Slide

2D limit equilibrium slope stability
for soil and rock slopes

Verification Manual

Part I

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Introduction

This document contains a series of verification slope stability problems that have been analyzed using SLIDE version 5.0. 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 verification files can be found in the Examples > Verification folder in your SLIDE installation folder. The file names are **verification#1.sli**, **verification#2.sli** 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.

1.1 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 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 required.

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

1.3 Geometry and Properties

Table 1.1: Material Properties

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

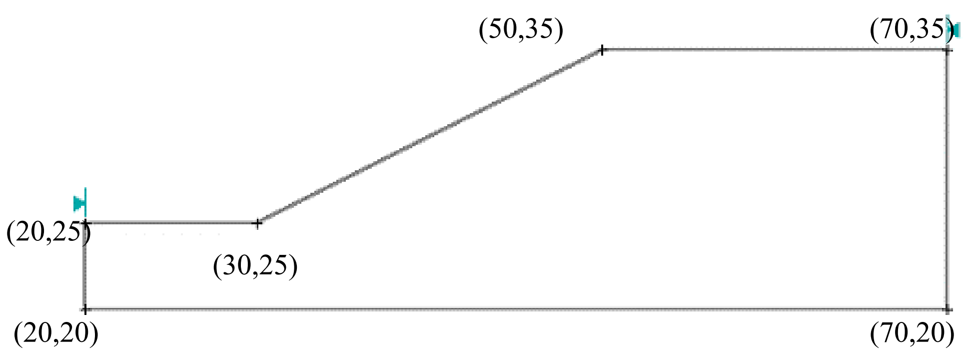


Figure 1

1.4 Results

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

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

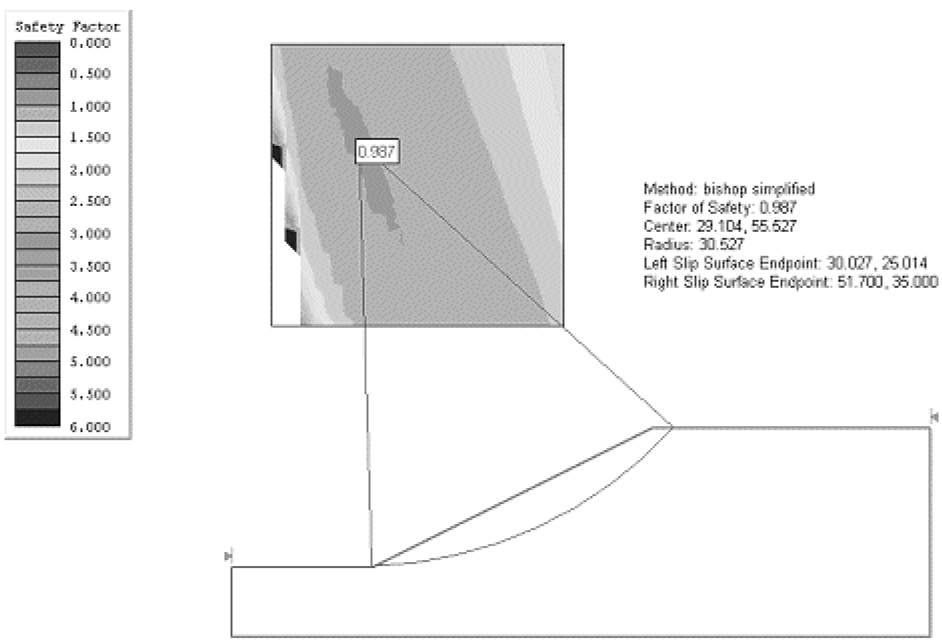


Figure 1.4.1 – Solution Using the Bishop Method

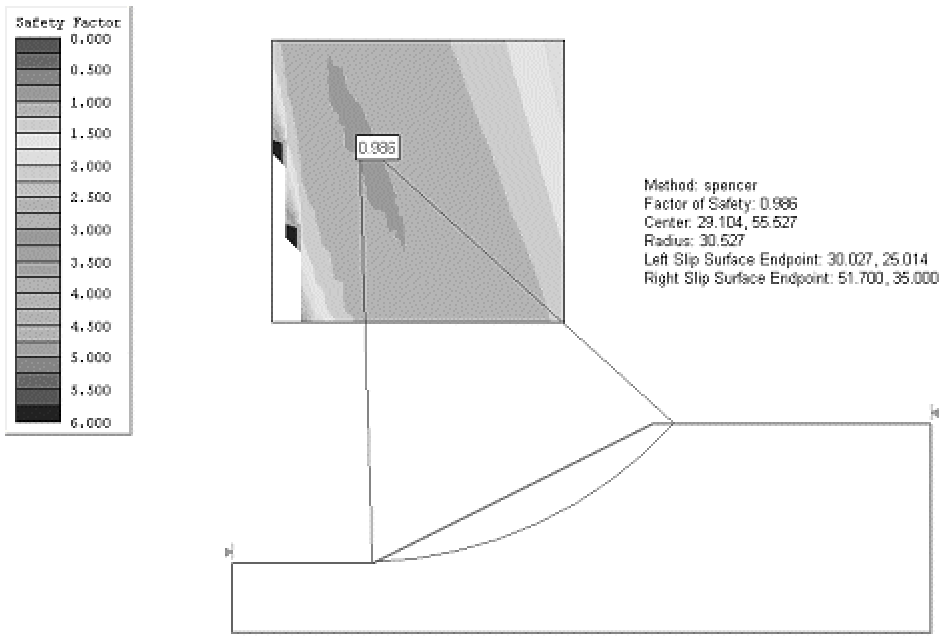


Figure 1.4.2 – Solution Using the Spencer Method

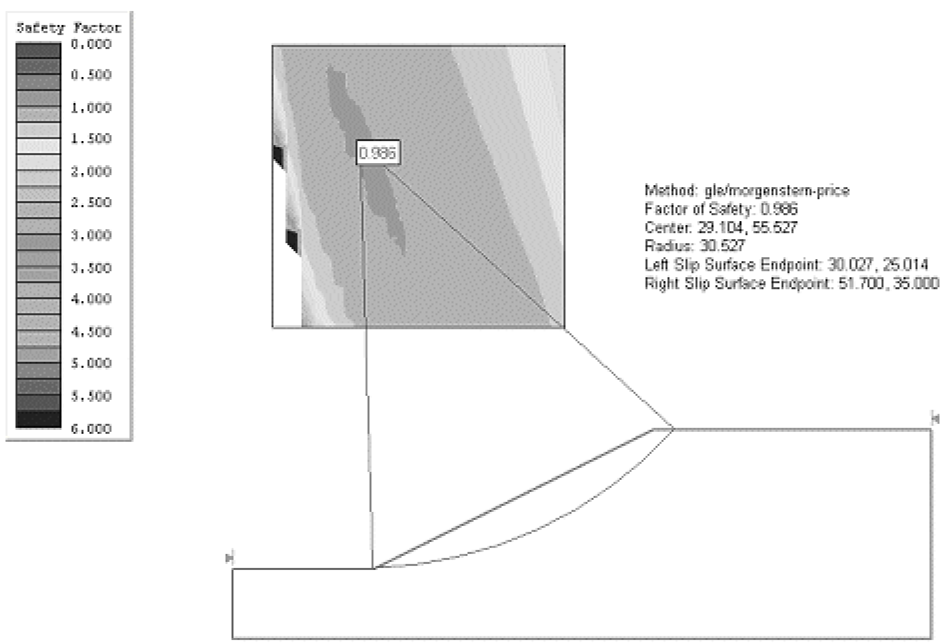


Figure 1.4.3 – Solution Using the GLE Method

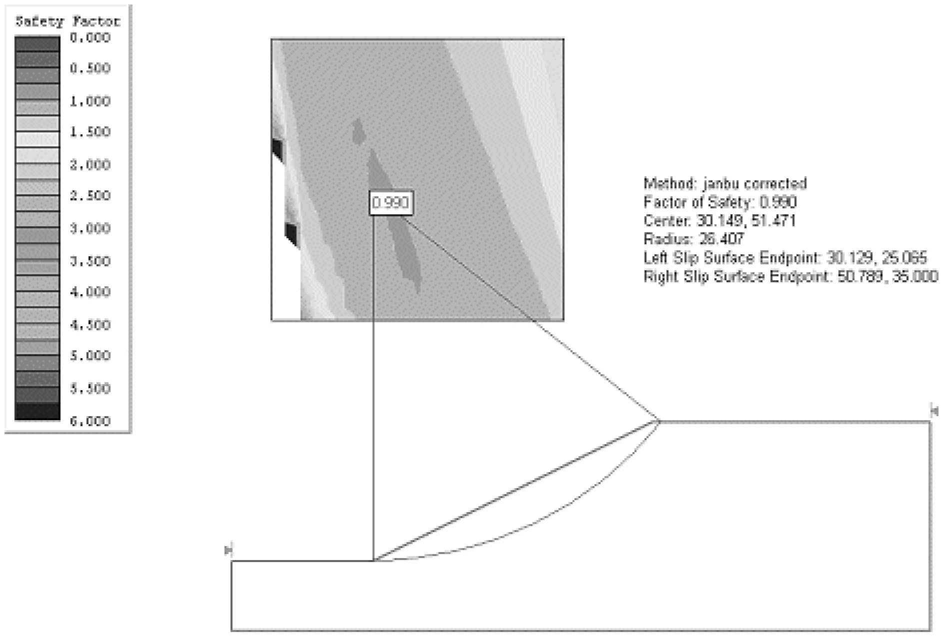


Figure 1.4.4 – Solution Using the Janbu Corrected Method

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. 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 gridpoint, generating a total of 4851 slip surfaces. Grid located at (31,49), (47,49), (31,34), (47,34). Tolerance is 0.0001.

2.3 Geometry and Properties

Table 2.1: Material Properties

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

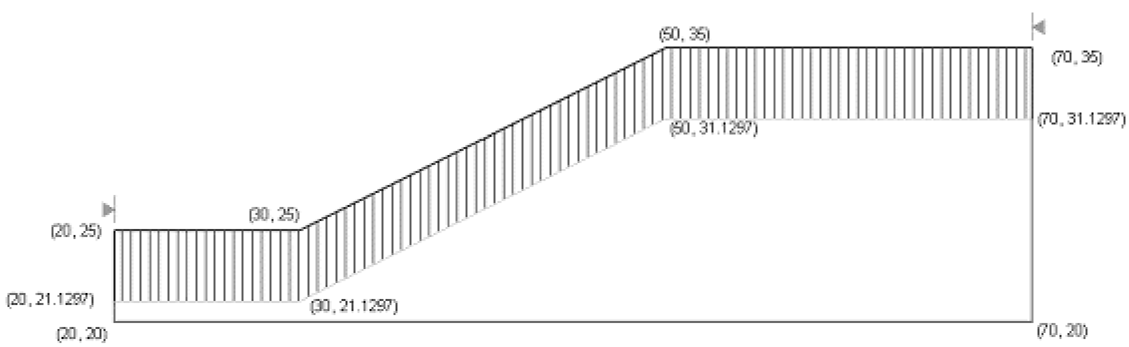


Figure 2

2.4 Results

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

Note : Referee Factor of Safety = 1.65 [Giam]

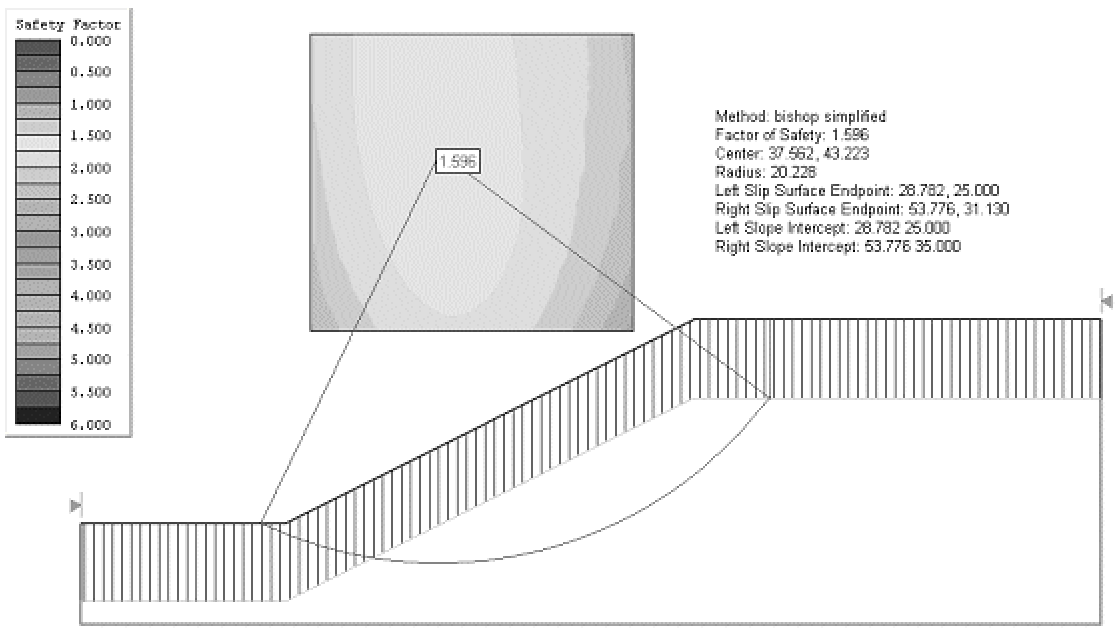


Figure 2.4.1 – Solution Using the Bishop Method

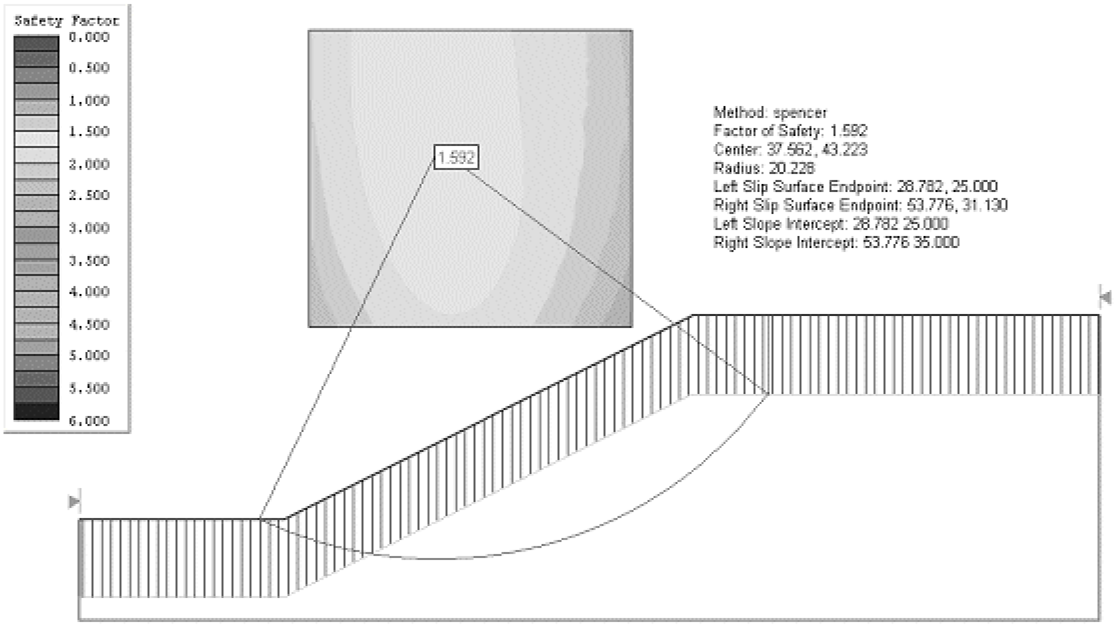


Figure 2.4.2 – Solution Using the Spencer Method

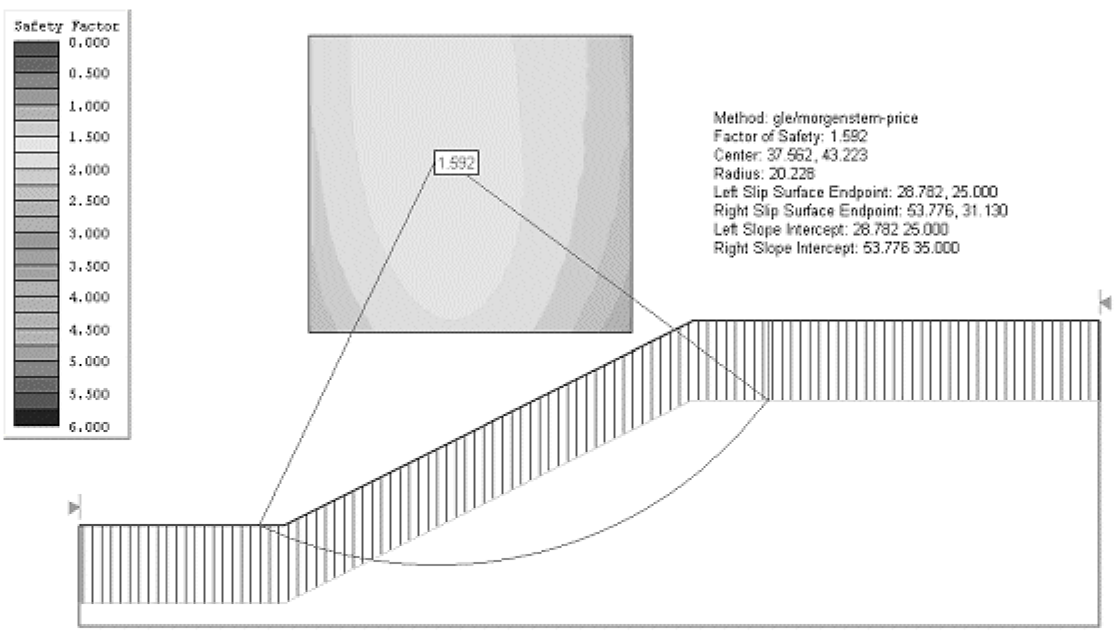


Figure 2.4.3 – Solution Using the GLE Method

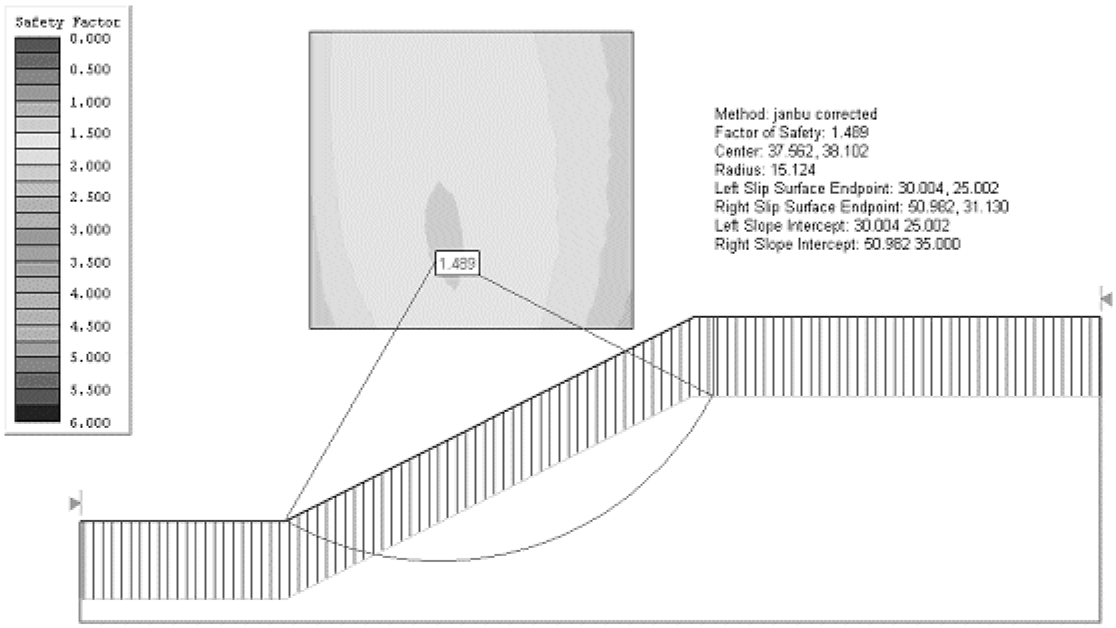


Figure 2.4.4 – Solution Using the Janbu Corrected Method

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 required.

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

3.3 Geometry and Properties

Table 3.1: Material 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

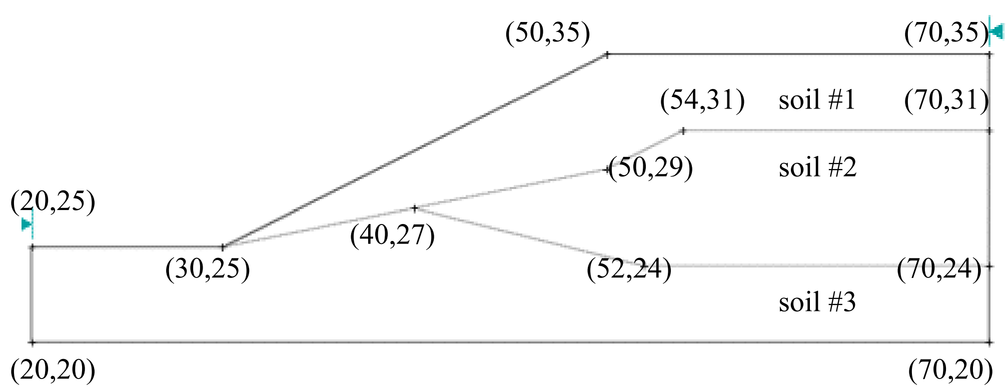


Figure 3

3.4 Results

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

Note : Referee Factor of Safety = 1.39 [Giam]
Mean Bishop FOS (16 samples) = 1.406
Mean FOS (31 samples) = 1.381

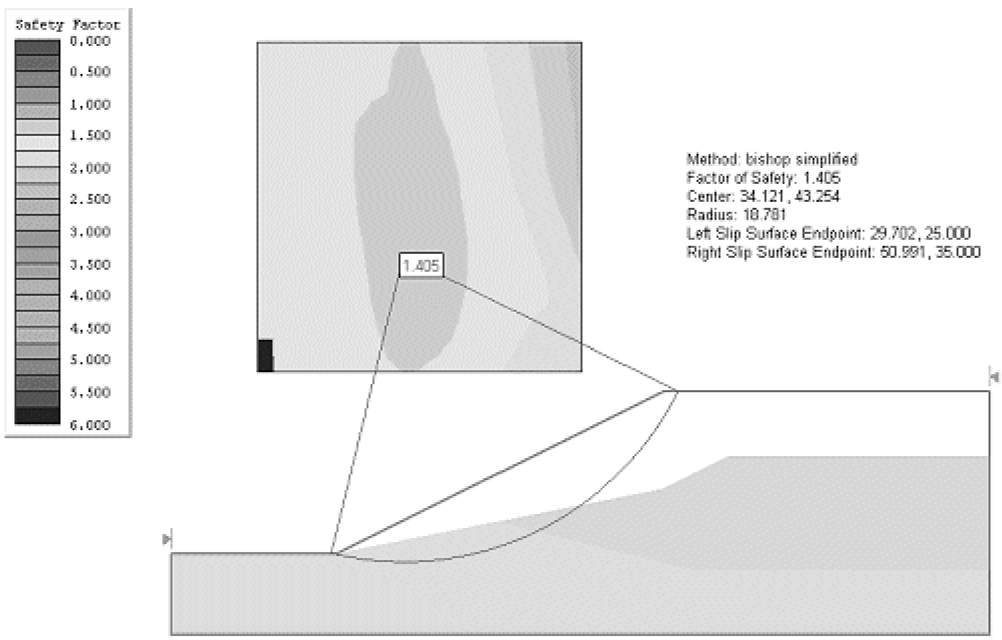


Figure 3.4.1 – Solution Using the Bishop Method

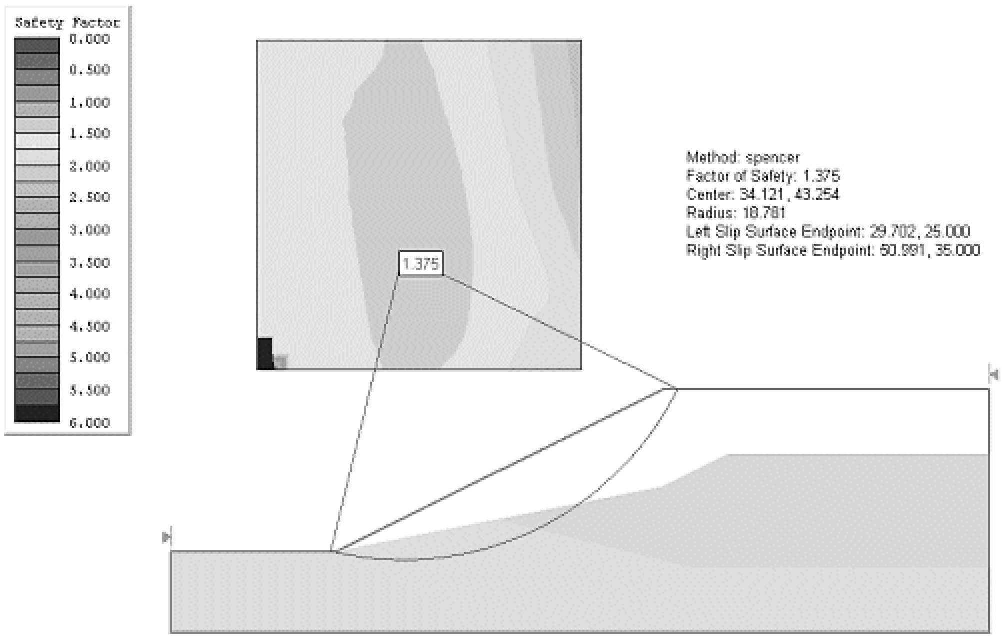


Figure 3.4.2 – Solution Using the Spencer Method

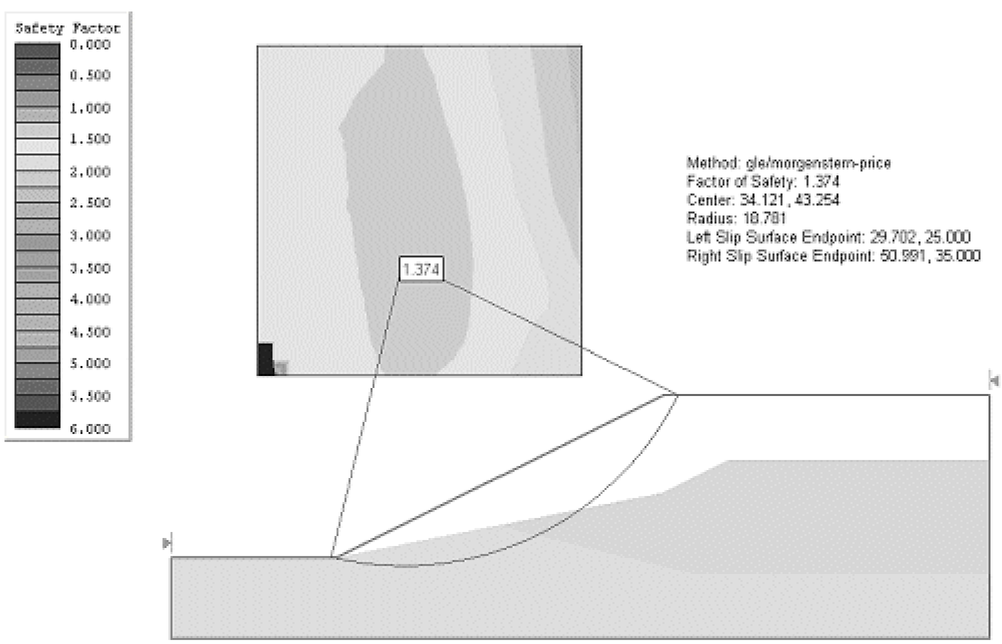


Figure 3.4.3 – Solution Using the GLE Method

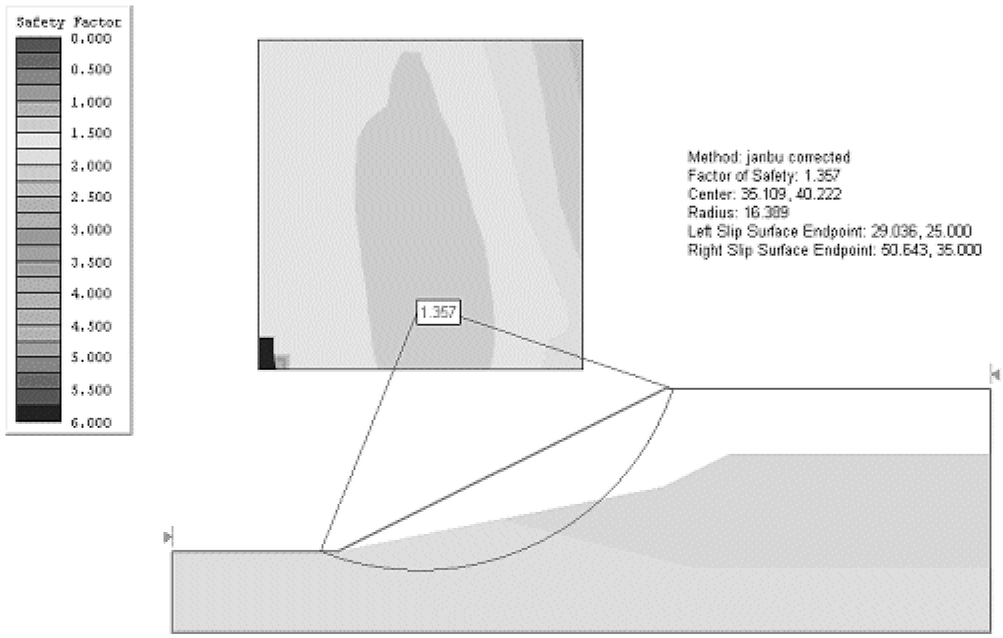


Figure 3.4.4 – Solution Using the Janbu Corrected Method

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. 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 required.

