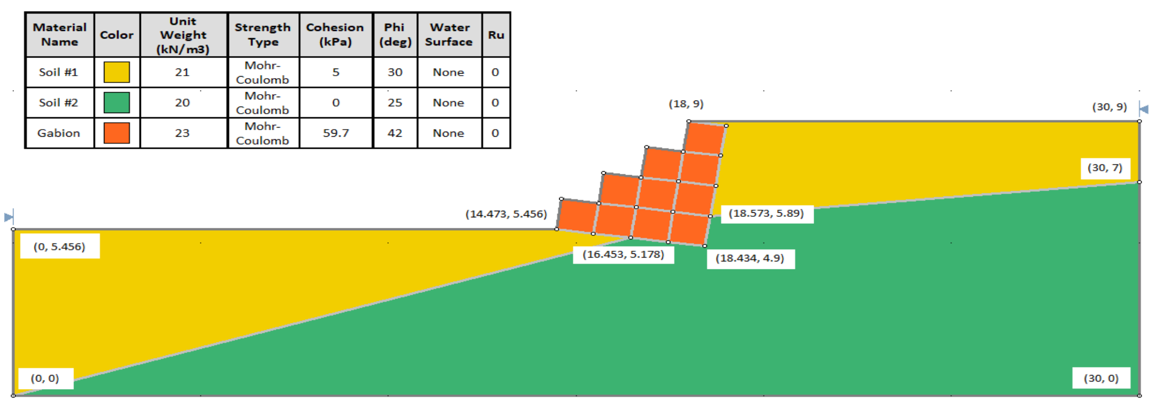
108.1. Introduction

This example is a stepped gabion wall with the steps facing outwards. The purpose of this verification is to demonstrate the analysis of a gabion wall using (a) an equivalent cohesion method and (b) a mesh method.

108.2. Problem Description

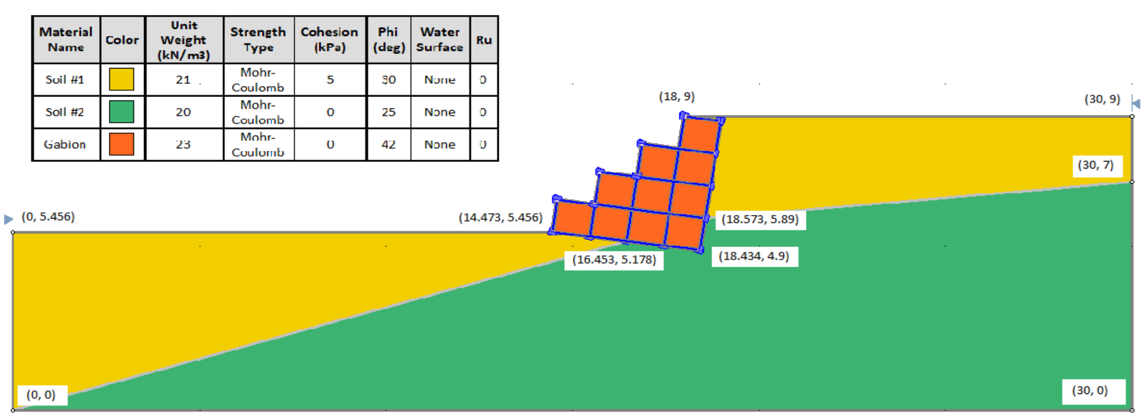
The wall consists of a 4m tall gabion wall composed of 1m tall x 1m wide x 1m long gabions. While **Slide** does not conduct internal stability calculations, the results of the overall slope stability are of interest. The equivalent cohesion method simulates the existence of steel mesh via a non-zero value of c, while the mesh method explicitly models the steel mesh using geosynthetic supports.

108.3. Geometry and Material Properties



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface	Ru
Soil #1		21	Mohr-Coulomb	5	30	None	0
Soil #2		20	Mohr-Coulomb	0	25	None	0
Gabion		23	Mohr-Coulomb	59.7	42	None	0

Figure 108.1: Gabion Wall Model in **Slide** (equivalent cohesion method)



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface	Ru
Soil #1		21	Mohr-Coulomb	5	30	None	0
Soil #2		20	Mohr-Coulomb	0	25	None	0
Gabion		23	Mohr-Coulomb	0	42	None	0

Figure 108.2: Gabion Wall Model in **Slide** (mesh method)

A helpful feature is the ability to specify the length of any line and its angle in the prompt line from a selected point. The format is as follows:

@#<Deg

The # symbol represents the line length. Deg is a value between 0 to 360 representing the angle. Note that the angle is relative to the horizontal on the right side of a selected point. This can be used to draw the gabion wall.

A second set of limits is defined at the bottom of the wall (14.473, 5.456) and the top of the slope (18, 9) for the mesh method to filter out smaller slip surfaces.

Table 108.1: Soil Properties

	c´ (kN/m^2)	**ϕ´ (deg.)**	**γ (kN/m^3)**
Soil #1	5	30	21
Soil #2	0	25	20
Gabion Wall	**59.7***	42	23

*For the mesh method, cohesion = 0. For the equivalent cohesion method, the cohesion of the gabion wall can be estimated using the following equations (Grodecki, 2017):

$$c_r = \frac{\Delta\sigma_3}{2}\tan\left(45^{\circ} + \frac{\varphi}{2}\right)$$

$$\Delta\sigma_3 = \frac{2f_t\varepsilon_c}{d\varepsilon_a(1-\varepsilon_a)}$$

$$\varepsilon_c = \frac{1-\sqrt{1-\varepsilon_a}}{1-\varepsilon_a}$$

Table 108.2: Additional Assumed Gabion Properties

$\boldsymbol{f_t}$ [kN/m]	**100**
d [m]	1
ε_a	0.06
c_r [kPa] (Calculated)	**59.7**

Table 108.3: Geosynthetic Support Properties

Force Application	Active
Force Direction	Tangent to Slip Surface
Strip Coverage	100%
Allowable Tensile Strength	100
Anchorage	Both Ends
Connection Strength Input	Constant
Connection Strength	100

108.4. Results

The critical FS for each method is shown below.

