Slide

2D limit equilibrium slope stability
for soil and rock slopes

Verification Manual

Part 2

40.1 Introduction

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

40.2 Problem Description

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

40.3 Geometry and Properties

Table 40.1: Material Properties

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

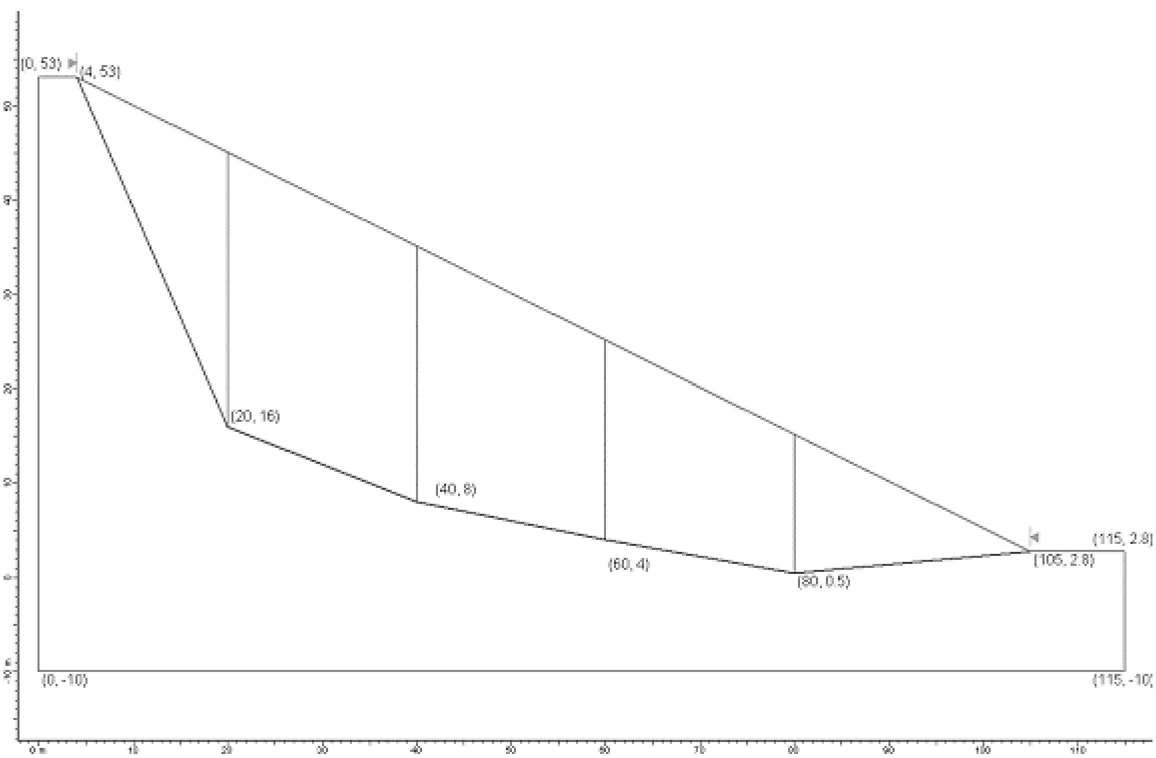


Figure 40.1

40.4 Results

Method	Factor of Safety
Janbu Simplified	0.944

Note : Referee Factor of Safety = 0.98 [Perry]

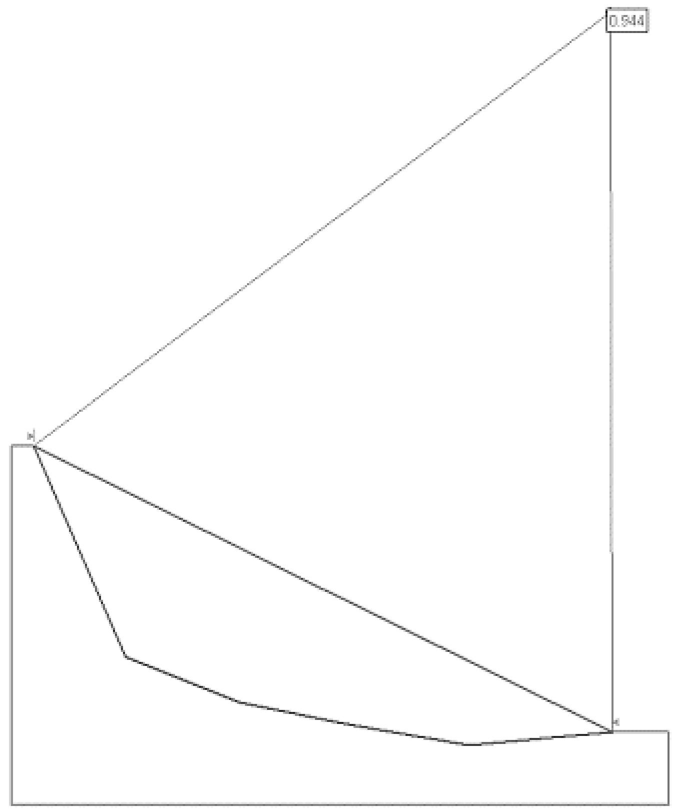


Figure 40.2 – Solution Using the Janbu Simplified Method

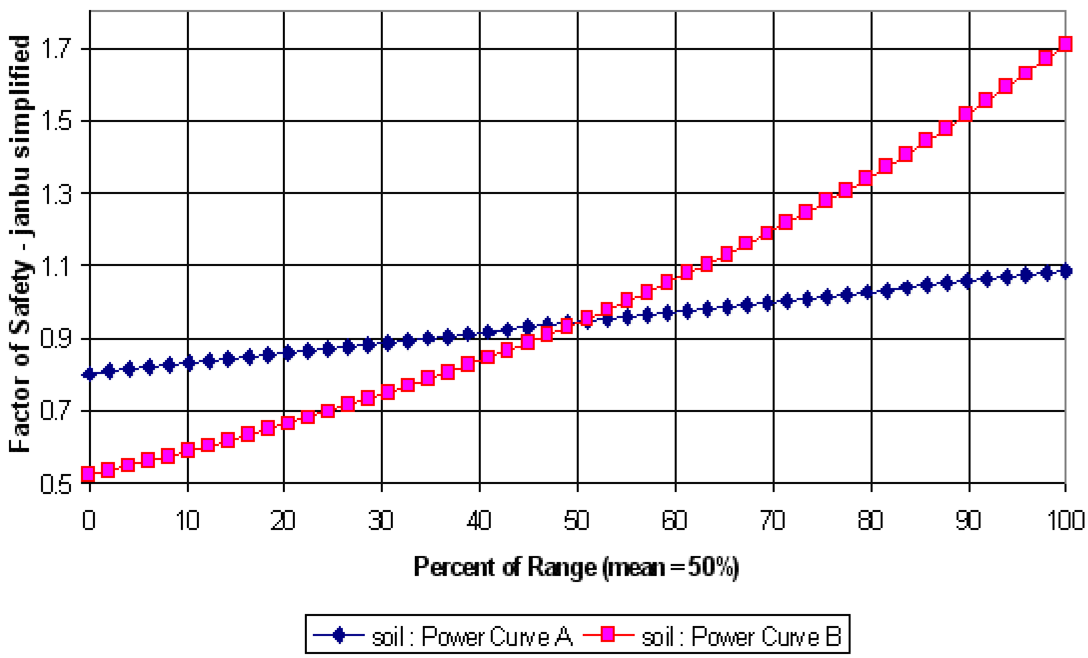


Figure 40.3 – Sensitivity Analysis on A and b.

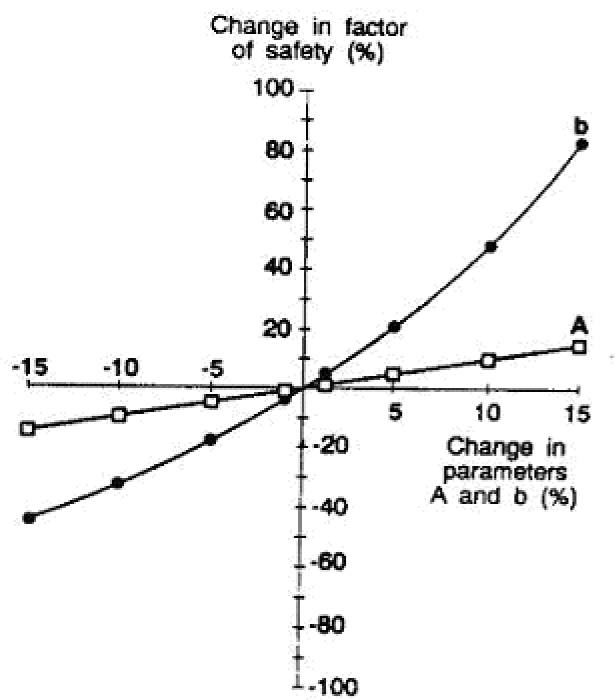


Figure 40.4 – Perry's variation of factor safety with shear strength parameters.