4.3 Geometry and Properties

Table 4.1: Material 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

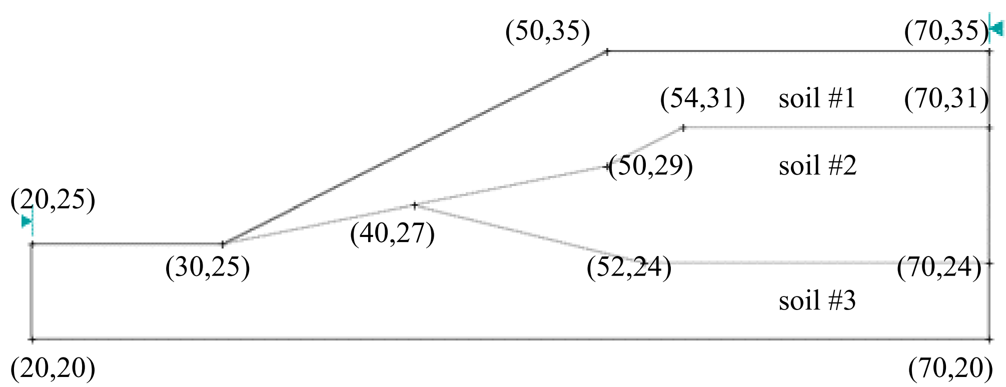


Figure 4

4.4 Results

Method	Factor of Safety
Bishop	1.015
Spencer	0.991
GLE	0.989
Janbu Corrected	0.965

Note : Referee Factor of Safety = 1.00 [Giam]
Mean FOS (15 samples) = 0.973

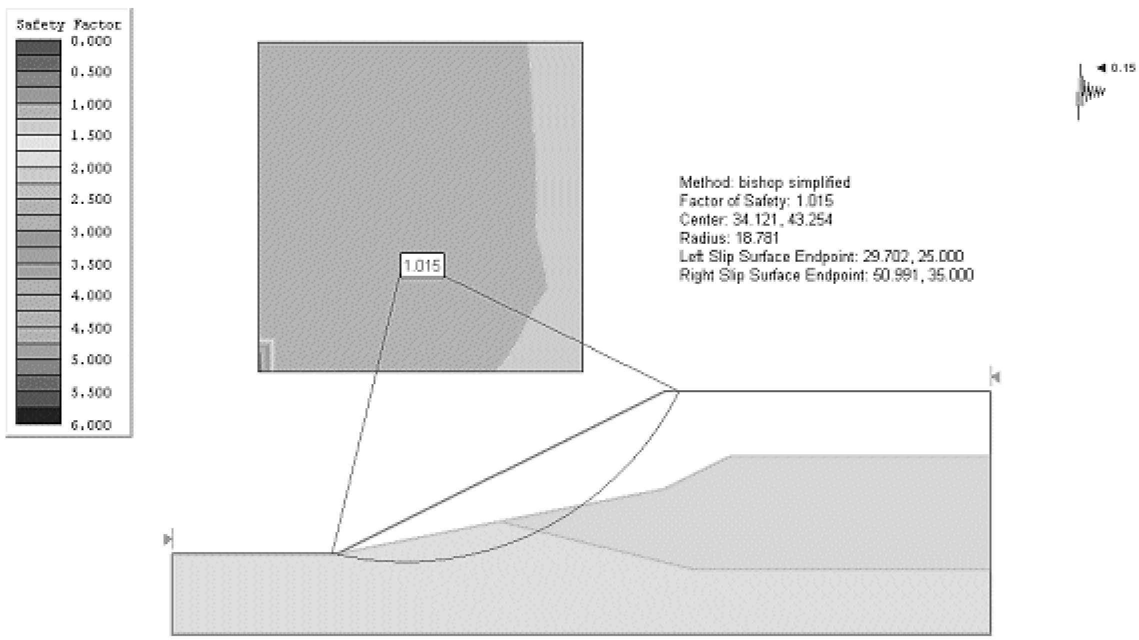


Figure 4.4.1 – Solution Using the Bishop Method

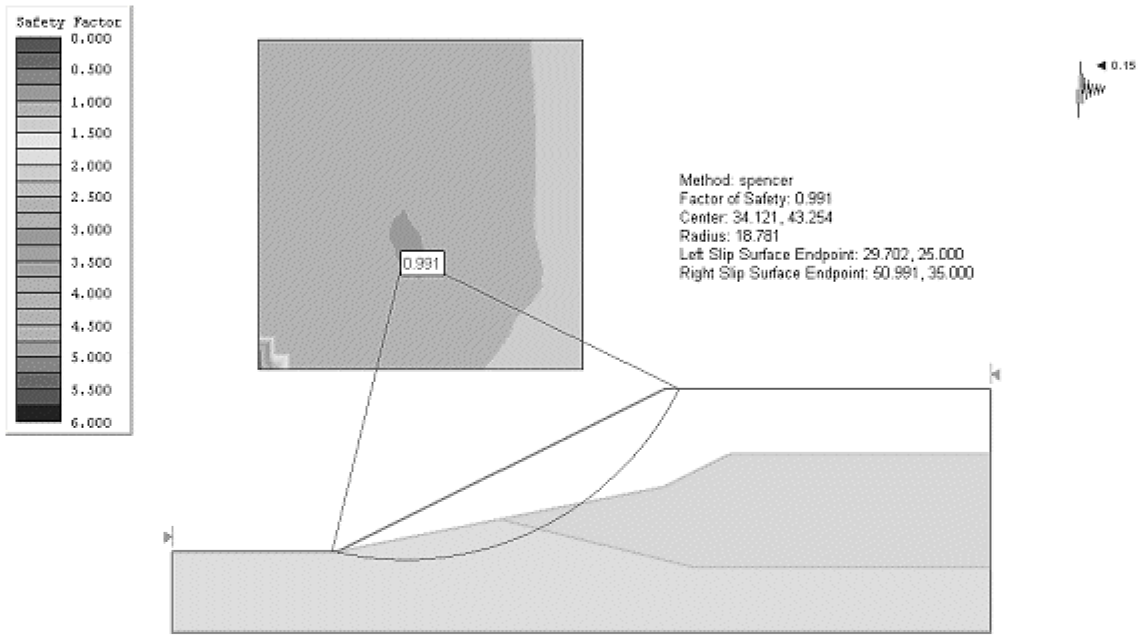


Figure 4.4.2 – Solution Using the Spencer Method

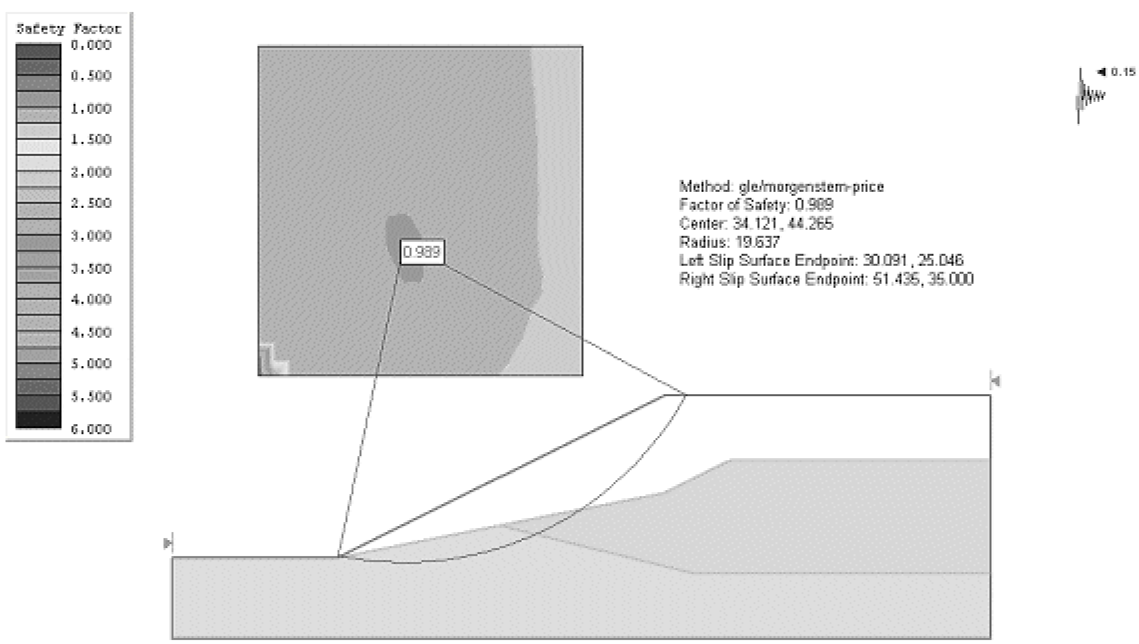


Figure 4.4.3 – Solution Using the GLE Method

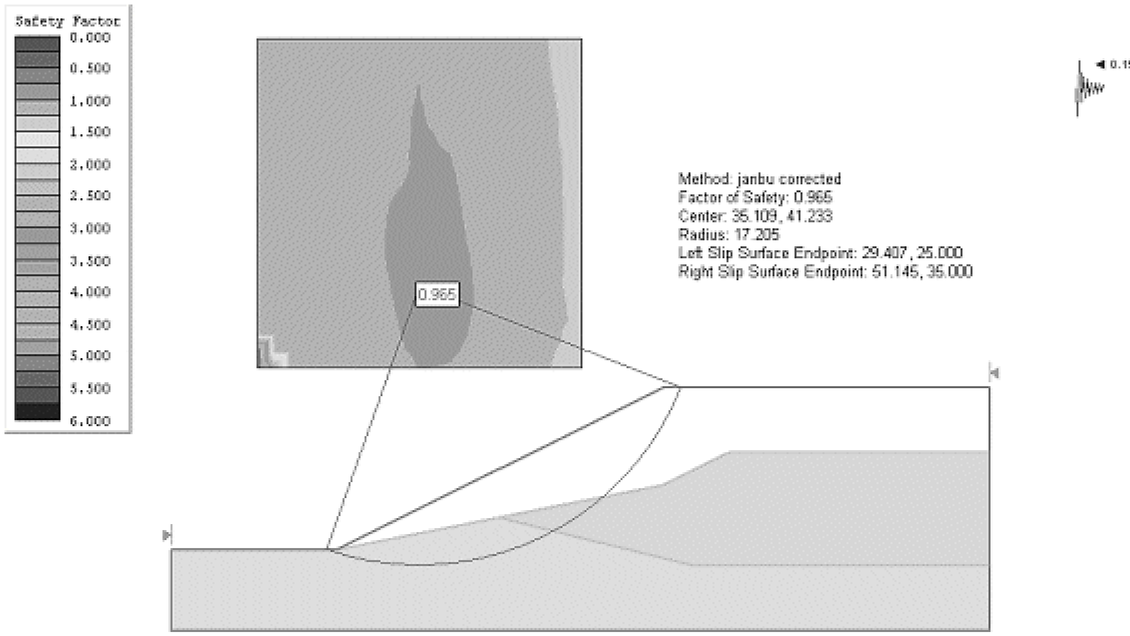


Figure 4.4.4 – Solution Using the Janbu Corrected Method

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. The material properties for 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 required.

5.3 Geometry and Properties

Table 5.1: Material 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	-	-	-

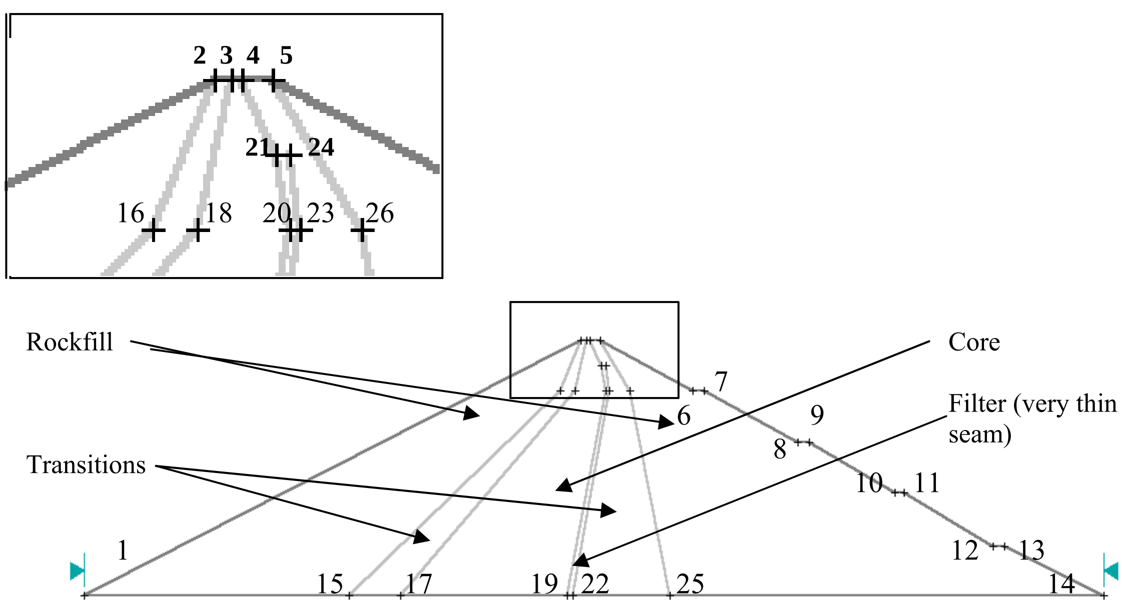


Figure 5

5.4 Results

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

Note : Referee Factor of Safety = 1.95 [Giam]
Mean FOS (24 samples) = 2.0

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

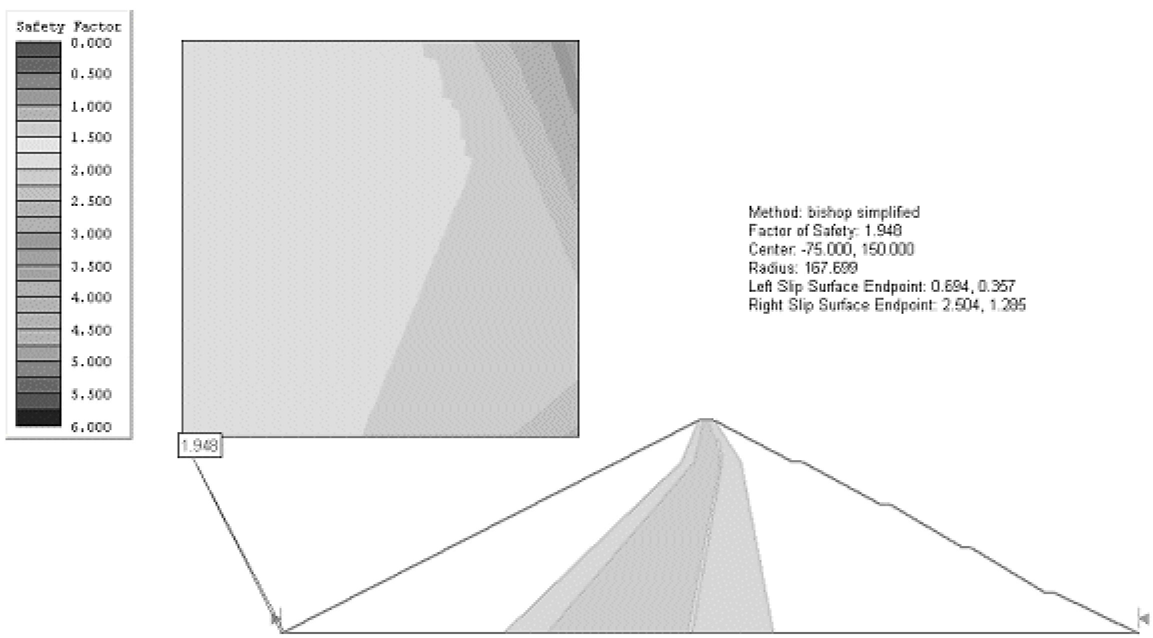


Figure 5.4.1 – Solution Using the Bishop Method

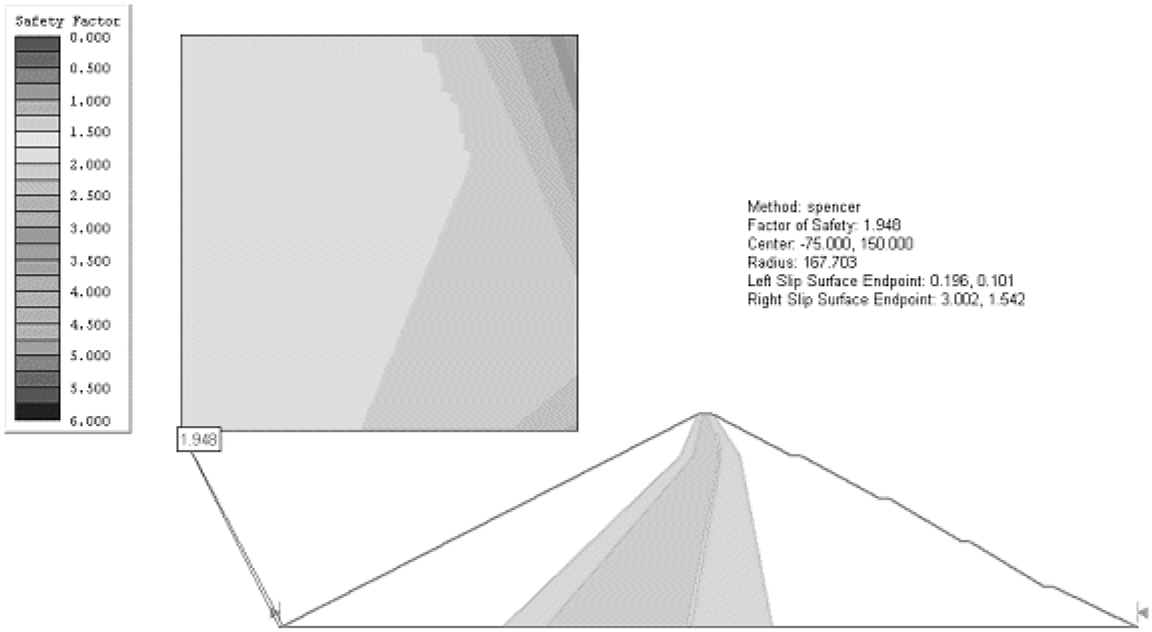


Figure 5.4.2 – Solution Using the Spencer Method

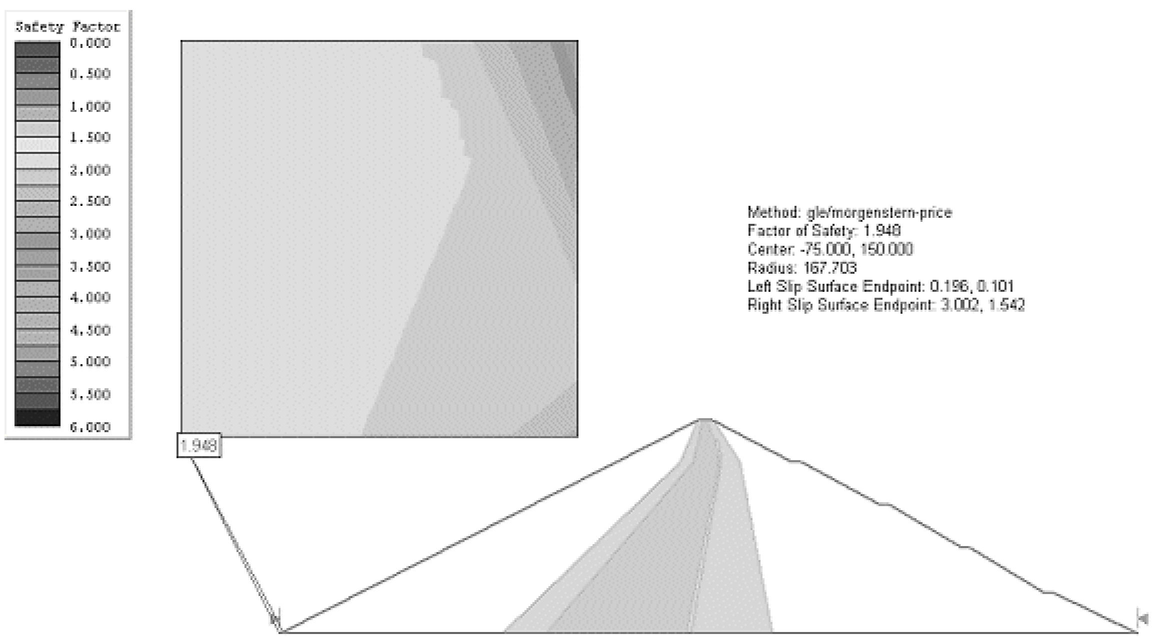


Figure 5.4.3 – Solution Using the GLE Method

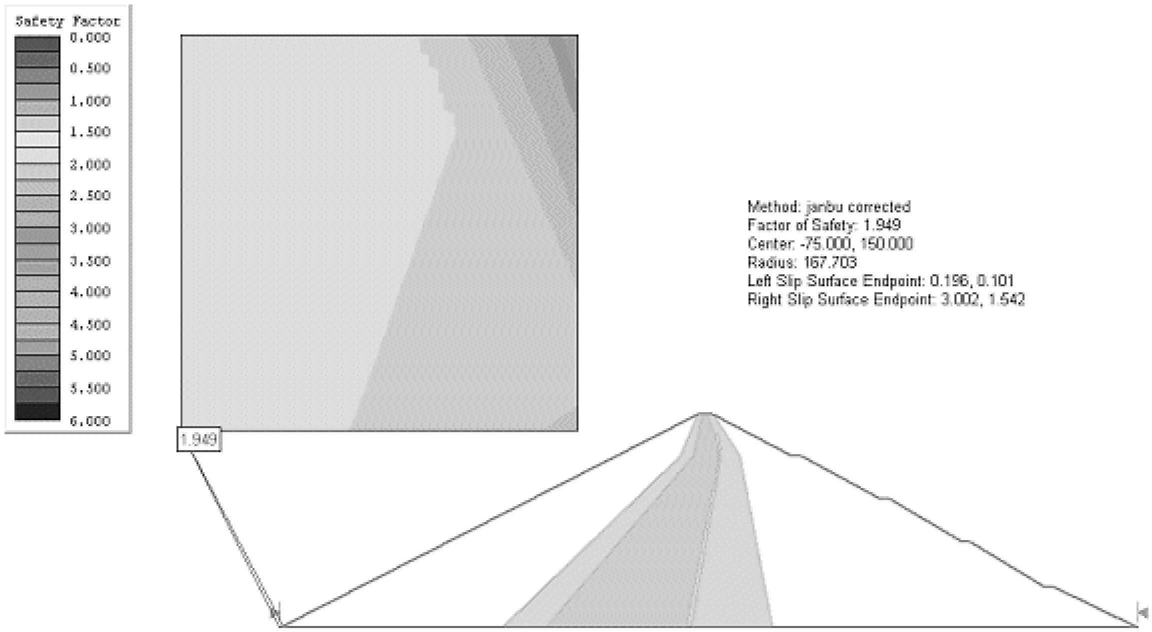


Figure 5.4.4 – Solution Using the Janbu Corrected Method

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

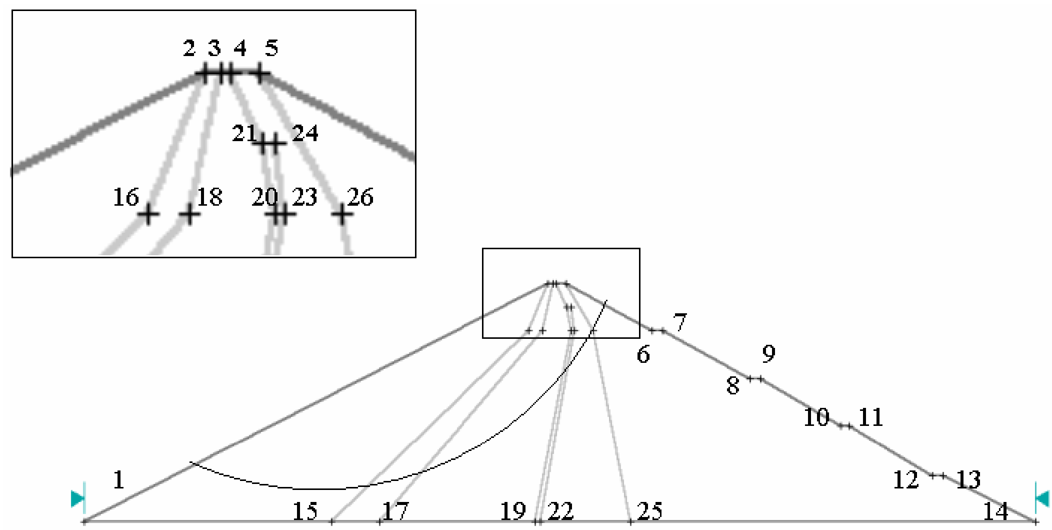


Figure 6

Table 6.3: Data for slip circle

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

6.4 Results

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

Note : Referee Factor of Safety = 2.29 [Giam]
Mean Bishop FOS (11 samples) = 2.204
Mean FOS (24 samples) = 2.239

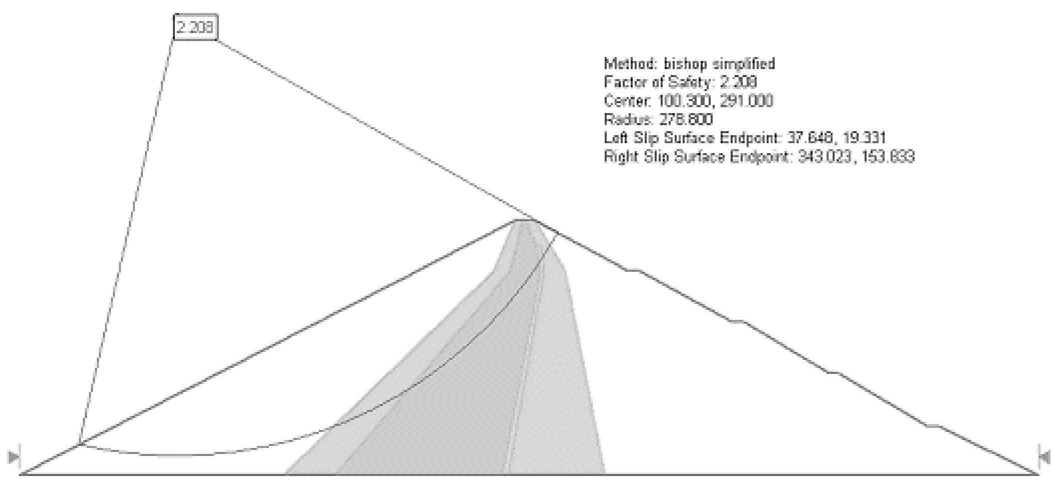


Figure 6.4.1 – Solution Using the Bishop Method

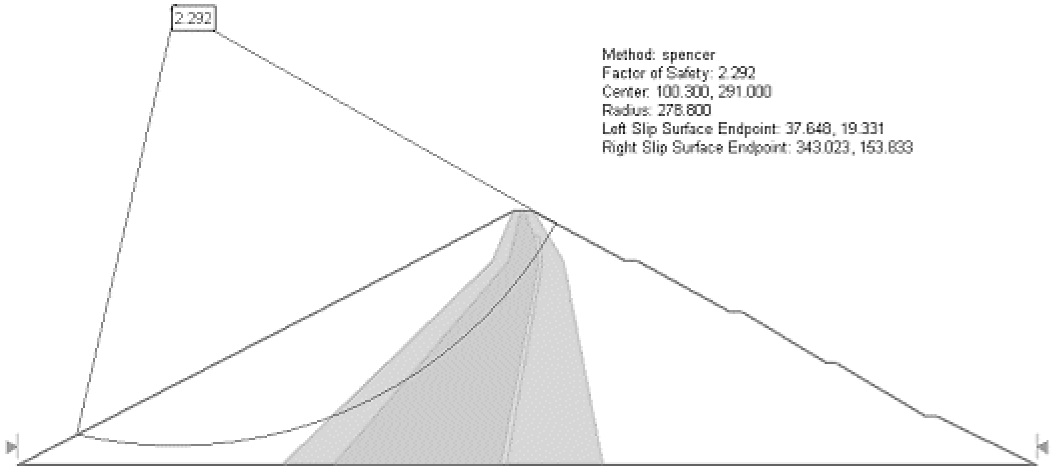


Figure 6.4.2 – Solution Using the Spencer Method

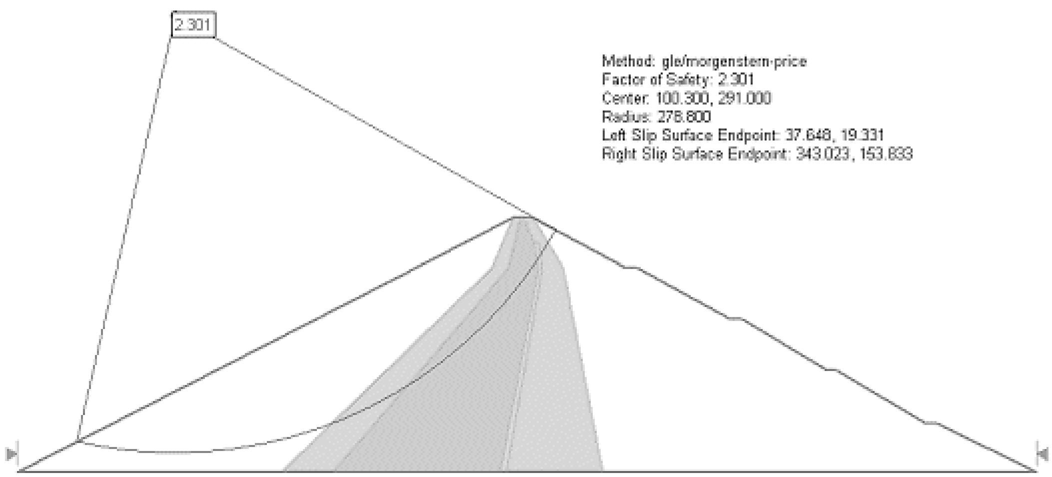


Figure 6.4.3 – Solution Using the GLE Method

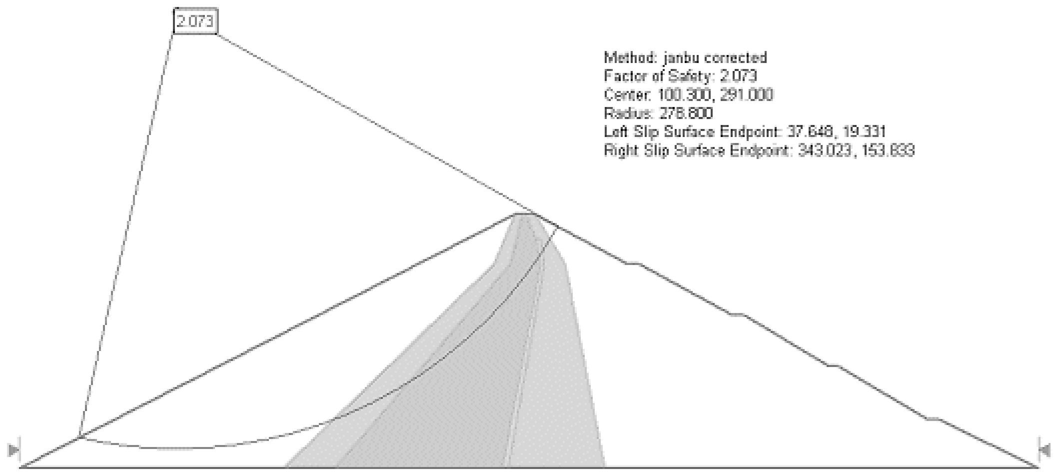


Figure 6.4.4 – Solution Using the Janbu Corrected Method

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 is shown in Figure 7. 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 required.
Note: Default values of 35,65,135, and 155 degrees are used for block search line projection angles. Line should be in the middle of the seam.

7.3 Geometry and Properties

Table 7.1: Material 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

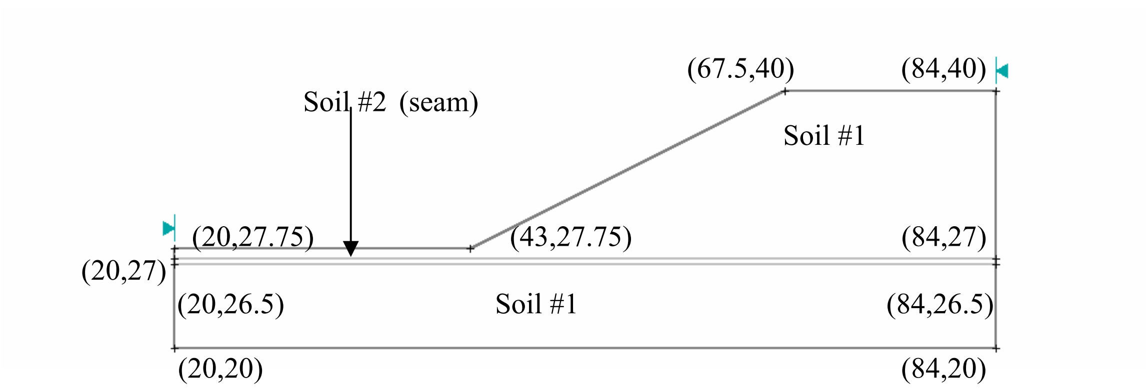


Figure 7

7.4 Results

Method	Factor of Safety
Spencer	1.258
GLE	1.246
Janbu Corrected	1.275

Note : Referee Factor of Safety = 1.24 – 1.27 [Giam]
Mean Non-circular FOS (19 samples) = 1.293

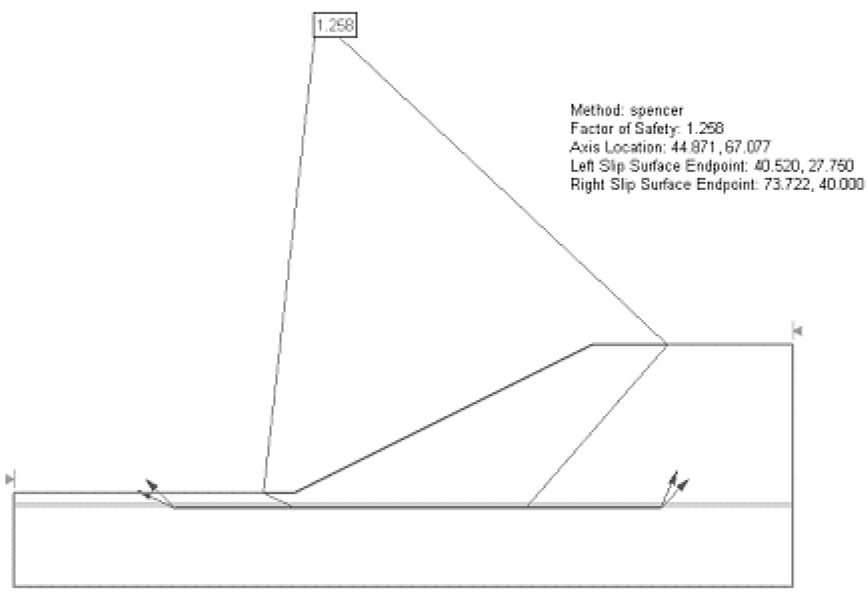


Figure 7.4.1 – Solution Using the Spencer Method

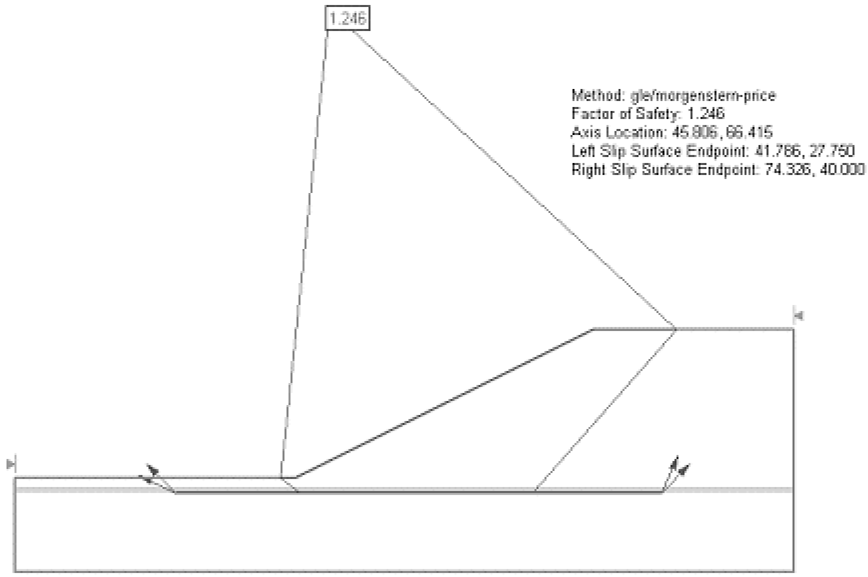


Figure 7.4.2 – Solution Using the GLE Method

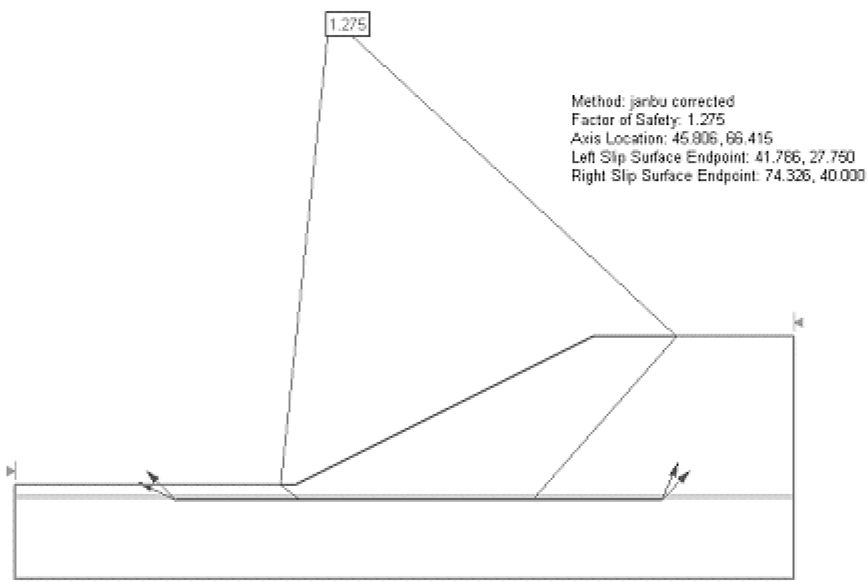


Figure 7.4.3 – Solution Using the Janbu Corrected Method

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 a single non-circular slip surface of known coordinates is analyzed.