Table 108.4

Model	**Equivalent Cohesion Method**		**Mesh Method**	
Method	**FS, Grid Search (Circular)**	**FS, Cuckoo Search (Non-Circular)**	**FS, Grid Search (Circular)**	**FS, Cuckoo Search (Non-Circular)**
Bishop	1.787	1.512	1.835	1.522
Janbu	1.566	1.43	1.604	1.44
Spencer	1.791	1.72	1.839	1.731
GLE	1.791	1.723	1.837	1.716

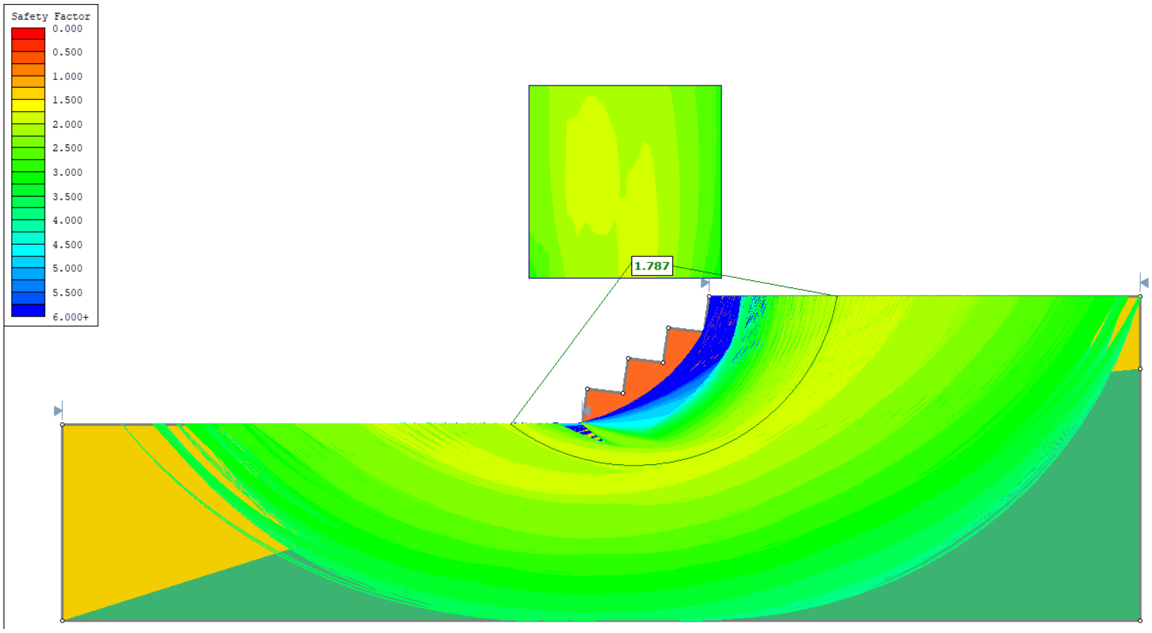


Figure 108.3: Solution for Equivalent Cohesion Method Using Circular Search and Bishop Method

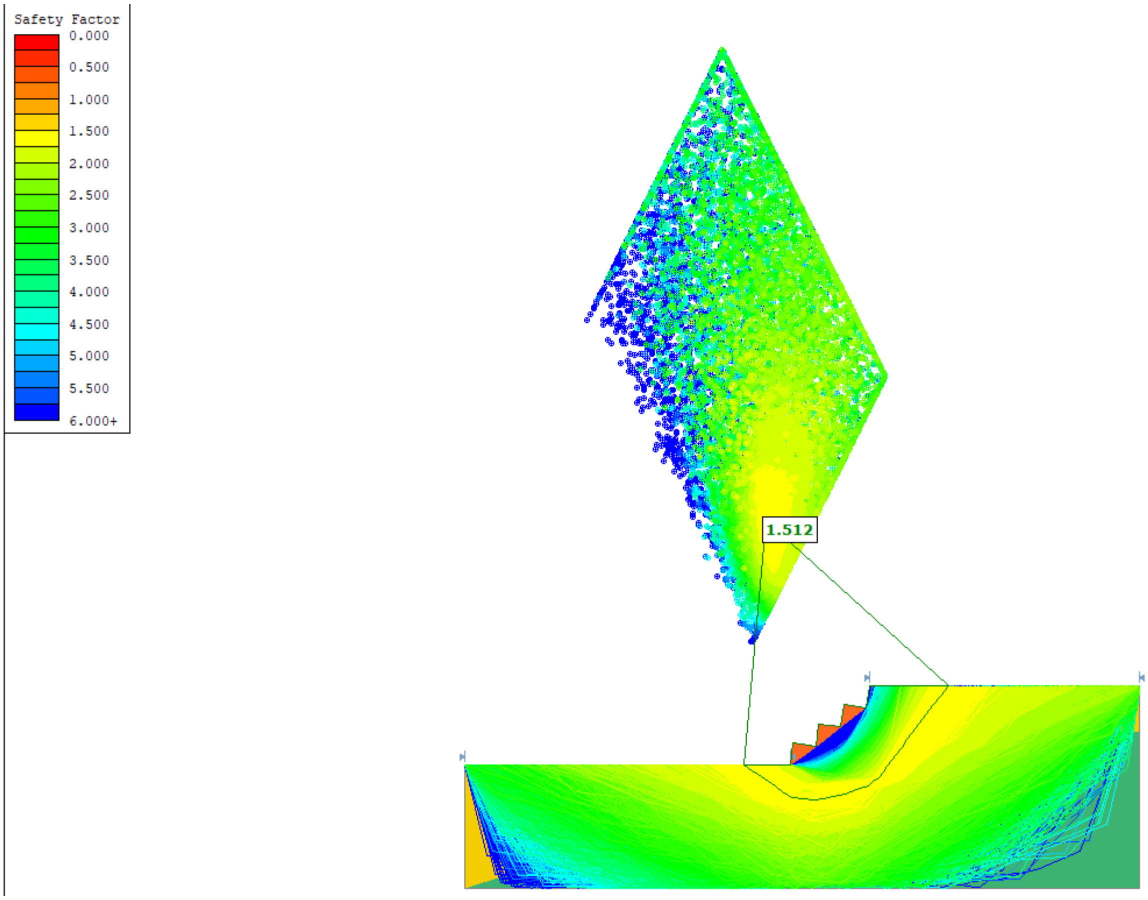


Figure 108.4: Solution for Equivalent Cohesion Method Using Cuckoo Search and Bishop Method