41.1 Introduction

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

41.2 Problem Description

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

41.3 Geometry and Properties

Table 41.1: Material Properties

A	B	γ (kN/m^3)
1.4	0.8	20.0

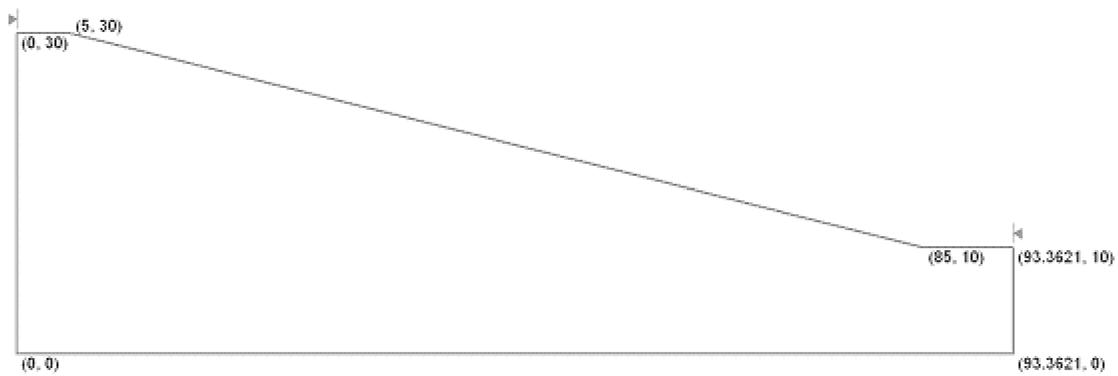


Figure 41.1

41.4 Results

Method	Factor of Safety
Janbu Simplified	1.563
Bishop	1.656

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

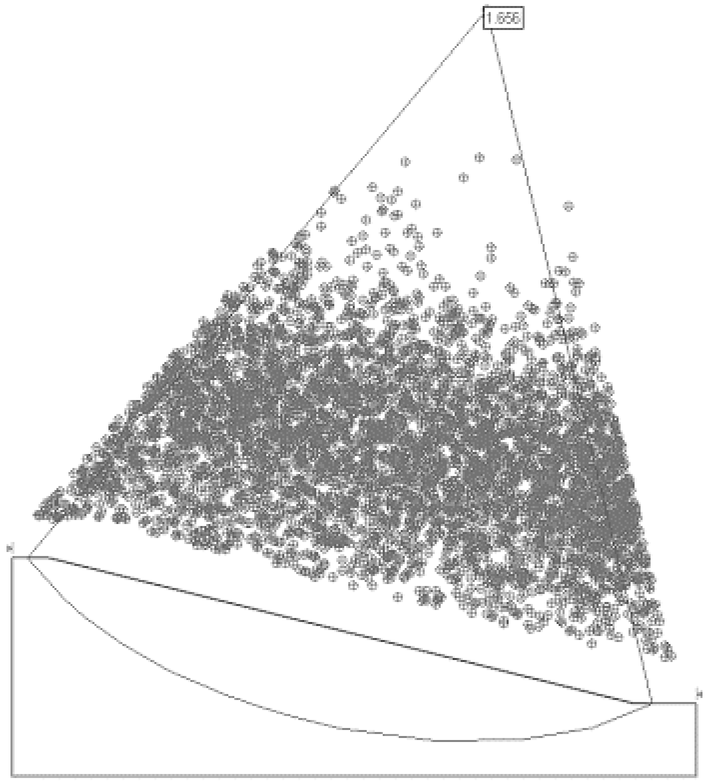


Figure 41.2 – Solution using Bishop method

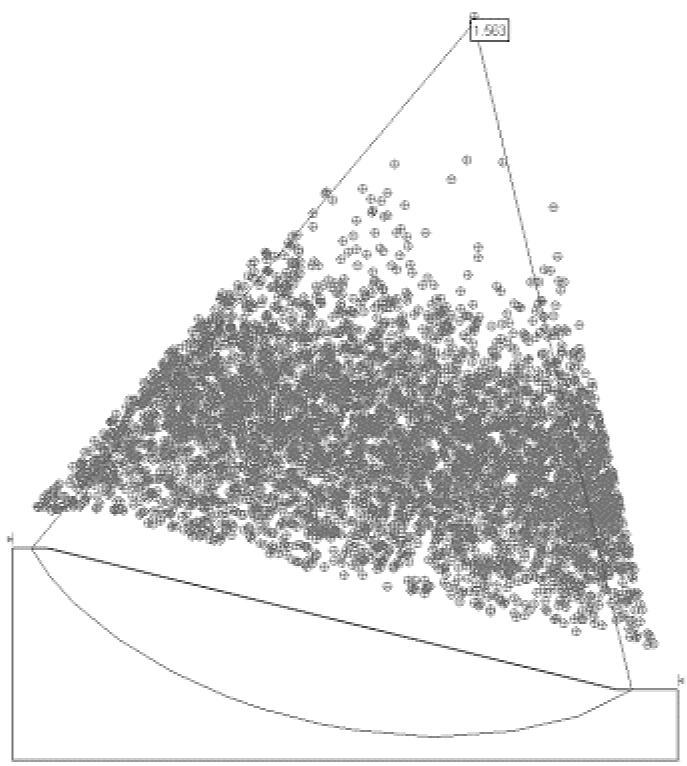


Figure 41.3 – Solution using Janbu Simplified method

42.1 Introduction

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

42.2 Problem Description

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

42.3 Geometry and Properties

Table 42.1: Material Properties

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

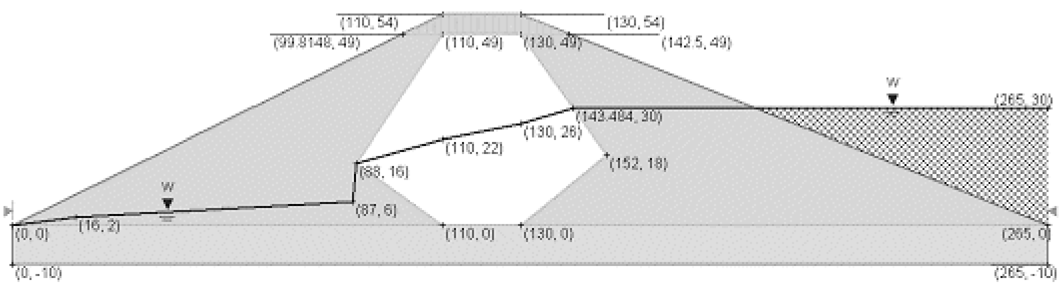


Figure 42.1 - Geometry

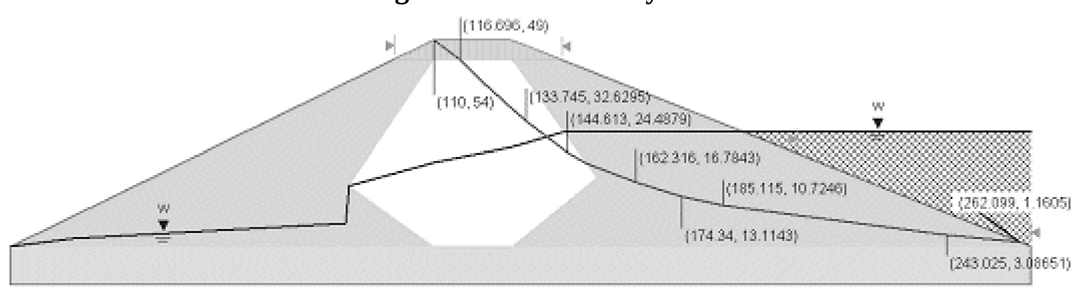


Figure 42.2 – Location of noncircular failure surface

42.4 Results – Circular failure surface, 80x80 grid.

Method	Factor of Safety
Spencer	1.923

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

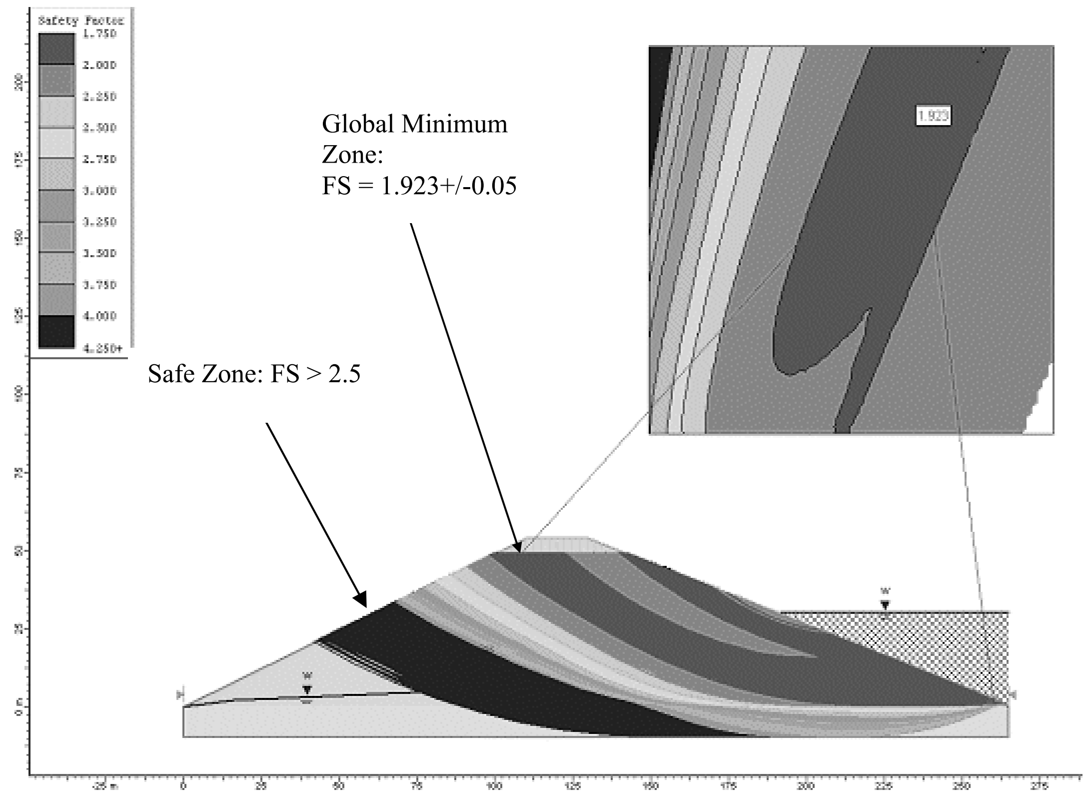


Figure 42.3 – Safety map featuring global minimum zone using Spencer method

Note: Contour Settings were modified to achieve detailed safety map.

42.5 Results – Noncircular using Random search with Optimization (zero faces)

Method	Factor of Safety
Spencer	1.857

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

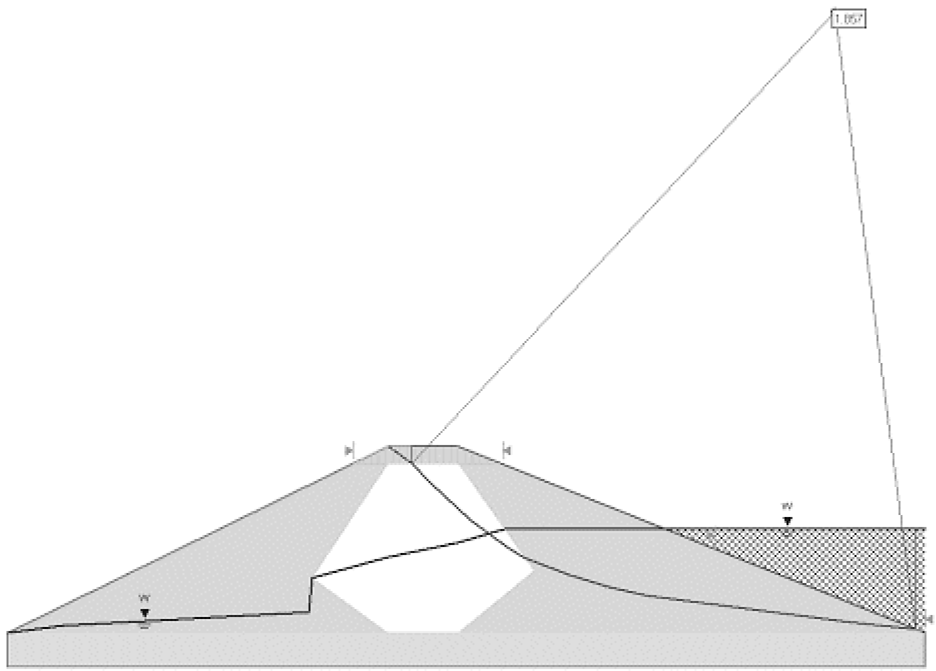


Figure 42.4 – Noncircular failure surface using Random search with optimization

43.1 Introduction

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

43.2 Problem Description

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

43.2 Geometry and Properties

Table 43.1: Material Properties

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

Figure 43.1

Note: For critical planar surface solution, use a block search with a focus point at the toe and a focus line along the bench. For the circular search, move the left limit (11,10) to only include Zone A. Grid should go no higher than 17.5 to avoid anomalous results. Janbu simplified must be used to coincide with the author's use of the Culmann method.

43.4 Results

Method	Factor of Safety	Angle (deg)
Janbu Simplified	1.352	49.5
RocPlane 2.0	1.351	49.5

Note: Baker (2001) Culmann FS = 1.35

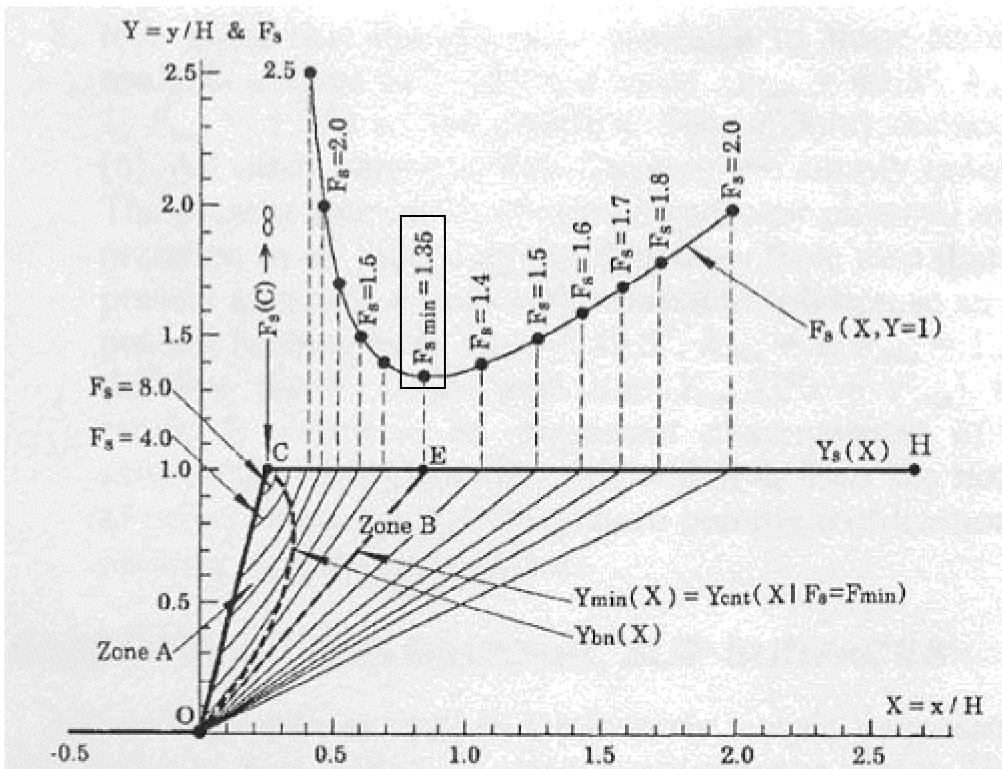
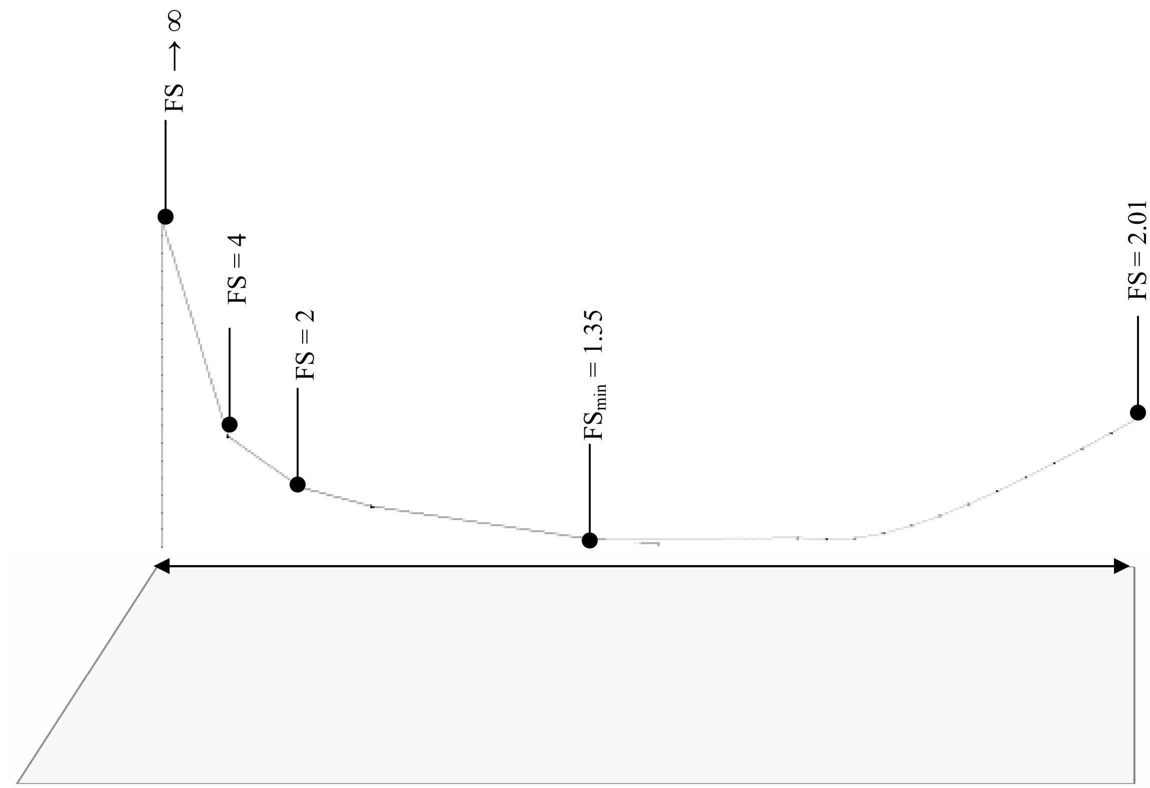


Figure 43.4.1 – Baker's Distribution (Referee plot)



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

Figure 43.4.2 – FS spatial distribution with failure surface distribution along x-axis.

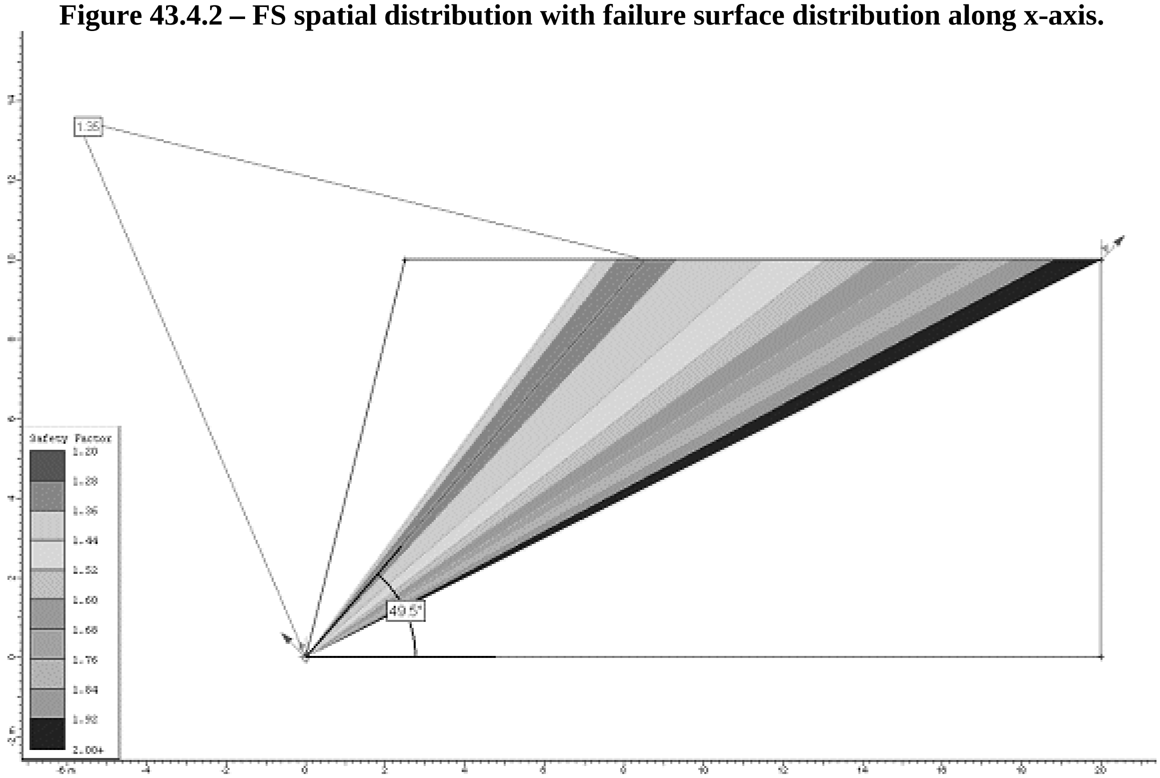


Figure 43.4.3 – Planar failure surfaces using Janbu simplified method

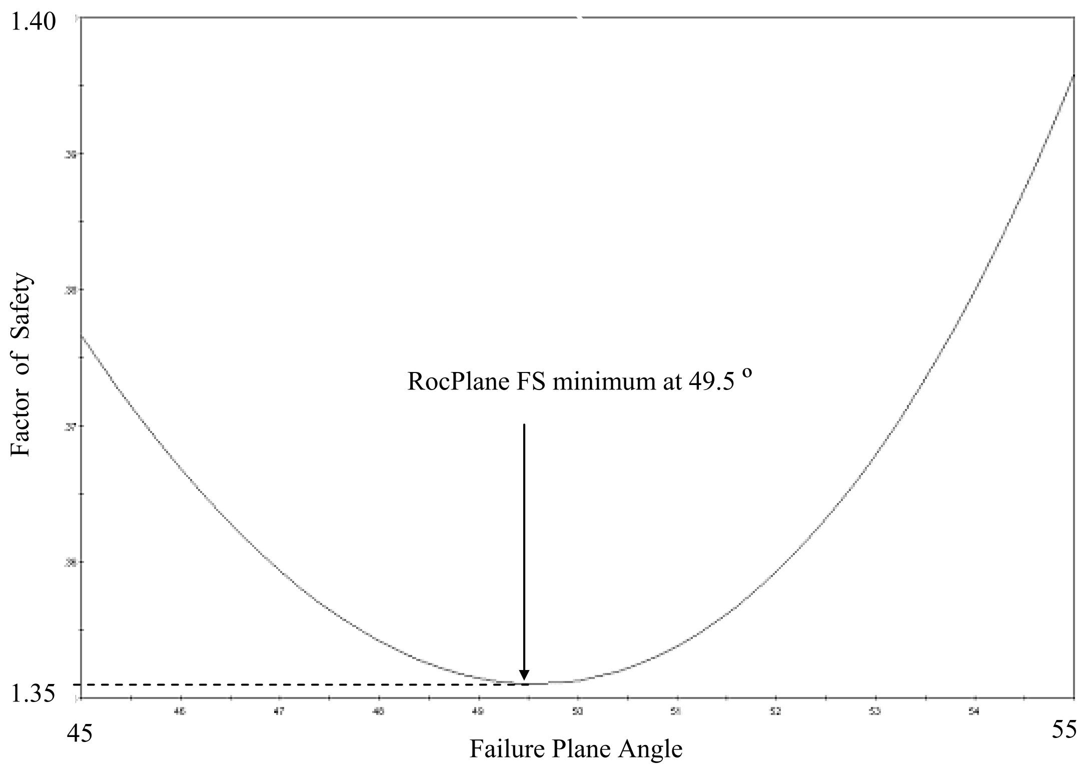


Figure 43.4.4 – Solution using RocPlane 2.0

44.1 Introduction

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

44.2 Problem Description

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

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

The power curve variables are in the form:

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

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

44.3 Geometry and Properties

Table 44.1 Material Properties

Material	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)	A	n	T	a	b	c
Clay	11.64	24.7	18	0.58	0.86	0	1.107	0.86	0
Clay, iterative results	0.39	38.6	18						

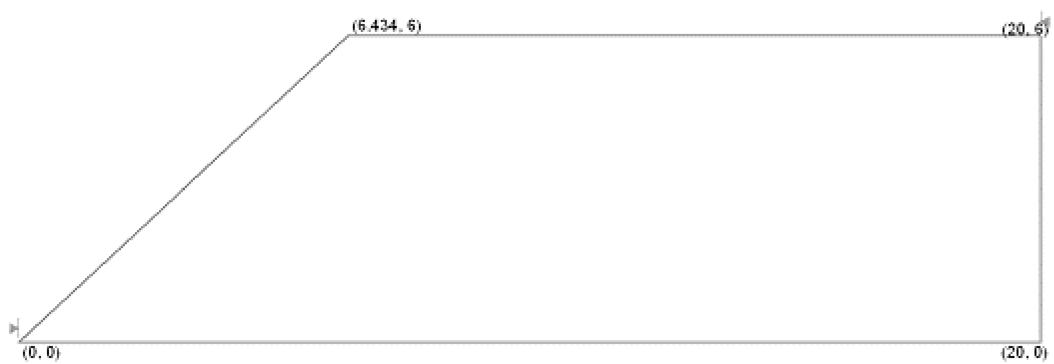


Figure 44.1 - Geometry

44.4 Results – Circular

Strength Type	Method	Factor of Safety	Maximum effective normal stress (kPa)
Power Curve	Janbu Simplified	0.92	15.37
	Spencer	0.96	11.51
Mohr-Coulomb	Janbu Simplified	1.47	41.84
	Spencer	1.54	37.55
Mohr-Coulomb with iteration results ($c' = 0.39$ kPa, $\phi' = 38.6°$)	Janbu simplified	0.96	9.6
	Spencer	0.98	8.83

Baker (2003) non-linear results: FS = 0.97, $\sigma_{max} = 8.7$

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

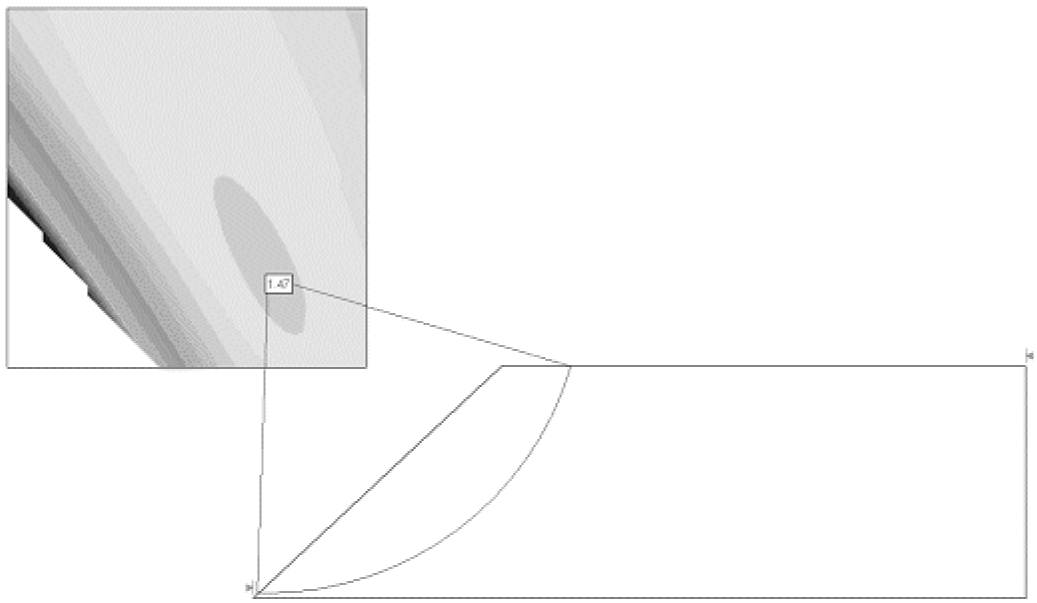


Figure 44.2 – Critical failure surface using Mohr-Coulomb criterion, Janbu simplified

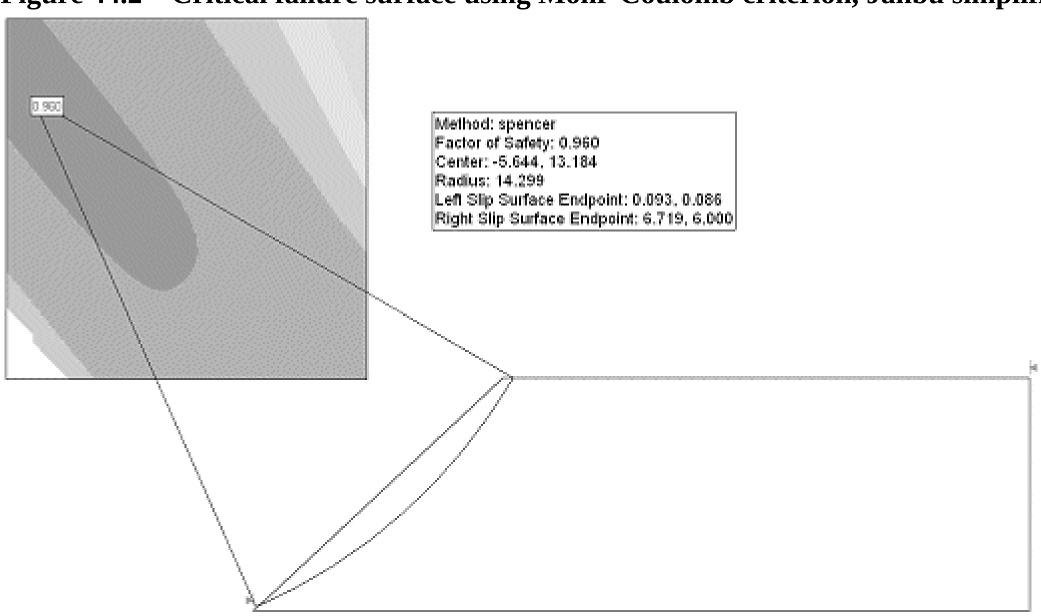


Figure 44.3 – Critical failure surface using power curve criterion, Spencer

45.1 Introduction

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

45.2 Problem Description

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

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

The power curve variables are in the form:

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

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

45.3 Geometry and Properties

Table 45.1: Material Properties

Material	c´ (kN/m^2)	ϕ´ (deg.)	γ (kN/m^3)	A	n	T	a	b	c
Clay	11.64	24.7	18	0.58	0.86	0	1.107	0.86	0
Clay, iterative results	0.39	38.6	18						

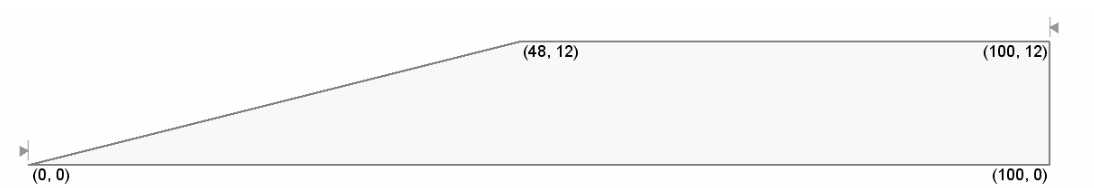


Figure 45.1 - Geometry

45.4 Results – circular, Janbu simplified

Strength Type	Method	Factor of Safety	Maximum effective normal stress (kPa)
Power Curve	Janbu Simplified	2.56	99.53
	Spencer	2.66	93.03
Mohr-Coulomb	Janbu Simplified	2.66	117.88
	Spencer	2.76	106.16

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

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

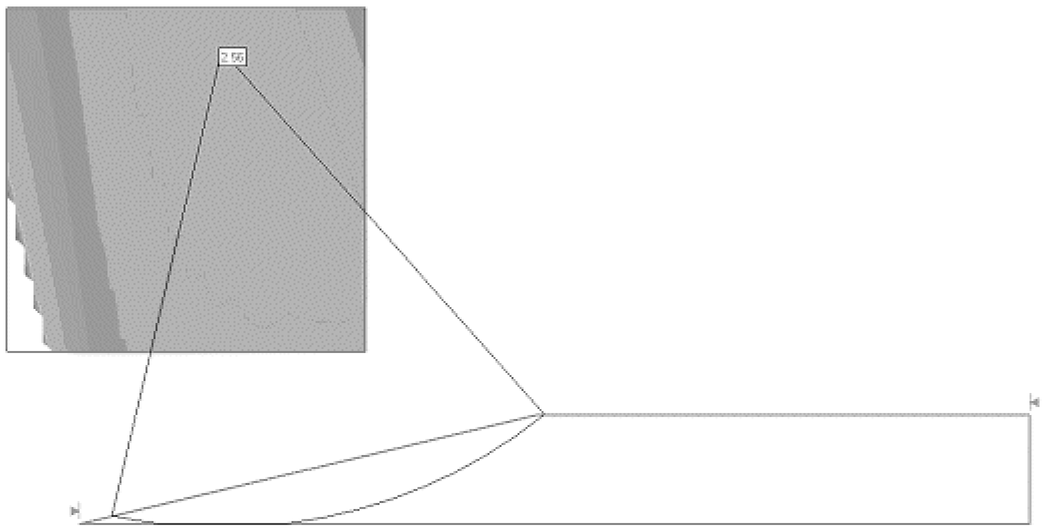


Figure 45.2 – Critical failure surface using power curve criterion.

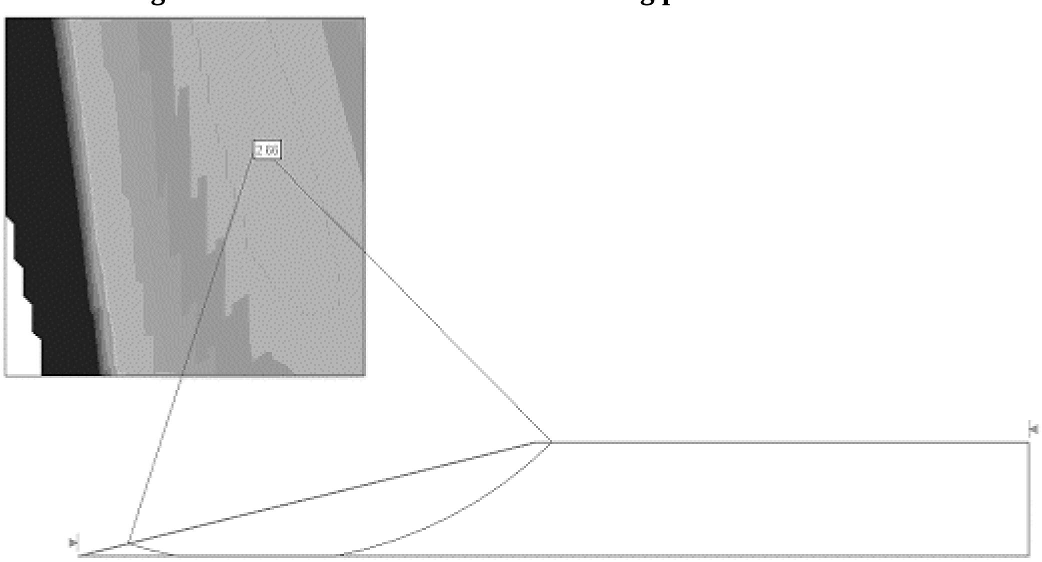


Figure 45.2 – Critical failure surface using Mohr-Coulomb criterion.

46.1 Introduction

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

46.2 Description

Problem #46 is divided into three loading conditions. All stages analyze the same dam (Figure 46.1,46.2) with the same material properties (Table 1), given in Baker (1993).
Stage 1 requires the factor of safety and noncircular critical surface of the dam when the reservoir is dry and empty (i.e. post-construction).
Stage 2 utilizes a finite element groundwater analysis, and the factor of safety and noncircular critical surface of the dam are required under steady state conditions. The water is 10 m deep, and the water table is horizontal at elevation 0 m.
Stage 3 requires the factor of safety and noncircular failure surface of the dam after it has been subjected to rapid draw-down (i.e. undrained loading conditions). Undrained shear strength is not known at this stage, and must be manually extracted from the author's data (Figure 46.3). This data can also be found as <Compacted Clay.fn6> and <Natural Clay.fn6>, which is included with the Verification Programs.

46.3 Geometry and Properties

Table 46.1: Material Properties

Material	c' (kN/m^2)	ϕ' (deg.)	γ (kN/m^3)	K_s	K2/K1	K1 Angle	a	n
Compacted Clay	6.5	40	18	7e-5	0.1	0	0	0
Natural Clay	0	32	18	7e-5	0.1	0	0.06	2

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

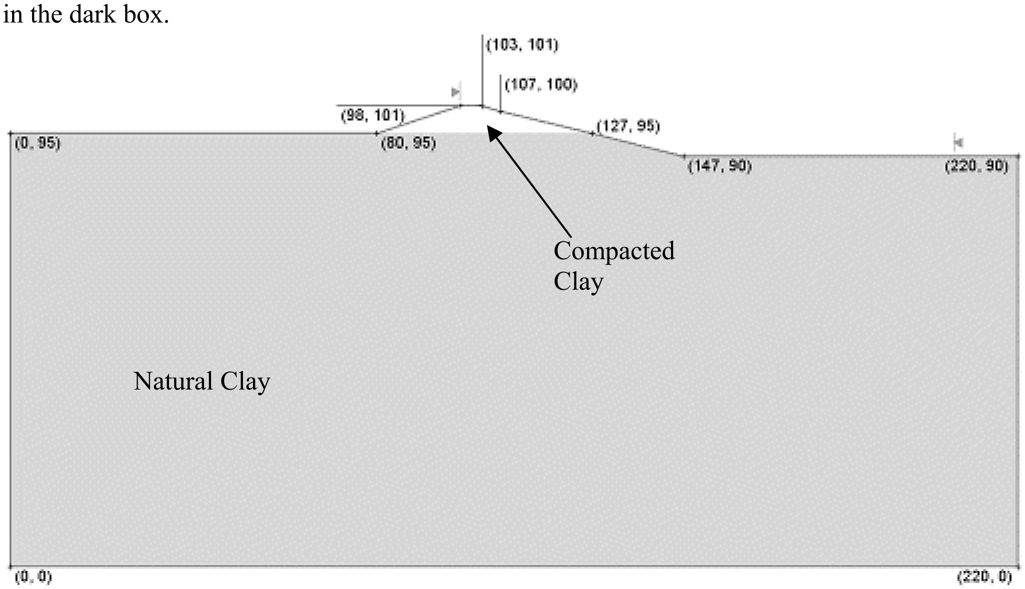


Figure 46.1 – Geometry: Stage 1

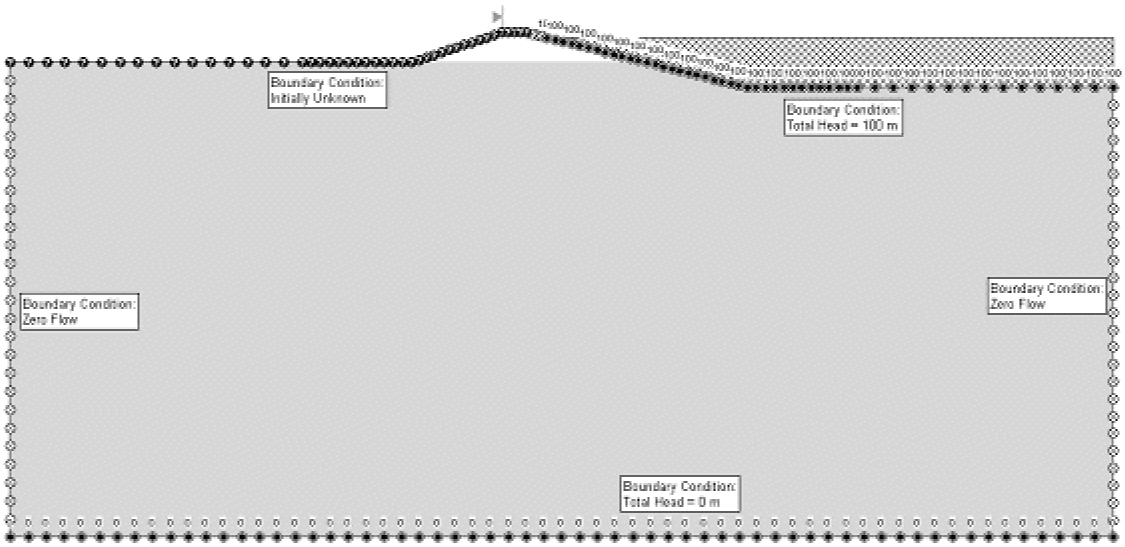


Figure 46.2 – Geometry: Stage 2

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

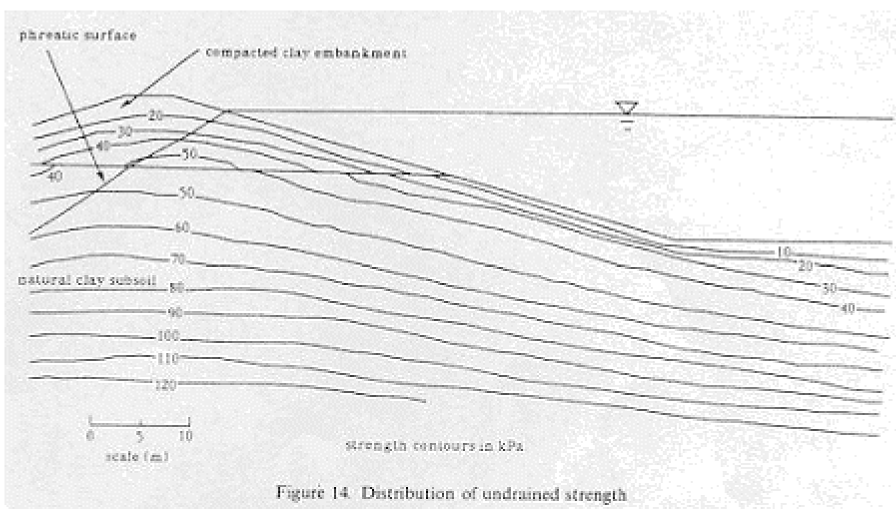


Figure 46.3 – Baker's parameters for stage 3.