8.3 Geometry and Properties

Table 8.1: Material 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

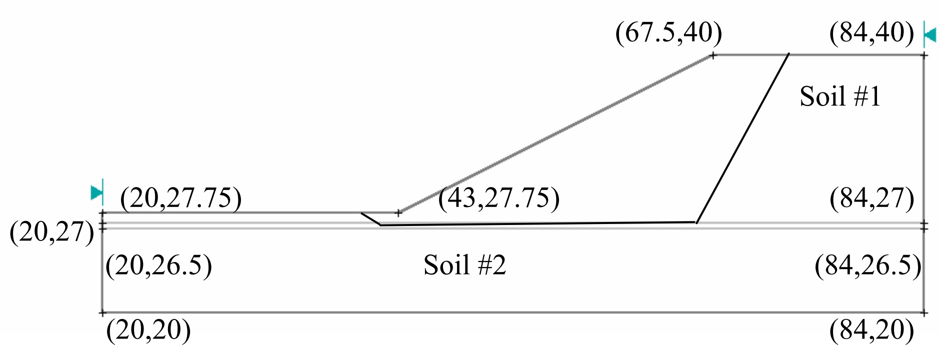


Figure 8

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

Axis of Rotation: (53.3, 45)

8.4 Results

Method	Factor of Safety
Spencer	1.277
GLE	1.262
Janbu Corrected	1.294

Note : Referee Factor of Safety = 1.34 [Giam]
Mean FOS (30 samples) = 1.29

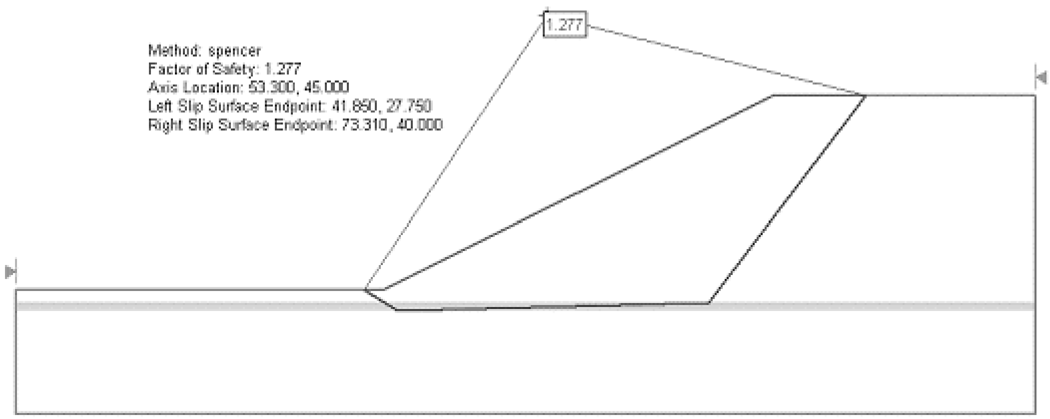


Figure 8.4.1 – Solution Using the Spencer Method

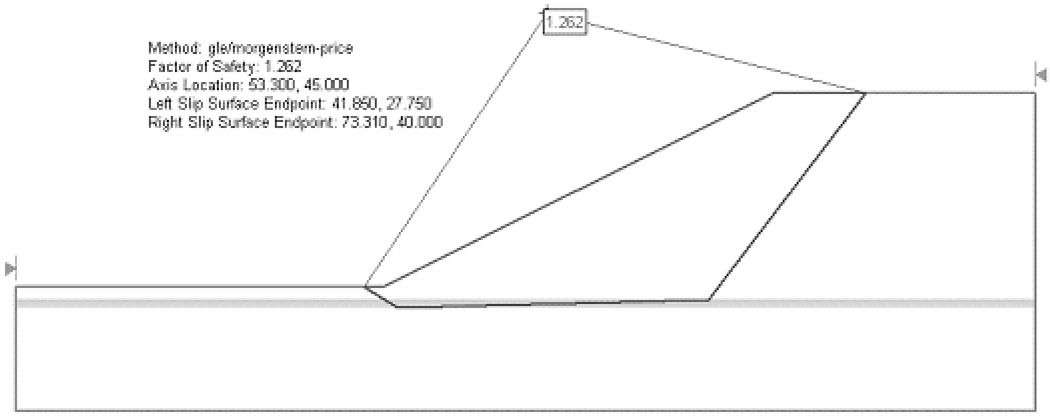


Figure 8.4.2 – Solution Using the GLE Method

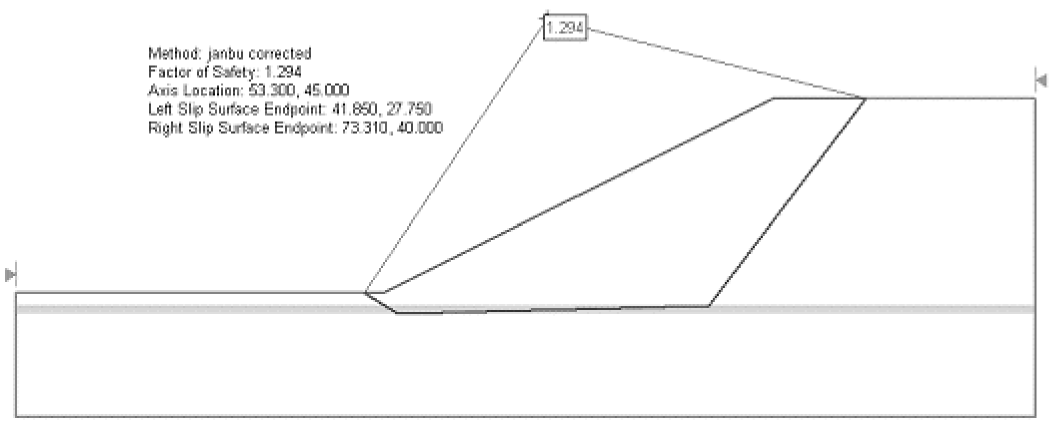


Figure 8.4.3 – Solution Using the Janbu Corrected Method

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. The soil parameters, 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 are required.

A block search for the critical non-circular failure surface was carried out by defining two line search objects within the weak layer, and variable projection angles from the weak layer to the slope surface. A total of 1000 random surfaces were generated by the search. 5000 iterations were done. The results are compared with optimization results.

9.3 Geometry and Properties

Table 9.1: Material 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

Pt.# : Refer to Figure 9

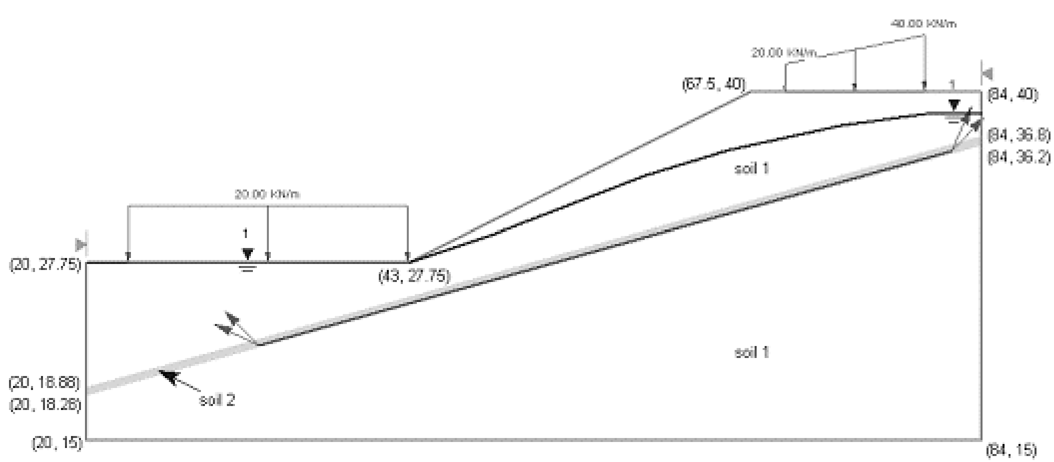


Figure 9

9.4 Results – no optimization

Method	Factor of Safety
Spencer	0.760
GLE	0.721
Janbu Corrected	0.734

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

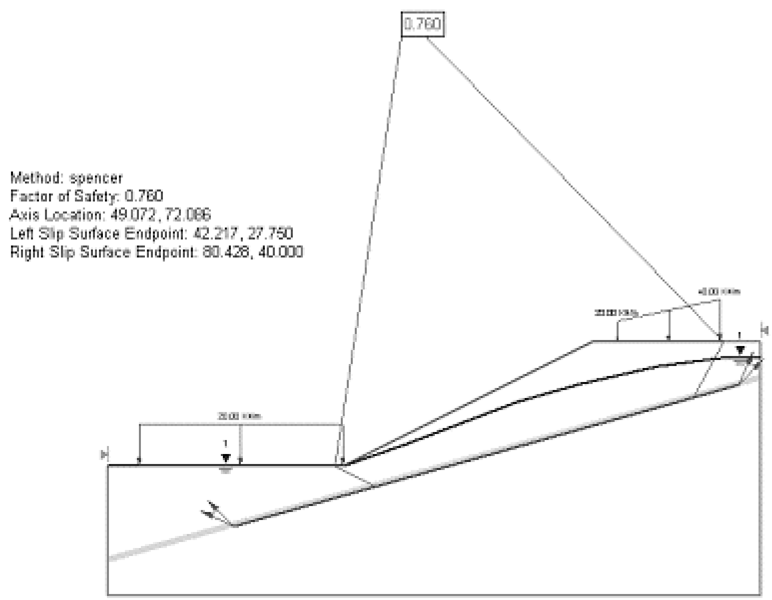


Figure 9.4.1 – Solution Using the Spencer Method

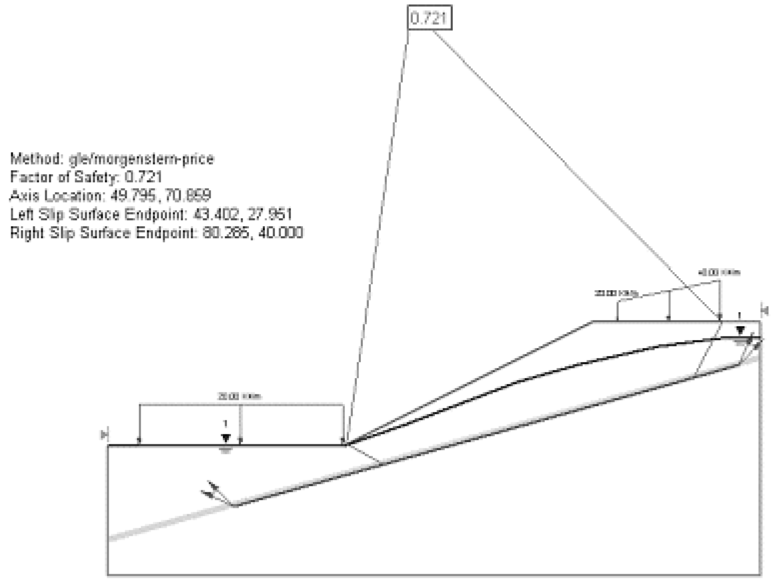


Figure 9.4.2 – Solution Using the GLE Method

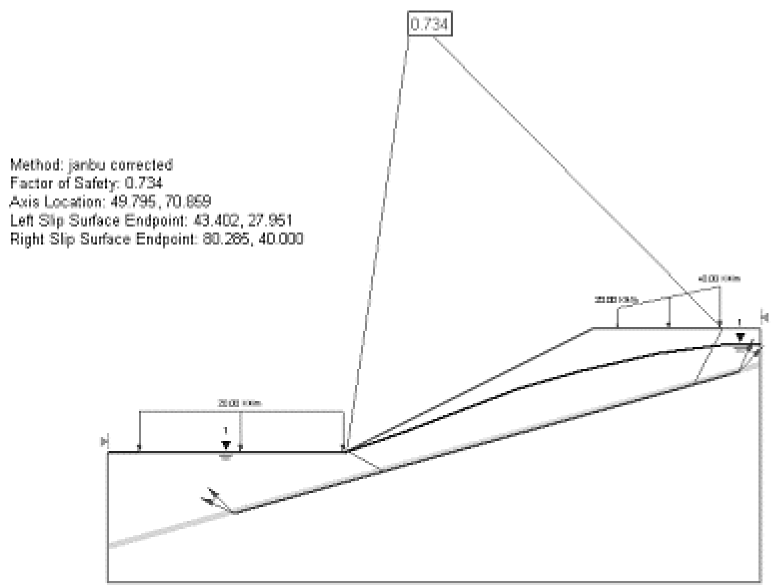


Figure 9.4.3 – Solution Using the Janbu Corrected Method

9.5 Results – Block search with optimization

Method	Factor of Safety
Spencer	0.707
GLE	0.683
Janbu Corrected	0.699

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

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(a) . 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 pressures may be derived from the given boundary conditions or from the approximate flow net provided in Figure 10(b). If information is required beyond the geometrical limits of Figure 10(b), 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 are required.

10.3 Geometry and Properties

Table 10.1: Material Properties

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

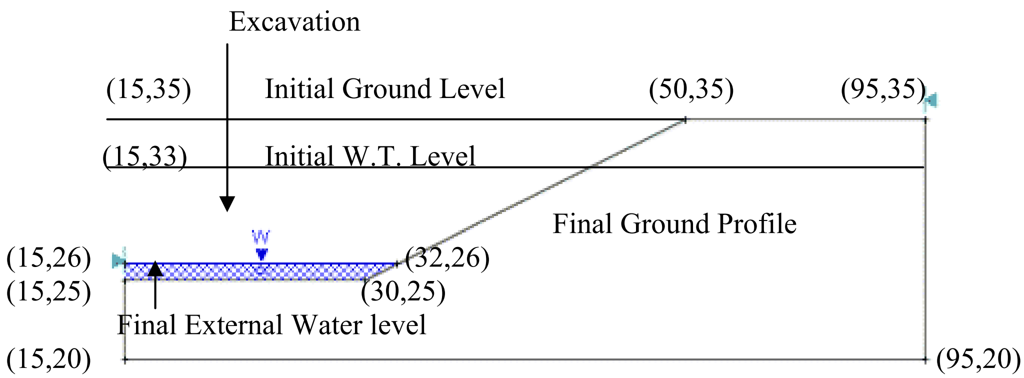


Figure 10(a)

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

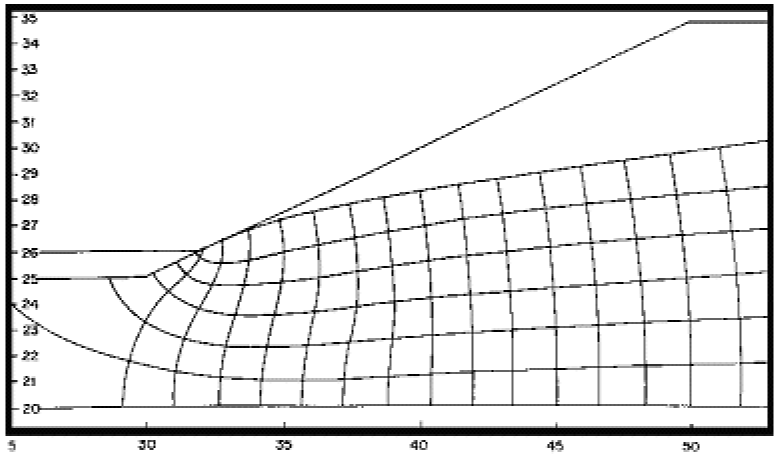


Figure 10(b)

10.4 Results

Method	Factor of Safety
Bishop	1.498
Spencer	1.501
GLE	1.500
Janbu Corrected	1.457

Note: Referee Factor of Safety = 1.53 [Giam]
Mean FOS (23 samples) = 1.464

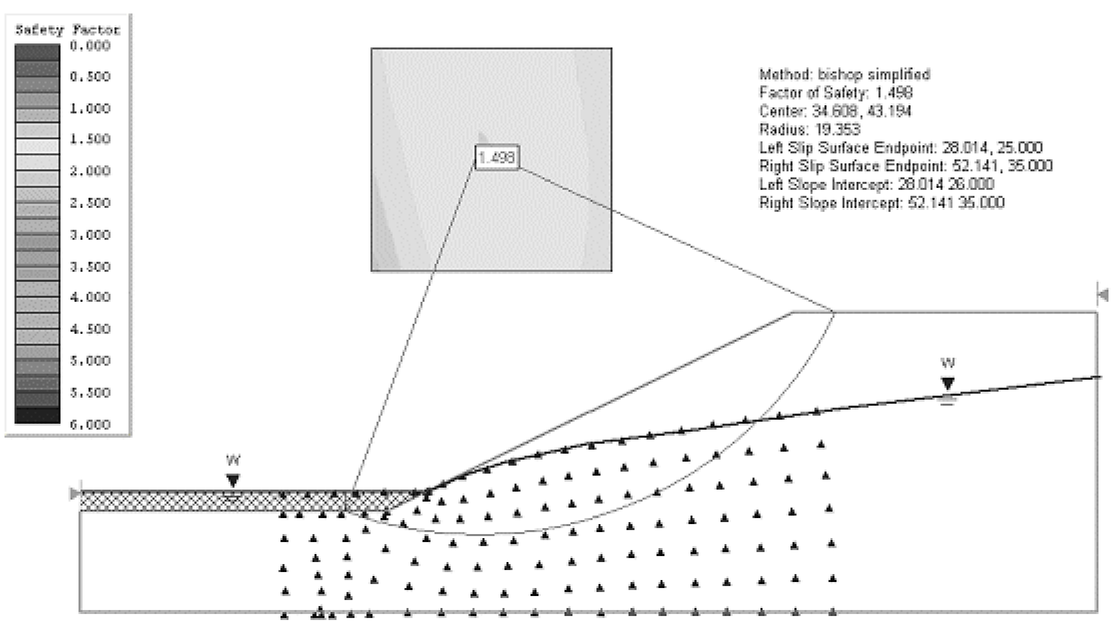


Figure 10.4.1 – Solution Using the Bishop Method

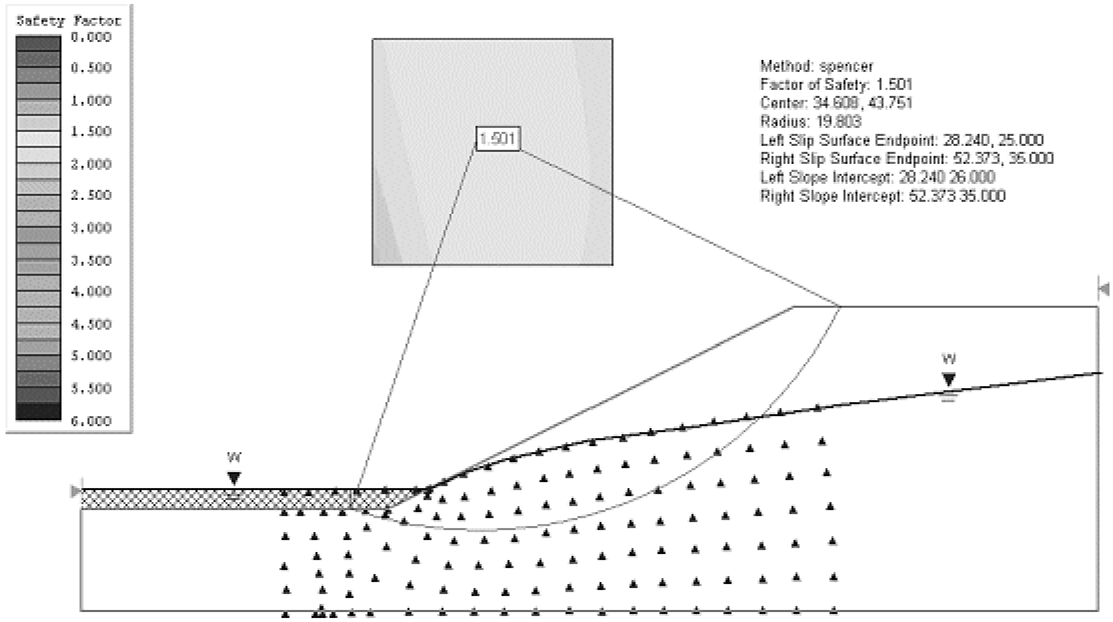


Figure 10.4.2 – Solution Using the Spencer Method

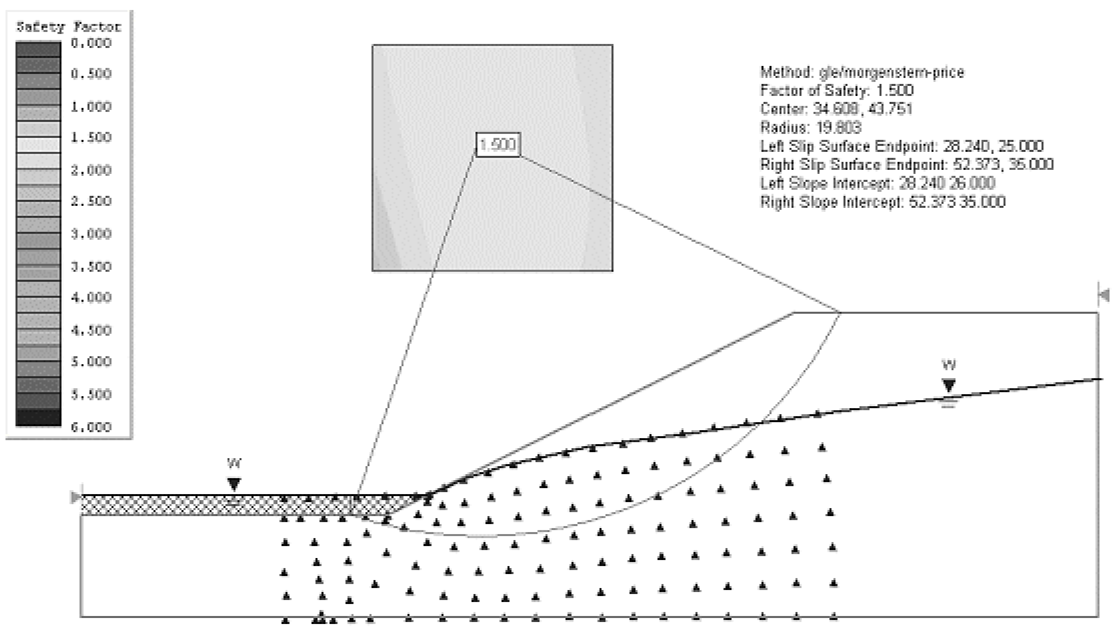


Figure 10.4.3 – Solution Using the GLE Method

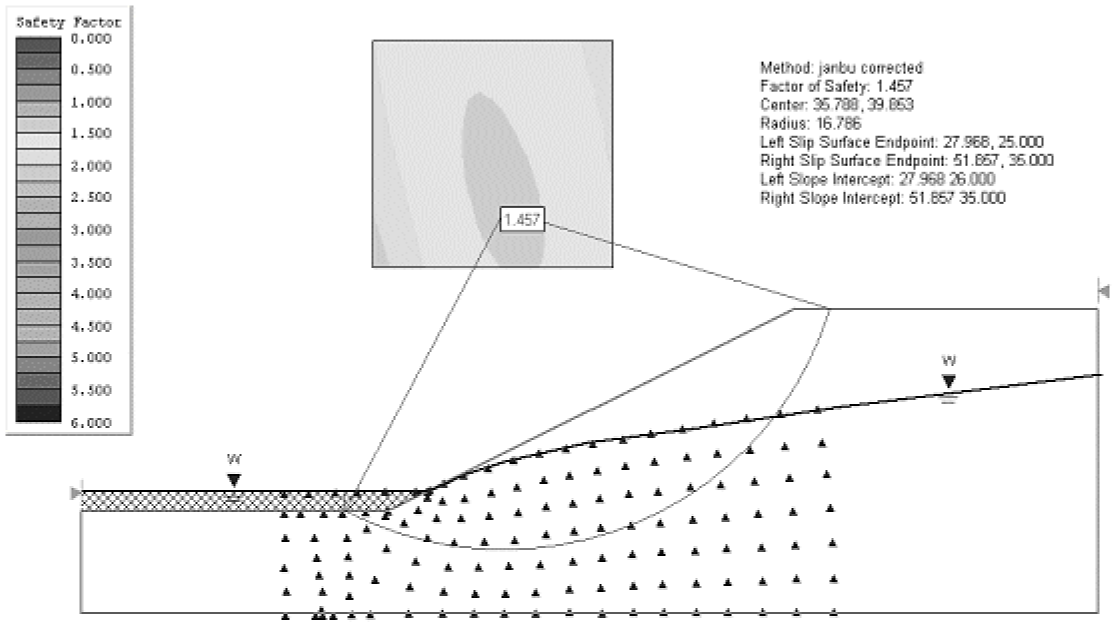


Figure 10.4.4 – Solution Using the Janbu Corrected Method

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. 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. using the Thin-Plate Spline interpolation method.

11.3 Geometry and Properties

Table 11.1: Material Properties

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

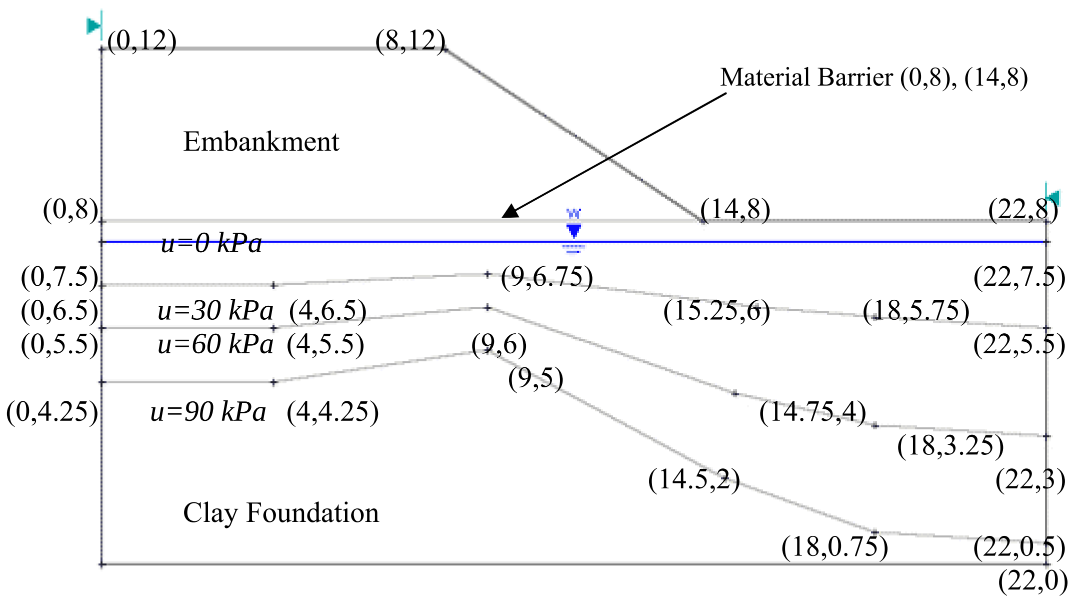


Figure 11

11.4 Results

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

Note: Referee Factor of Safety = 1.04 [Pilot]

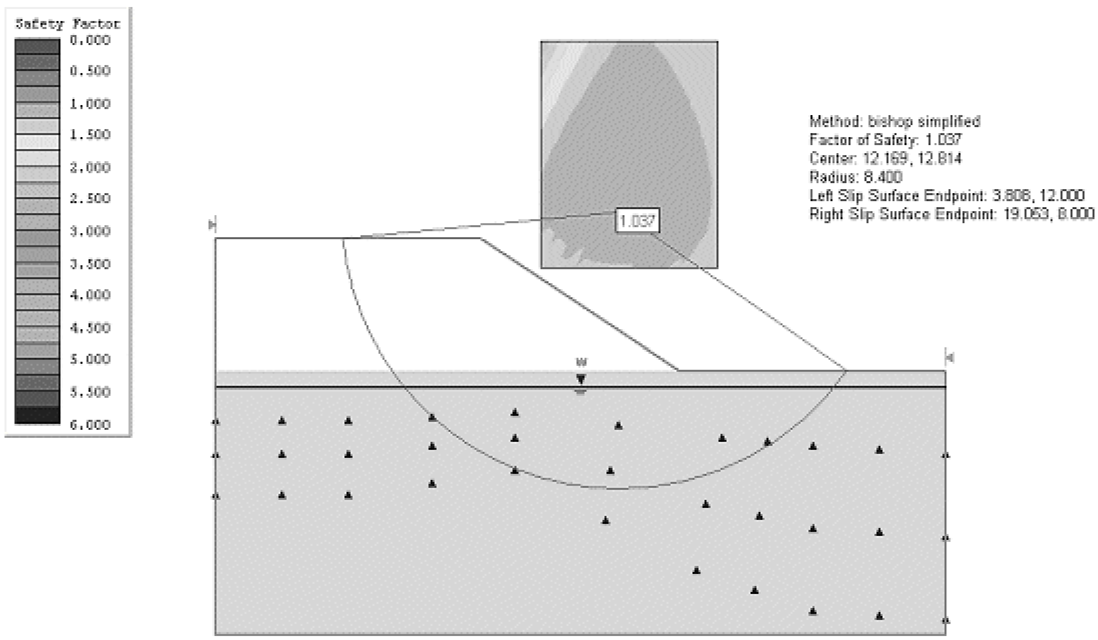


Figure 11.4.1 – Solution Using the Bishop Method

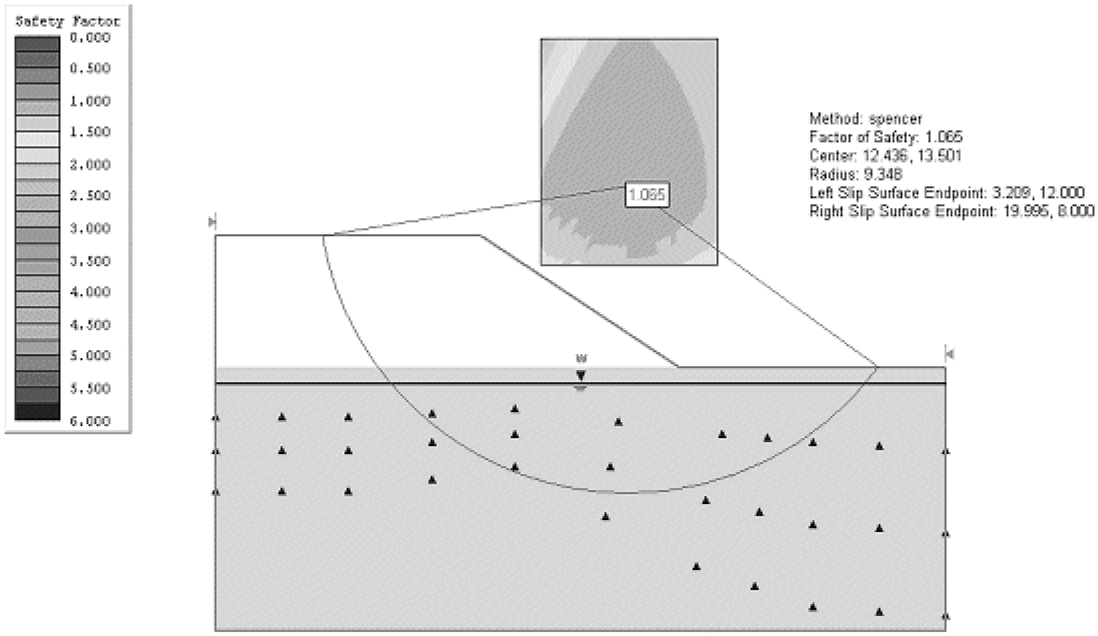


Figure 11.4.2 – Solution Using the Spencer Method

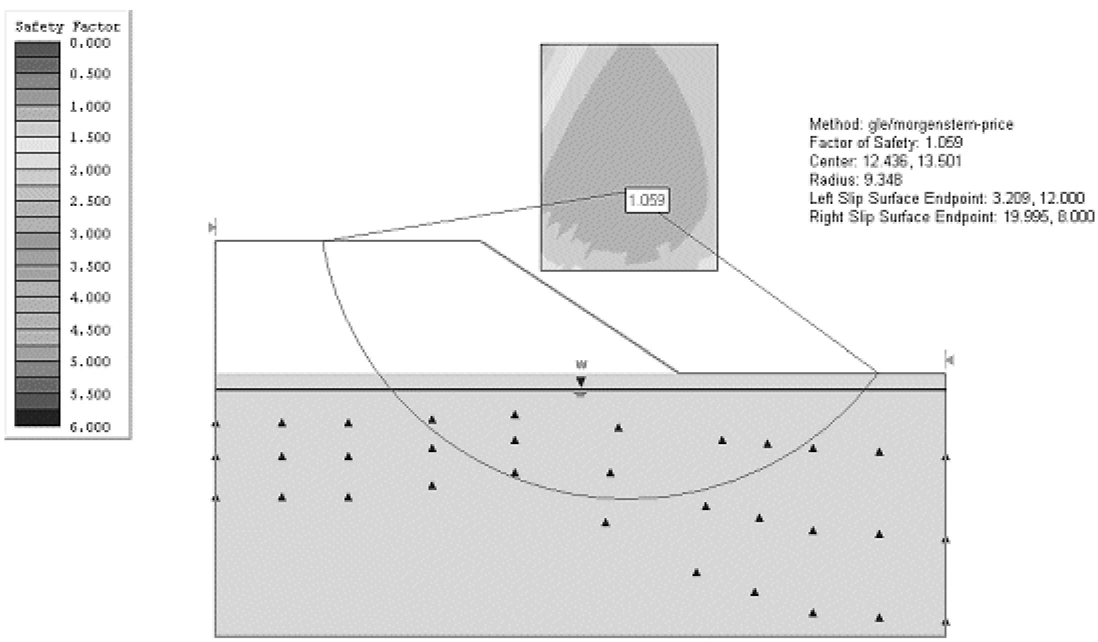


Figure 11.4.3 – Solution Using the GLE Method

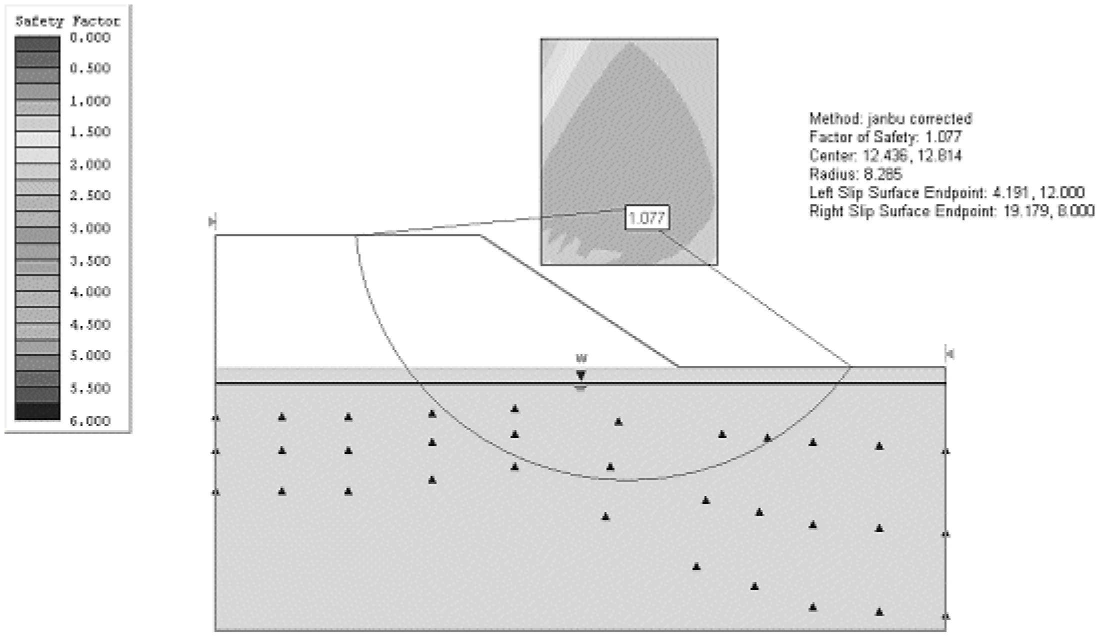


Figure 11.4.4 – Solution Using the Janbu Corrected Method

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. 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 are required. Pore water pressure was derived from the data in Table 12.2 using the Thin-Plate Spline interpolation method. Note: 30 slices used.