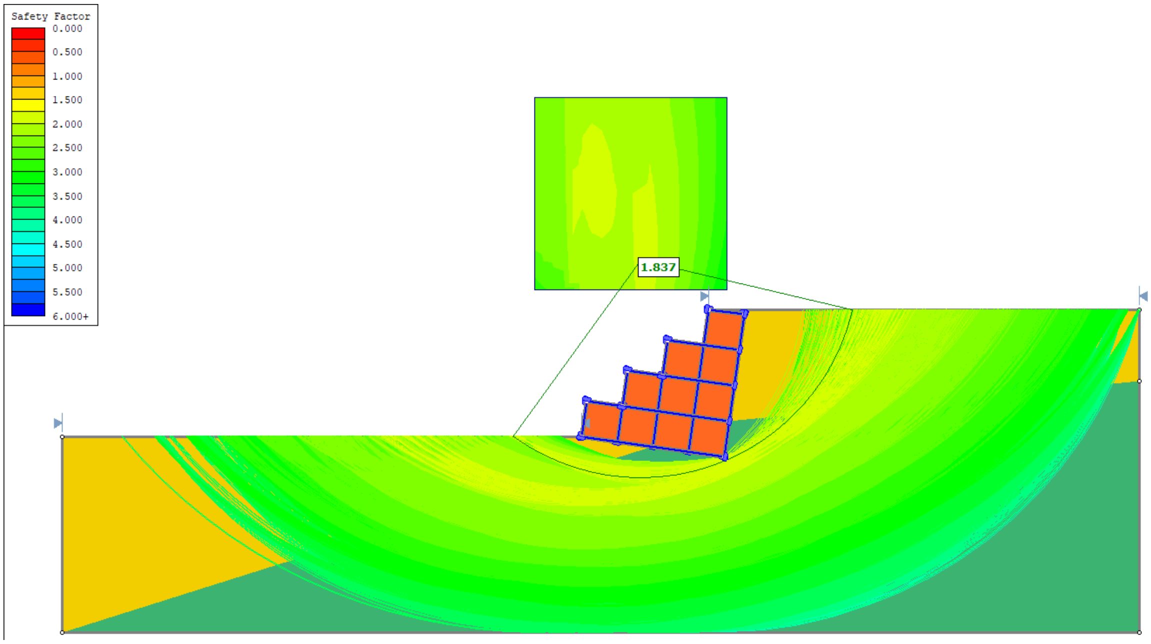


Figure 108.5: Solution for Mesh Method Using Circular Search and Bishop Method

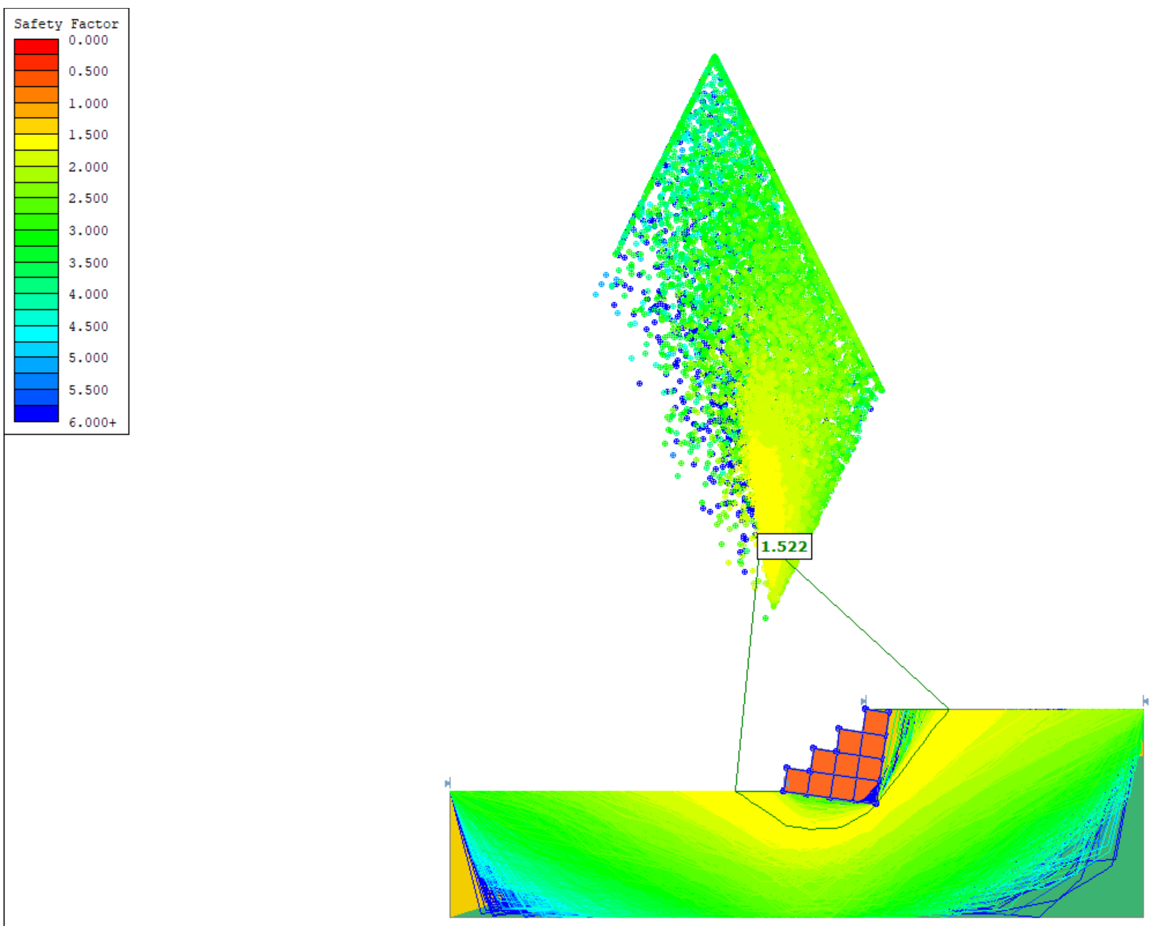


Figure 108.6: Solution for Mesh Method Using Cuckoo Search and Bishop Method

109. Slide Verification Problem #109

Retaining walls, gabion walls, weak layers

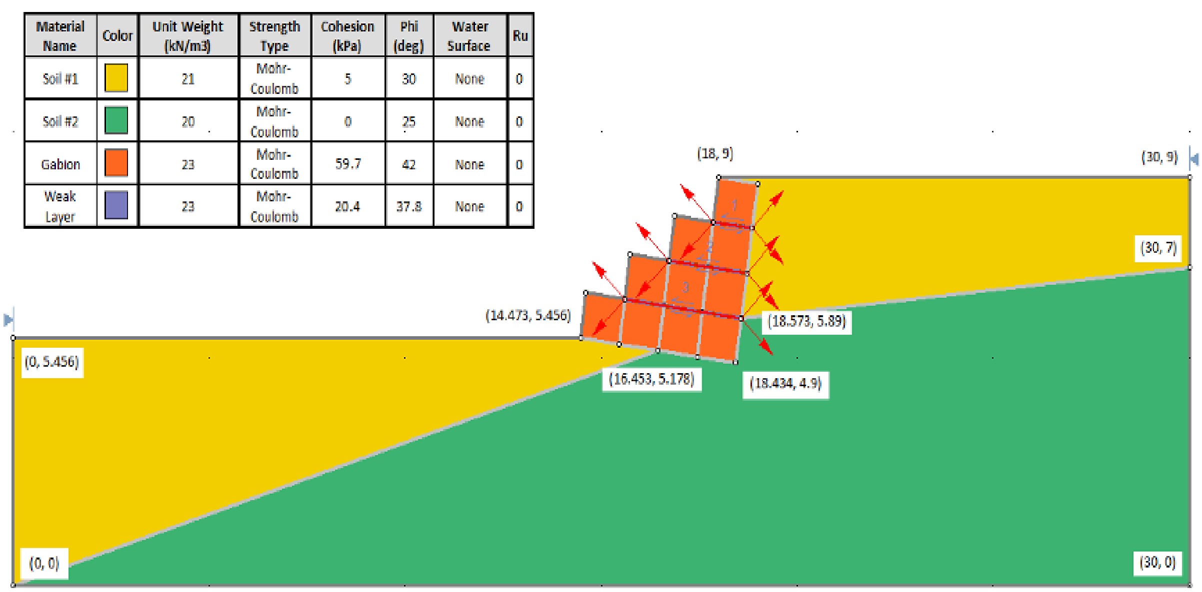
109.1. Introduction

This example is a stepped gabion wall with the steps facing outwards. Weak layers have been added to the gabion wall to simulate potential weak joint failure or shear failure through the gabion wall. The purpose of this verification is to demonstrate the modeling of gabion walls using an equivalent cohesion method along with weak layers.

109.2. Problem Description

The wall consists of a 4m tall gabion wall composed of 1m tall x 1m wide x 1m long gabions. A series weak layers have been specified and added between the horizontal lines of the gabion wall. Note that vertical weak layers would cause the slip surfaces to clip vertically and should be avoided in general.

109.3. Geometry and Material Properties



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface	Ru
Soil #1		21	Mohr-Coulomb	5	30	None	0
Soil #2		20	Mohr-Coulomb	0	25	None	0
Gabion		23	Mohr-Coulomb	59.7	42	None	0
Weak Layer		23	Mohr-Coulomb	20.4	37.8	None	0

Figure 109.1: Gabion Wall Model in in **Slide**

A helpful feature is the ability to specify the length of any line and its angle in the prompt line from a selected point. The format is as follows:

@#<Deg

The # symbol represents the line length. Deg is a value between 0 to 360 representing the angle. Note that the angle is relative to the horizontal on the right side of a selected point. This can be used to draw the gabion wall.