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

46.4 Results

46.4.1 - Stage 1 Results – Post-construction, Random search

Method	Factor of Safety
Spencer	2.53

Baker (1993) FS = 2.41
Theoretical FS = 2.5

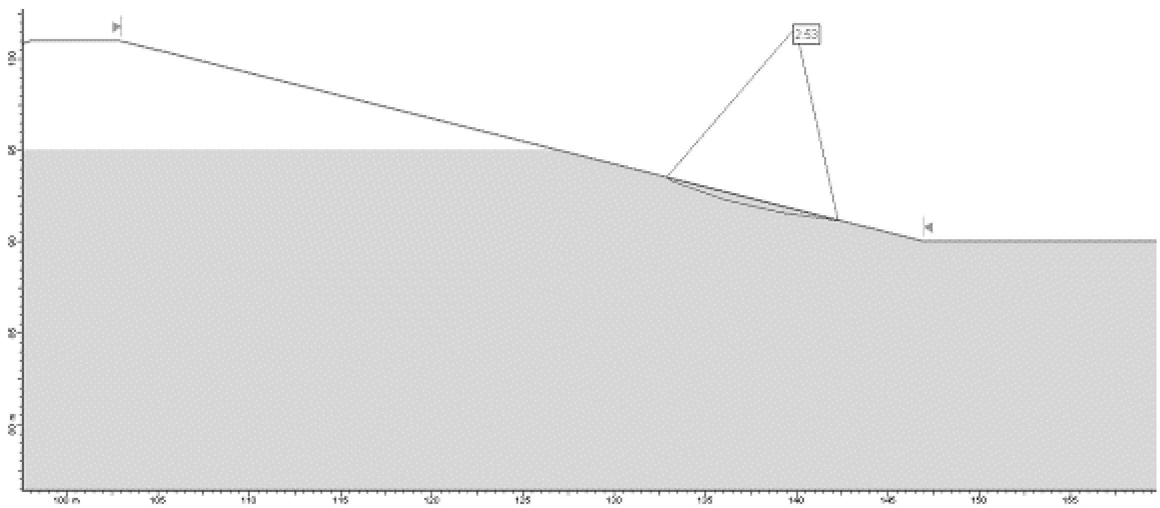


Figure 46.4.1 – Critical failure surface using Spencer's method.

46.4.2 - Stage 2 Results – steady state conditions, random search

Method	Factor of Safety
Spencer	7.01

Baker (1993) FS = 6.98

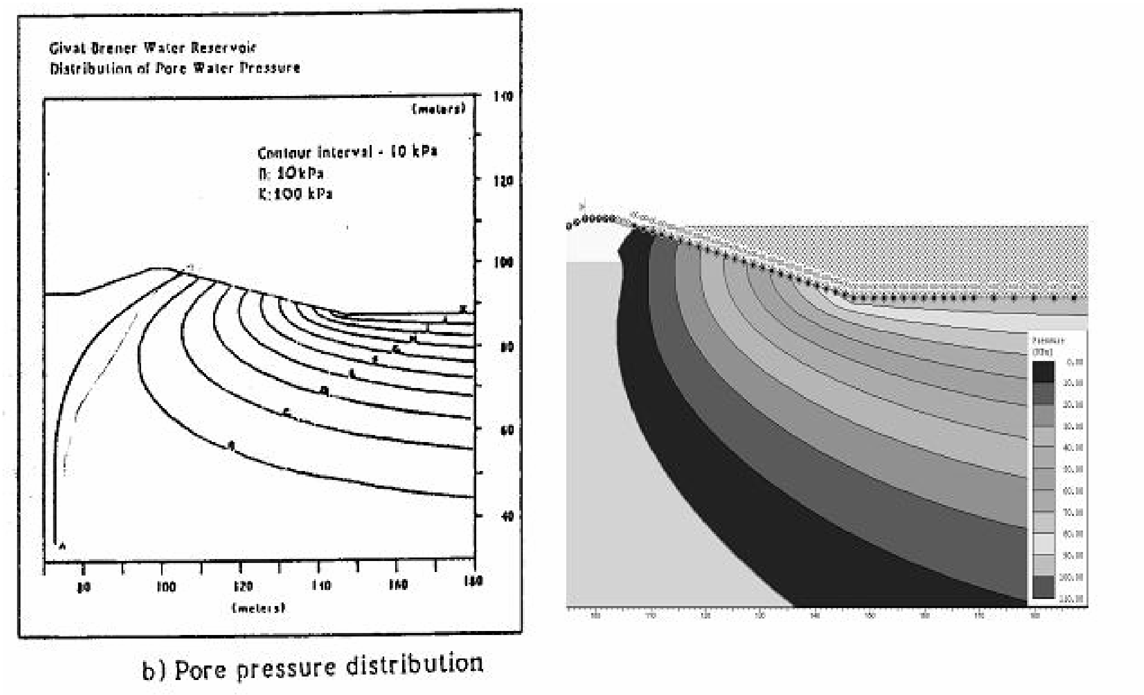


Figure 46.4.2 – Comparison of Baker's pore pressure contours with SLIDE's

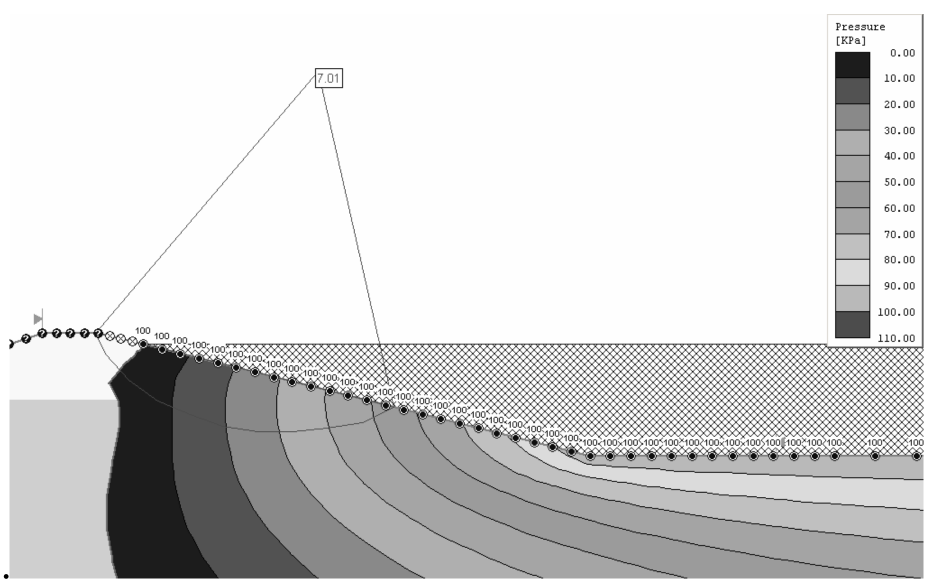
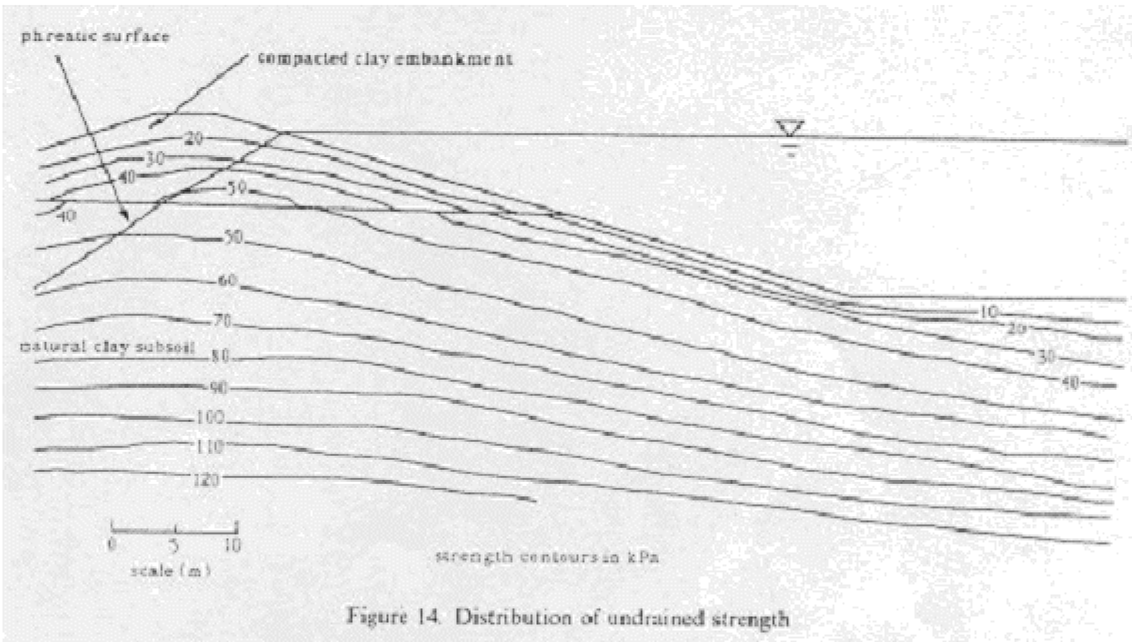


Figure 46.4.3 – Critical failure surface using Spencer's method.

46.4.3 – Stage 3 Results – Rapid draw-down conditions, random search with optimization

Method	Factor of Safety
Spencer	2.18

Baker (1993) FS = 2.18



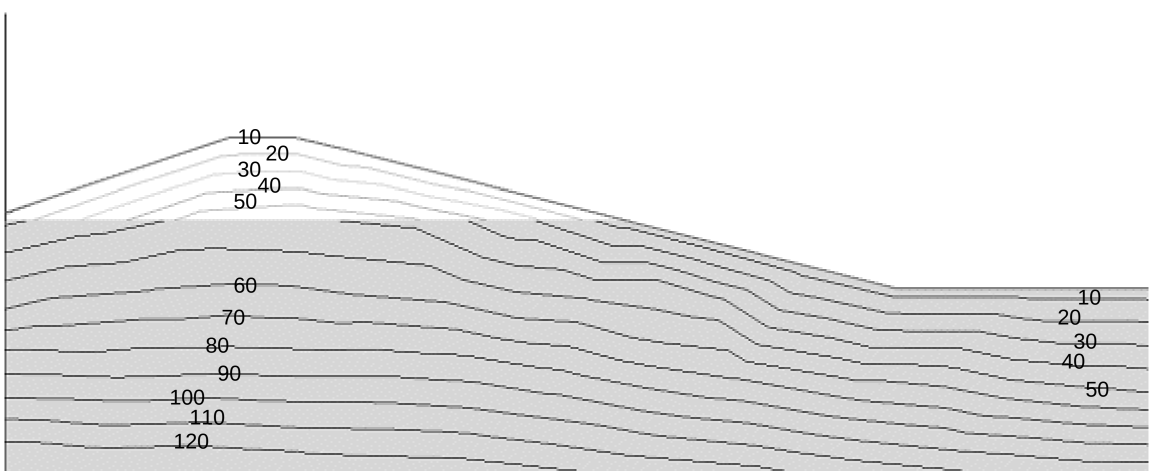


Figure 46.4.4 – Comparison of Baker's strength contour with SLIDE's contours.

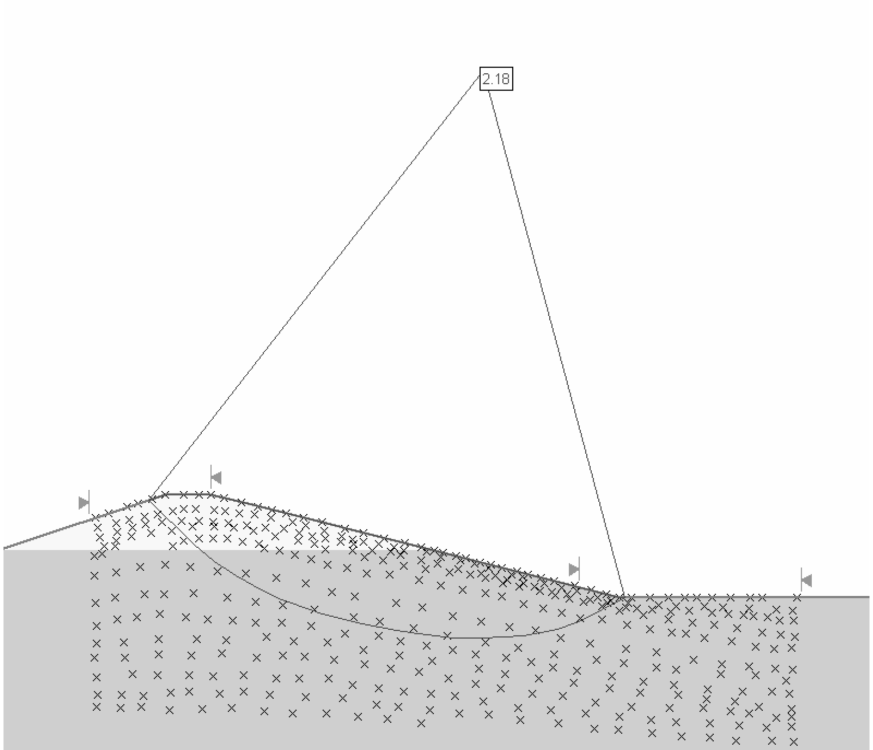


Figure 46.4.5 – Critical failure surface using Spencer's method.

47.1 Introduction

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

47.2 Description

Verification Problem #46 examines planar failure of a soil nailed wall, and its associated factor of safety. The wall is undrained and homogeneous (Table 1), and is reinforced by two rows of soil nails (Table 2). The shotcrete plate on the soil nails has a weight of 14.6 kN/m, which is modeled as a point load on top of the wall face.. The critical planar slip surface and associated factor of safety are required.