12.3 Geometry and Properties

Table 12.1: Material 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	-	-	-

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

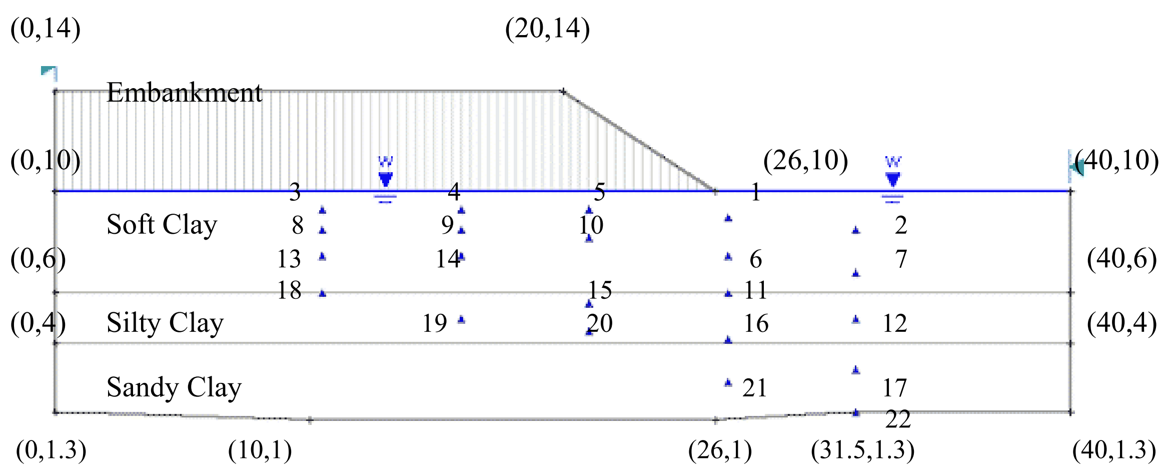


Figure 12.1 - Geometry

12.4 Results

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]

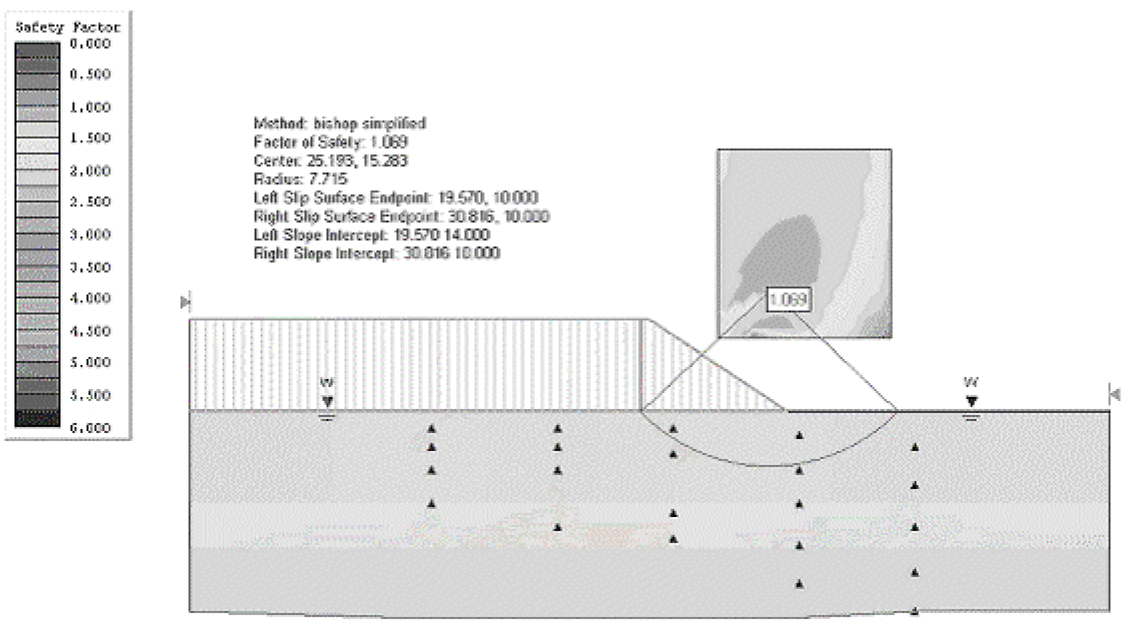


Figure 12.4.1 – Solution Using the Bishop Method

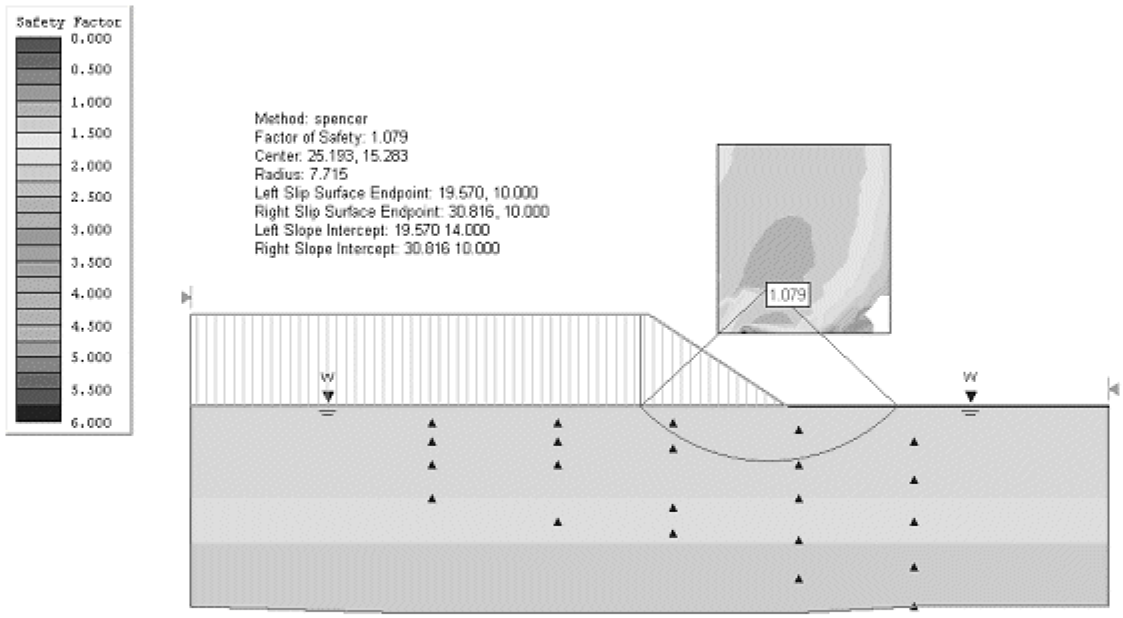


Figure 12.4.2 – Solution Using the Spencer Method

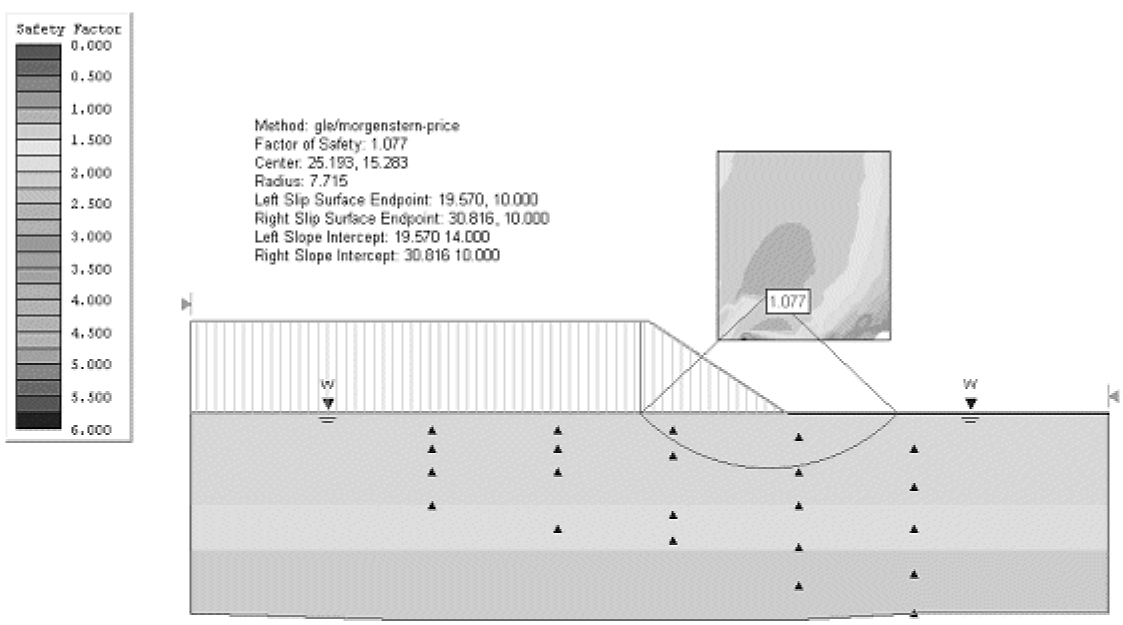


Figure 12.4.3 – Solution Using the GLE Method

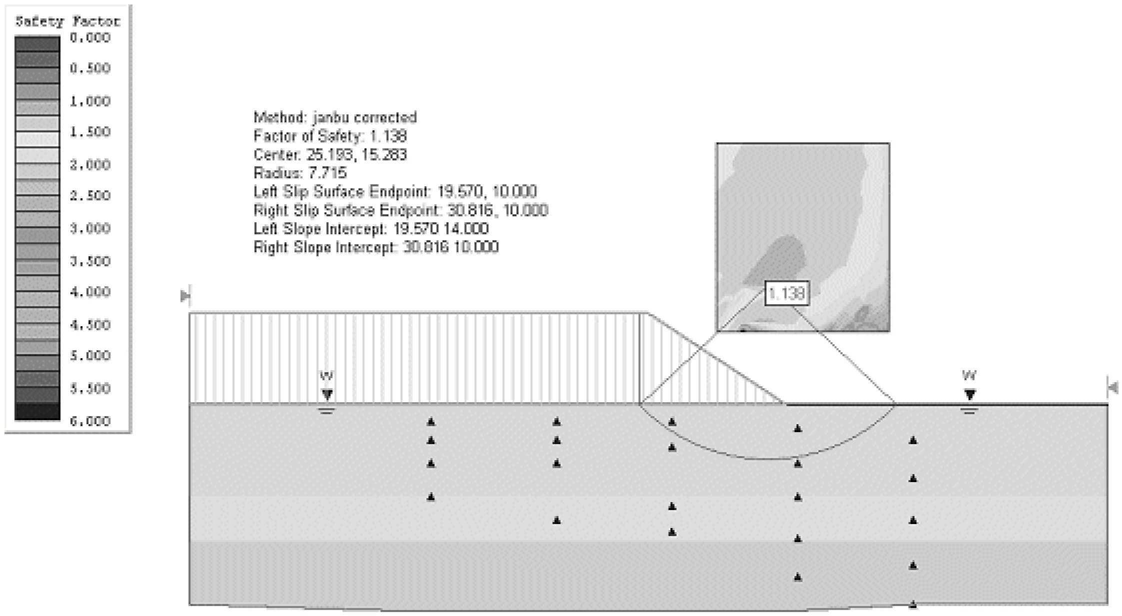


Figure 12.4.4 – Solution Using the Janbu Corrected Method

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. The material properties are given in Table 13.1. The position of the critical slip surface and the corresponding factor of safety are required. Pore water pressure was derived from the data in Table 13.2 using the Thin Plate Spline interpolation method.

13.3 Geometry and Properties

Table 13.1: Material 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	-	-	-

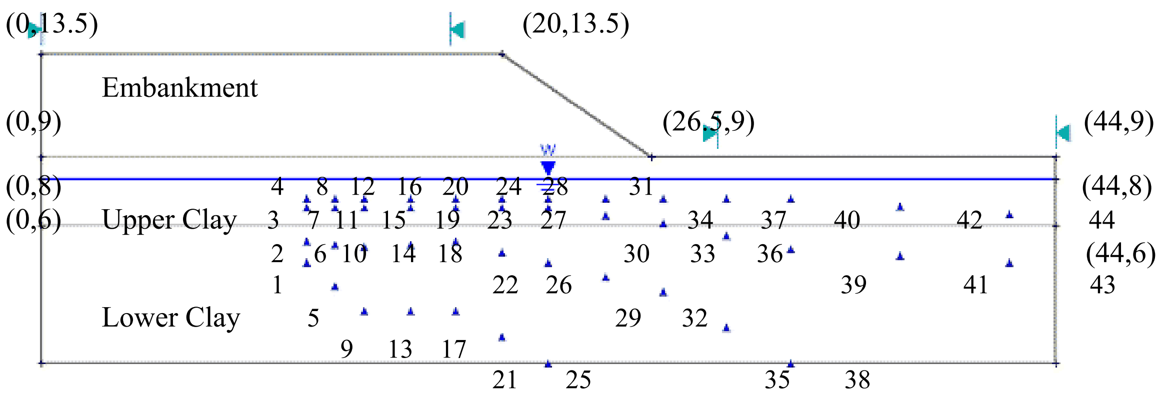


Figure 13

13.4 Results

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]

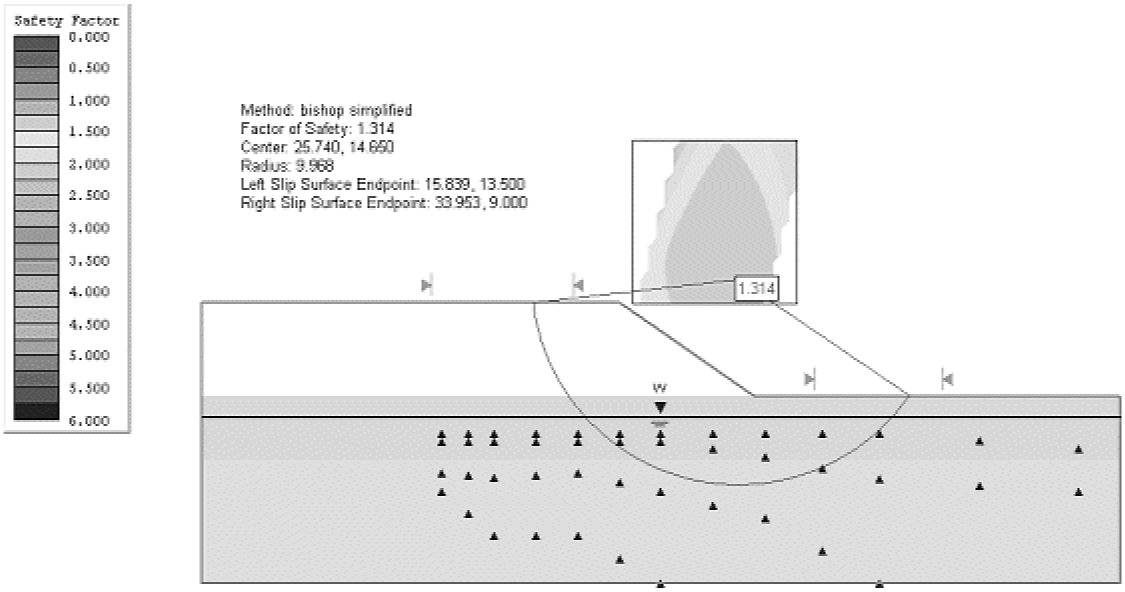


Figure 13.4.1 – Solution Using the Bishop Method

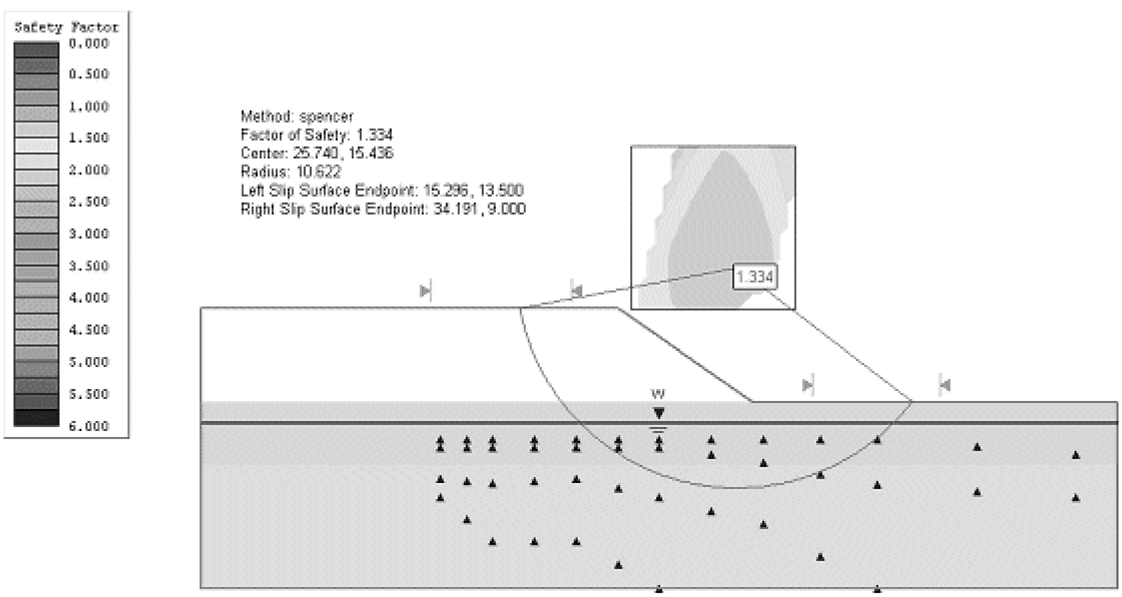


Figure 13.4.2 – Solution Using the Spencer Method

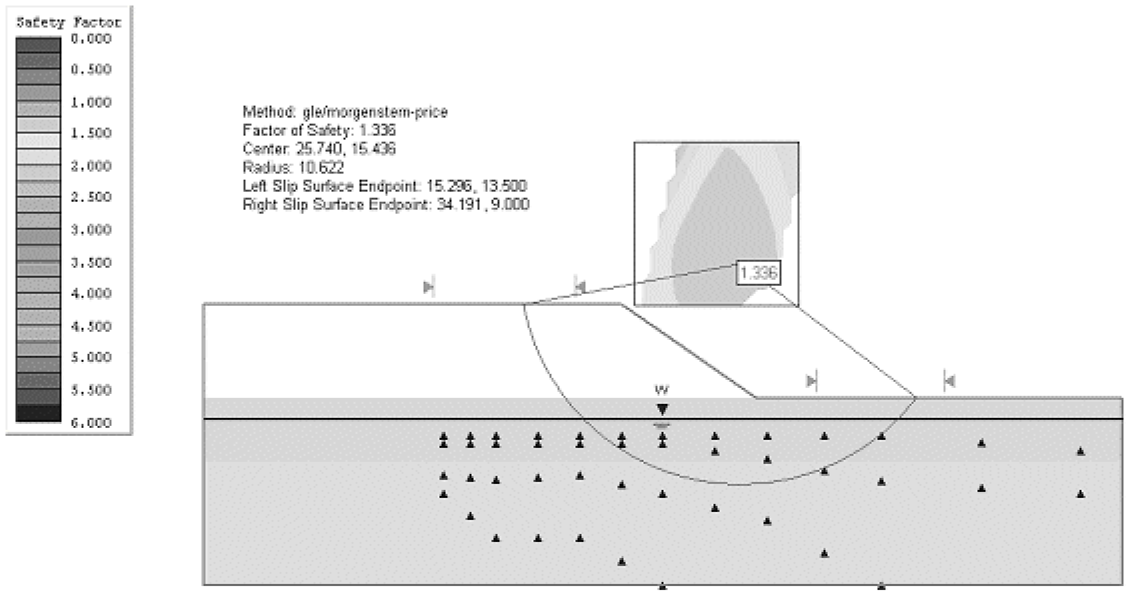


Figure 13.4.3 – Solution Using the GLE Method

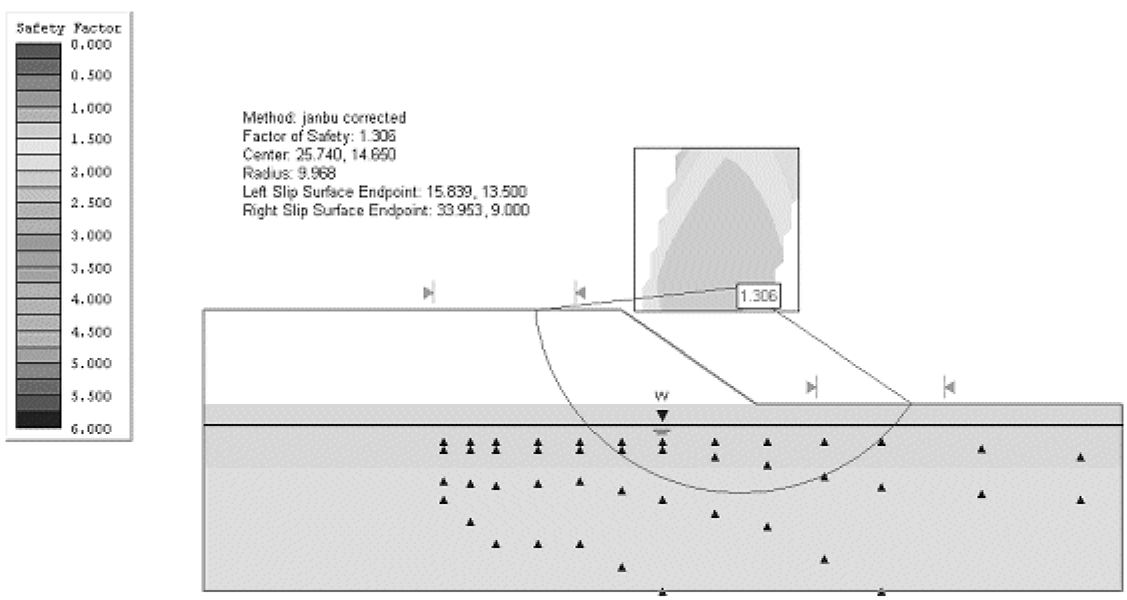


Figure 13.4.4 – Solution Using the Janbu Corrected Method

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 material properties are given in Table 14.1. 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.

14.3 Geometry and Properties

Table 14.1: Material Properties

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

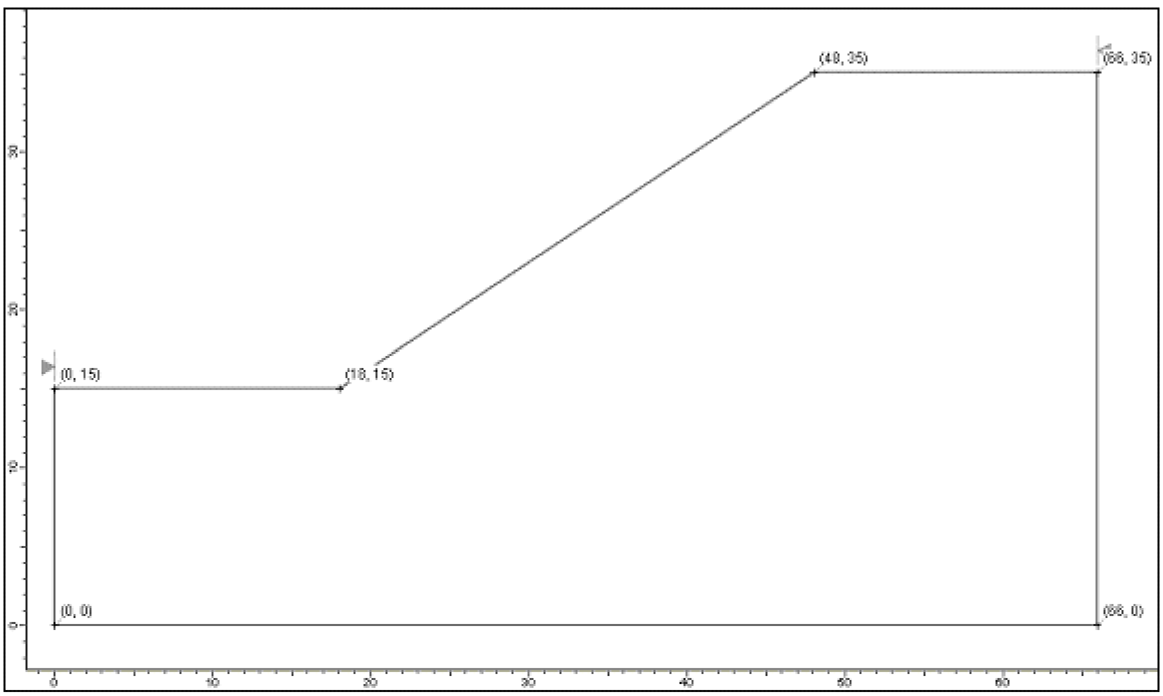


Figure 14.1 - Geometry

14.4 Circular Results – using auto refine search

Method	Factor of Safety
Bishop	1.409
Janbu Simplified	1.319
Janbu Corrected	1.414
Spencer	1.406

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

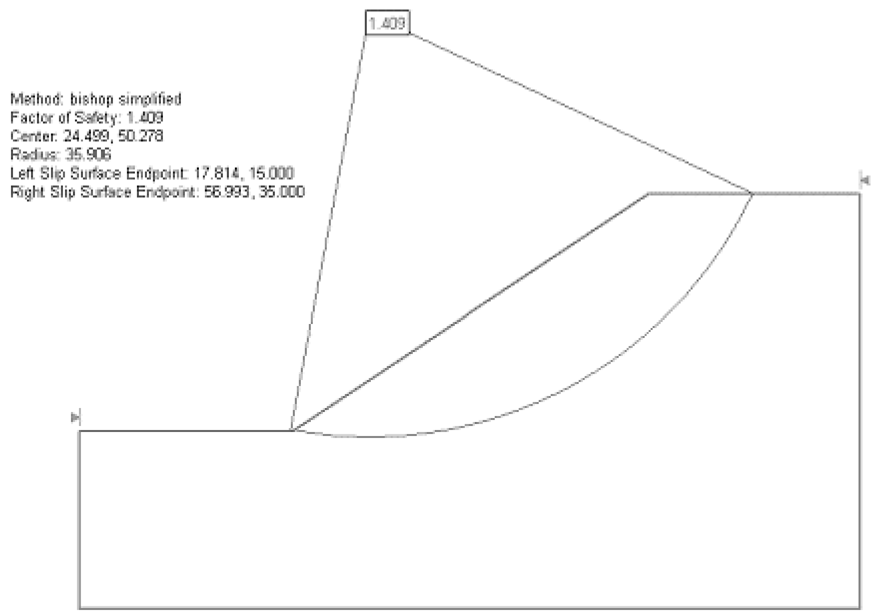


Figure 14.2 – Circular failure surface using Bishop simplified method

14.5 Noncircular Results – using Path search with Optimization

Method	Factor of Safety
Janbu Simplified	1.253
Janbu Corrected	1.346
Spencer	1.388

Arai and Tagyo (1985) Janbu Simplified Factor of Safety = 1.265
Arai and Tagyo (1985) Janbu Corrected Factor of Safety = 1.357

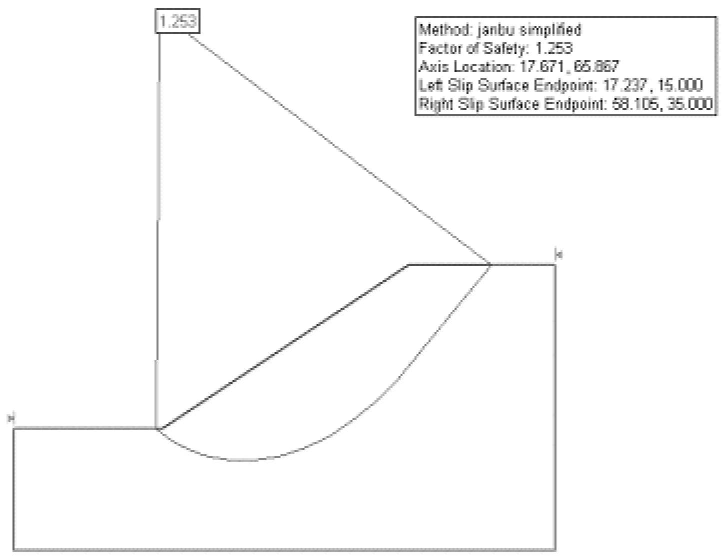


Figure 14.3 – Noncircular failure surface using janbu simplified method

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 material 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 Properties

Table 15.1: Material Properties

	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)
Upper Layer	29.4	12	18.82
Middle Layer	9.8	5	18.82
Lower Layer	294	40	18.82

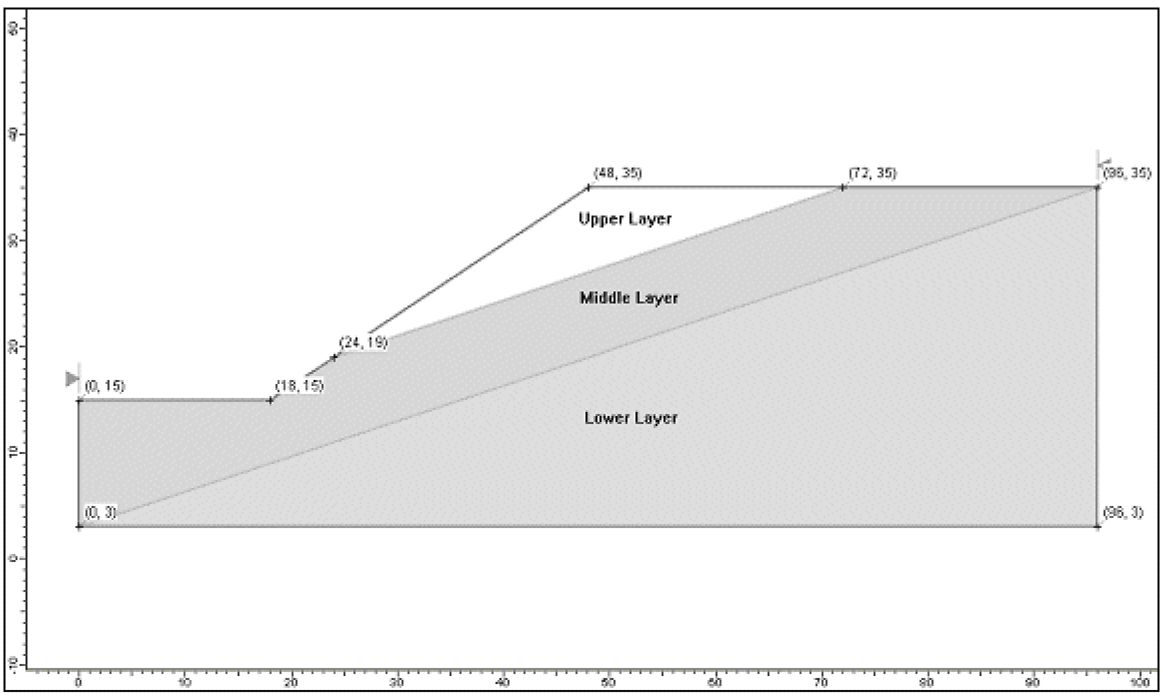


Figure 15.1 – Geometry

15.4 Circular Results – using auto refine search

Method	Factor of Safety
Bishop	0.421
Janbu Simplified	0.410
Janbu Corrected	0.437
Spencer	0.424

Arai and Tagyo (1985) Bishops Simplified Factor of Safety = 0.417
Kim et al. (2002) Bishops Simplified Factor of Safety = 0.43

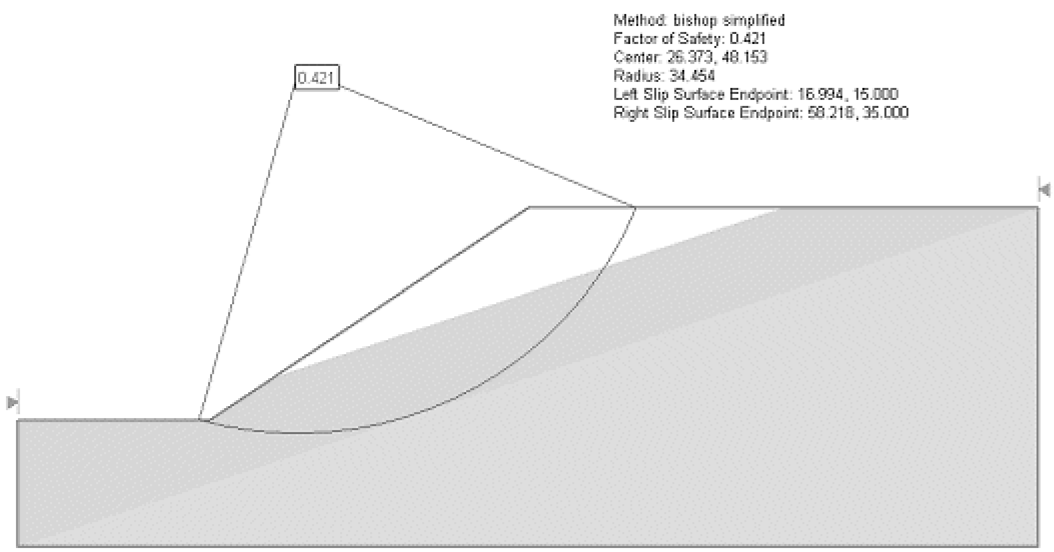


Figure 15.2 – Circular failure surface using Bishop simplified method

15.5 Noncircular Results – using Random search with Optimization (1000 surfaces)

Method	Factor of Safety
Janbu Simplified	0.394
Janbu Corrected	0.419
Spencer	0.412

Greco (1996) Spencers method using monte carlo searching = 0.39
Kim et al. (2002) Spencers method using random search = 0.44
Kim et al. (2002) Spencers method 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