Table 109.1: Soil Properties

	c´ (kN/m²)	**ϕ´ (deg.)**	**γ (kN/m³)**
Soil #1	5	30	21
Soil #2	0	25	20
Gabion Wall	**59.7***	42	23

*The cohesion of the gabion wall can be estimated using the following equations (Grodecki, 2017):

$$c_r = \frac{\Delta\sigma_3}{2}\tan\left(45^\circ + \frac{\varphi}{2}\right)$$

$$\Delta\sigma_3 = \frac{2f_t\varepsilon_c}{d\varepsilon_a(1-\varepsilon_a)}$$

$$\varepsilon_c = \frac{1-\sqrt{1-\varepsilon_a}}{1-\varepsilon_a}$$

Table 109.2: Additional Assumed Gabion Properties

$\boldsymbol{f_t}$ [kN/m]	100
d [m]	1
ε_a	0.06
c_r [kPa] (Calculated)	**59.7**

For properties, the weak layer is assumed have a friction angle of 90% of the gabion fill. The joint has a tensile strength of 20.4kN/m. Cohesion can then be determined by multiplying the width of the gabion (1m) by the tensile strength. Cohesion is therefore 20.4kPa.

Block search polylines should be defined at the weak layers.

Note: Values of 45 to -45 and 135 to 225 degrees are used for the block search line projection angles.

A second set of limits is defined at the bottom of the wall (14.473, 5.456) and the top of the slope (18, 9) to filter out smaller slip surfaces.

109.4. Results

The critical FS for each method is shown below.

Table 109.2

Method	FS, Block Search (Non-Circular)
Bishop	1.799
Janbu	1.610
Spencer	1.803
GLE	1.804

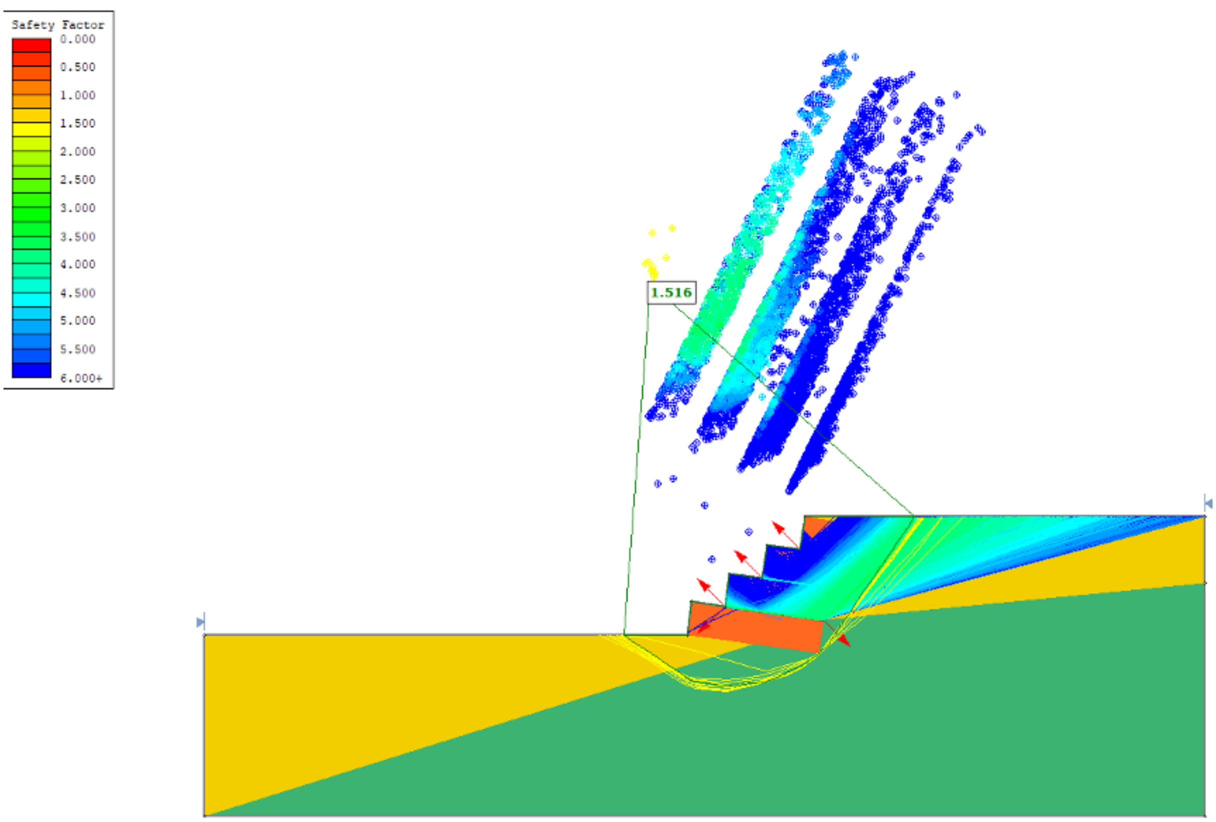


Figure 109.2: Solution, using Block Search and Bishop method

110. Slide Verification Problem #110

Retaining walls, equivalent fluid pressure

110.1. Introduction

The Retaining Wall (EFP) support type is used to model retaining walls whose capacity is defined by an equivalent fluid pressure (EFP) profile. This verification problem will do a simple verification for this support type.