47.3 Geometry and Properties

Table 47.1: Material Properties

Material	c′ (kN/m^2)	γ (kN/m^3)
Amherst Clay	25	18.9

Table 47.2: Soil Nail Properties

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

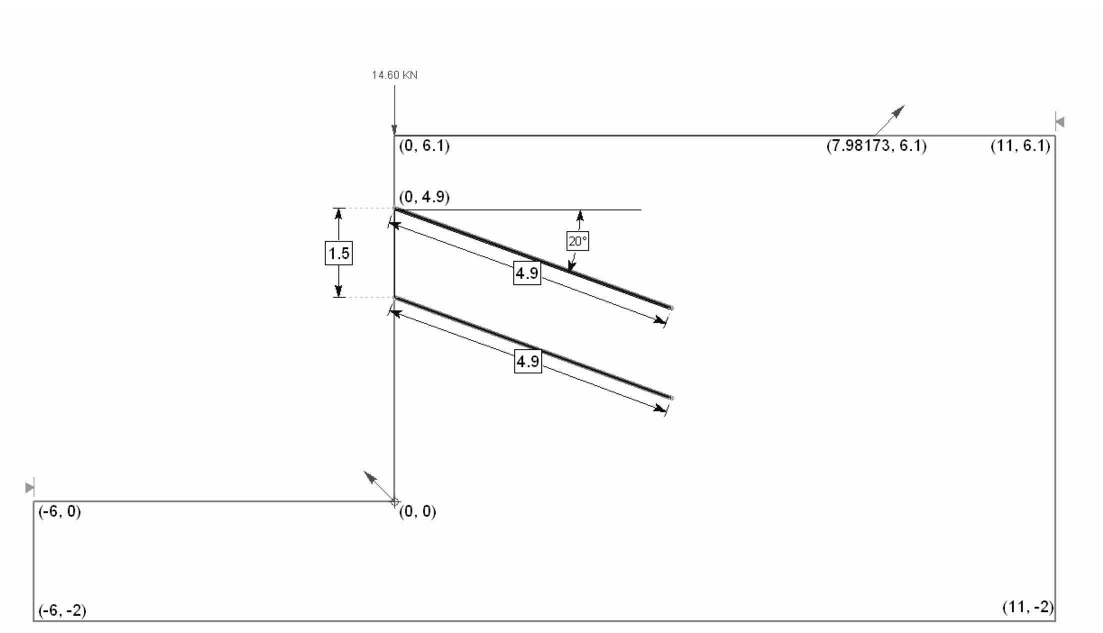


Figure 47.1 - Geometry

47.4 Results – Block search

Method	Factor of Safety
Janbu Simplified	0.888
Janbu corrected	0.888

Sheahan (2003) FS = 0.887

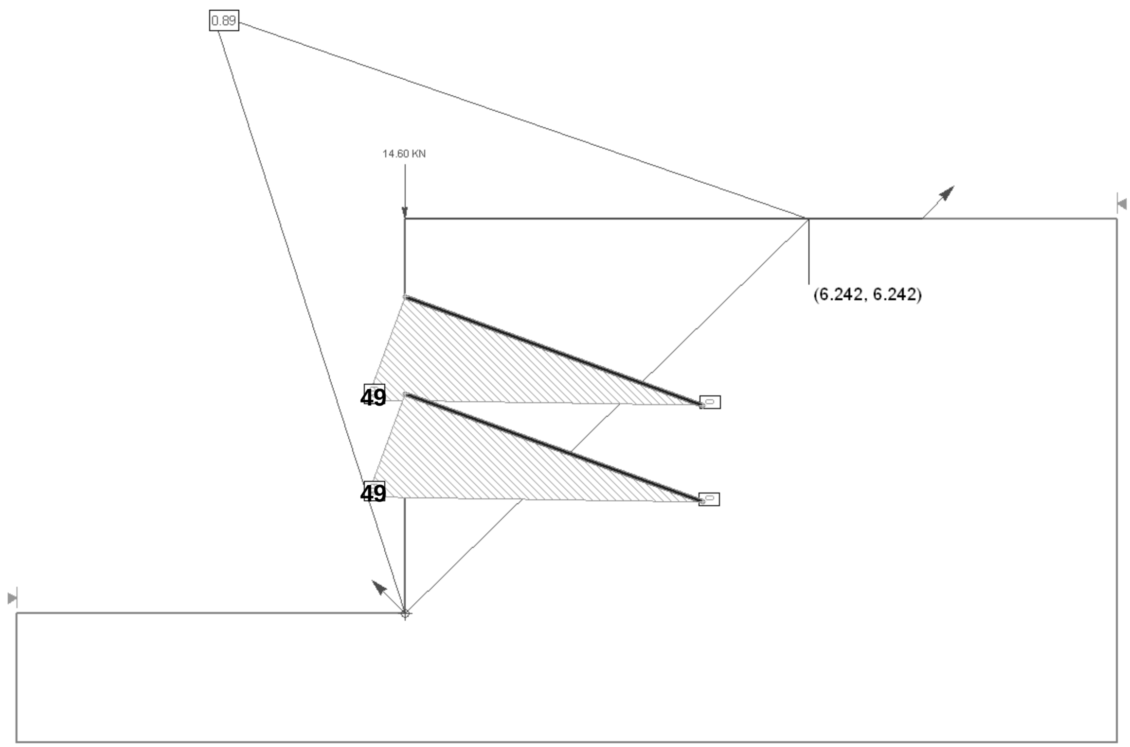


Figure 47.2 – Critical failure surface using the Janbu simplified method.

48.1 Introduction

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

48.2 Description

Verification Problem #48 examines the relationship between failure slope angle and factor of safety for a homogeneous slope in which the primary resistance against failure is friction generated by soil weight. The test wall is reinforced by seven rows of soil nails (Table 3), with a shotcrete plate weighing 13.2 kN/m, which is modeled as a point load acting on the wall face. The geometry, material properties, and reinforcement properties are given in Section 48.3. The factor of safety is required for six different failure plane angles, ranging from 45–70 degrees.

48.3 Geometry and Properties

Table 48.1: Material Properties

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

Table 48.2: Soil Nail Properties

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

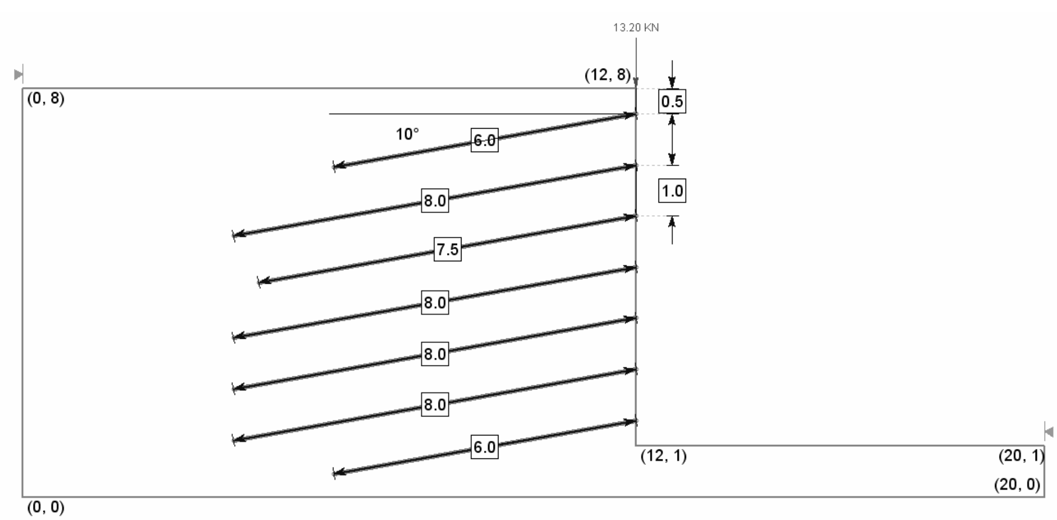


Figure 48.1 – Geometry

48.4 Results – Janbu simplified Block Search

Slope Angle (deg.)	SLIDE Factor of Safety	Sheahan Factor of Safety
45	1.124	1.176
50	1.043	1.070
55	0.989	0.989
60	0.946	0.929
65	0.921	0.893
70	0.922	0.887

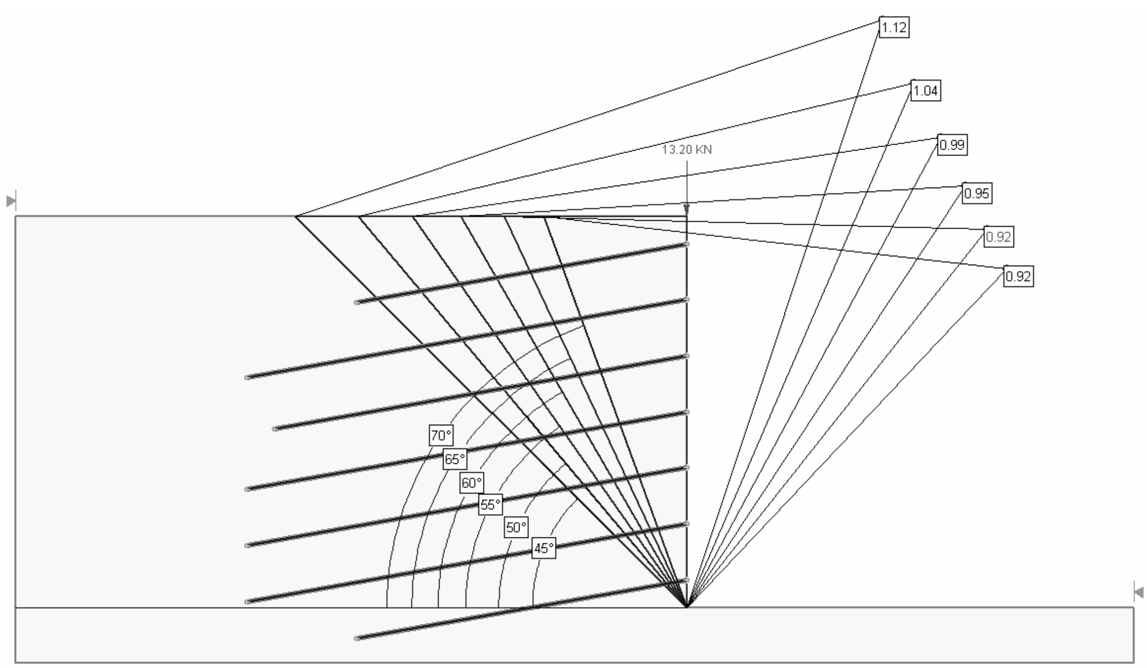


Figure 48.2 – Failure planes and corresponding safety factors

49.1 Introduction

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

49.2 Description

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

49.3 Geometry and Properties

Table 49.1: Material Properties

Material	c′ (psf)	ϕ′ (deg.)	γ (pcf)
Layer 1	600	24	120
Layer 2	300	34	130

Table 49.2: Soil Nail Properties (Active)

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

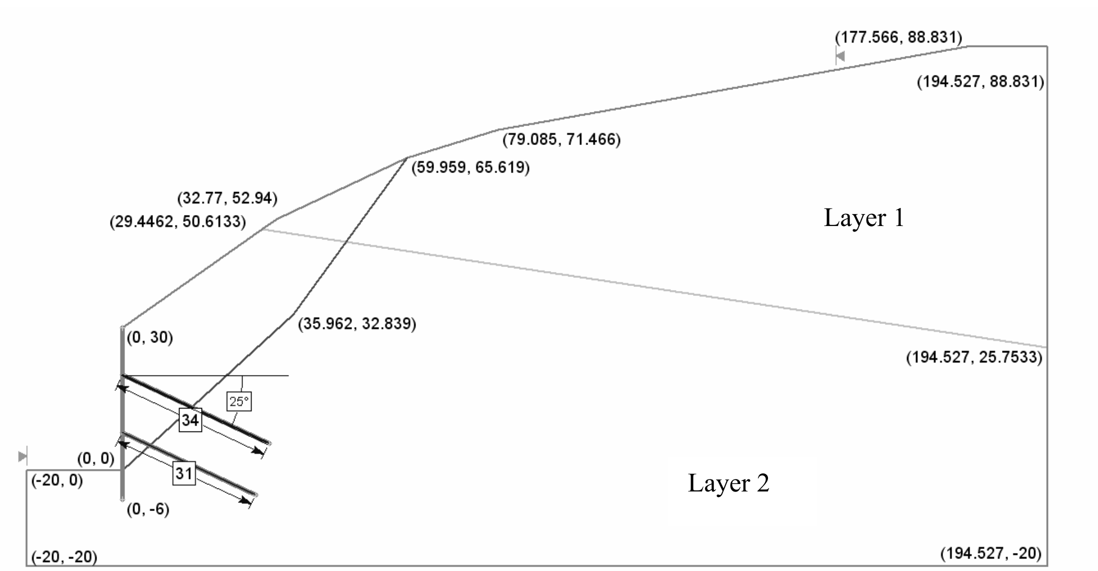


Figure 49.1 – Geometry

49.4 Results

Method	Factor of Safety
Janbu simplified	1.446
Janbu corrected	1.479

SNAILZ Factor of Safety = 1.52

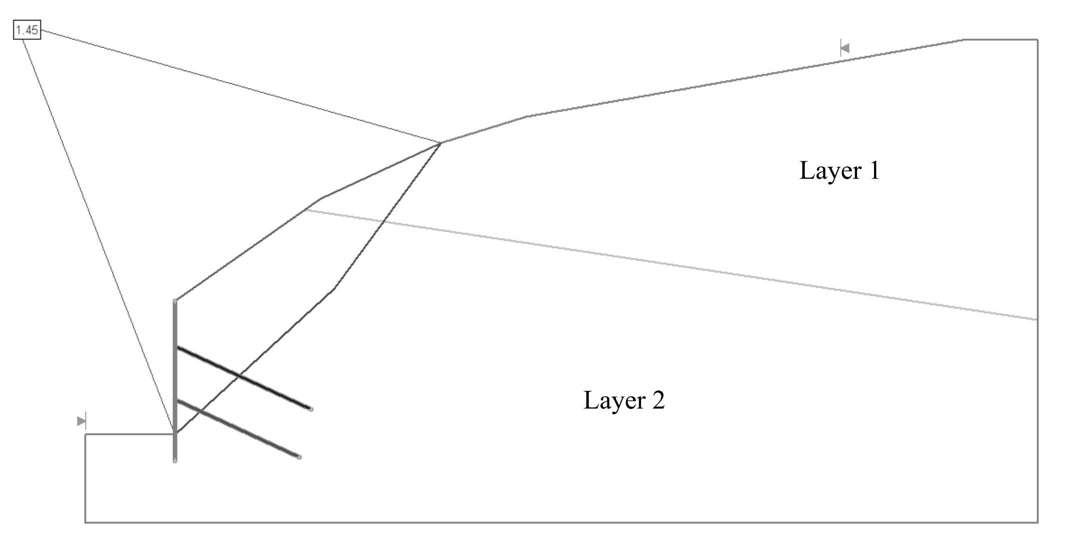


Figure 49.2 – Critical failure surface using Janbu's simplified method.