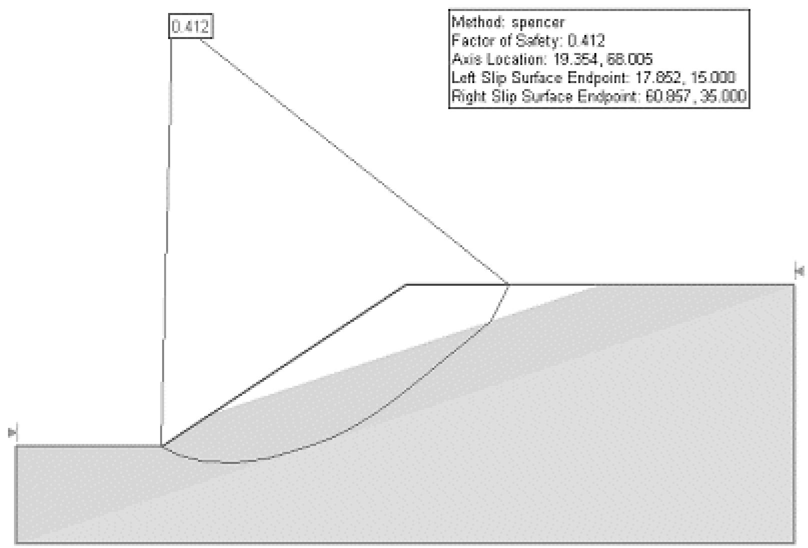


Figure 15.3 – Noncircular failure surface using Spencers method and random search

16.1 Introduction

This model is taken from Arai and Tagyo (1985) example#3 and 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 are 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 Properties

Table 16.1: Material Properties

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

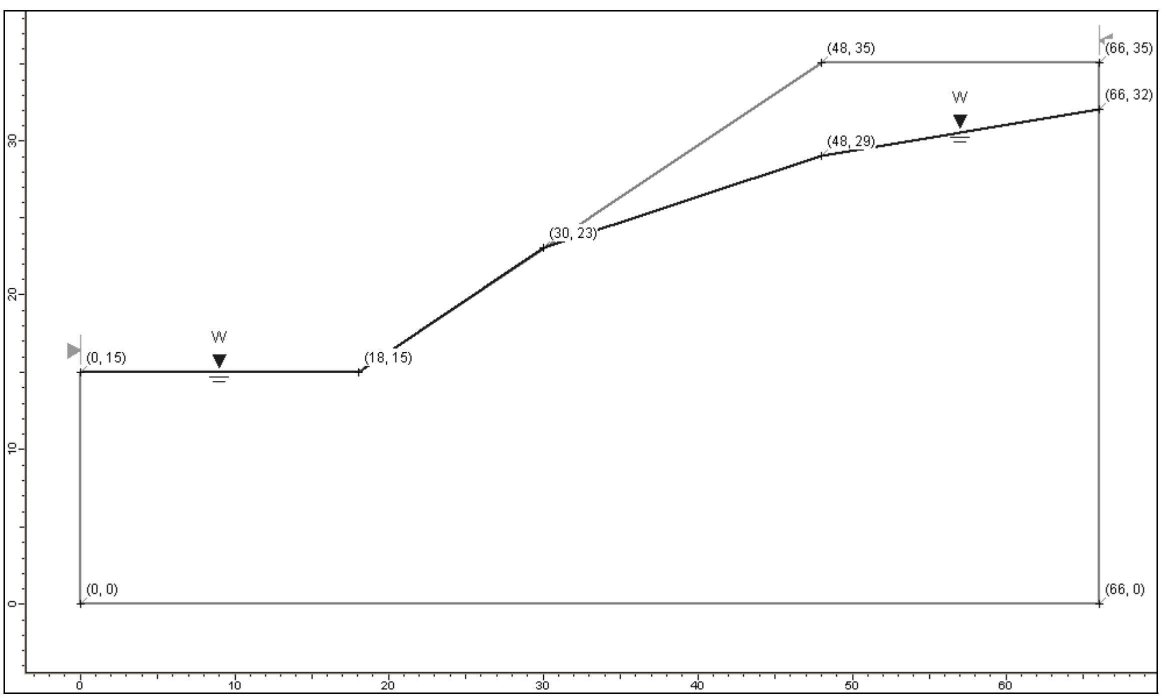


Figure 16.1 - Geometry

16.4 Circular Results – using auto refine search

Method	Factor of Safety
Bishop	1.117
Janbu Simplified	1.046
Janbu Corrected	1.131
Spencer	1.118

Arai and Tagyo (1985) Bishops Simplified Factor of Safety = 1.138

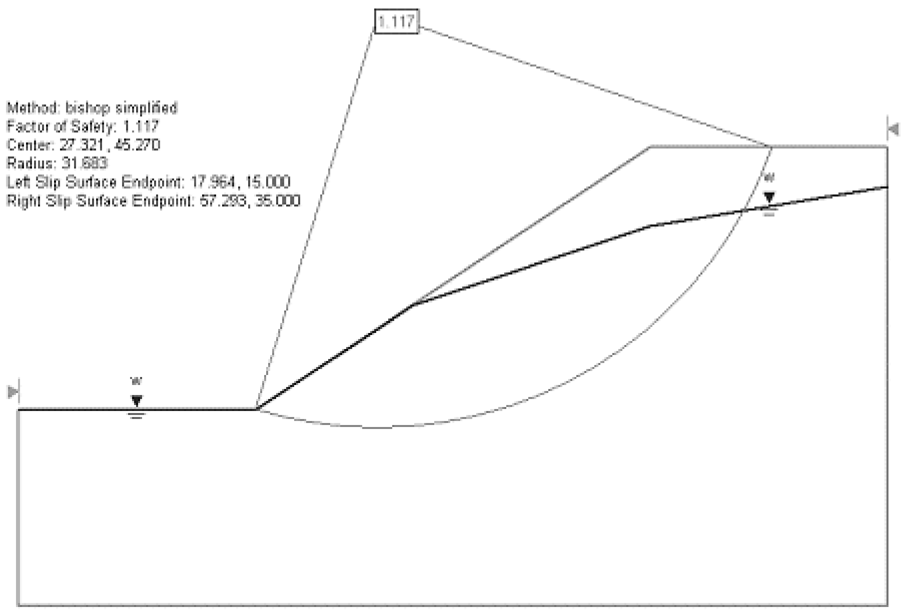


Figure 16.2 - Failure surface using Bishop simplified method

16.5 Noncircular Results – using Random search with Monte-Carlo optimization

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

Arai and Tagyo (1985) Janbu Simplified Factor of Safety = 0.995
Arai and Tagyo (1985) Janbu Corrected Factor of Safety = 1.071

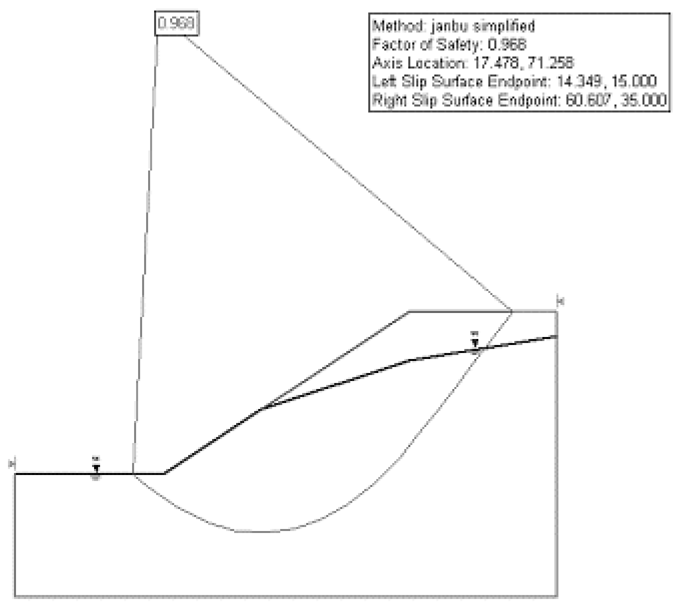


Figure 16.3 – Noncircular failure surface using janbu simplified method

17.1 Introduction

This model is taken from Yamagami and Ueta (1988) and 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 are calculated for both a circular and noncircular slip surface. There are no pore pressures in this problem.

17.3 Geometry and Properties

Table 17.1: Material Properties

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

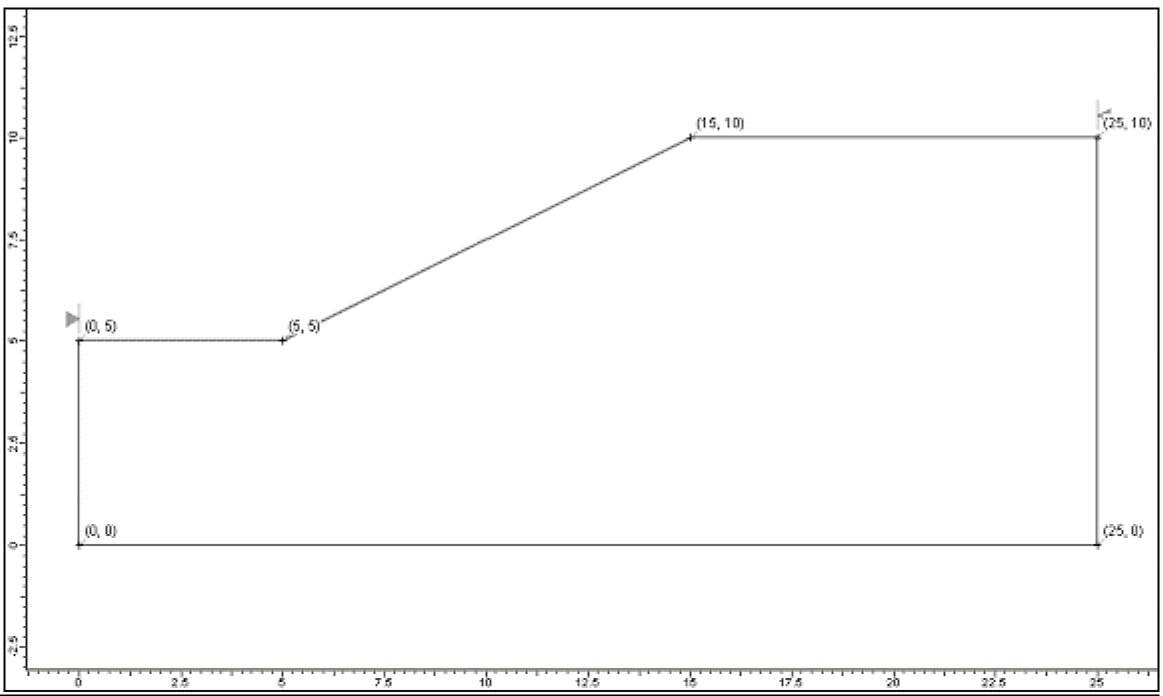
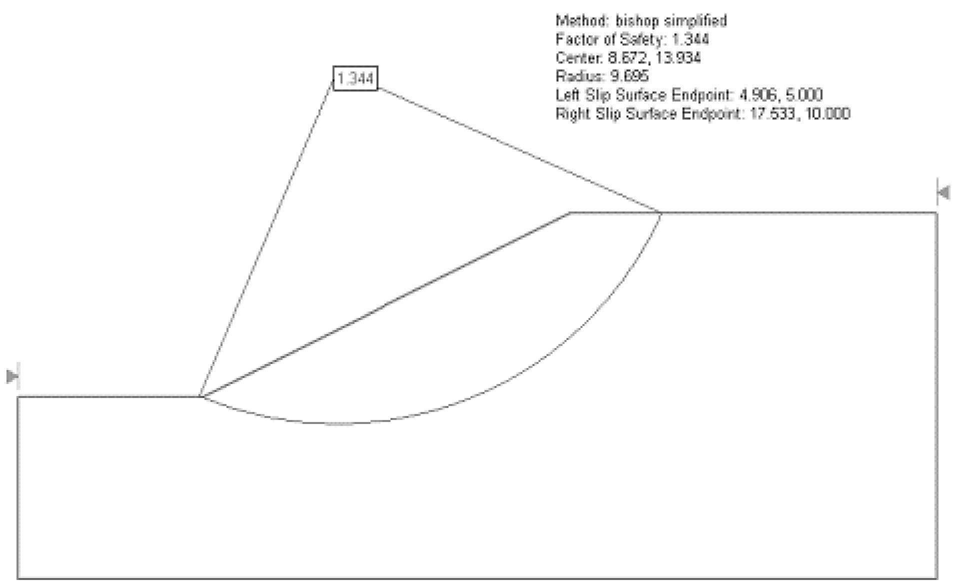


Figure 17.1 - Geometry

17.4 Circular Results – using auto refine search

Method	Factor of Safety
Bishop	1.344
Ordinary	1.278

Yamagami and Ueta (1988) Bishops Simplified Factor of Safety = 1.348
Yamagami and Ueta (1988) Fellenius/Ordinary Factor of Safety = 1.282



17.2 - Failure surface using Bishop simplified method

17.5 Noncircular Results – using Random search with Monte-Carlo optimization

Method	Factor of Safety
Janbu Simplified	1.178
Spencer	1.324

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

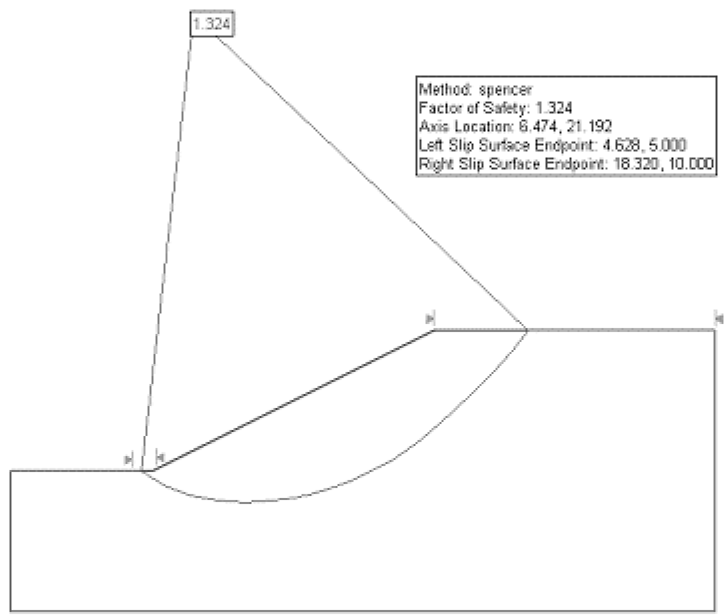


Figure 17.3 – Noncircular failure surface using spencer method

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 are calculated for a noncircular slip surface. The pore pressure within the slope is modeled using an Ru value of 0.5.

18.3 Geometry and Properties

Table 18.1: Material Properties

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

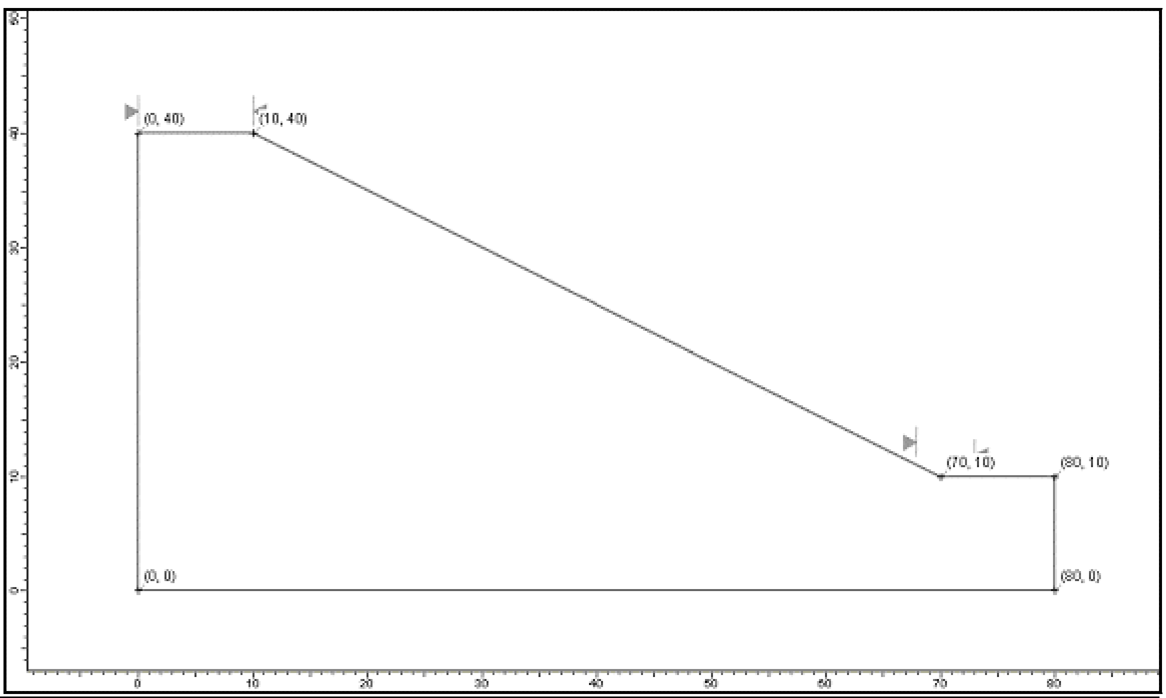


Figure 18.1 - Geometry

18.4 Noncircular Results – using Random search with Monte-Carlo optimization

Method	Factor of Safety
Spencer	1.01

Baker (1980) Spencer Factor of Safety = 1.02
Spencer (1969) Spencer Factor of Safety = 1.08

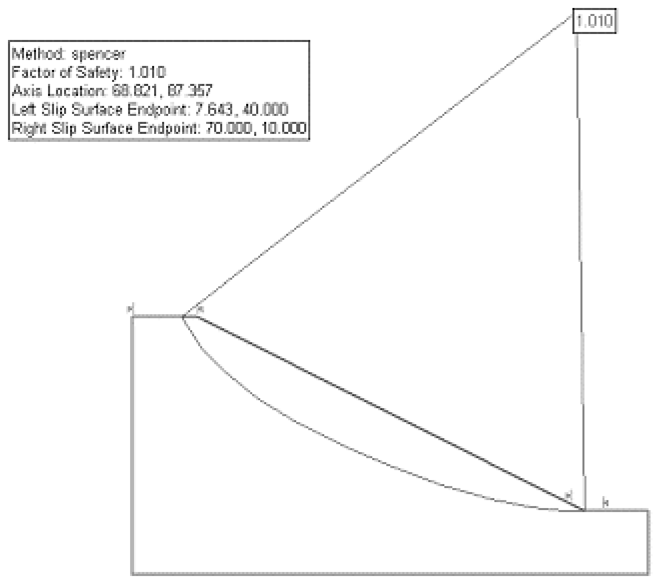


Figure 18.2 – Noncircular failure surface using spencer method

19.1 Introduction

This model is taken from Greco (1996) example #4 and 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 Properties

Table 19.1: Material 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

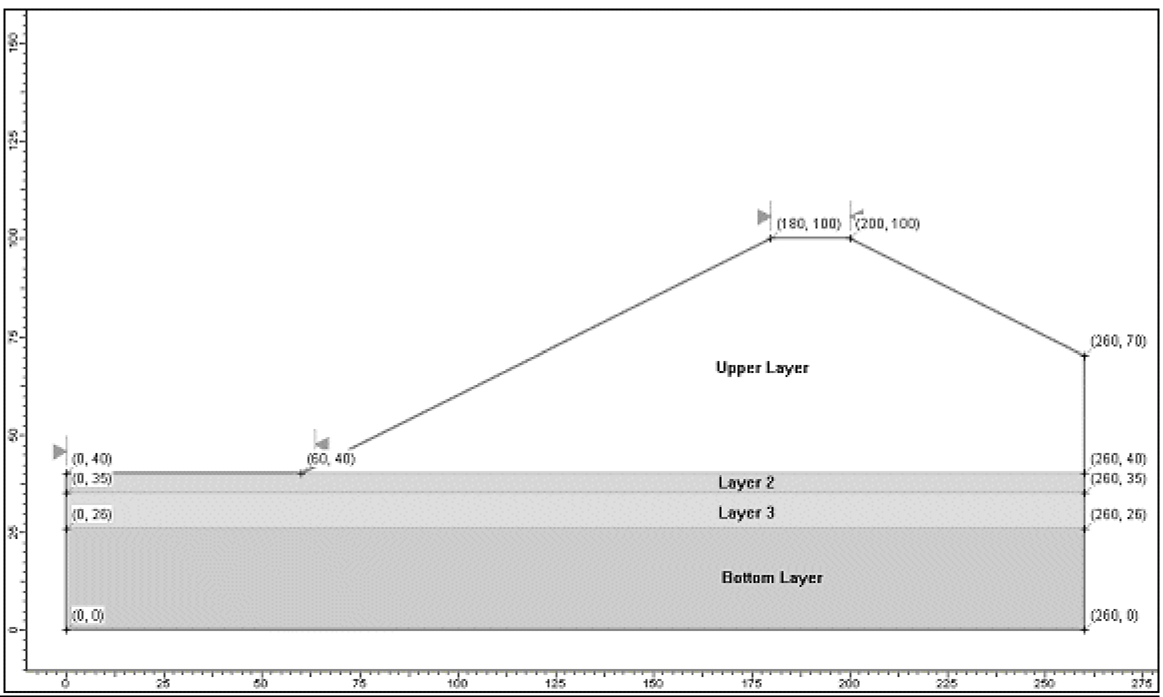


Figure 19.1 - Geometry

19.4 Noncircular Results – using Random search with Monte-Carlo optimization, convex surfaces only.

Method	Factor of Safety
Spencer	1. 398

Greco (1996) Spencer Factor of Safety = 1.40 - 1.42
Spencer (1969) Spencer Factor of Safety = 1.40 - 1.42

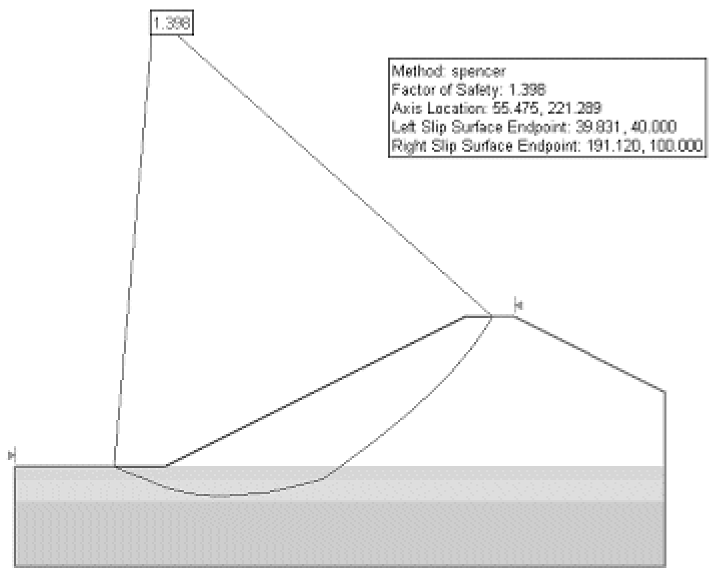


Figure 19.2 – Noncircular failure surface using spencer method

20.1 Introduction

This model is taken from Greco (1996) example #5 and 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 are 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 Properties

Table 20.1: Material Properties

	c′ (kN/m²)	ϕ′ (deg.)	γ (kN/m³)
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

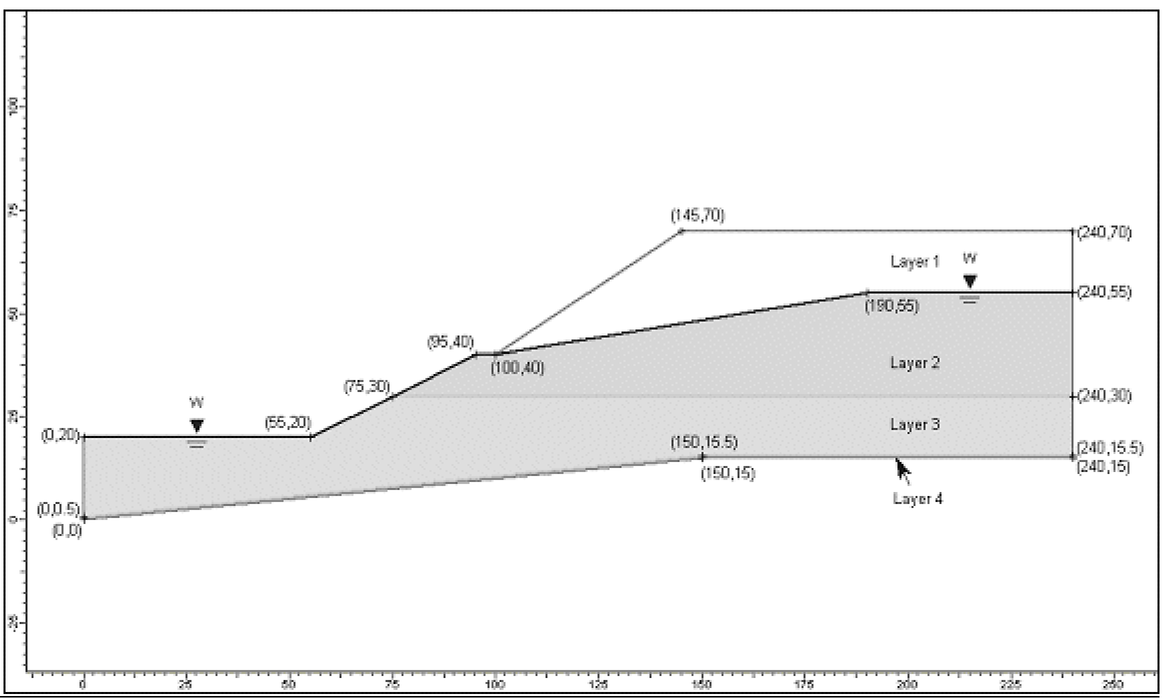
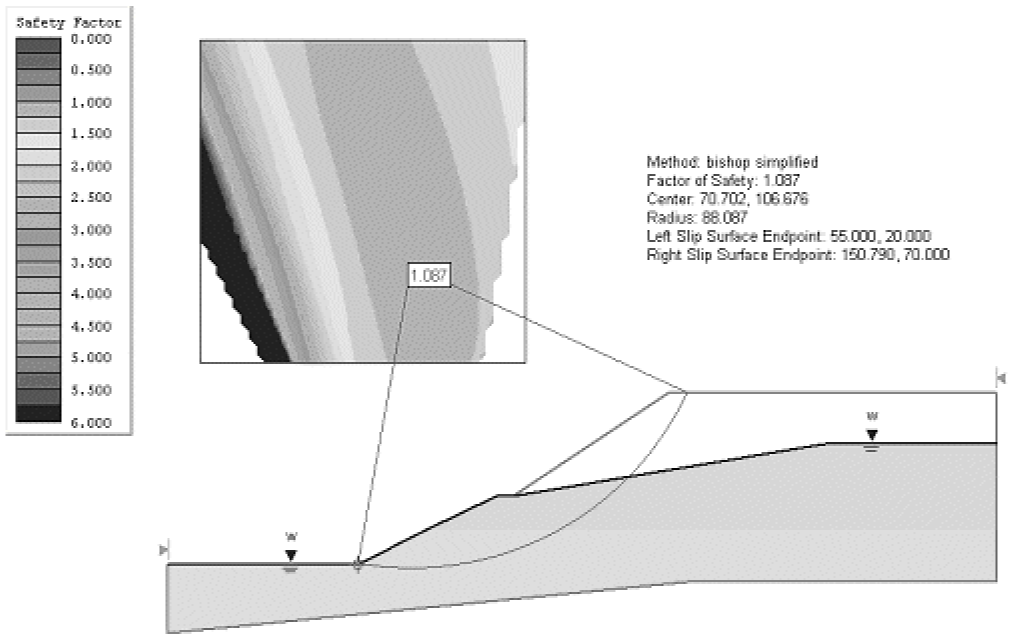


Figure 20.1 - Geometry

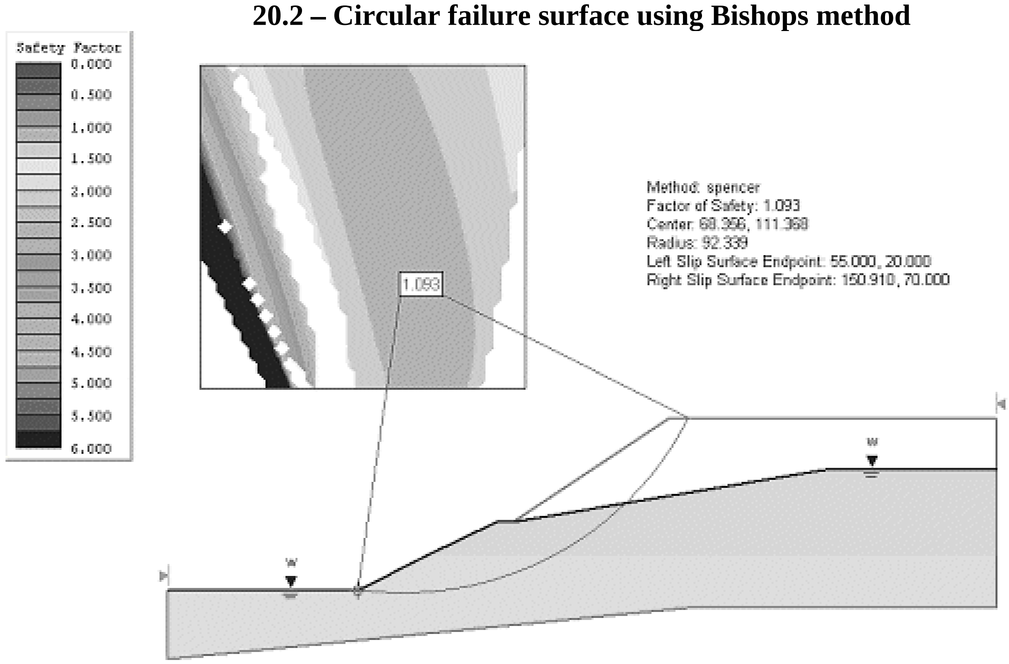
20.4 Circular Results – using grid search and a focus object at the toe (40x40 grid)

Method	Factor of Safety
Bishop	1.087
Spencer	1.093

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



20.2 – Circular failure surface using Bishops method



20.3 – Circular failure surface using Spencer's method

20.5 Noncircular Results – using Block search polyline in the weak seam and Monte-Carlo optimization

Method	Factor of Safety
Spencer	1. 007

Chen and Shao (1988) Spencer Factor of Safety = 1.01 - 1.03
Greco (1996) Spencer Factor of Safety = 0.973 - 1.1

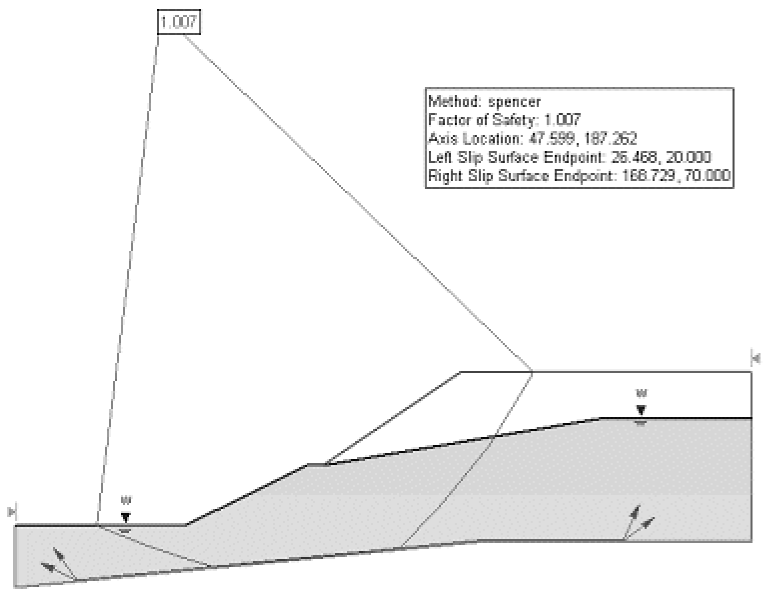


Figure 20.4 – Noncircular failure surface using spencer method and block search

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 pressure, 3) pore pressures defined using a water table. The model is done in imperial units to be consistent with the original paper. Quite a few other authors, such as Baker (1980), Greco (1996), and Malkawi (2001) have also analyzed this slope.

21.2 Problem description

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

Table 21.1: Material Properties

	c′ (psf)	φ′ (deg.)	γ (pcf)	Ru (case2)
soil	600	20	120	0.25

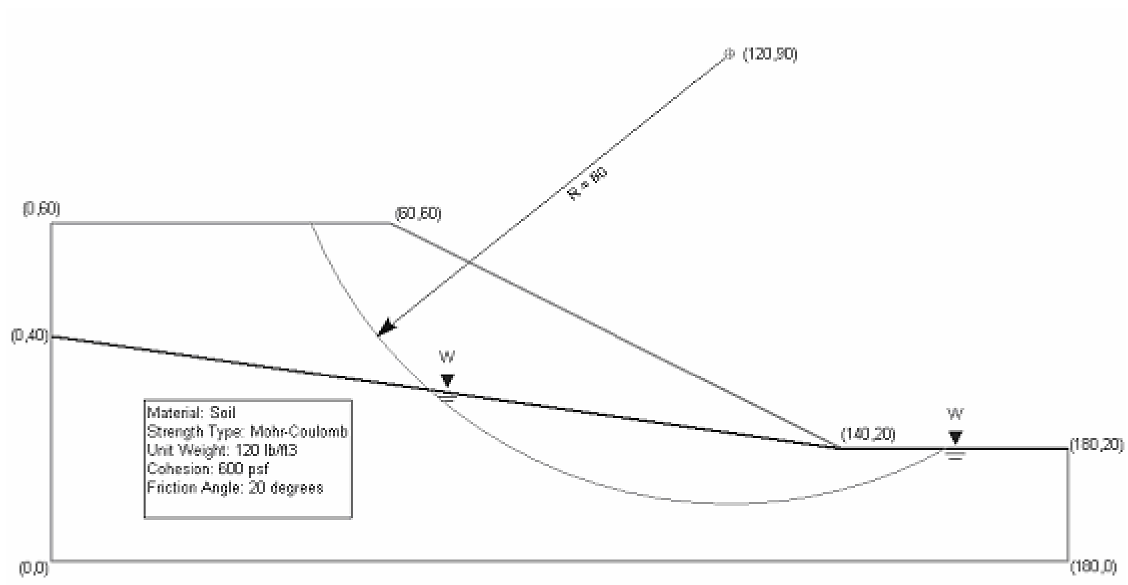


Figure 21.1 - Geometry

21.3 Circular Results

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	1.609	1.766	1.763	1.761	1.760	1.764	1.760
3-WT	1.693	1.697	1.834	1.833	1.830	1.831	1.832	1.831

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 pressure, 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.