110.2. Problem Description

In this model a retaining wall with a triangular pressure distribution will be considered.

110.3. Geometry and Material Properties

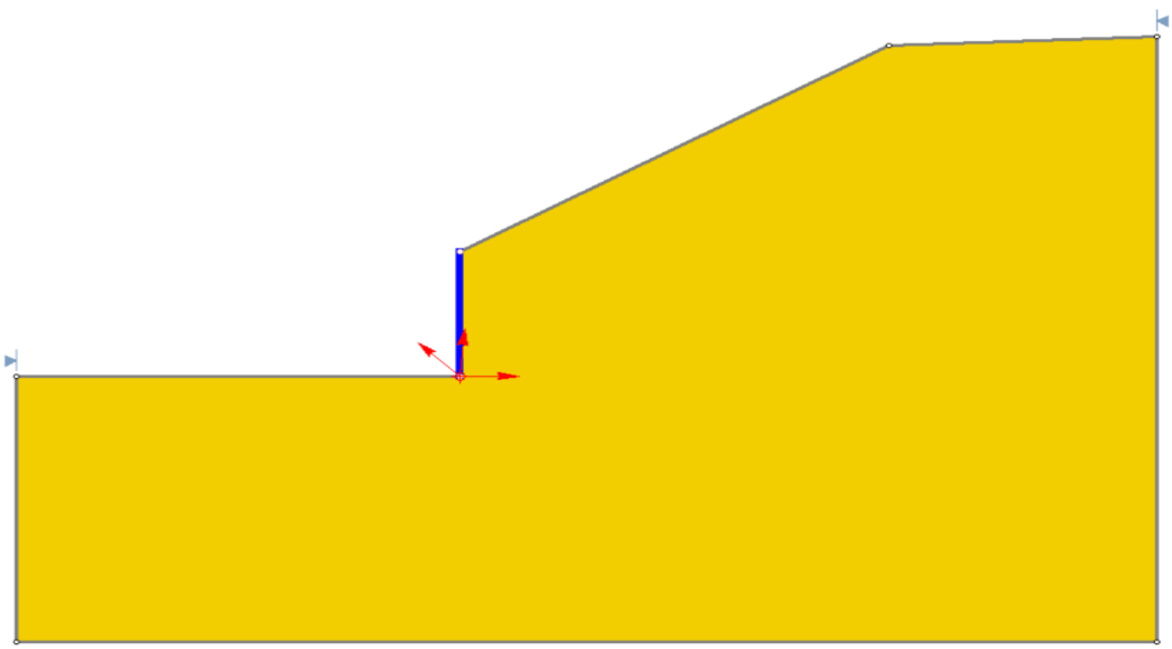


Figure 110.1: Cantilevered Retaining Wall (triangular pressure profile)

The wall is five feet tall, and the equivalent fluid pressure profile is defined as follows:

Table 110.1

Relative Distance	Equivalent Fluid Pressure (psf)
0 (top of wall)	0
1 (bottom of wall)	125

The results will be verified using a triangular distributed load. This is a good verification because the distributed load is integrated and applied to the slice at the centroid. This is precisely what the Retaining Wall (EFP) support type does as well.

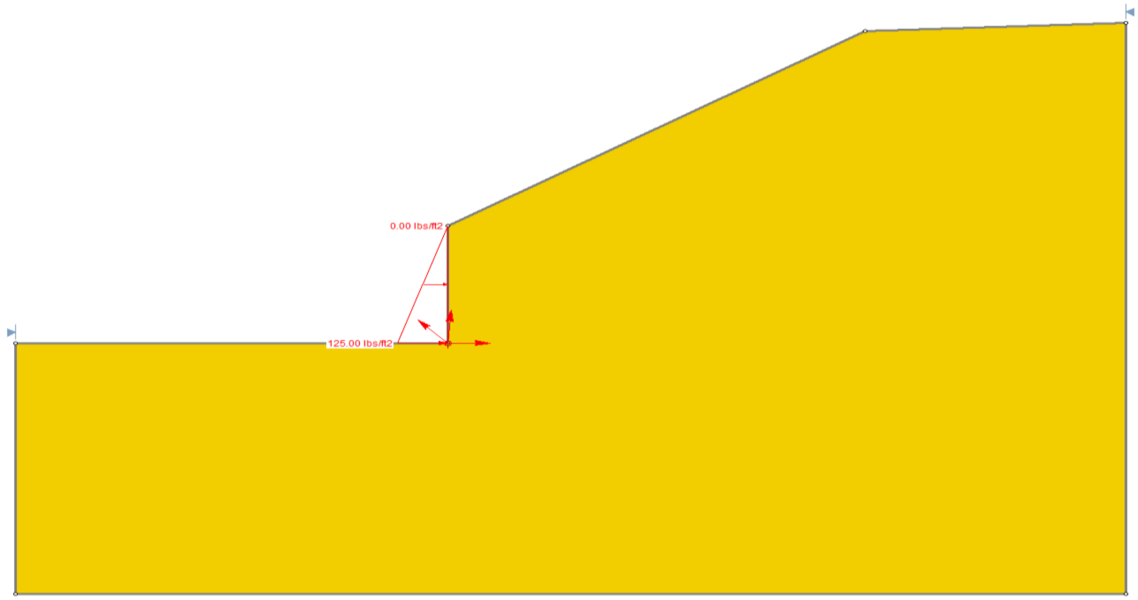


Figure 110.2: Triangular distributed load used for verification

110.4. Results

The results using Spencer method are shown below. As expected, the results are identical:

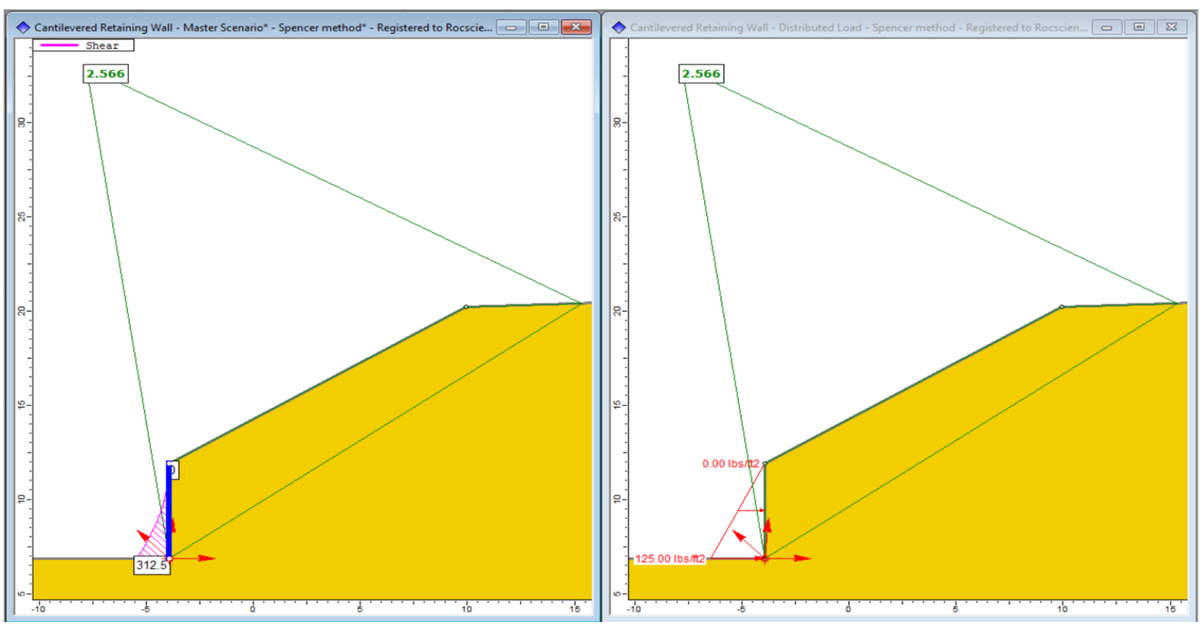


Figure 110.3 – Results using Spencer's method are matching as expected

As an additional verification, it should be noted that the last force in the support force diagram is 312.5, or the area of the pressure profile (5*125/2).

111. Slide Verification Problem #111

Helical anchor

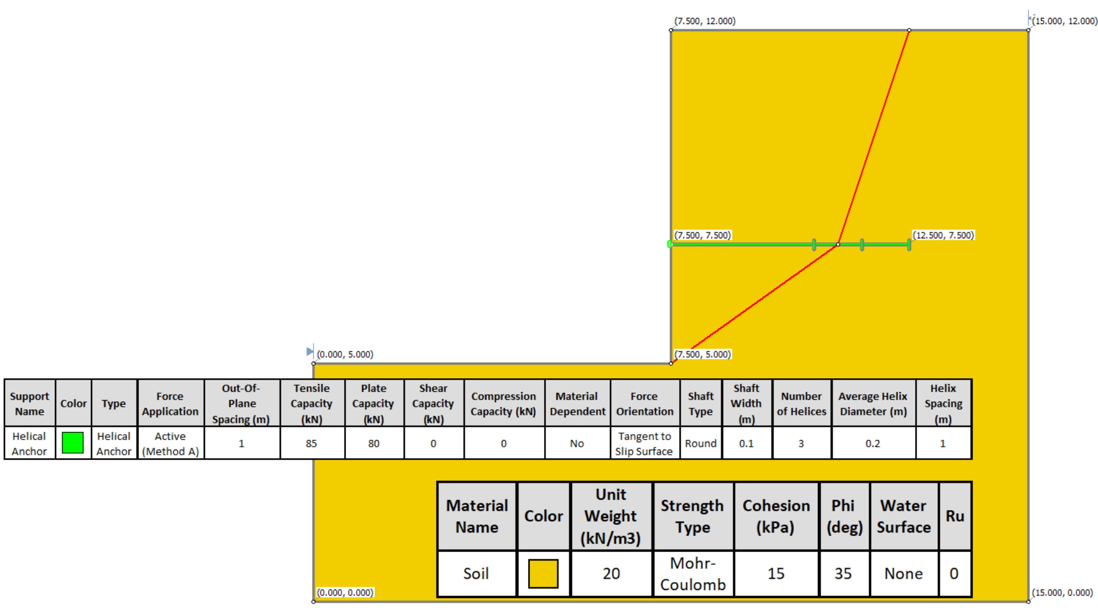
111.1. Introduction

The Helical Anchor support type is used to model helical anchors. This verification problem will demonstrate how the support capacity is calculated and used in Slide2 through a hand calculation.

111.2. Problem Description

A helical anchor in a model with a single pre-defined critical surface is considered. Considering only a single surface will make the hand calculation feasible.

111.3. Geometry and Properties



Support Name	Color	Type	Force Application	Out-Of-Plane Spacing (m)	Tensile Capacity (kN)	Plate Capacity (kN)	Shear Capacity (kN)	Compression Capacity (kN)	Material Dependent	Force Orientation	Shaft Type	Shaft Width (m)	Number of Helices	Average Helix Diameter (m)	Helix Spacing (m)
Helical Anchor		Helical Anchor	Active (Method A)	1	85	80	0	0	No	Tangent to Slip Surface	Round	0.1	3	0.2	1

Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface	Ru
Soil		20	Mohr-Coulomb	15	35	None	0

Figure 111.1: Model with single surface and helical anchor

111.4. Hand Calculation

We will calculate by hand the force diagram of the capacity of the anchor by determining the capacities of the three failure modes and their associated failure types.

1. Pullout

   a. Shallow Failure
   b. Cylindrical Shear

    c. Individual Bearing

2. Stripping
    a. Shallow Failure
    b. Cylindrical Shear
    c. Individual Bearing

3. Tensile

The location of the bottom plate is assumed to be at the end of the anchor. Subsequent plates are generated and separated based on the number of helices and spacing. In this example, given that there are 3 plates spaced apart 1m, the plates are located at (10.5, 7.5), (11.5, 7.5), and (12.5, 7.5,).

Soil Shear Strength

The shear strength τ developed by each increment of soil along the anchor is given by:

(111.1) $$\tau = c + q' tan\phi_s$$

where c is the cohesion of the soil, q' is the effective normal stress, and ϕ_s is the friction angle of the soil. The cohesion, normal stress, and angle of friction are assumed to be effective stress parameters. In this example, the shear strength is constant along the anchor.

Failure Mode 1: Pullout

The three failure types considered for pullout (shallow failure, cylindrical shear, and individual bearing) are also considered for stripping. We will go over them here.