50.1 Introduction

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

50.2 Description

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

50.3 Geometry and Properties

Table 50.1: Material Properties

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

Table 50.2: Soil Nail Properties (Active)

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

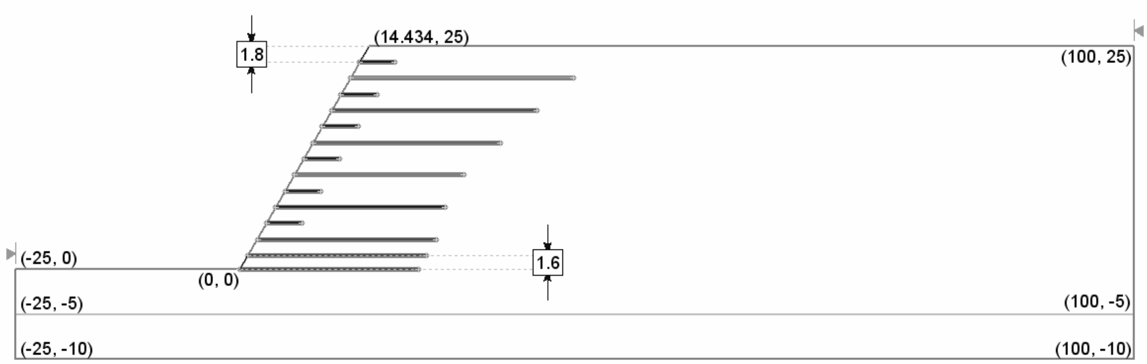


Figure 50.1: Geometry

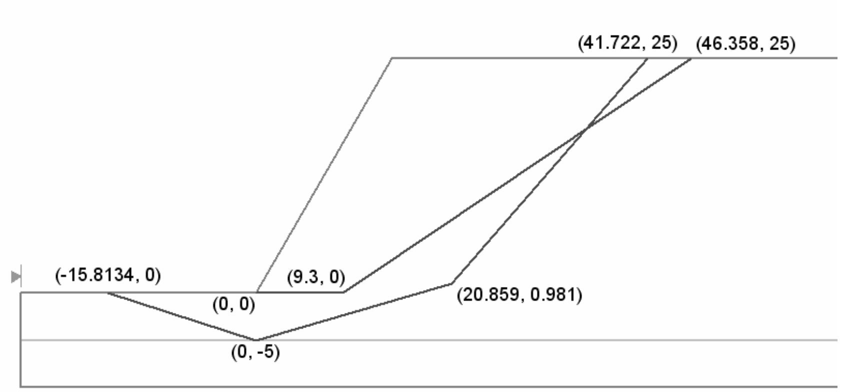
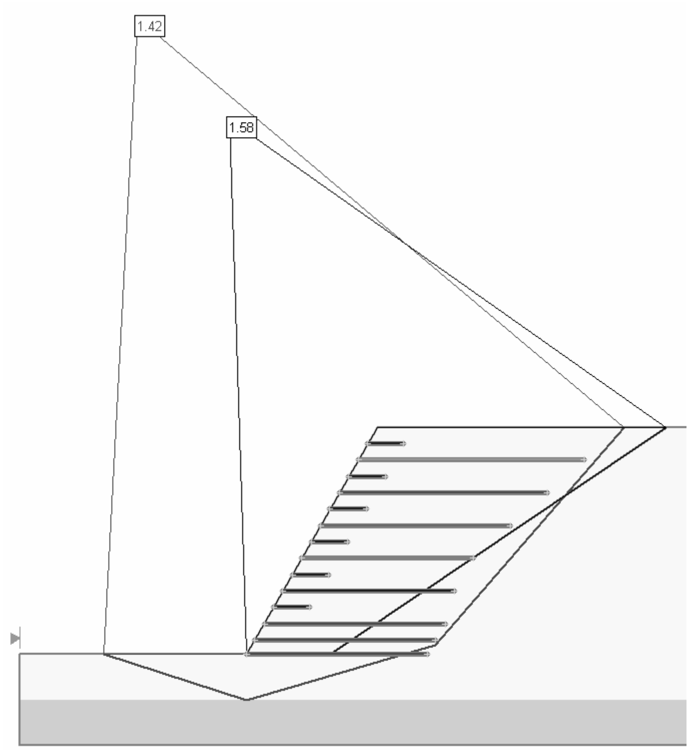


Figure 50.2 – Location of failure surfaces

50.4 Results – Janbu corrected

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



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

Figure 50.2: Safety factors for the given failure surfaces, Nail forces.

51.1 Introduction

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

51.2 Description

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

51.3 Geometry and Properties

Table 51.1: Material Properties

Material	c′ (kN/m^2)	ϕ′ (deg.)	γ (kN/m^3)
Layer 1 (top)	20	32	18.2
Layer 2	25	30	18
Layer 3	40	18	18.5
Layer 4 (bottom)	40	28	18.8

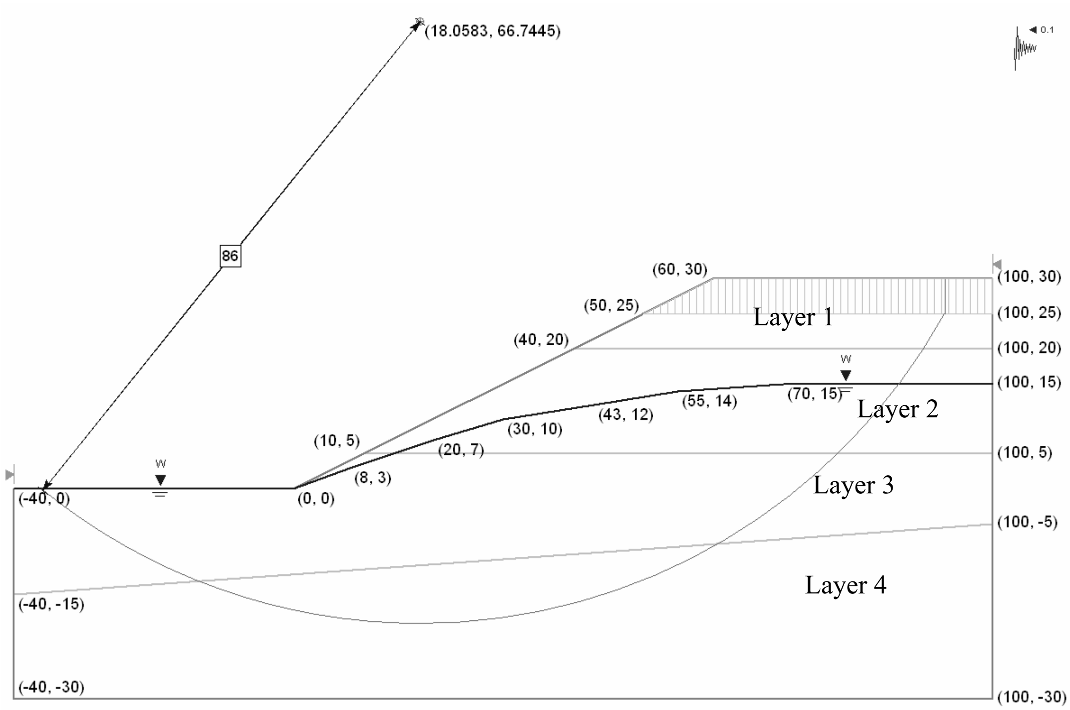


Figure 51.1: Geometry

51.4 Results

Method	SLIDE Factor of Safety	Zhu Factor of Safety
Ordinary	1.075	1.066
Bishop Simplified	1.288	1.278
Janbu Simplified	1.121	1.112
Corps of Engineers 2	1.420	1.377
Lowe & Karafiath	1.288	1.290
Spencer	1.302	1.293
GLE/Morgenstern & Price	1.313	1.303

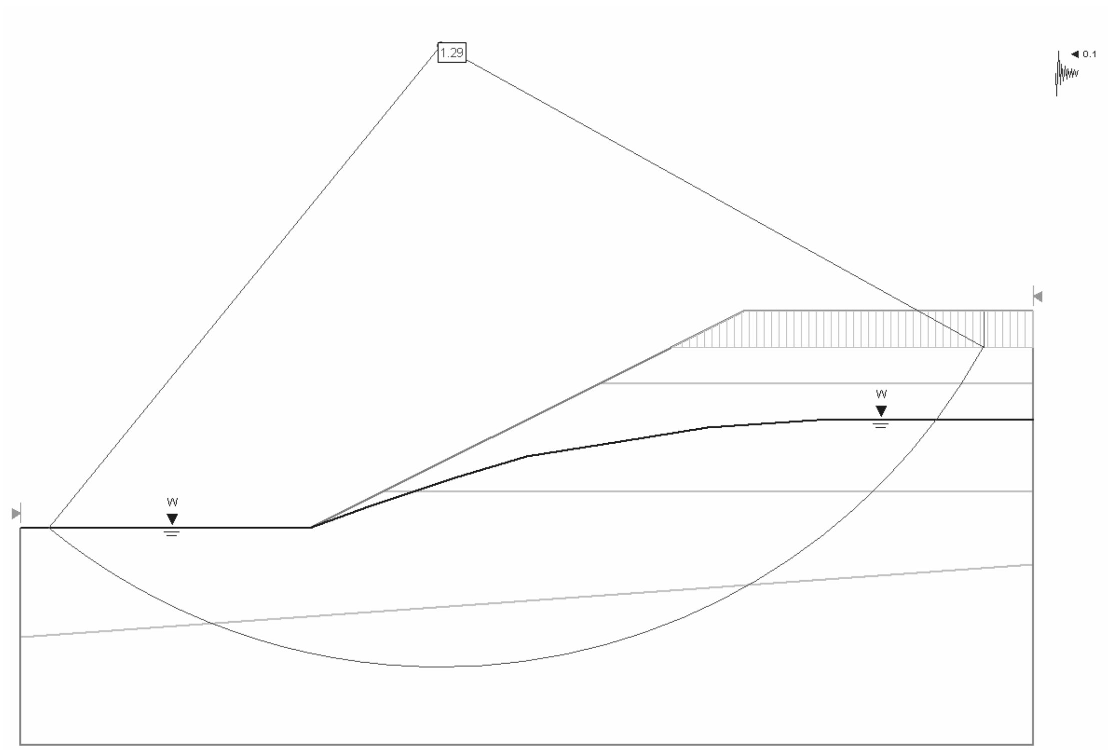


Figure 51.2: Safety factor using the Lowe & Karafiath method.

52.1 Introduction

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

52.2 Description

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

52.3 Geometry and Properties

Table 52.1: Material Properties

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

Table 52.2: Water Table Geometry – wet condition

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

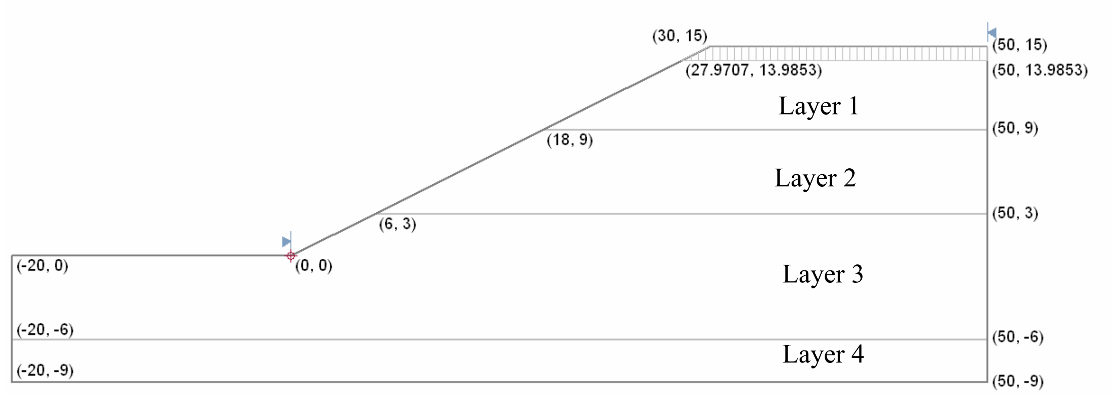


Figure 52.1 - Geometry

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

52.4 Results – Surface 1 – Circular, shallow

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

Zhu's limit equilibrium Factor of Safety = 2.035

WET		
Method	SLIDE Factor of Safety	Zhu Factor of Safety
Bishop simplified	1.526	1.534
Ordinary	1.460	1.496
Morgenstern-Price	1.533	1.559
Spencer	1.533	1.559

Zhu's limit equilibrium Factor of Safety = 1.560

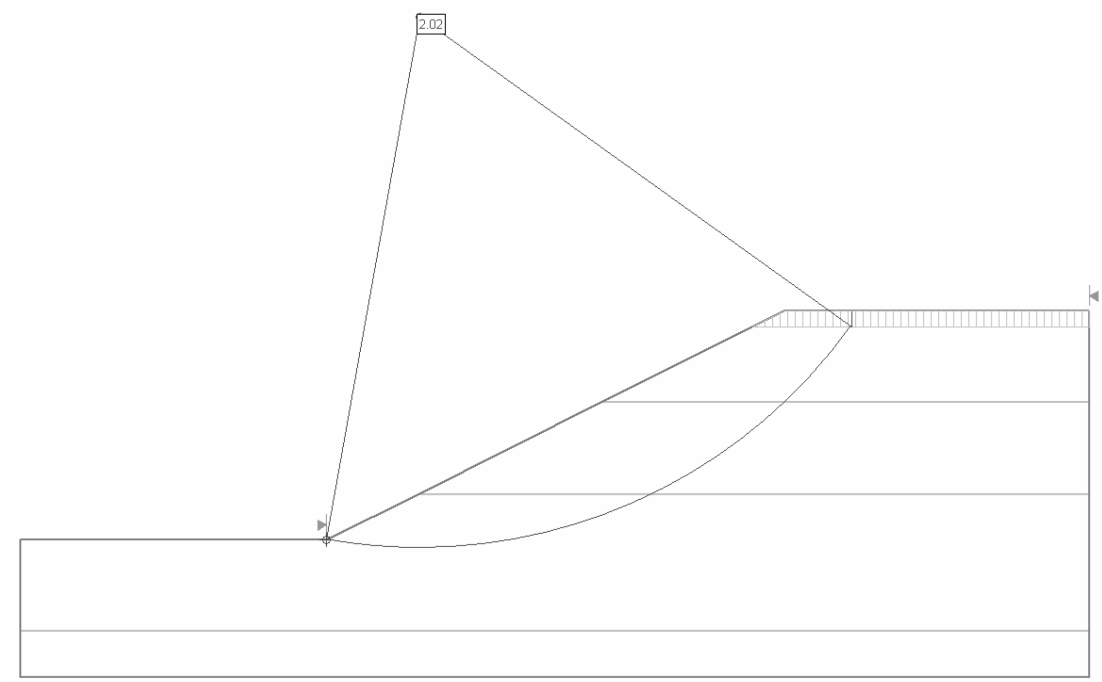


Figure 52.2 – Surface 1, using the Spencer method.

Results – Surface 2 – Noncircular, shallow – Block search

DRY		
Method	SLIDE Factor of Safety	Zhu Factor of Safety
Bishop simplified	2.073	N/a
Ordinary	1.981	N/a
Morgenstern-Price	2.176	2.104
Spencer	2.184	2.087

Zhu's limit equilibrium Factor of Safety = 2.049

WET		
Method	SLIDE Factor of Safety	Zhu Factor of Safety
Bishop simplified	1.485	N/a
Ordinary	1.436	N/a
Morgenstern-Price	1.549	1.628
Spencer	1.554	1.616

Zhu's limit equilibrium Factor of Safety = 1.584

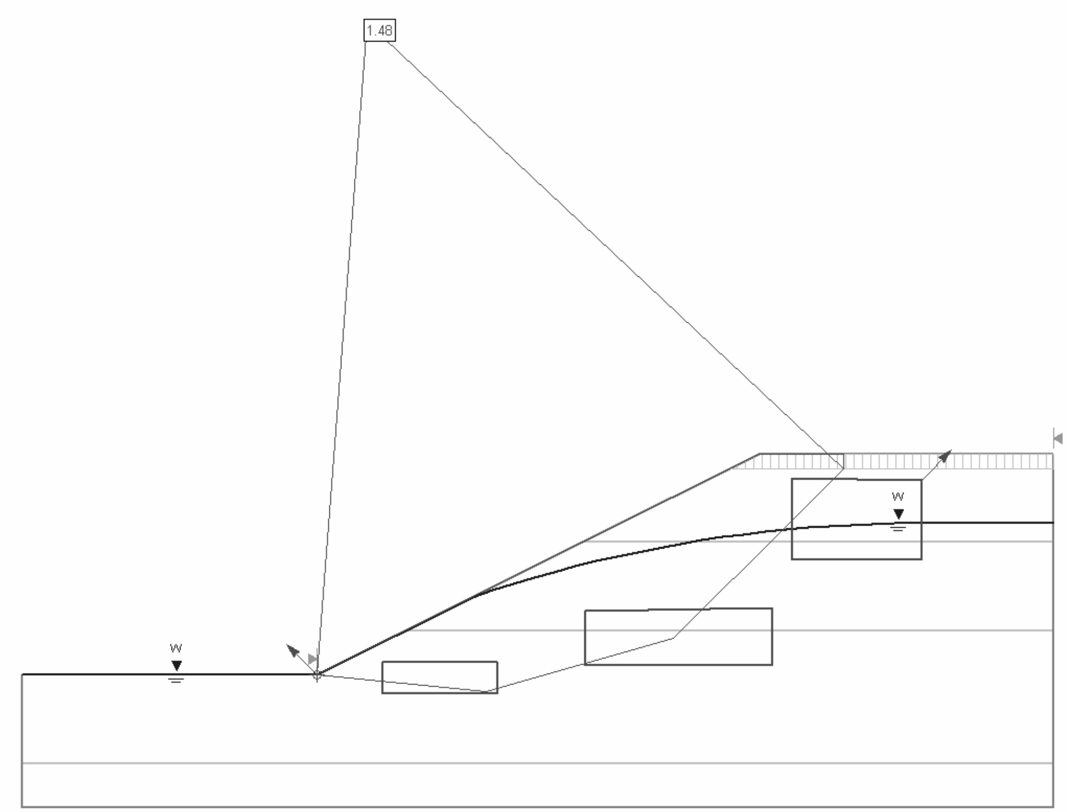


Figure 52.3 – Surface 2 with water table, using the Bishop simplified method

Results – Surface 3 – Circular, deep – Grid search (30x30)