Table 22.1: Material Properties

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

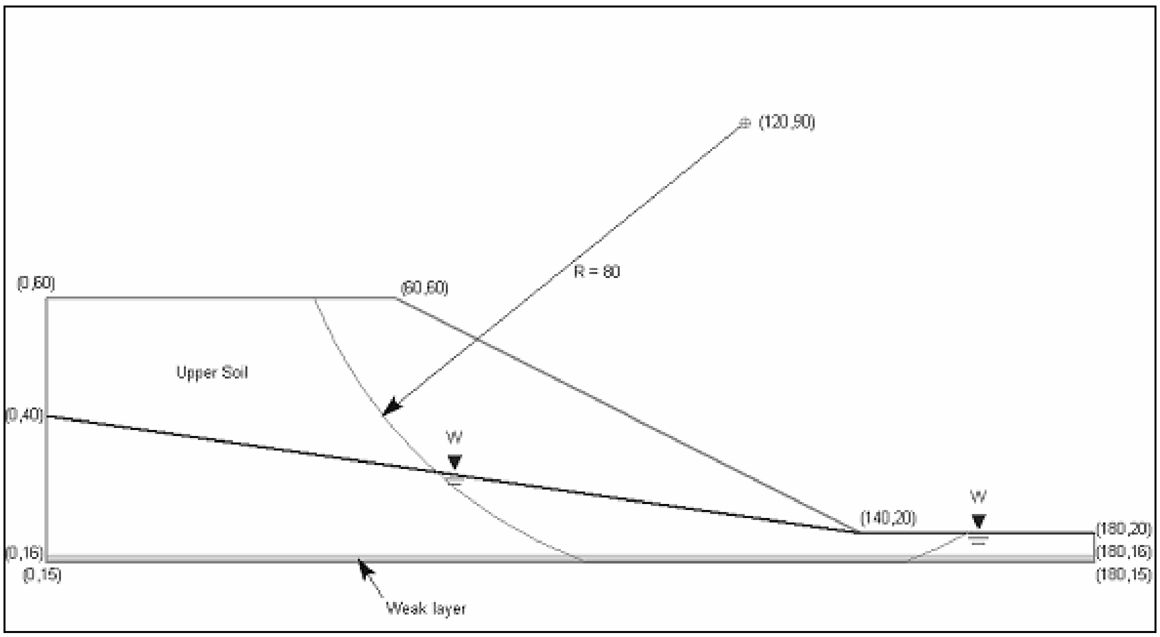


Figure 22.1 – Geometry

22.3 Composite Circular Results - SLIDE

Method	Case 1: Dry	Case 2: Ru	Case 3: WT
Ordinary	1.300	1.039	1.174
Bishop Simplified	1.382	1.124	1.243
Spencer	1.382	1.124	1.244
GLE/Morgenstern-Price	1.372	1.114	1.237

Composite Circular Results – 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

Composite Circular Results – 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

23.1 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 are calculated for a circular slip surface using both the bishop and ordinary/fellenius methods.

Table 23.1: Material Properties

	Cu_{top} (KN/m2)	Cu_{bottom} (KN/m2)	ϕ (deg.)	γ (KN/m3)
Upper Soil	95	95	15	20
Middle Soil	15	15	0	20
Lower Soil	15	30	0	20

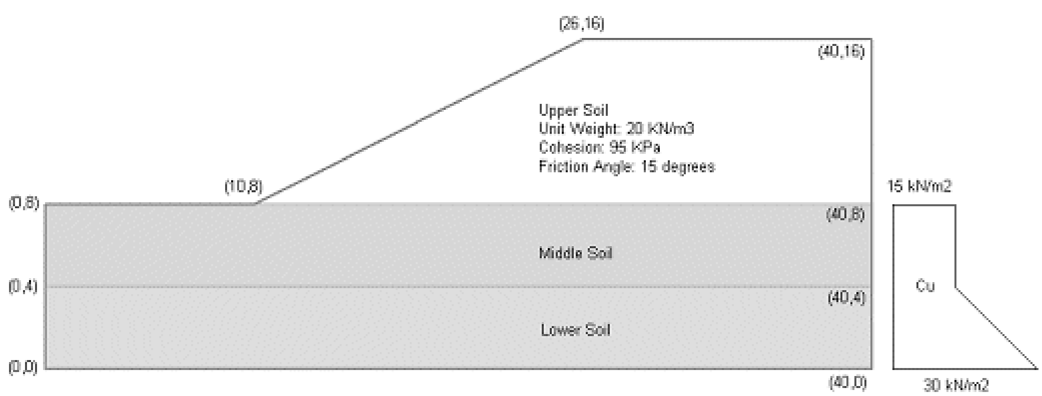
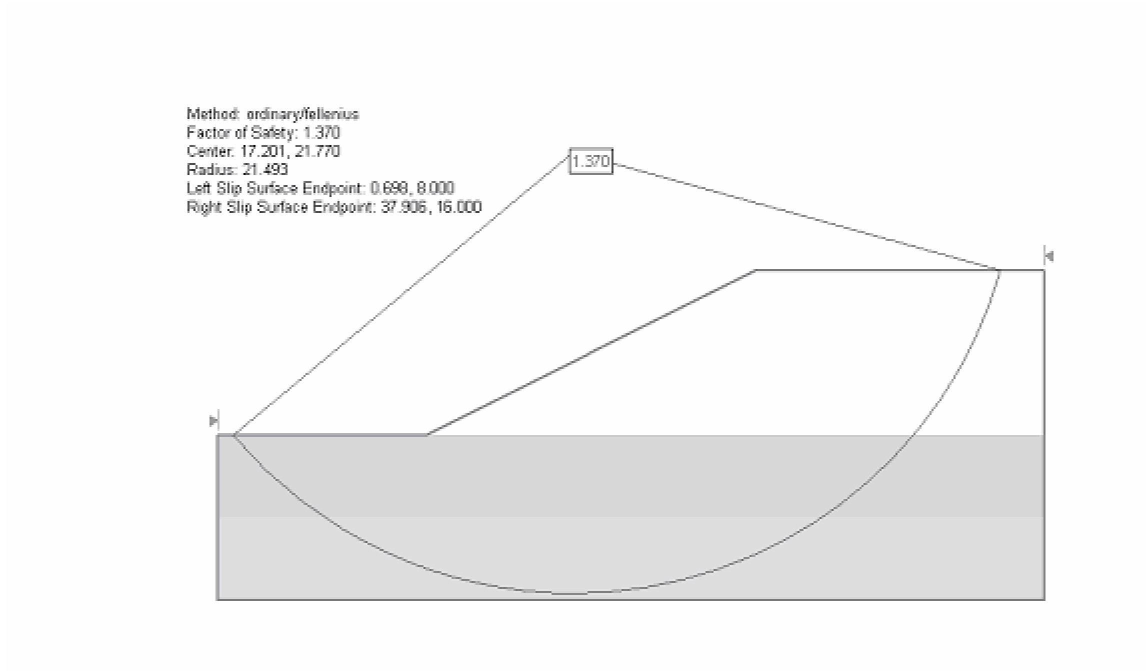


Figure 23.1 – Geometry

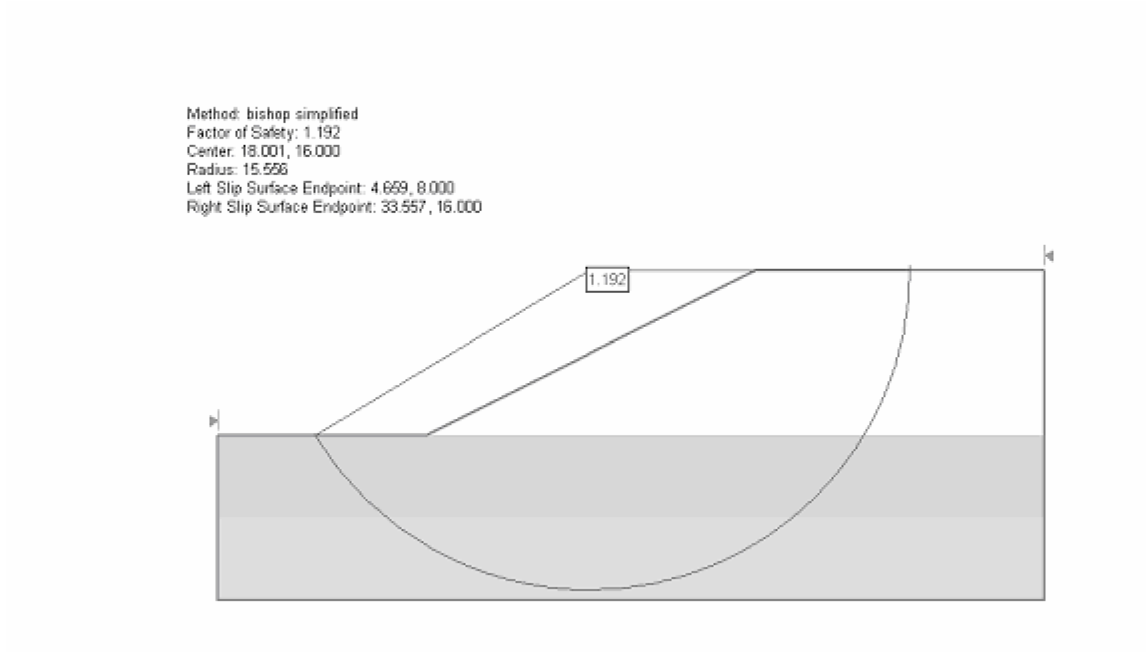
22.3 Circular Results – Auto refine search

Method	Factor of Safety
Ordinary	1.370
Bishop	1.192

Low (1989) Ordinary Factor of Safety=1.36
Low (1989) Bishop Factor of Safety=1.14
Kim (2002) Factor of Safety=1.17



23.2 – Circular failure surface using Ordinary/Fellenius method



23.3 – Circular failure surface using Bishops method

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 material properties are given in Table 24.1. The position of the critical slip surface and the corresponding factor of safety are calculated for a circular slip surface using both the bishop and ordinary/fellenius methods.

Table 24.1: Material Properties

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

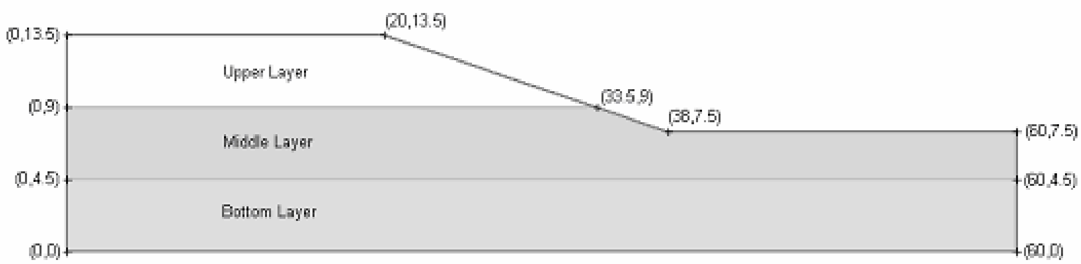
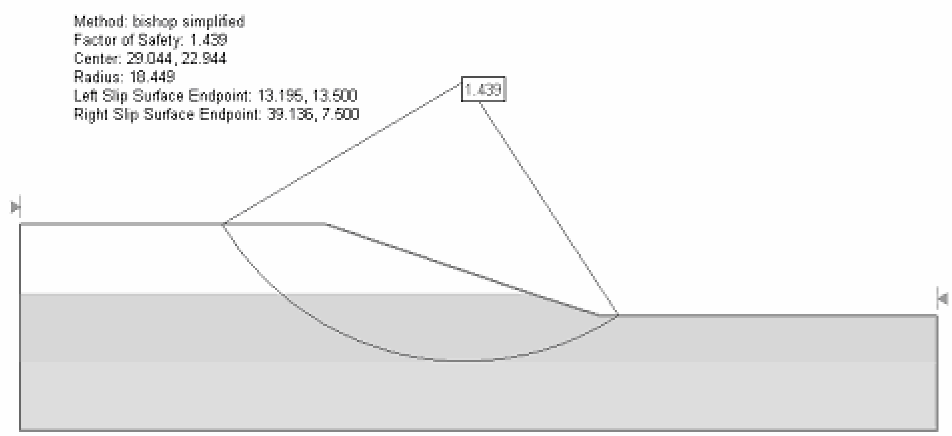


Figure 24.1 – Geometry

24.3 Circular Results – auto refine search

Method	Factor of Safety
Ordinary	1.439
Bishop	1.439

Low (1989) Ordinary Factor of Safety=1.44
Low (1989) Bishop Factor of Safety=1.44



24.2 – Circular failure surface using Bishops method

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 25.1. The slope geometry, equation for the critical load, and position of the critical slip surface is defined by Prandtl and 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.

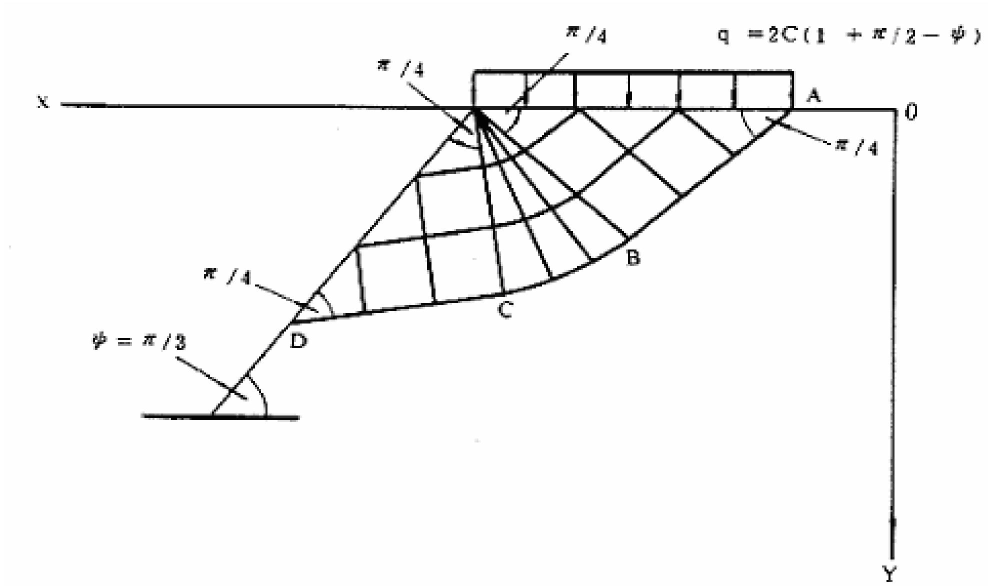
Note: The GLE/discrete Morgenstern-Price results used the following custom interslice force function. This function was chosen to approximate the theoretical force distribution shown in Chen and Shao.

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

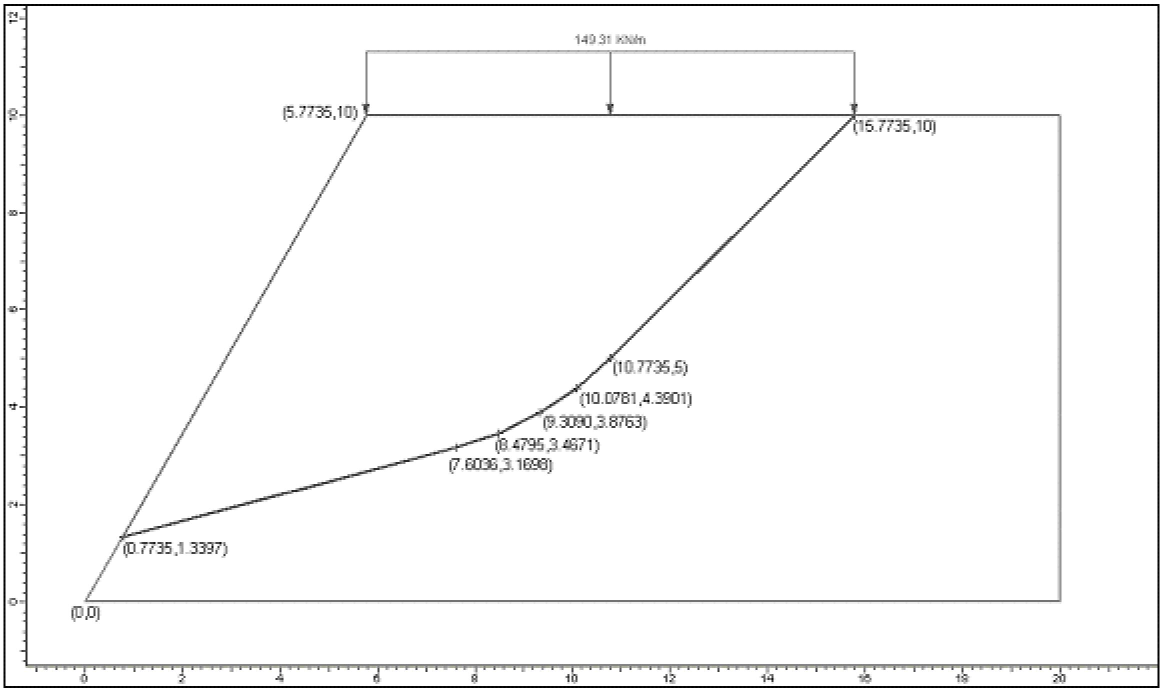
25.3 Geometry and Properties

Table 25.1: Material Properties

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



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



25.2 – Geometry modeled using Slide

25.4 Results

Method	Factor of Safety
Spencer	1. 051
GLE/M-P	1. 009

Chen and Shao (1988) Spencer Factor of Safety = 1.05

26.1 Introduction

This verification test models the well-known Prandtl solution of bearing capacity:

$q_c=2C(1+\pi/2)$

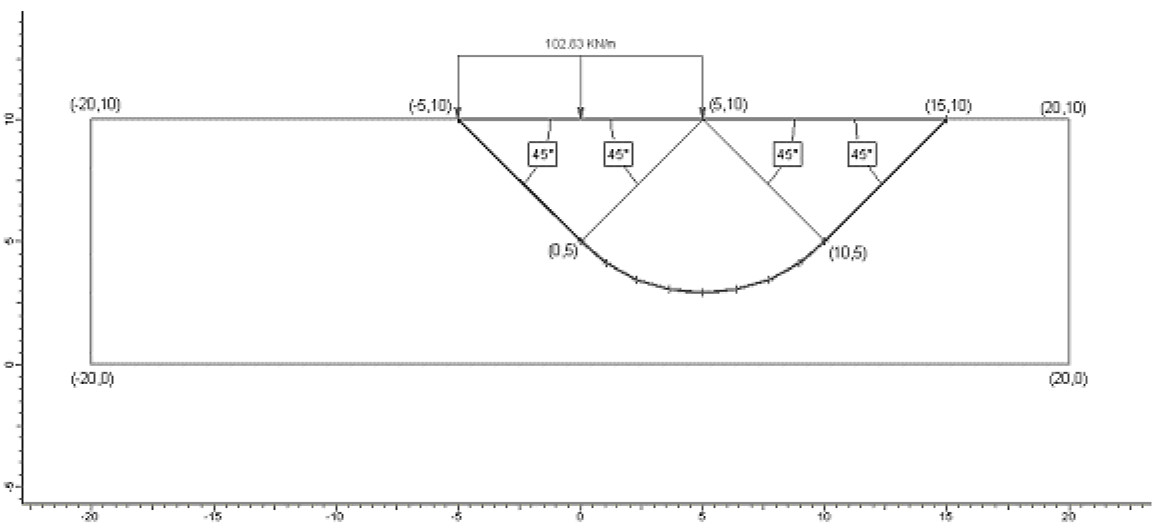
26.2 Problem description

Verification problem #26 is shown in Figure 26.1. The material properties are given in Table 26.1. With cohesion of 20kN/m2, 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 below figure. The theoretical noncircular critical failure surface was used.

26.3 Geometry and Properties

Table 26.1: Material Properties

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



26.1 – Geometry modeled using Slide

26.4 Results

Method	Factor of Safety
Spencer	0.941

Theoretical factor of safety=1.0

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 and moist and saturated unit weights for one of the materials. The other material has zero strength. The model is done with imperial units (feet,psf,pcf) to be consistent with the original XSTABL analysis.

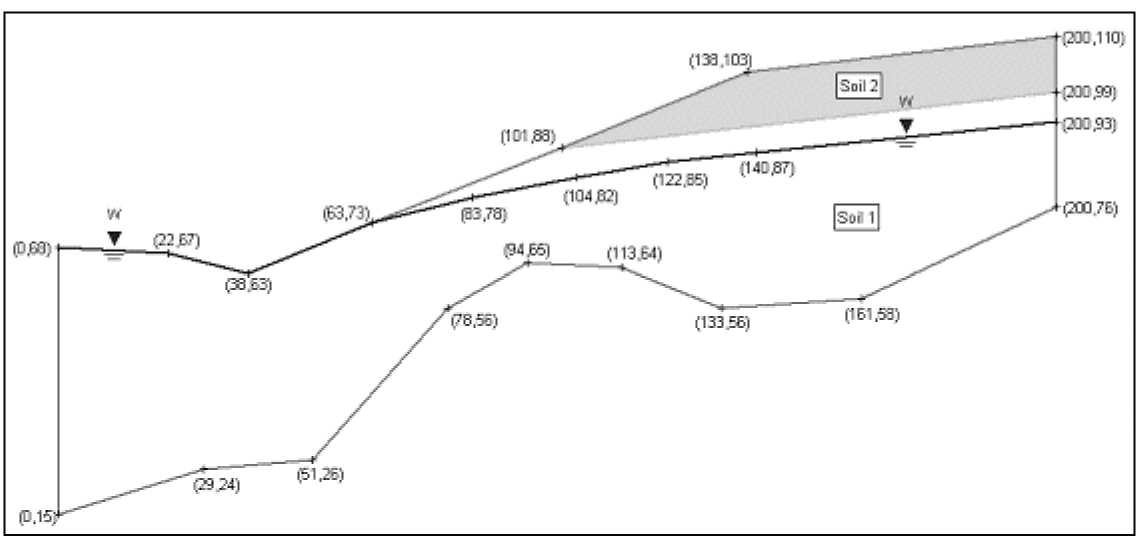
27.2 Problem description

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 Properties

Table 27.1: Material 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



27.1 – Geometry

27.4 Analysis 1 Circular Results – 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

27.5 Analysis 2 Circular Results – auto search

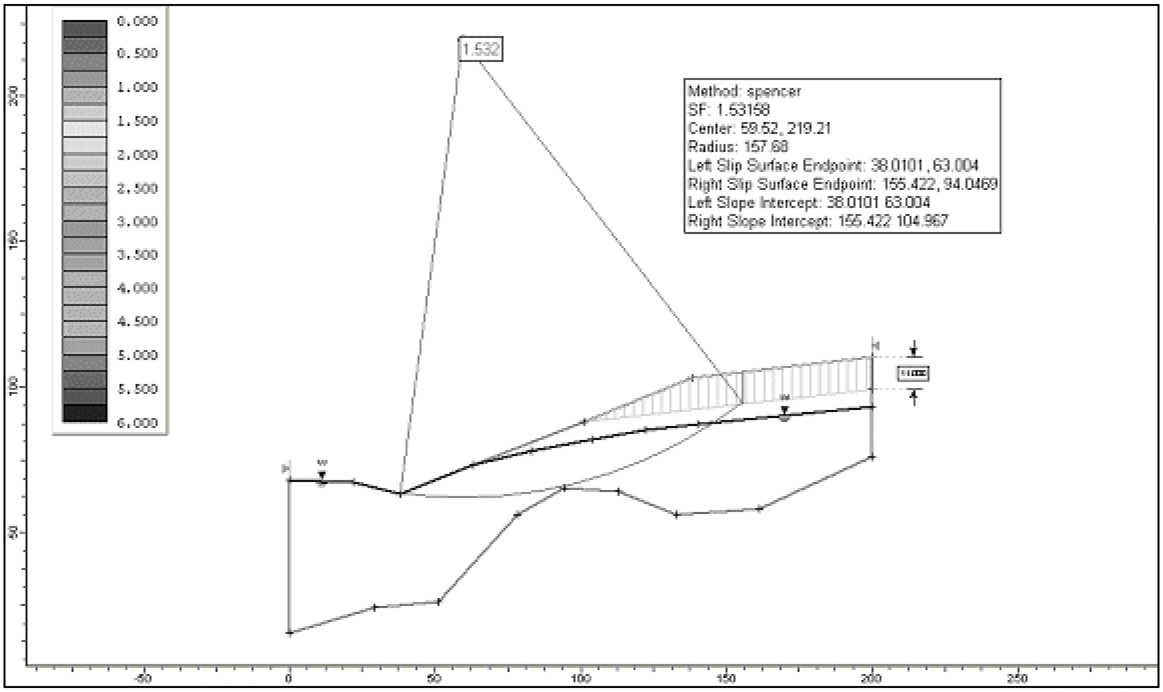
Method	SLIDE
Bishop	1.376
Janbu Corrected	1.345
Corp. Engineers 1	1.394
Corp. Engineers 2	1.396
Lowe & Karafiath	1.392
Spencer	1.382
GLE/M-P (half-sine)	1.378

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.

27.6 Analysis 3 Circular Results – single center @ xc=59.52,yc=219.21,radius=157.68

A 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



27.2 – Analysis 3 results for Spencers method

27.7 Analysis 4 Circular Results – 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

28.1 Introduction

The set of models in this verification problem were 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 Examples 1 to 4 in Verification #28 is shown in Figure 28.1. 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 weights of the slope materials in Examples 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.

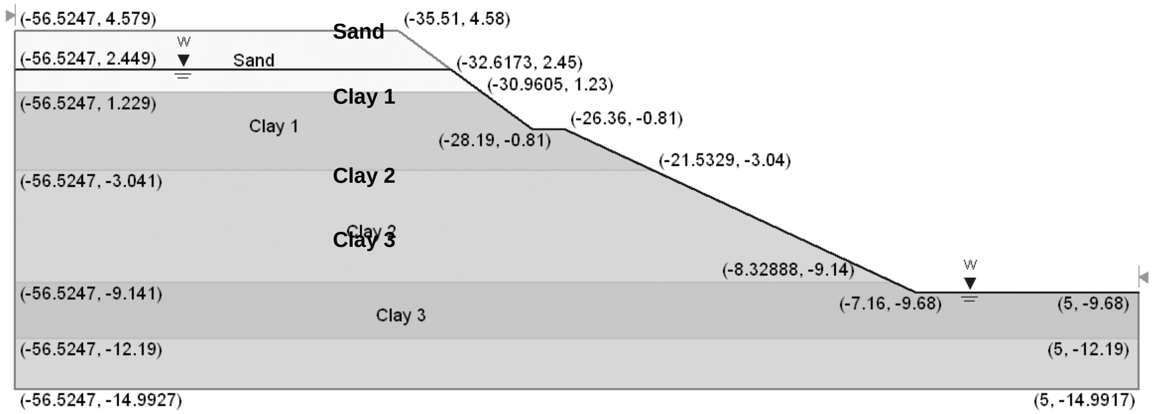
In Example 5, Chowdhury and Xu examine the stability of an embankment on a soft clay foundation. Again they consider two sets of circular slip surfaces; one set is tangent to the interface of the embankment and the foundation, while the other is tangent to the lower boundary of the soft clay foundation.

The Chowdhury and Xu 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.

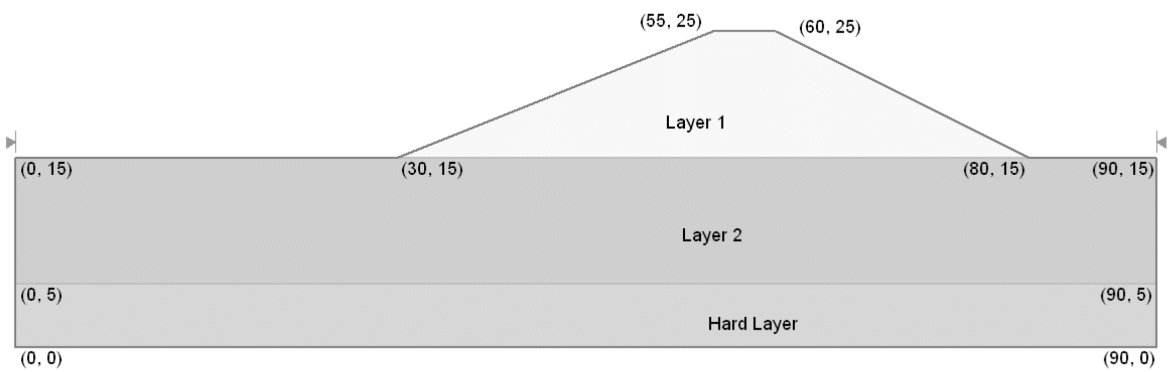
28.3 Geometry and Properties

Table 20.1: Material Properties

	c (kN/m^2)	ϕ (deg.)	γ (kN/m^3)
Sand	0	0	21



28.1 – Geometry for Examples 1 - 4



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

28.4 Example 1

Input Data

(The three clay layers are assumed frictionless.)

	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

*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.

Results (Maximum iterations: 100)

	Chowdhury & Xu		Slide	
Failure Mode (Layer)	**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

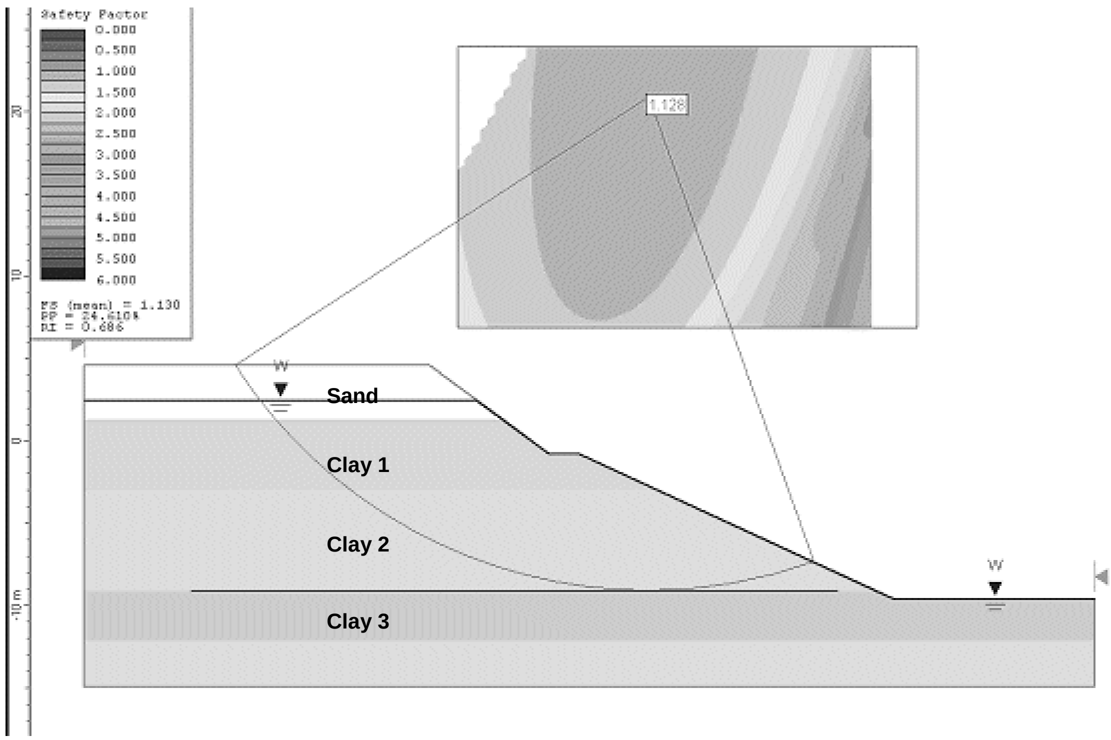


Figure 28.3 – Critical slip circle tangential to lower boundary of clay layer 2

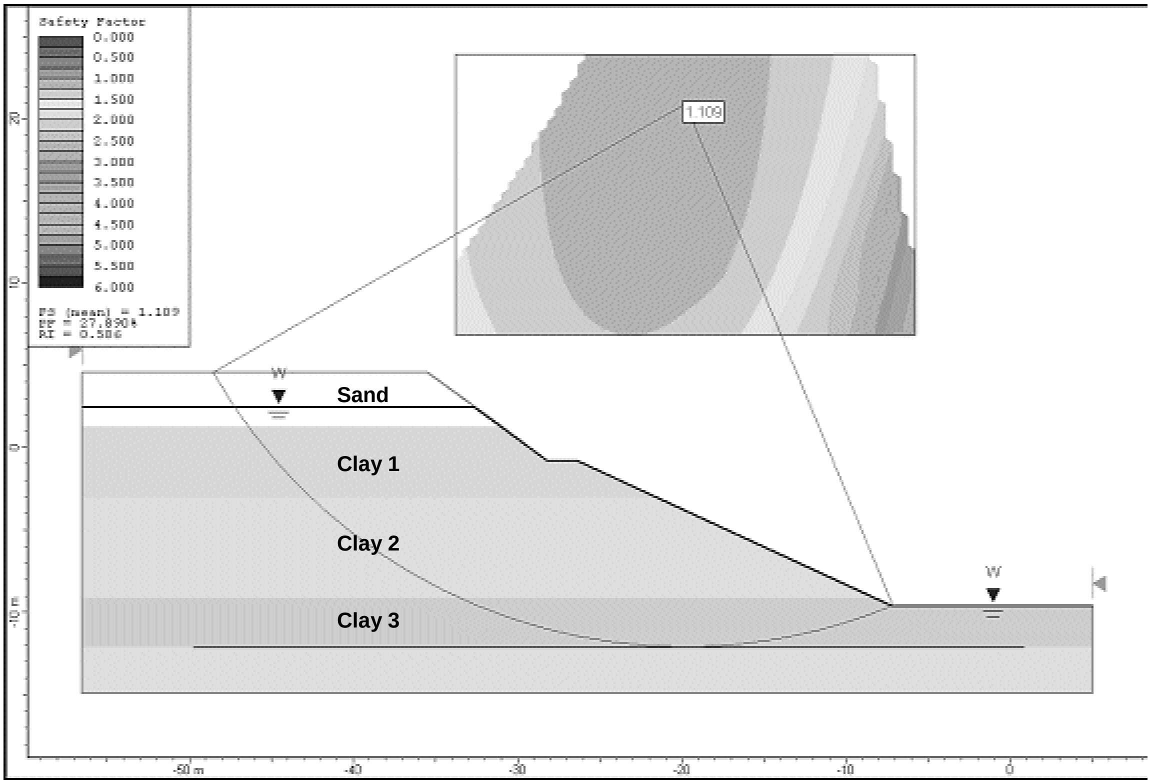


Figure 28.4 – Critical slip circle tangential to lower boundary of clay layer 3

28.5 Example 2

Input Data

(The three clay layers are assumed frictionless.)

	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

*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.