Shallow failure occurs when the soil failure surface of the mobilized soil within the anchor extends to the surface. In **cylindrical shear**, the mobilized soil between the plates forms a cylindrical volume of soil. In **individual bearing**, all plates fail within an area of localized soil, independent of one another (Perko, 2009).

At any point along the support, the ultimate pullout capacity for shallow failure can be determined using the following equation:

(111.2) $$Pu_s = \tau(\pi d_a h + \pi d_a (n-1)s)$$
$$Pu_s = \tau \pi d_a (h + (n-1)s)$$

where *h* is the distance from the slip surface to the shallowest helix along the anchor, also known as embedment depth, d_a is average helix diameter, *n* is the total number of helices within the soil, and *s* is the spacing between helices.

At any point along the support, the ultimate pullout capacity in **cylindrical shear** can be determined using the following equation:

(111.3) $$Pu_c = \tau \pi d_a (n-1)s + A_{sh}\left(1.3cN_c + q'N_q\right)$$

where A_{sh} is the area of the shallowest helix from the slip surface. N_c and N_q are bearing capacity factors and can be determined using the following equations (Perko, 2009):

(111.4) $$N_q = e^{\pi tan\phi} tan^2(45 + \phi_s/2)$$

(111.5) $$N_c = (N_q - 1)cot\phi_s$$

At any point along the support, the ultimate pullout capacity for **individual bearing** can be determined using the following equations:

(111.6) $$Pu_b = \sum_{i=1}^{n} A_i\left(1.3cN_c + q'N_q\right)$$

where A_i is the area of helix *i* (Perko, 2009).

Note that if the slip surface passes through the anchor such that no plate exists within the slope, no capacity is developed in the anchor. This holds true for stripping as well, but with the slip surface passing through the anchor such no plate exists within the moving soil mass.

Failure Mode 2: Stripping

The stripping capacity of the helical anchor utilizes the same equations for pullout with the addition of the head assembly capacity *H*. Stripping is taken as an inverse pullout situation, in which the embedment depth *h* is now from the slip surface to the shallowest plate within the moving soil mass. The equations for shallow failure, cylindrical shear, and individual bearing, respectively are as follows:

(111.7) $$Su_s = \tau\pi d_a(h + (n-1)s) + H$$

(111.8) $$Su_c = \tau\pi d_a(n-1)s + A_{sh}\left(1.3cN_c + q'N_q\right) + H$$

(111.9) $$Su_b = \sum_{i=1}^{n} A_i\left(1.3cN_c + q'N_q\right) + H$$

Failure Mode 3: Tensile

The tensile capacity is simply the input tensile capacity divided by the spacing:

(111.10) $$Tensile\ force = T/S$$

Overall Capacity and Force Diagram

The maximum force which can be mobilized by each failure mode, per unit width of slope, is given by the following equations:

(111.11) $$Pullout: F1 = min(Pu_s, Pu_c, Pu_b)/S$$

(111.12) $$Tensile: F2 = T/S$$

(111.13) $$Stripping: F3 = min(Su_s, Su_c, Su_b)/S$$

At any point along the length of the tieback, the force which is applied to the slip surface by the tieback, is given by the MINIMUM of these three forces.

(111.14) $$Applied\ Force = min(F1, F2, F3)$$

Hand Calculations

The maximum force which can be mobilized by each failure mode, per unit width of slope, is given by the following equations:

Assume the point at which capacity is to be calculated is (11, 7.5). The failure capacity types are calculated though the following method:

Shear strength:

Since surface and anchor are horizontal, the effective stress is the same at any point along the anchor.

q’ = Unit weight x depth

q’ = $20kN/m^3 \times (12 - 7.5)$

q’ = $90kN/m^3$

Soil shear strength can then be calculated as:

$\tau = c + q'tan\phi_s$

$\tau = 15 + (90)\tan(35)$

$\tau = 78.0187kN/m^3$

Equivalent Plate Area

$EPA = \frac{\pi}{4}({d_a}^2 - {d_{shaft}}^2)$

$EPA = \frac{\pi}{4}(0.2^2 - 0.1^2)$

$EPA = 0.02356m^2$

Bearing Capacity Factors

$N_q = e^{\pi tan\phi}tan^2(45 + \phi_s/2)$

$N_q = e^{\pi\tan(35)}tan^2(45 + (35)/2)$

$N_q = 33.2961$

$N_c = (N_q - 1)cot\phi_s$

$N_c = (33.2961 - 1)\cot(35)$

$N_c = 46.1236$

Pullout – Shallow Failure

$Pu_s = \tau\pi d_a(h + (n - 1)s)$

$Pu_s = (78.0187)\pi(0.2)[(11.5 - 11) + (2 - 1)(1)]$

$Pu_s = 73.5309kN$

Pullout – Cylindrical Shear Failure

$Pu_c = \tau\pi d_a(n - 1)s + A_{sh}(1.3cN_c + q'Nq)$

$Pu_c = (78.0187)\pi(0.2)(2 - 1)(1) + (0.02356)[1.3(15)(46.1236) + 90(33.2961)]$

Pu_c = 140.8117kN

Pullout – Individual Bearing Failure

$$Pu_b = \sum_{i=1}^{n} A_i\left(1.3cN_c + q'N_q\right)$$

$$Pu_b = (2)0.02356[1.3(15)(46.1236) + 90(33.2961)]$$

$$Pu_b = 183.5823kN$$

Stripping – Shallow Failure

$$Su_s = \tau\pi d_a(h + (n-1)s) + H$$

$$Su_s = (78.0187)\pi(0.2)[(11 - 10.5) + (1 - 1)(1)] + 80$$

$$Su_s = 104.5103$$

Stripping – Cylindrical Shear Failure

$$Su_c = \tau\pi d_a(n-1)s + A_{sh}(1.3cN_c + q'Nq) + H$$

$$Su_c = (78.0187)\pi(0.2)(1-1)(1) + (0.02356)[1.3(15)(46.1236) + 90(33.2961)] + 80$$

Su_c = 171.7912kN

Stripping – Individual Bearing Failure

$$Su_b = \sum_{i=1}^{n} A_i\left(1.3cN_c + q'N_q\right) + H$$

$$Su_b = (1)0.02356[1.3(15)(46.1236) + 90(33.2961)] + 80$$

$$Su_b = 171.7912\text{kN}$$

Minimum and Applied Force

F1 = $\min(Pu_s, Pu_c, Pu_b)\,/S$

F1 = $\min(73.5309, 140.8117, 183.5823)\,/1$

F1 = 73.5309kN/m

F2 = $85/1$

F2 = 85kN/m

F3 = $\min\,(140.5103, 171.7912, 171.7912)/1$

F3 = 140.5103kN/m

Applied Force = min (F1, F2, F3)