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

Zhu's limit equilibrium Factor of Safety = 1.744

WET		
Method	SLIDE Factor of Safety	Zhu Factor of Safety
Bishop simplified	1.176	1.079
Ordinary	0.812	0.922
Morgenstern-Price	1.174	1.197
Spencer	1.189	1.211

Zhu's limit equilibrium Factor of Safety = 1.166

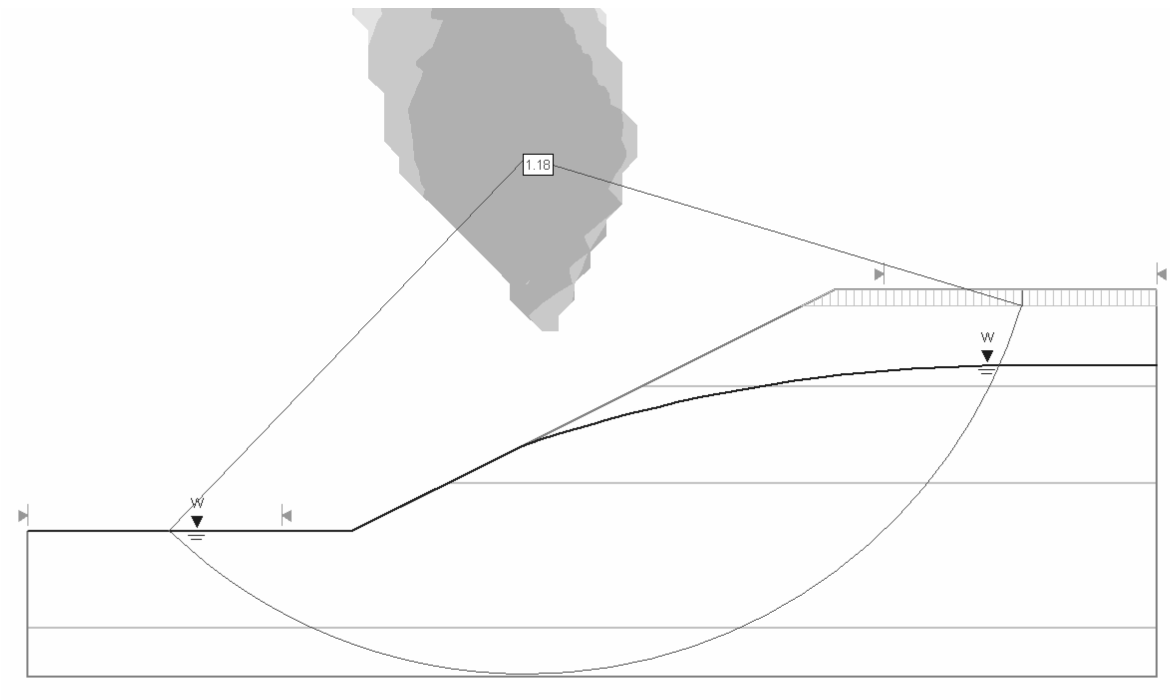


Figure 52.4 – Surface 3 with water table, using the Bishop simplified method

Results – Surface 4 – Noncircular, deep – Path search

DRY		
Method	SLIDE Factor of Safety	Zhu Factor of Safety
Bishop simplified	1.624	N/a
Ordinary	1.150	N/a
Morgenstern-Price	1.776	1.765
Spencer	1.797	1.772

Zhu's limit equilibrium Factor of Safety = 1.709

WET		
Method	SLIDE Factor of Safety	Zhu Factor of Safety
Bishop simplified	1.073	N/a
Ordinary	0.634	N/a
Morgenstern-Price	1.162	1.141
Spencer	1.176	1.150

Zhu's limit equilibrium Factor of Safety = 1.109

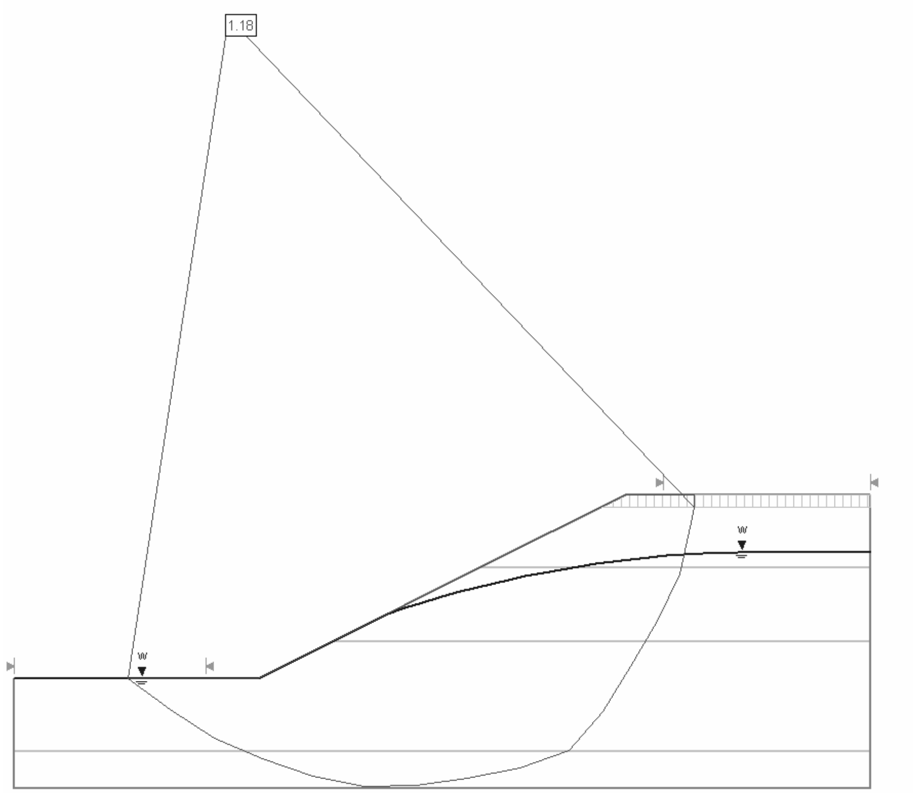


Figure 52.5 – Surface 4 with water table, using Spencer's method

53.1 Introduction

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

53.2 Description

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

53.3 Geometry and Properties

Table 53.1: Material Properties

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

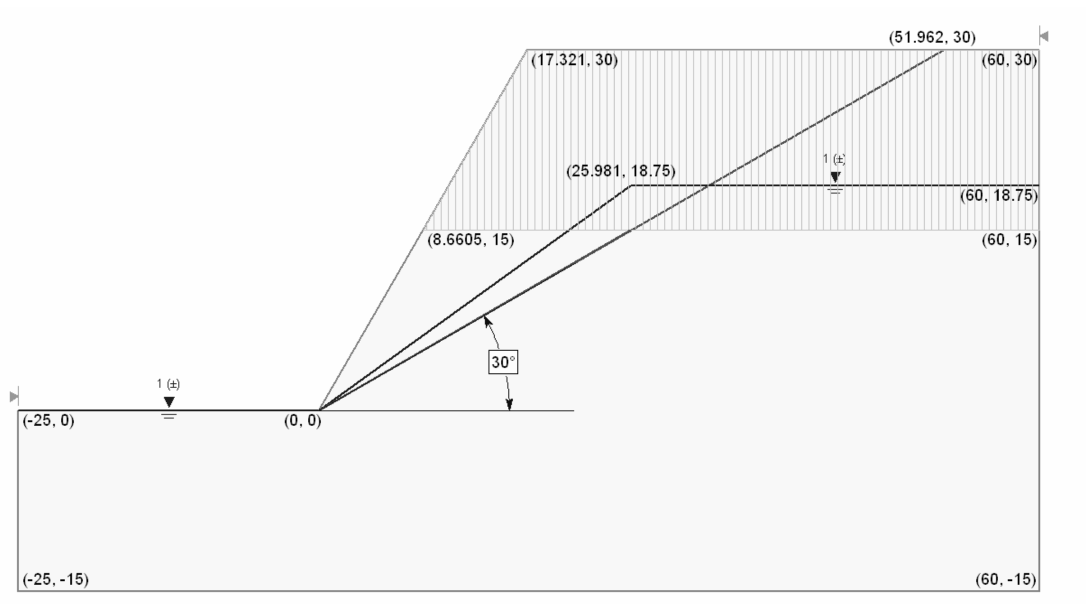


Figure 53.1 - Geometry

53.4 Results

Method	Factor of Safety
Slide -Janbu Simplified	1.049
Rocplane	1.049

Preist's factor of safety = 1.049

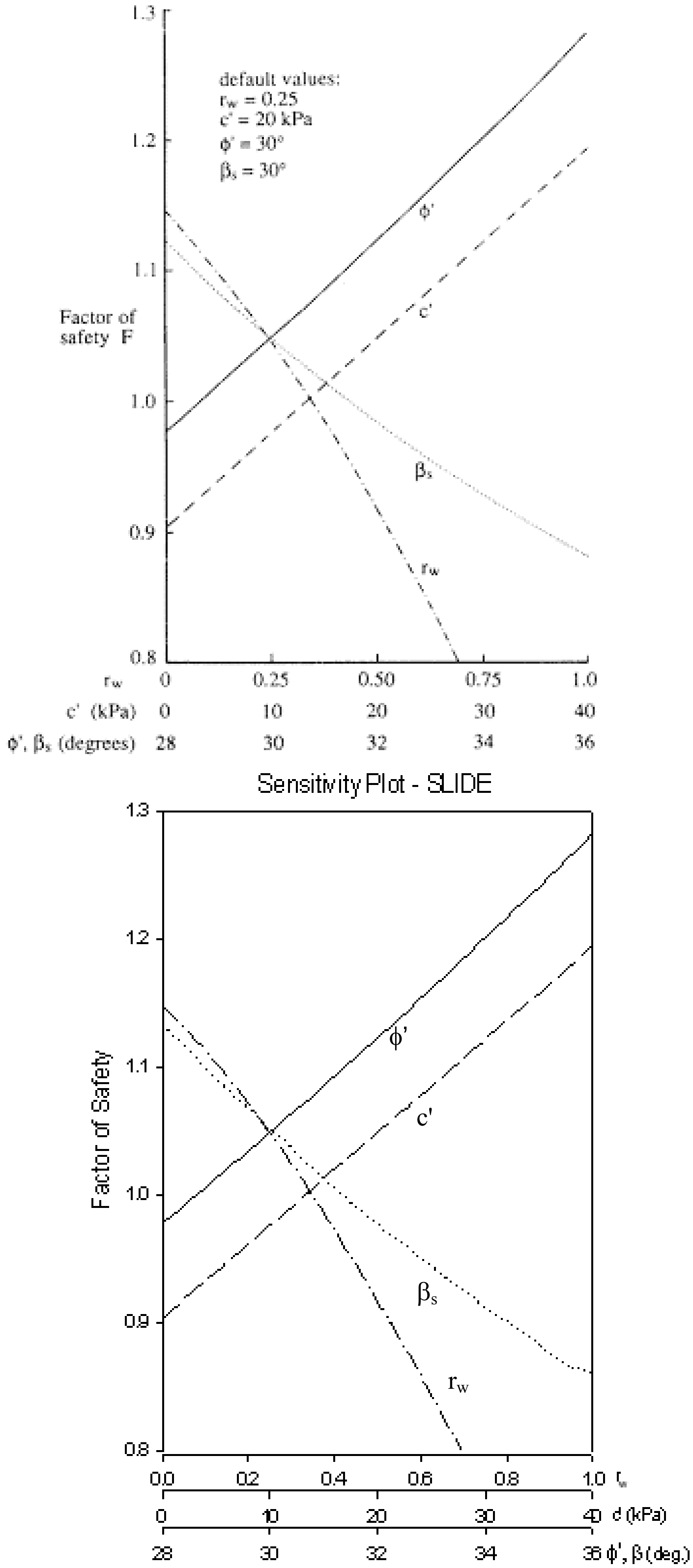


Figure 53.2

Sensitivity plots from Priest and Slide, compared.

54.1 Introduction

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

54.2 Description

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

54.3 Geometry and Properties

Table 54.1: Material Properties

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

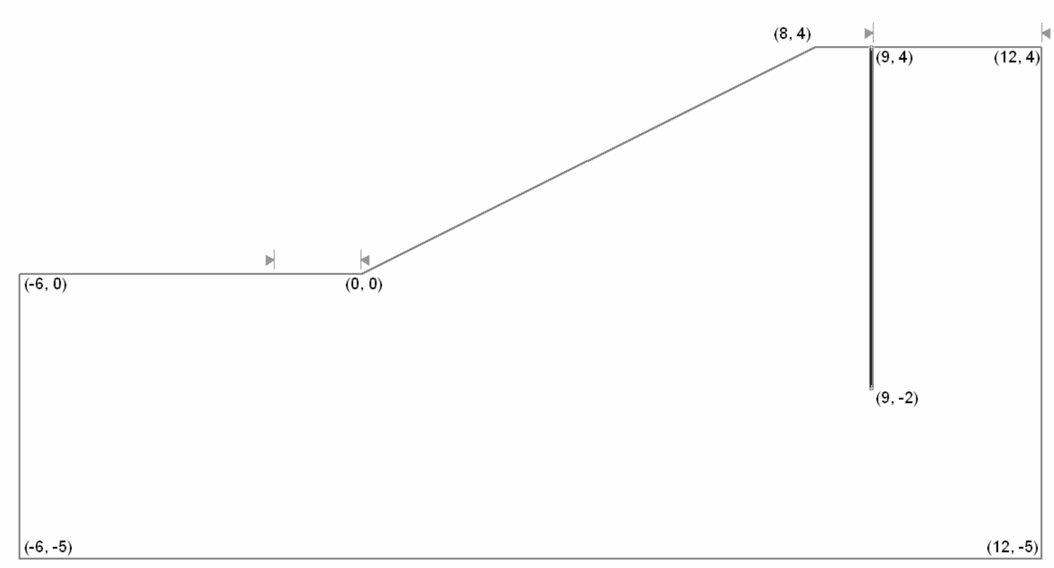


Figure 54.1 – Geometry

54.4 Results – Bishop simplified

Case	Factor of Safety
Slide – no pile	1.10
Slide – with pile	1.19
Yamagami – no pile	1.10
Yamagami – with pile	1.20