Results

	Chowdhury & Xu		Slide	
Failure Mode (Layer)	**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

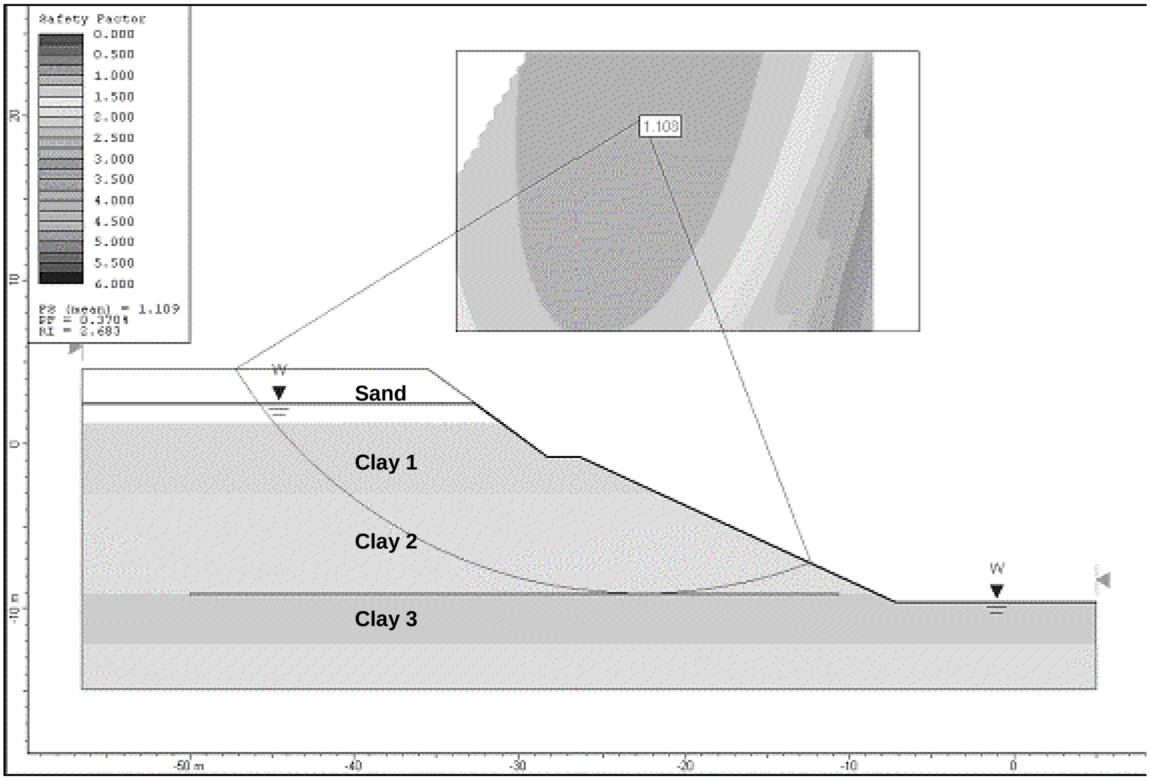


Figure 28.5 – Critical slip circle tangential to lower boundary of clay layer 2

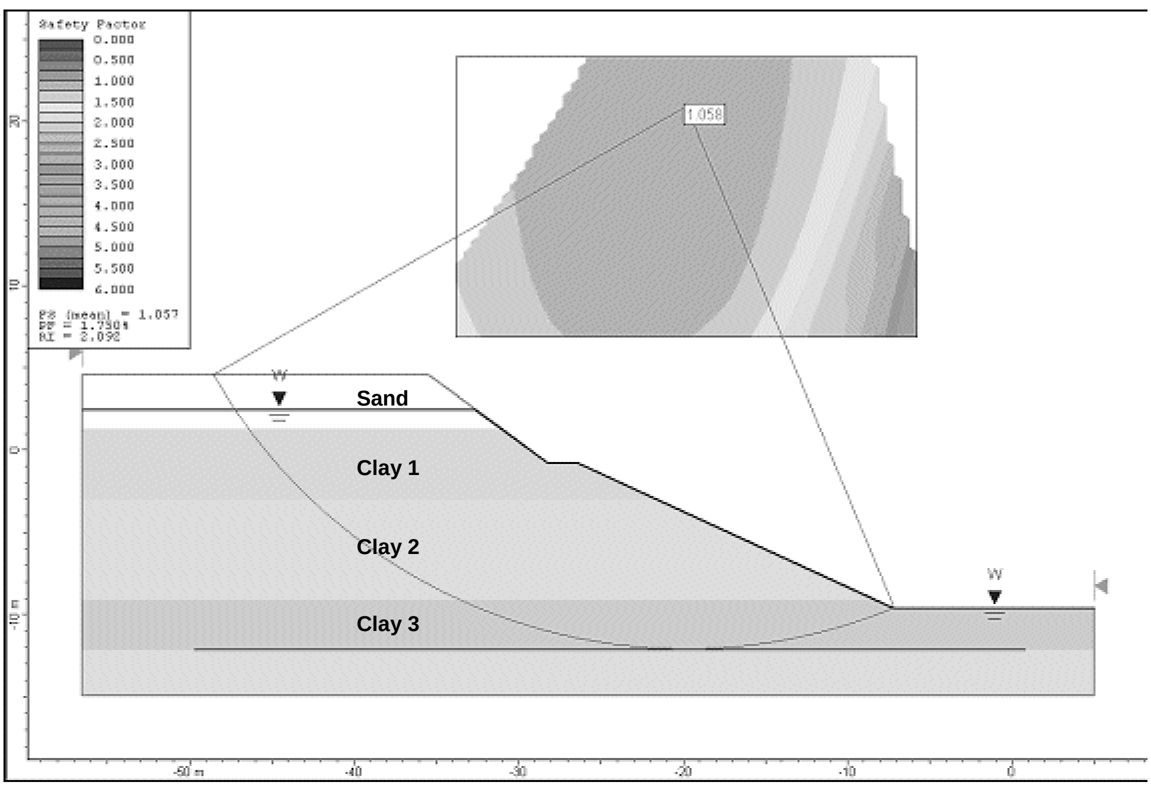


Figure 28.6 – Critical slip circle tangential to lower boundary of clay layer 3

28.5 Example 3

Input Data

(The three clay layers are assumed frictionless.)

	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

*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.

Results

	Chowdhury & Xu		Slide	
Failure Mode (Layer)	**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

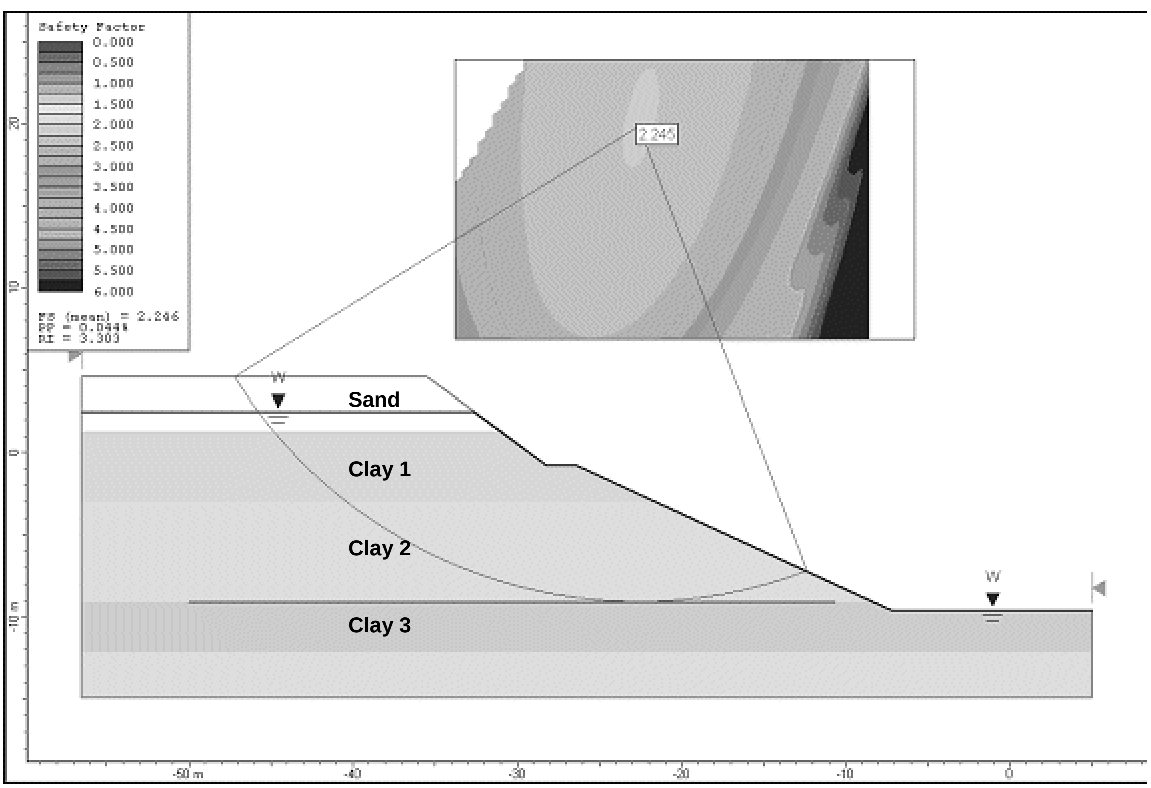


Figure 28.7 – Critical slip circle tangential to lower boundary of clay layer 2

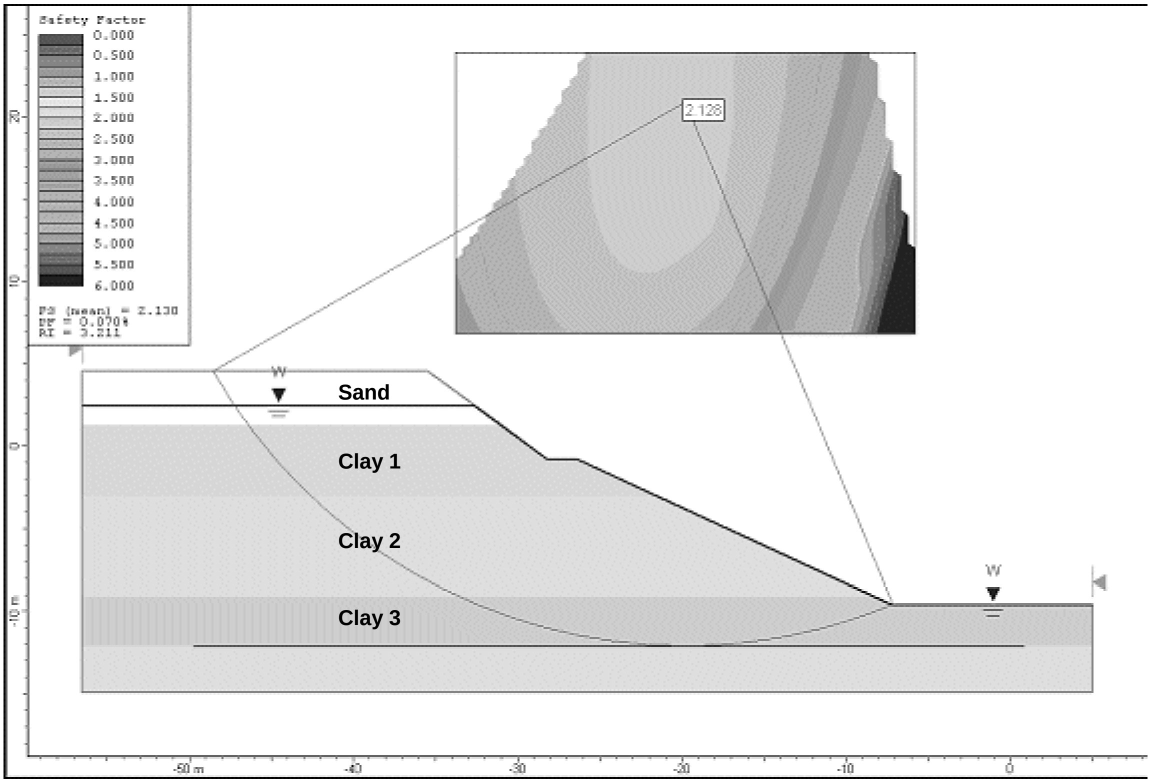


Figure 28.8 – Critical slip circle tangential to lower boundary of clay layer 3

28.6 Example 4

Input Data

	Soil Layer					
	Clay 1		Clay 2		Clay 3	
	c_1(kPa)	ϕ_1(^{o})	c_2 (kPa)	ϕ_2 (^{o})	c_3 (kPa)	ϕ_3 (^{o})
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	

*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.

Results

	Chowdhury & Xu		Slide	
Failure Mode (Layer)	**Factor of Safety (Bishop simplified)**	**Probability of Failure**	**Factor of Safety (Bishop simplified)**	**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

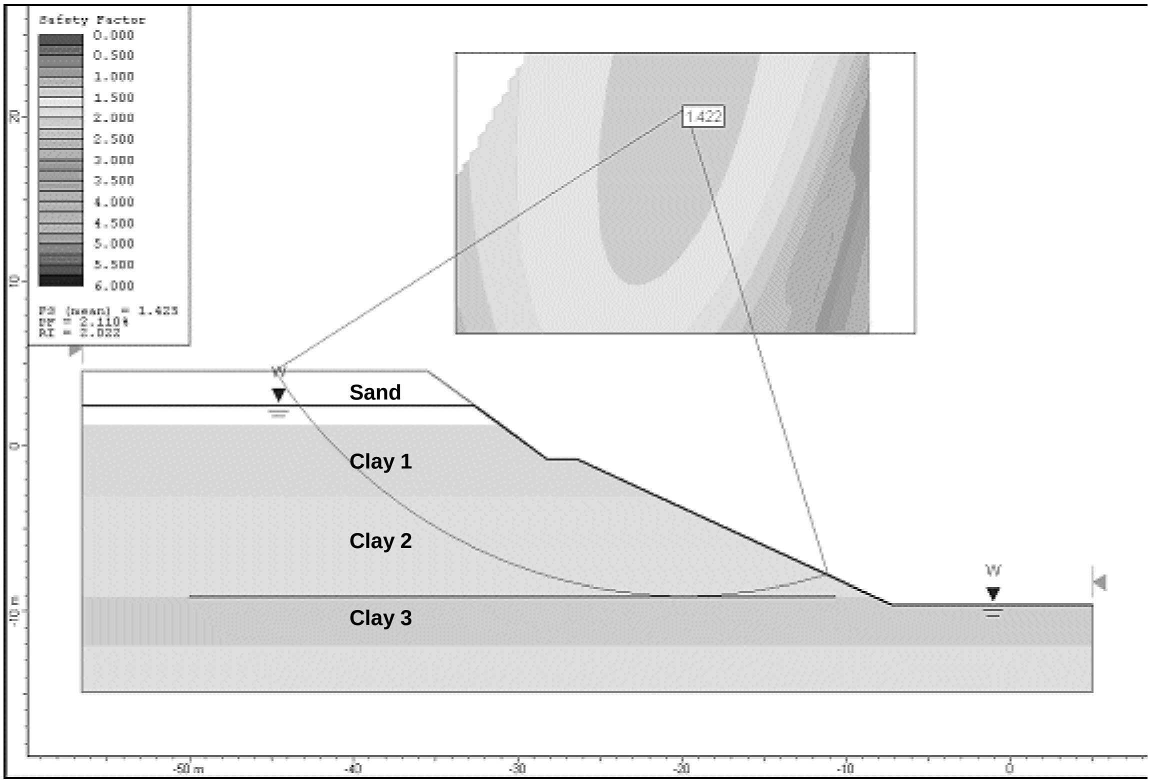


Figure 28.9 – Critical slip circle tangential to interface of clay layer 2

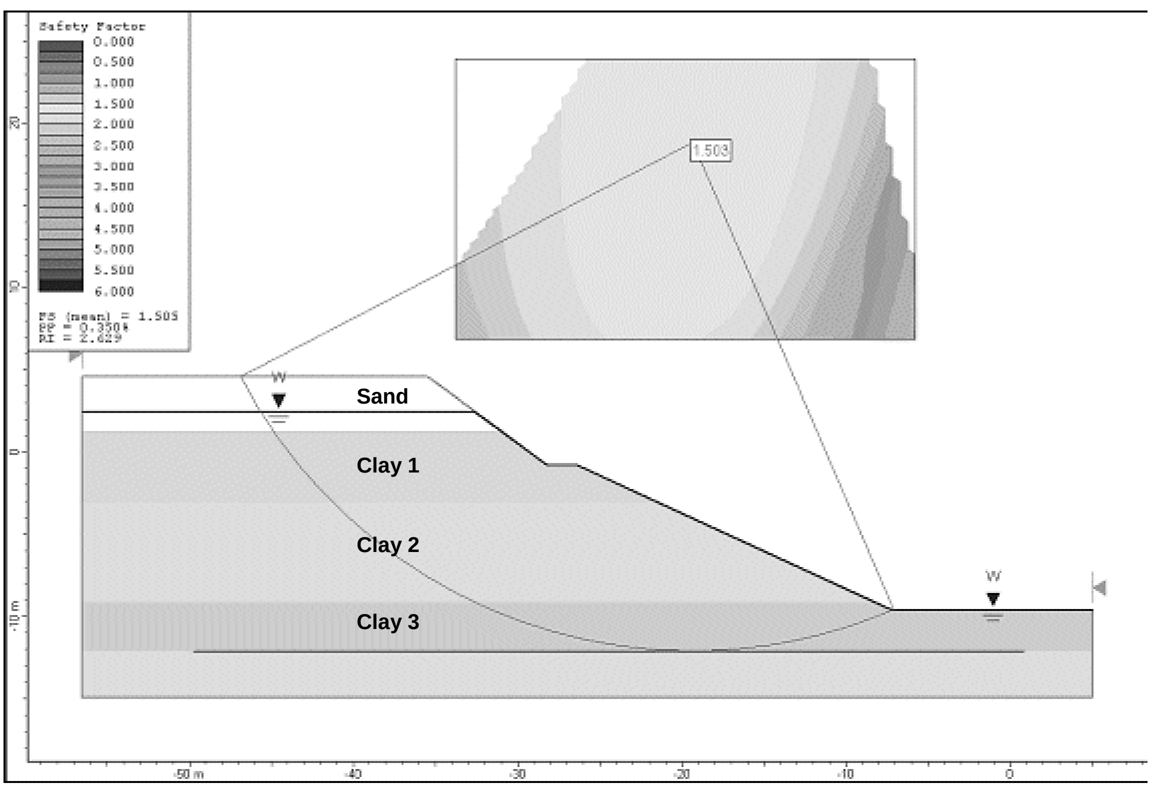


Figure 28.10 – Critical slip circle tangential to lower boundary of clay layer 3

28.7 Example 5

Input Data

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

Results

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

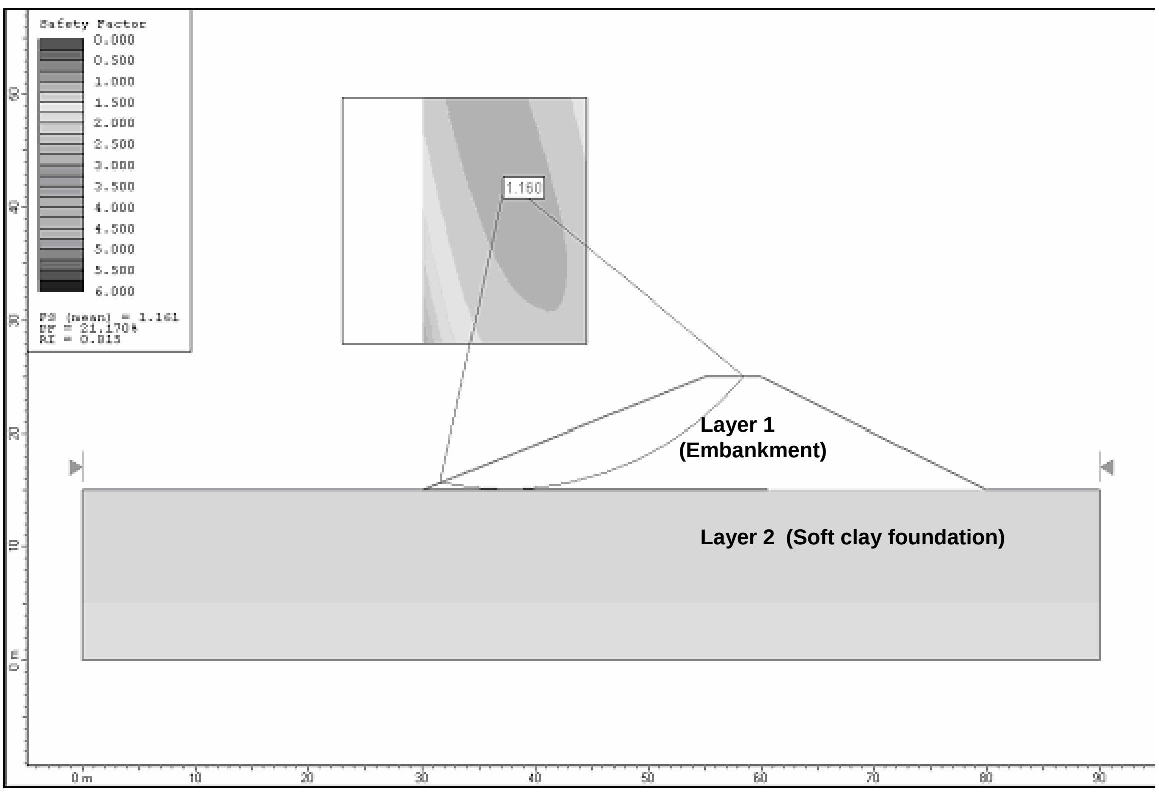


Figure 28.11 – Critical slip circle tangential to interface of embankment and foundation

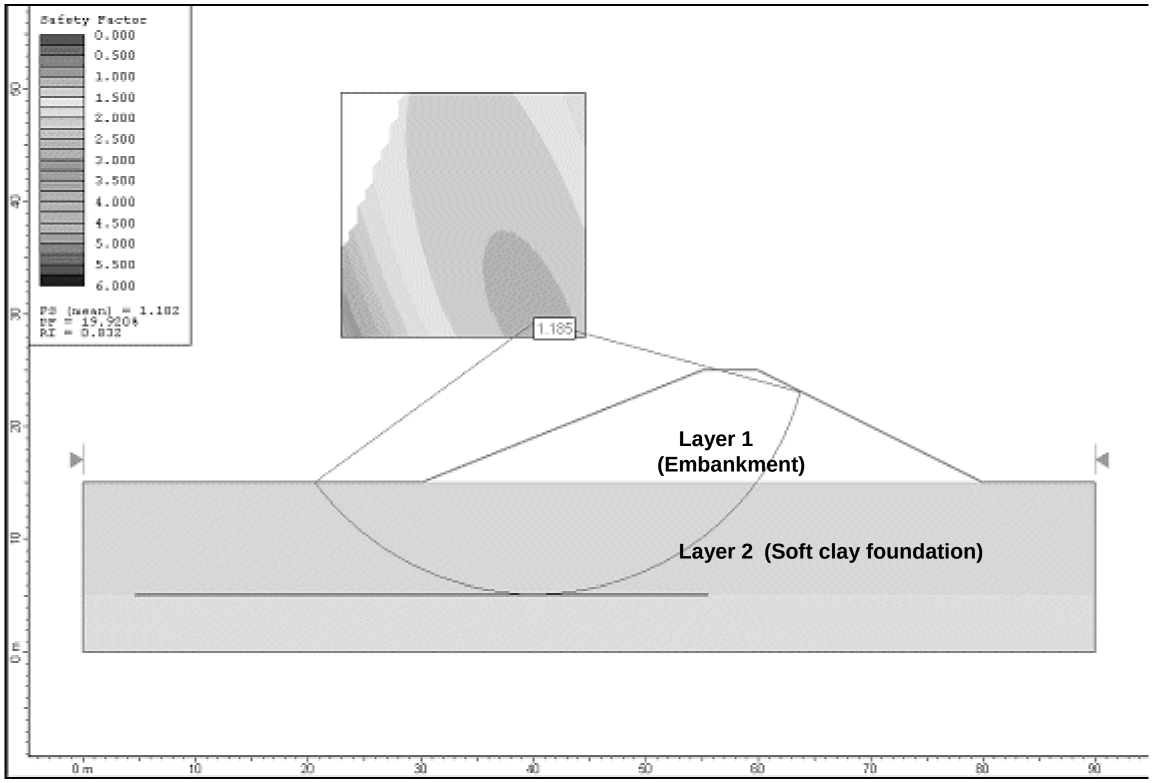


Figure 28.12 – Critical slip circle tangential to lower boundary of soft foundation layer

29.1 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 both 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 Properties

Table 29.1: Deterministic Material 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 Material Properties

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

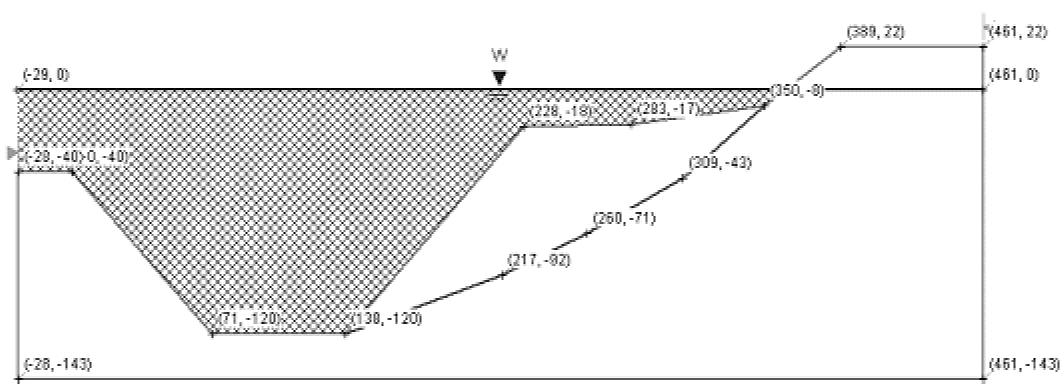


Figure 29.1 - Geometry

29.4 Results

Method	Deterministic Factor of Safety	Probability of Failure (%)	Reliability Index (lognormal)
Janbu Simplified	1.13	18	1.086
Janbu Corrected	1.17	15	1.0
Spencer	1.15	14	1.1
GLE	1.16	13	1.2

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.

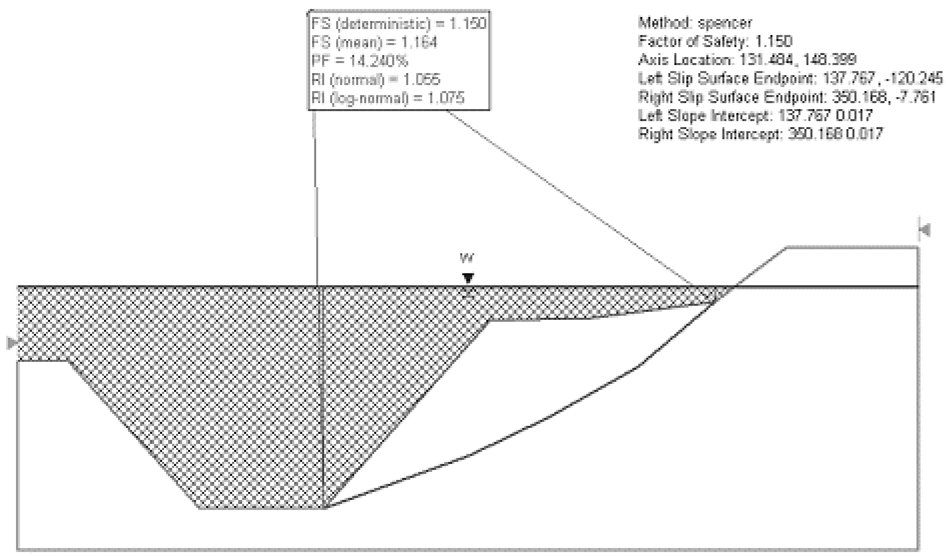


Figure 29.2

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 modeled as a passive force since this corresponds to how the authors implement the reinforcement force in their limit-equilibrium implementation.

30.3 Geometry and Properties

Table 30.1: Material Properties

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

	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

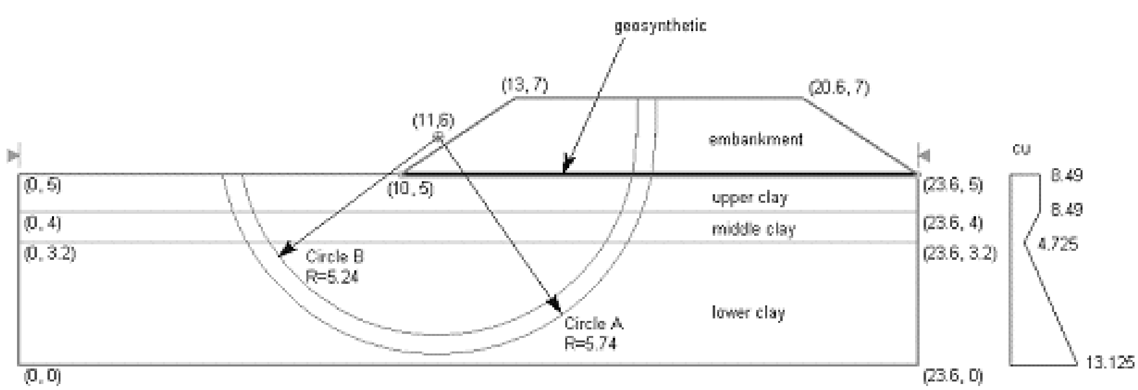


Figure 30.1 - Geometry

30.4 Results

	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.

31.1 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, 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 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 Properties

Table 31.1: Material Properties

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

	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

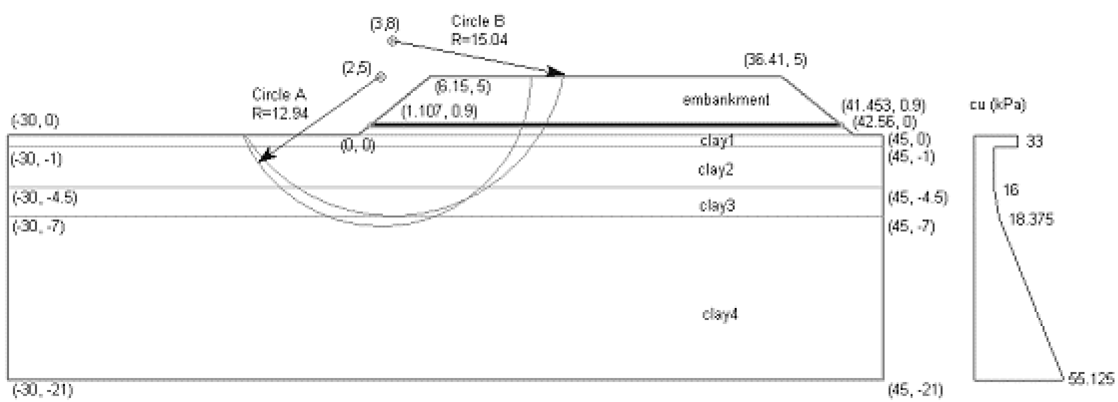


Figure 31.1

31.4 Results

	Factor of Safety	Overturning Moment (kN/m/m)	Resisting Moment (kN/m/m)
Circle A (Slide)	1.18	7521	8847
Circle A (Borges)	1.19	7667	9133
Circle B (Slide)	1.16	9463	11002
Circle B (Borges)	1.15	9540	10972

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 Figures 32.1 and 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 Properties

Table 32.1: Material Properties

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

	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

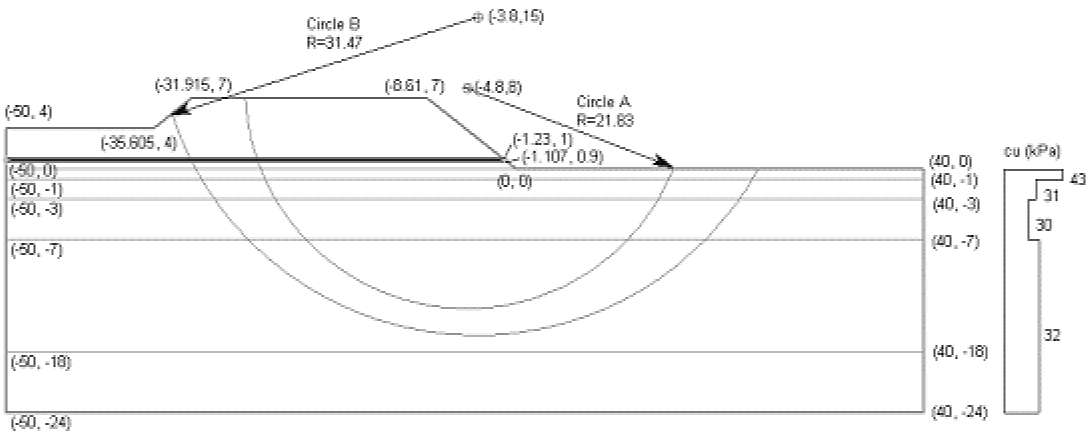


Figure 32.1 – Case 1 – Embankment height = 7m

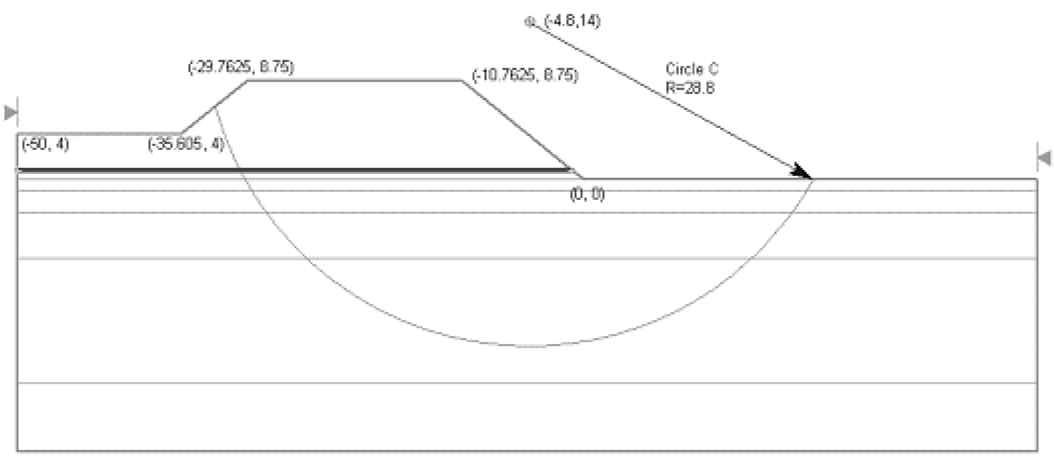


Figure 32.2– Case 2 – Embankment height = 8.75m

32.4 Results – Case 1 – Embankment height = 7m

	Factor of Safety	Overturning Moment (kN/m/m)	Resisting Moment (kN/m/m)
Circle A (Slide)	1.23	32832	40231
Circle A (Borges)	1.25	34166	42695
Circle B (Slide)	1.22	61765	75300
Circle B (Borges)	1.19	63870	75754

32.4 Results – Case 2 – Embankment height = 8.75m

	Factor of Safety	Overturning Moment (kN/m/m)	Resisting Moment (kN/m/m)
Circle C (Slide)	0.98	64873	63846
Circle C (Borges)	0.99	65116	64784

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 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 33.1 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.