Applied Force = 73.5309kN/m

Calculations Table

Splitting the anchor into 10 equal increments, table 111.1 contains the results for each capacity along the anchor:

Table 111.1: Capacity at 10 increments along the anchor

Segment (m)	Plate Location	Normal Stress (kPa)	Soil Shear Strength (kN/m)	Tensile (kN/m)	Pullout			Stripping			Min Capacity (kN/m)	Failure Model
					Shallow Failure (kN/m)	Individual Bearing (kN/m)	Cylindrical Shear (kN/m)	Shallow Failure (kN/m)	Individual Bearing (kN/m)	Cylindrical Shear (kN/m)		
0	-	90	78.0187	85	245.1029	275.3961	189.8399	80.0000	80.0000	80.0000	80.0000	Stripping
0.5	-	90	78.0187	85	220.5926	275.3961	189.8399	80.0000	80.0000	80.0000	80.0000	Stripping
1	-	90	78.0187	85	196.0823	275.3961	189.8399	80.0000	80.0000	80.0000	80.0000	Stripping
1.5	-	90	78.0187	85	171.5720	275.3961	189.8399	80.0000	80.0000	80.0000	80.0000	Stripping
2	-	90	78.0187	85	147.0617	275.3961	189.8399	80.0000	80.0000	80.0000	80.0000	Stripping
2.5	-	90	78.0187	85	122.5515	275.3961	189.8399	80.0000	80.0000	80.0000	80.0000	Stripping
3	1	90	78.0187	85	98.0412	183.5974	140.8193	80.0000	80.0000	80.0000	80.0000	Stripping
3.5	-	90	78.0187	85	73.5309	183.5974	140.8193	104.5103	171.7987	171.7987	73.5309	Pullout
4	2	90	78.0187	85	49.0206	91.7987	91.7987	129.0206	171.7987	171.7987	49.0206	Pullout
4.5	-	90	78.0187	85	24.5103	91.7987	91.7987	153.5309	263.5974	220.8193	24.5103	Pullout
5	3	90	78.0187	85	0.0000	0.0000	0.0000	178.0412	263.5974	220.8193	0.0000	Pullout

111.5. Results

The model was created in **Slide2**. The applied force at the point of interest was 73.5309 kN as shown below. This is in exact agreement with the segment at 3.5 m in the table.

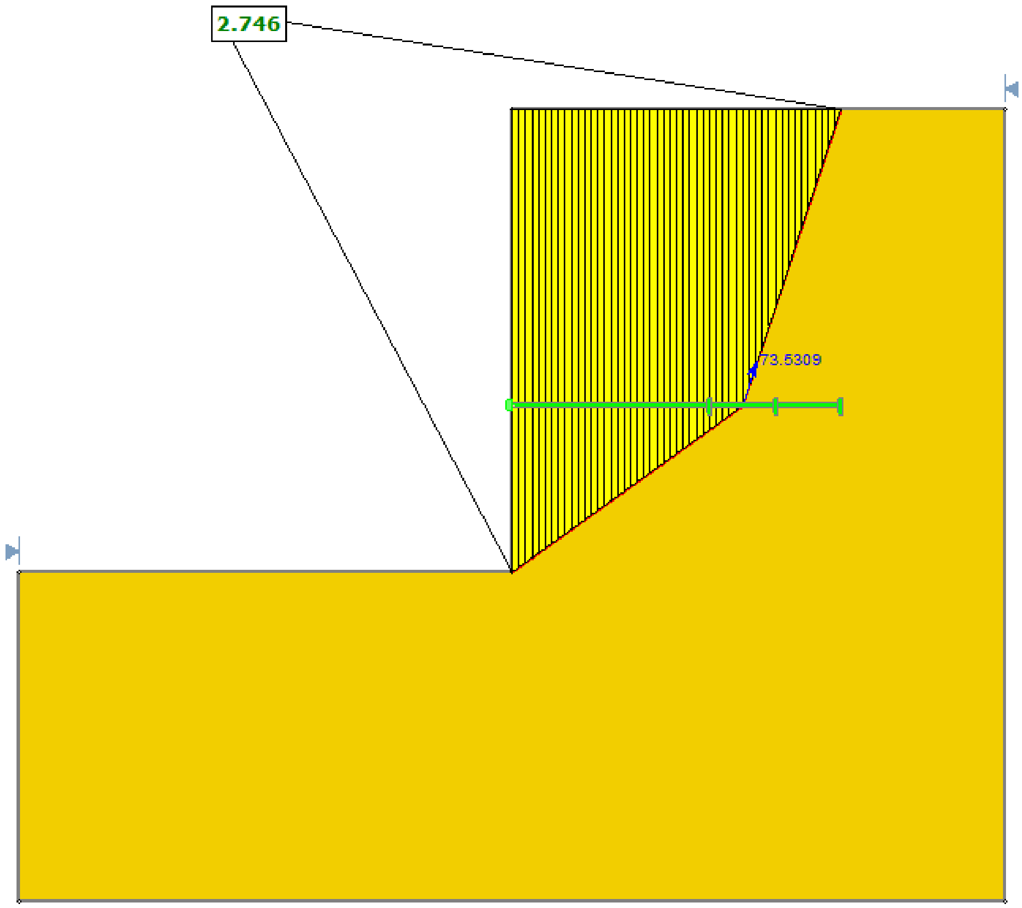
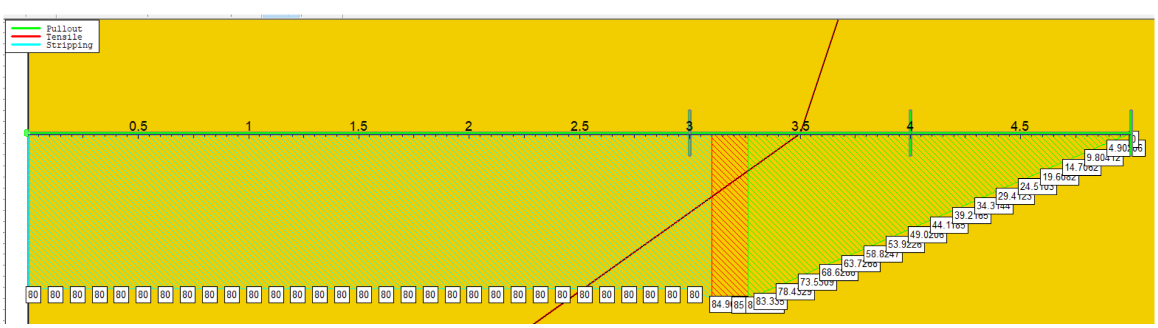


Figure 111.2: Force applied by helical anchor.

The support force diagram looks as follows. The failure modes and values are in perfect agreement with the hand calculations in Table 111.1.



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