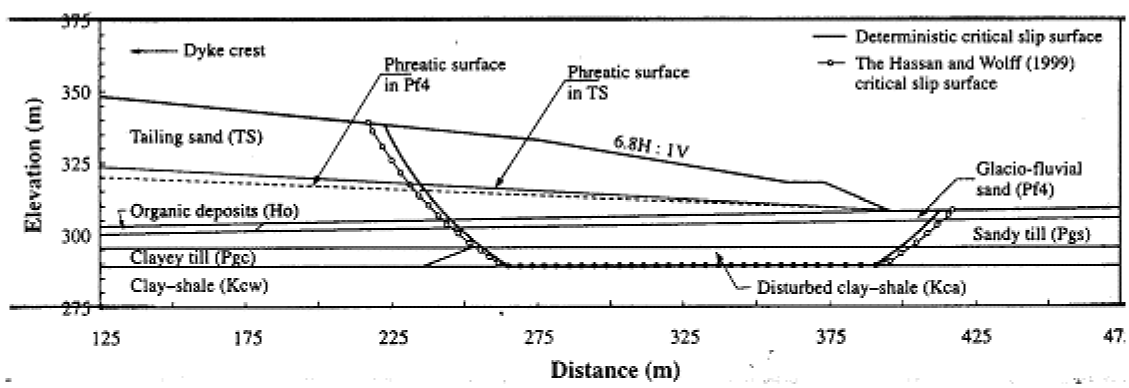


Figure 33.1

Table 33.1: Material 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

33.3 Geometry and Properties

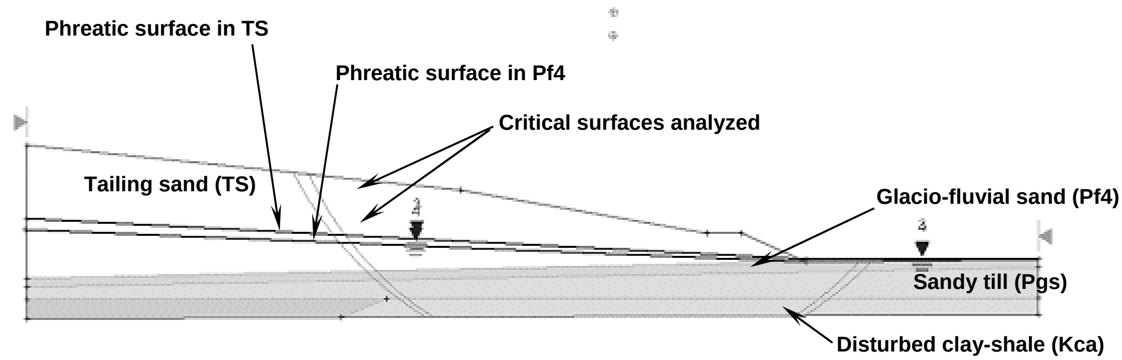
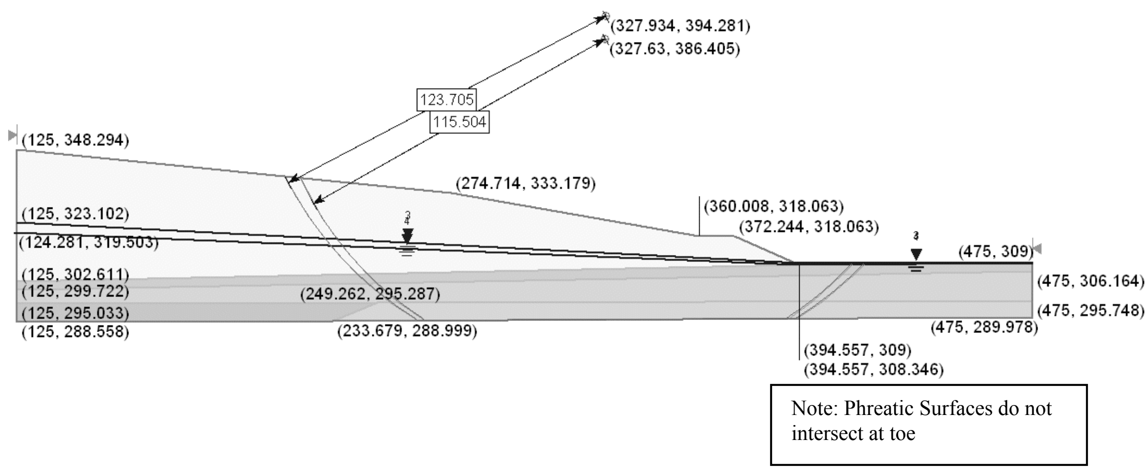


Figure 33.2a



33.4 Results

	Factor of Safety	Probability of Failure
Slide	1.305	1.54×10^{-2}
El-Ramly et al	1.31	1.6×10^{-2}

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.

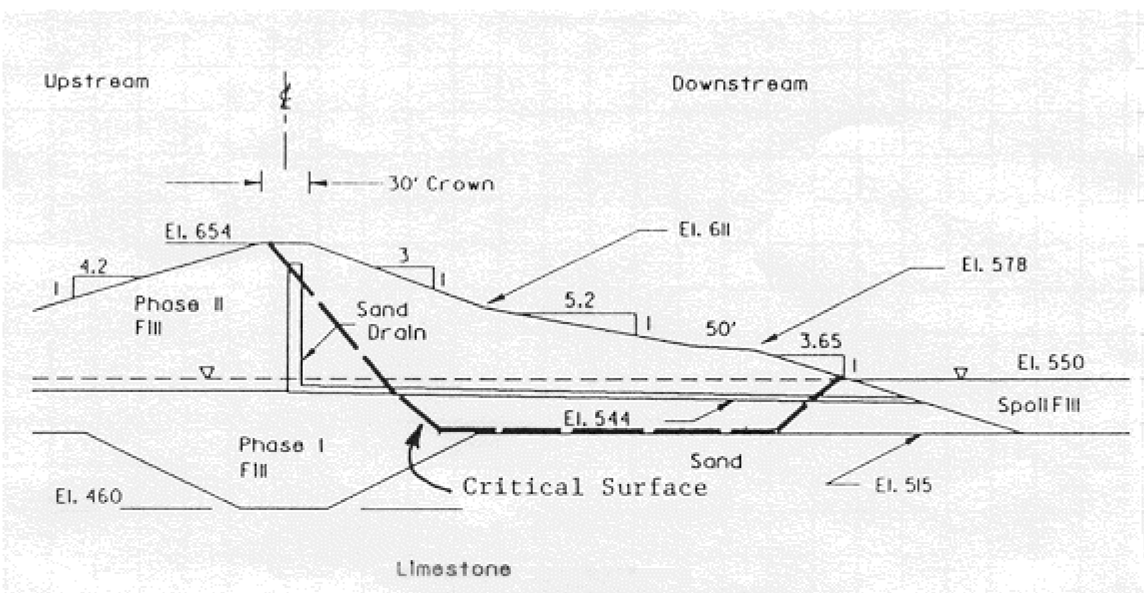


Figure 34.1

34.3 Geometry and Properties

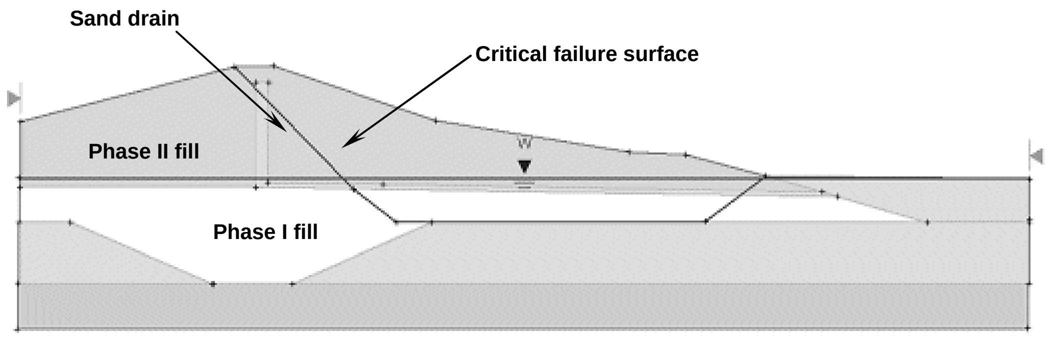


Figure 34.2

Table 34.1: Material 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

*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

	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}

35.1 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 circles, 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 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.

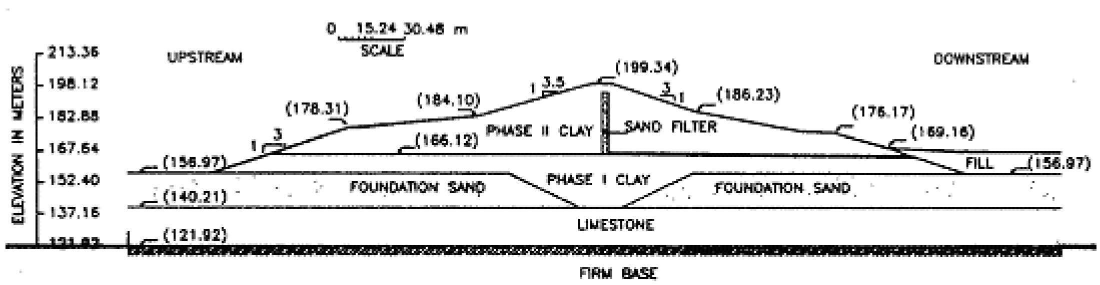


Figure 35.1 – Author's Geometry

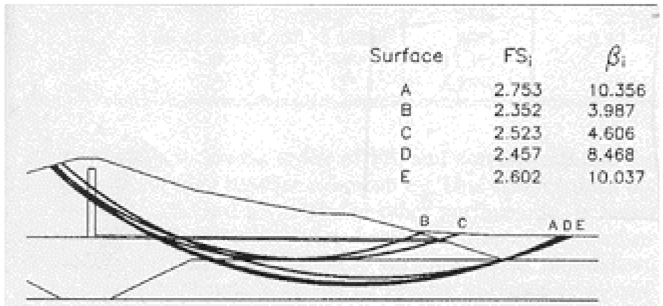


FIG. 7. Cannon Dam, Simplified Bishop Method (Failure Surfaces Obtained by Proposed Search Process)

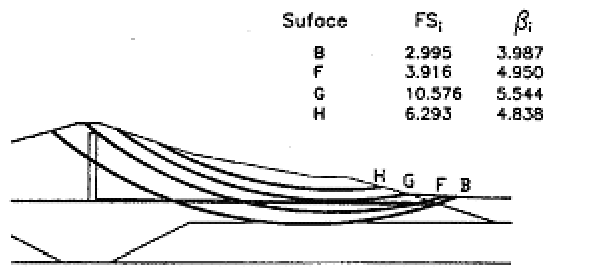


FIG. 8. Cannon Dam, Simplified Bishop Method (Search around Located Surface of Minimum Reliability Index)

Figure 35.2. Figures 7 and 8 from the Hassan and Wolff (1999) paper.

35.3 Geometry and Properties

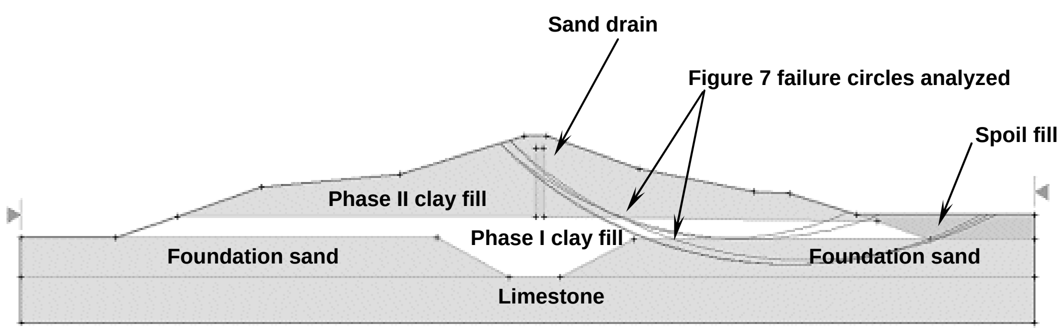


Figure 35.3

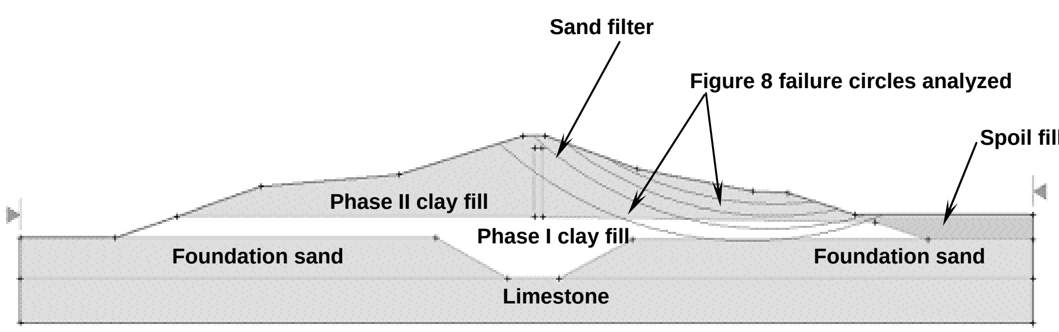


Figure 35.4

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

*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

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

36.1 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 material 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 shows the locations of the critical deterministic and probabilistic surfaces calculated by *Slide*.

36.3 Geometry and Properties

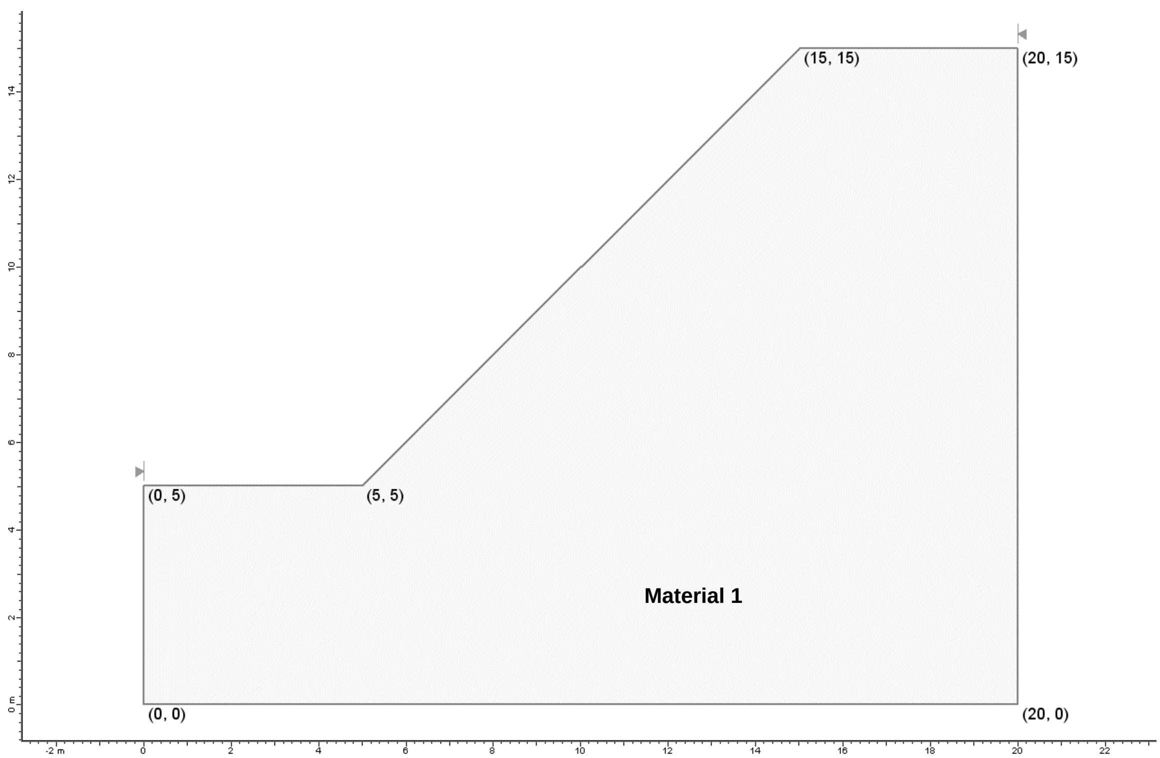


Figure 36.1

Table 36.1: Material 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 365.2: Results

Slide Results			Hasssan and Wolf Results	
Surface	Factor of Safety	Reliability Index (lognormal)	Factor of Safety	Reliability Index (lognormal)
Deterministic minimum factor of safety surface	1.339	2.471	1.334	2.336
Minimum reliability index surface	1.367	2.395	1.190	2.293
Overall slope (no particular surface)	1.349	2.382		

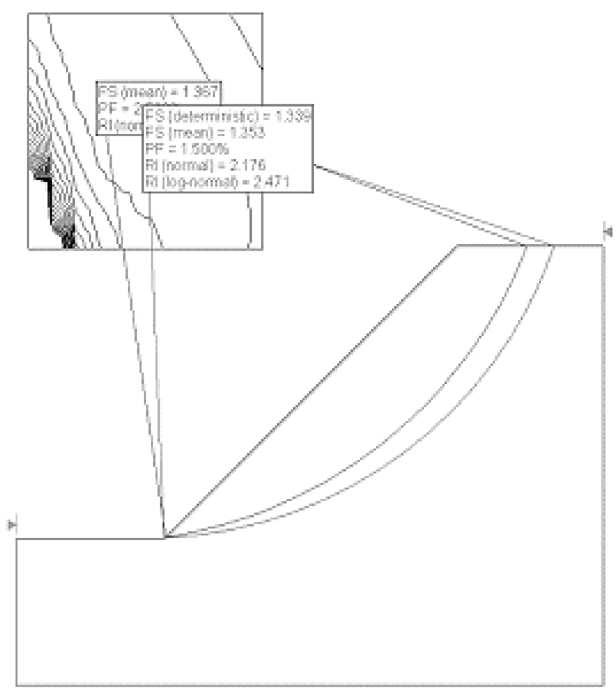


Figure 36.2. Slide critical deterministic and critical probabilistic surfaces.

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 describes 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 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 $F_r = \frac{F_{min}}{F_{crit}}$.

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.
All our results are provided in Table 37.1

37.3 Geometry and Properties

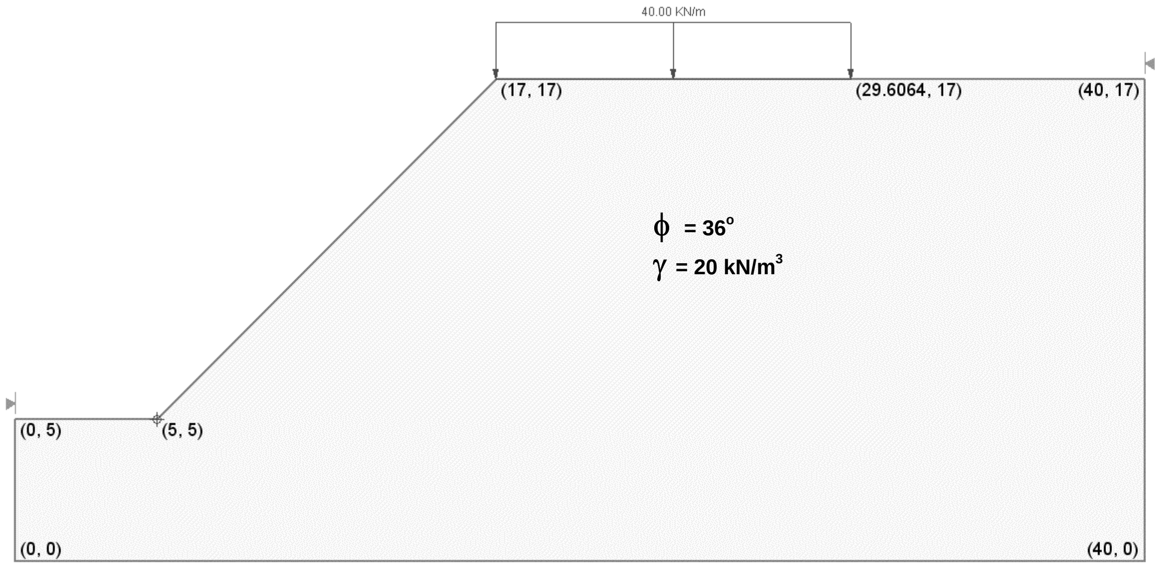


Figure 37.1

37.4 Results

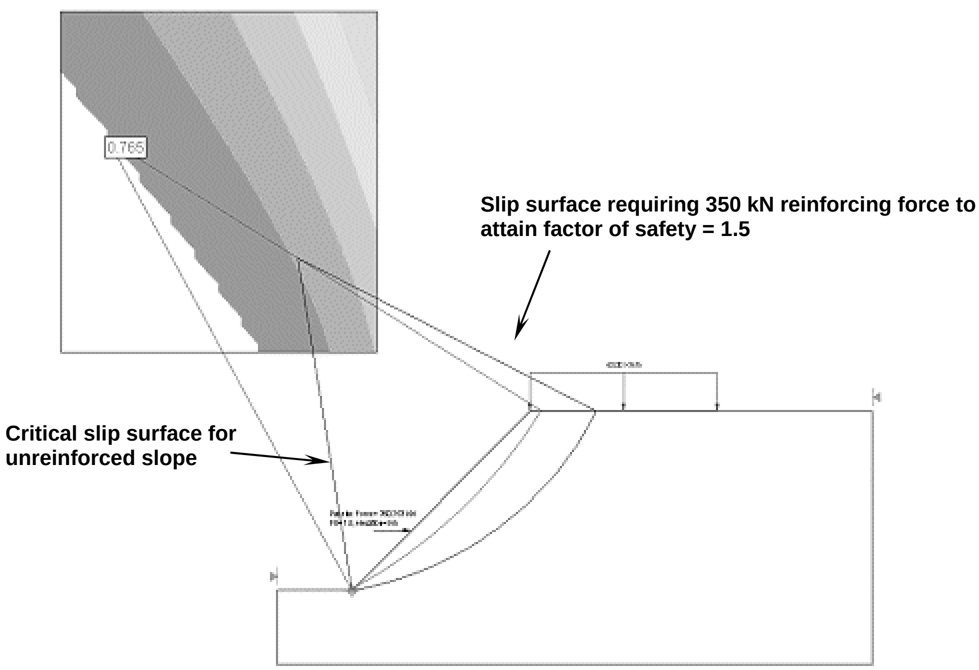


Figure 37.2

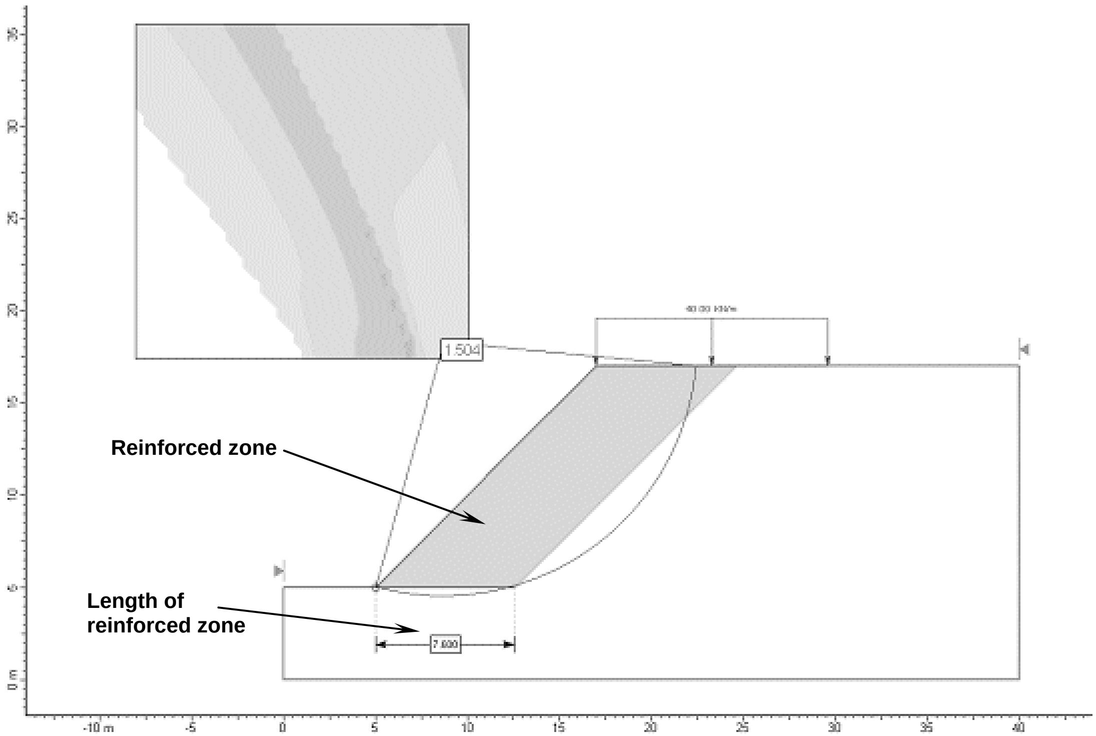


Figure 37.3

Table 37.1: Results

	Slide	XSTABL
Required reinforcement force (kN)	350	345
F_r	1.961	2.044
ϕ_{reinf} (^{o})	54.93	56.04
Length of reinforcement zone (m)	7.6	7.5

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 consists of a 24m thick soil layer, underlain by a 6m thick bedrock layer. Figure 37.1 describes the slope model.

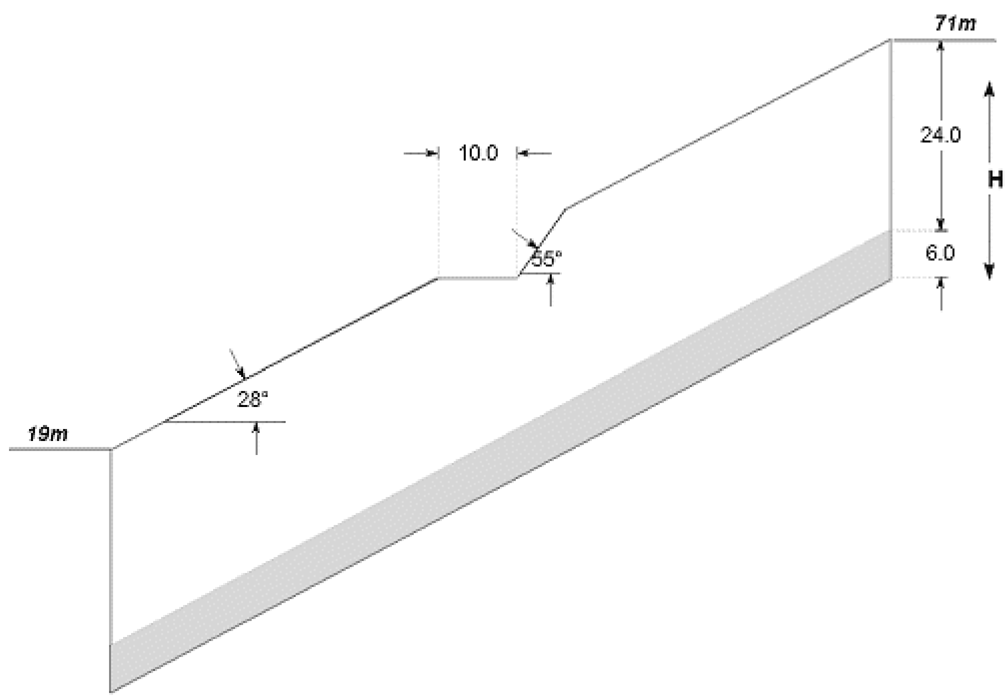


Figure 38.1 Model geometry

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, 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 37.3 shows the soil permeability function used to model the hydraulic conductivity of the soil, Ng (1998).

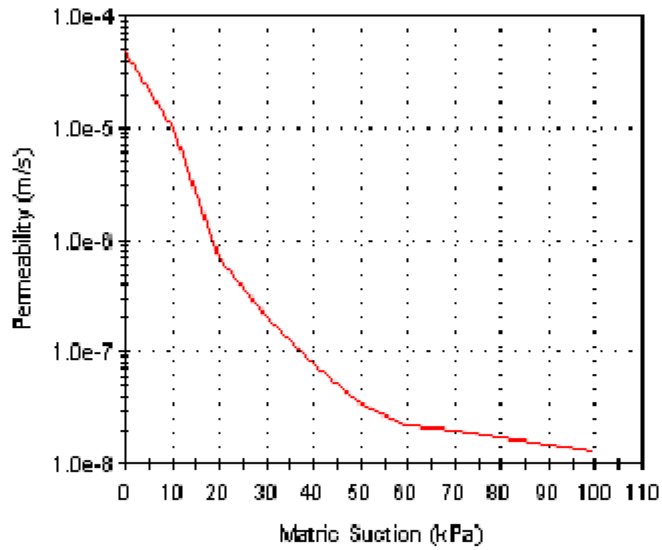


Figure 38.2 Hydraulic conductivity function

The negative pore water pressure, which is commonly refereed to as the matrix 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 matrix suction of the soil. Table 38.1 shows the material properties for the soil.

*The raw data for Figure 38.2 can be found in verification#38.sli.

Table 38.1 Material properties

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

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 Results (*tolerance = 0.0001*)

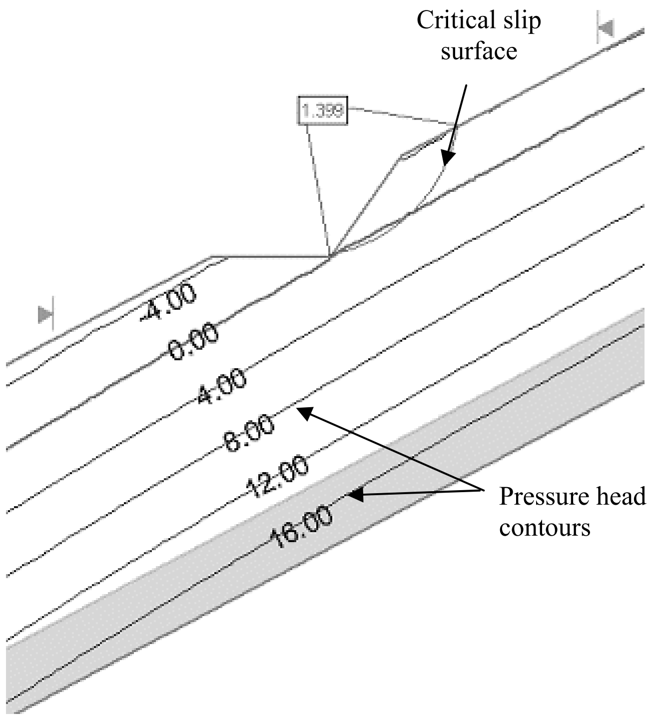


Figure 38.3 Slide groundwater and slope stability results for H=63m

Table 38.2: Factor of Safety results

H (total head at right side of slope)	***Slide***	**Ng. & Shi (1998)**
61m	1.616	1.636
62m	1.535	1.527
63m	1.399	1.436

39.1 Introduction

This model is taken from Tandjiria (2002), their problem 1 example. 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. modeled the force.

39.3 Geometry and Properties

Table 39.1: Material Properties

	Cu/c′ (kN/m^2)	ϕ′ (deg.)	γ (kN/m^3)
Clay Fill Embankment	20	0	19.4
Sand Fill Embankment	0	37	17
Soft Clay Foundation	20	0	19.4

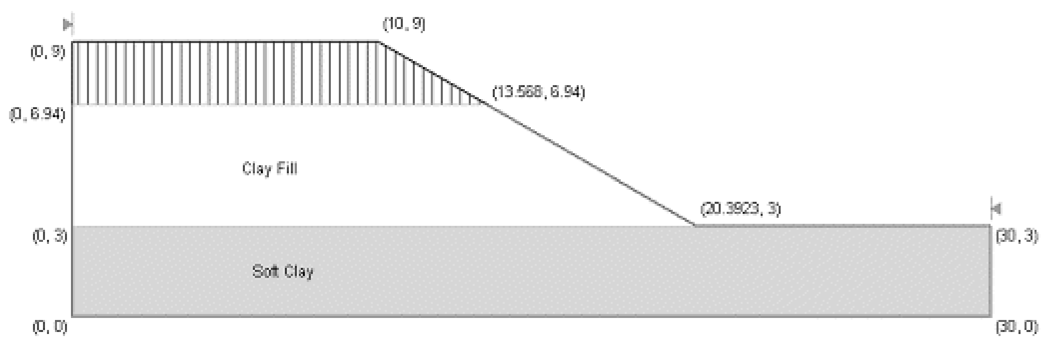


Figure 39.1 - Clay Fill Embankment

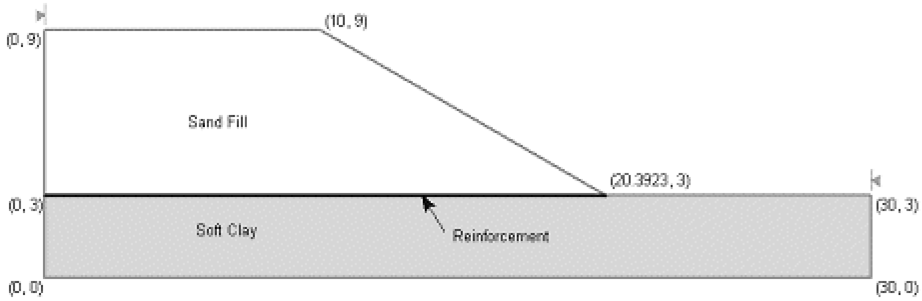


Figure 39.2 - Sand Fill Embankment

39.4 Circular Results – Clay embankment with no reinforcement

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

Tandjiria (2002) Spencer Factor of Safety = 0.981

39.5 Noncircular Results – Clay embankment with no reinforcement

Method	Factor of Safety
Spencer	0.932
GLE/M-P	0.941

Tandjiria (2002) Spencer Factor of Safety = 0.941

39.6 Circular Results – Sand embankment with no reinforcement

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

Tandjiria (2002) Spencer Factor of Safety = 1.219

39.7 Noncircular Results – Sand embankment with no reinforcement

Method	Factor of Safety
Spencer	1.189
GLE/M-P	1.196

Tandjiria (2002) Spencer Factor of Safety = 1.192

39.8 Circular Results – Clay embankment with reinforcement

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

Tandjiria (2002) Reinforcement Force = 170 KN/m

39.9 Noncircular Results – Clay embankment with reinforcement

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

Tandjiria (2002) Reinforcement Force = 190 KN/m

39.10 Circular Results – Sand embankment with reinforcement

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

Tandjiria (2002) Reinforcement Force = 45 KN/m

39.11 Noncircular Results – Sand embankment with reinforcement

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

Tandjiria (2002) Reinforcement Force = 56 KN/m