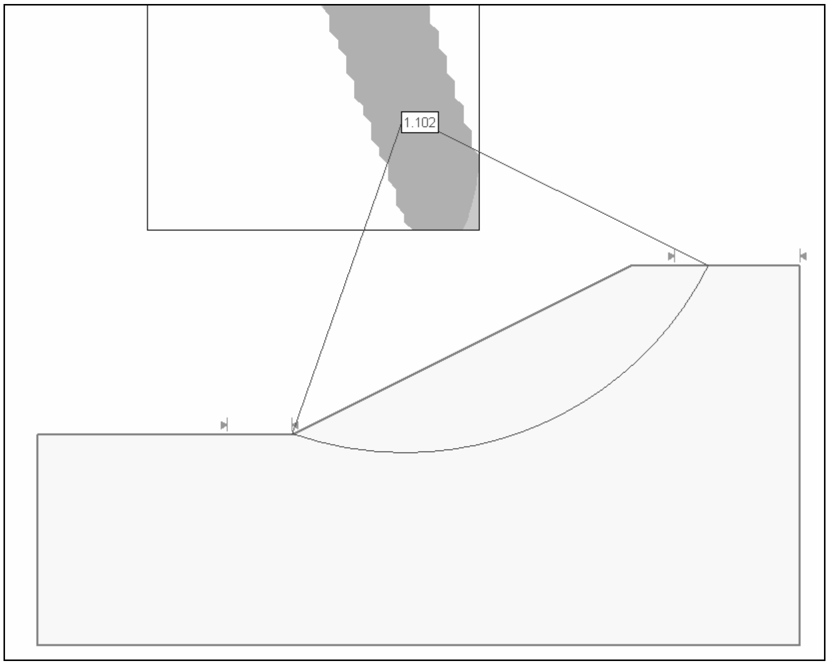


Figure 54.2 – Circular failure surface, no pile

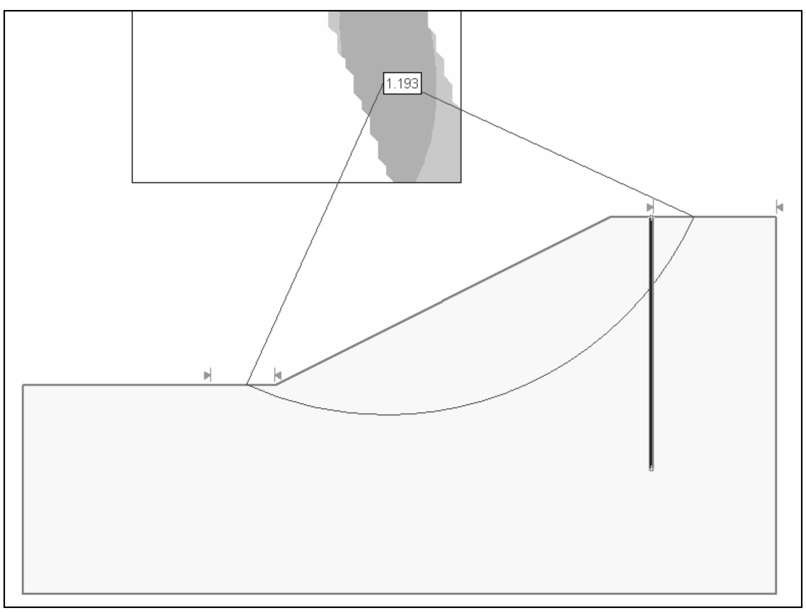


Figure 54.3 – Circular failure surface, with reinforcing pile

55.1 Introduction

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

55.2 Description

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

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

55.3 Geometry and Properties

Table 55.1: Material Properties

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

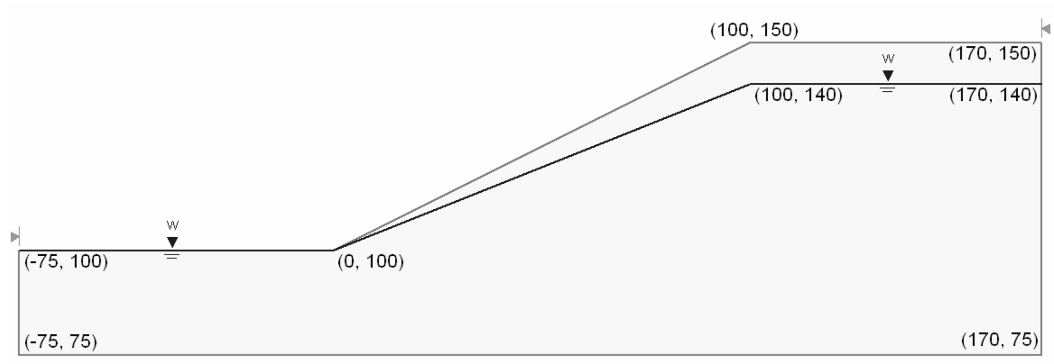


Figure 55.1 – Geometry

55.4 Results

Method	SLIDE	UTEXES4	SLOPE/W	WINSTABL	XSTABL	RSS
Spencer	1.30	1.30	1.30	1.34	-	-
Bishop simplified	1.29	1.29	1.29	1.34	1.29	1.29
Janbu simplified	1.15	1.15	1.15	1.20	1.24	1.15
Lowe-Karafiath	1.32	1.32	-	-	-	-
Ordinary	1.05	-	1.04	-	-	-

SNAIL FS = 1.22 (Wedge method)
GOLD-NAIL FS = 1.32 (Circular method)

56.1 Introduction

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

56.2 Description

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

56.3 Geometry and Properties

Table 56.1: Material Properties

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

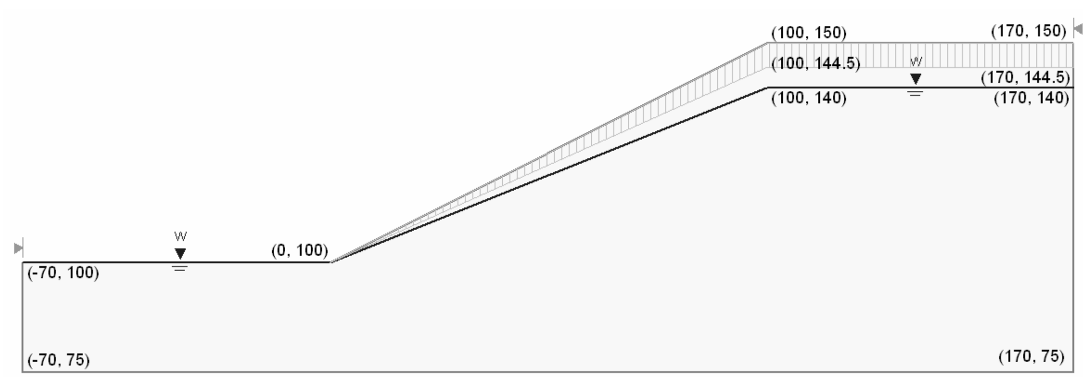


Figure 55.1 - Geometry

55.4 Results

Method	SLIDE	UTEXES4	SLOPE/W	WINSTABL	XSTABL	RSS
Spencer	1.30	1.29	1.29	1.32	-	-
Bishop simplified	1.29	1.28	1.28	1.31	1.28	1.28
Janbu simplified	1.14	1.14	1.14	1.18	1.23	1.13
Lowe-Karafiath	1.31	1.31	-	-	-	-
Ordinary	1.03	-	1.02	-	-	-

SNAIL FS = 1.18 (Wedge method)
GOLD-NAIL FS = 1.30 (Circular method)

57.1 Introduction

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

57.2 Description

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

57.3 Geometry and Properties

Table 57.1: Material Properties

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

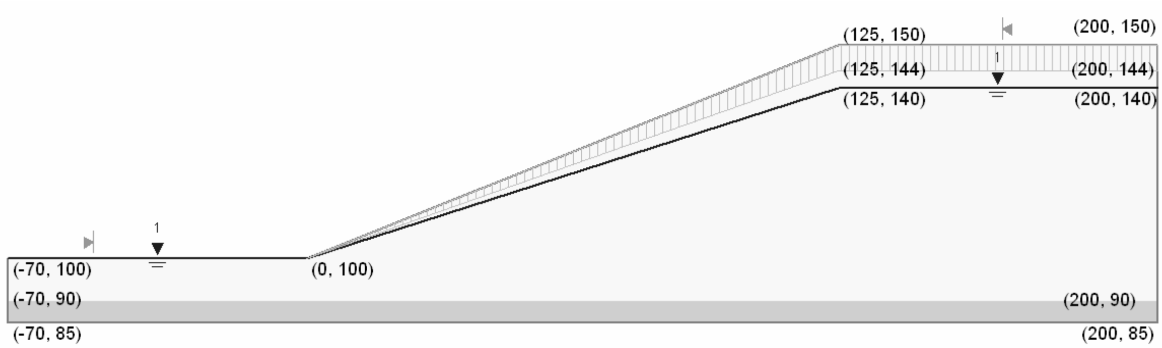


Figure 57.1 – Geometry

55.4.1 Results – Composite surfaces/Noncircular

Method	SLIDE	SLOPE/W	XSTABL
Spencer	1.40	1.40	-
Bishop simplified	1.39	1.39	1.41
Janbu simplified	1.22	1.21	1.34
Lowe-Karafiath	1.39	-	-
Ordinary	0.94	0.85	-

SNAIL FS = 1.39 (Wedge method)

55.4.2 Results – No composite surfaces/Circular

Method	SLIDE	UTEXAS4	WINSTABL	RSS
Spencer	1.42	1.42	1.45	-
Bishop simplified	1.42	1.41	1.39	1.41
Janbu simplified	1.26	1.20	1.23	1.24
Lowe-Karafiath	1.41	1.12	-	-
Ordinary	1.11	-	-	-

GOLD-NAIL FS = 1.40 (Circular method)

58.1 Introduction

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

58.2 Description

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

<u>Note:</u>

The problem gives reinforcement parameters in the form:

Tieback Spacing 4 ft.
1.08" Diameter 270 ksi Steel
4 k/ft Allowable Pullout

In order to convert these to SLIDE parameters for grouted tieback reinforcement:

Out-of-plane Spacing = Tieback spacing
Tensile *and* Plate Capacity = Yield strength * πr^2 (lbs)
Bond Strength = Allowable pullout (lbs/ft)***

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

58.3 Geometry and Properties

Table 58.1: Material Properties

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

Table 58.2: Grouted Tieback Properties – all rows

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

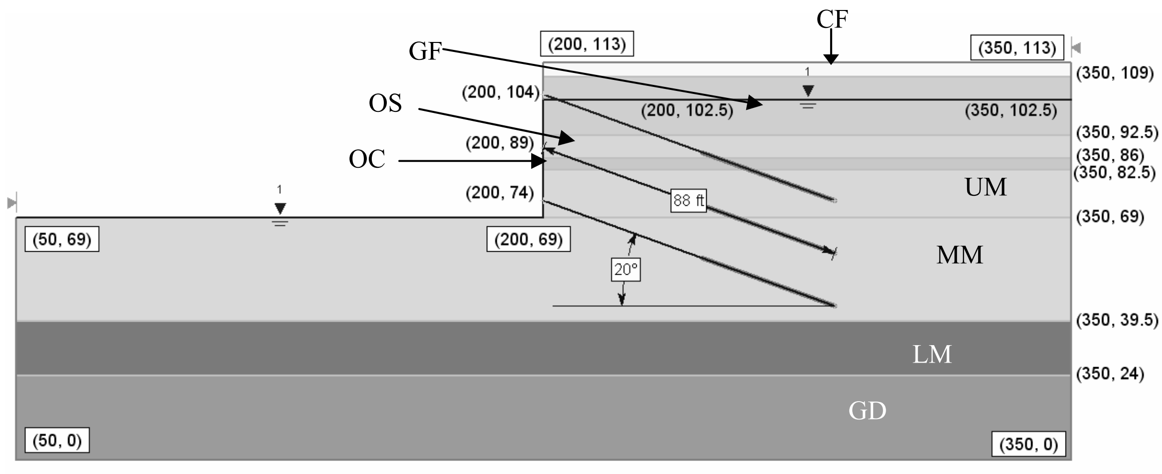


Figure 58.1 – Geometry

58.4 Results – Circular

Method	SLIDE	UTEXAS4	SLOPE/W	WINSTABL
Spencer	1.15	1.14	1.14	1.20
Bishop simplified	1.15	1.14	1.14	1.16
Janbu simplified	1.06	1.13	1.05	1.12
Lowe-Karafiath	1.18	1.20	-	-
Ordinary	1.13	-	1.12	-

GOLD-NAIL FS = 1.19 (Circular method)

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

59.1 Introduction

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

59.2 Description

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

59.3 Geometry and Properties

Table 59.1: Material Properties

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

Table 59.2: Grouted Tieback Properties

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

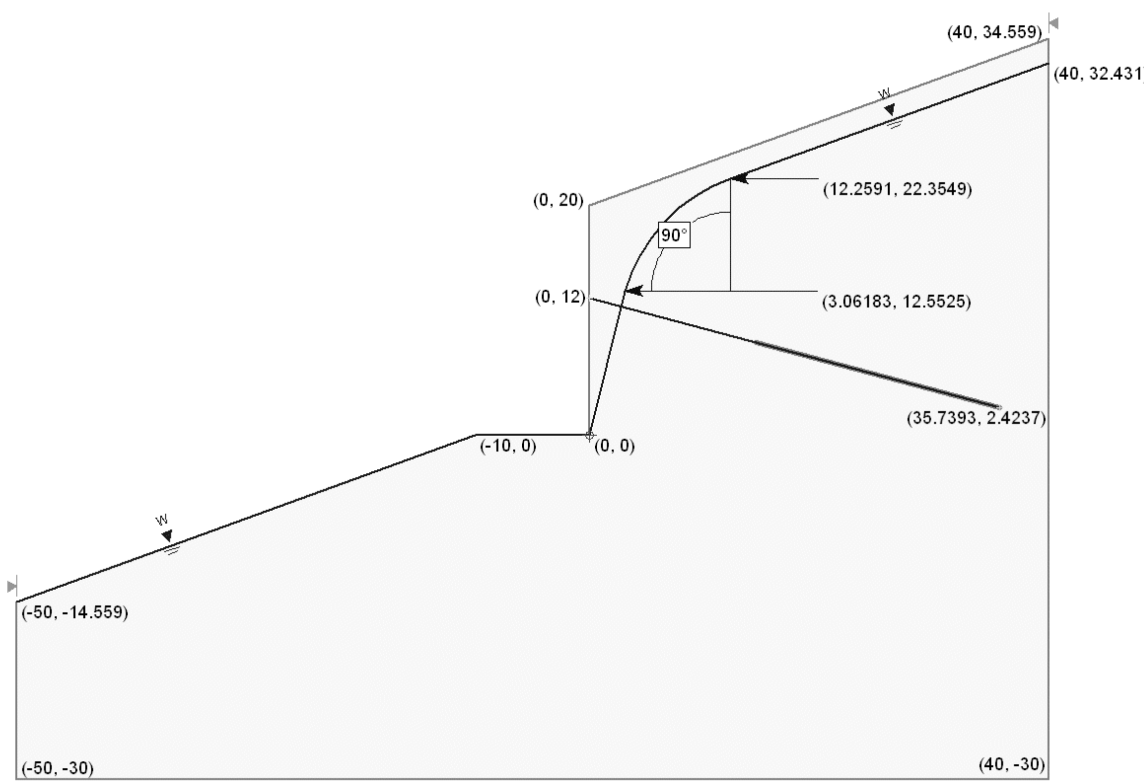


Figure 59.1 - Geometry

59.4 Results - Circular

Method	SLIDE	UTEXAS4	SLOPE/W	WINSTABL
Spencer	0.59	0.65	0.60	0.59
Bishop simplified	0.58	0.56	0.60	0.74
Janbu simplified	0.58	0.64	0.61	0.76
Lowe-Karafiath	0.59	0.76	-	-
Ordinary	0.63	-	0.62	-

GOLD-NAIL FS = 0.62 (Circular method)

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

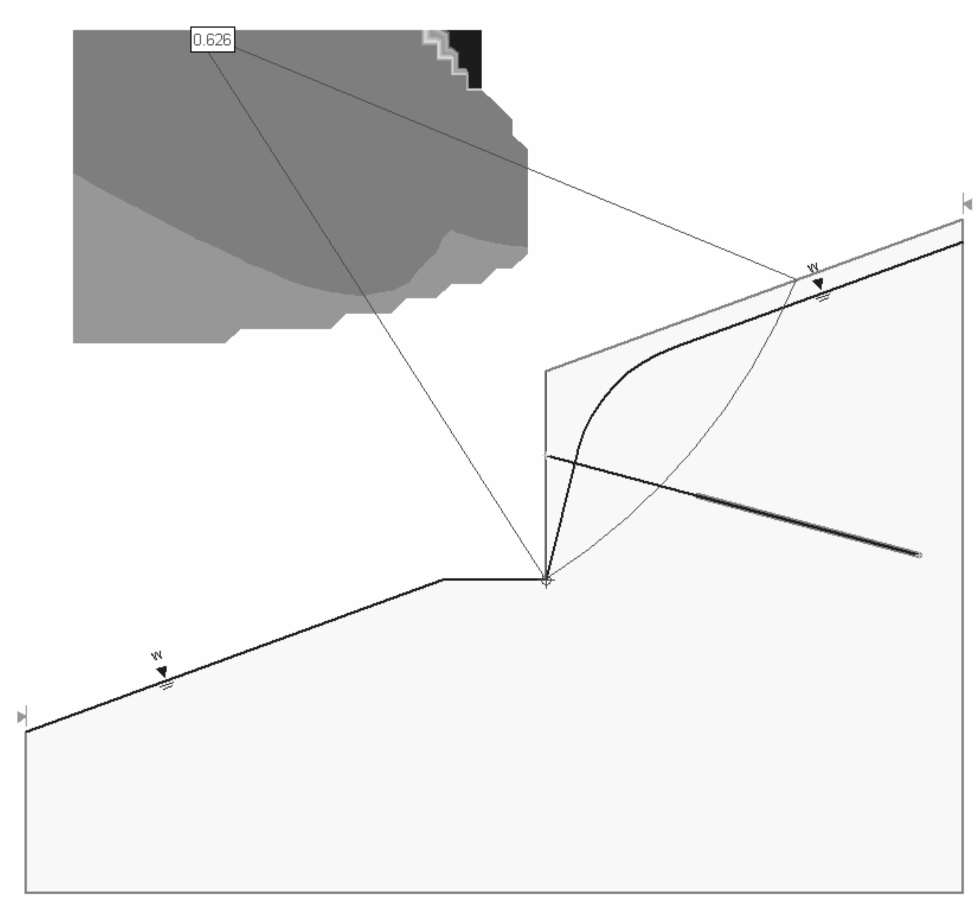


Figure 59.2 – Critical Failure surface using the Ordinary method.

60.1 Introduction

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

60.2 Description

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

60.3 Geometry and Properties

Table 60.1: Material Properties

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

Table 60.2: Soil Nail Properties

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

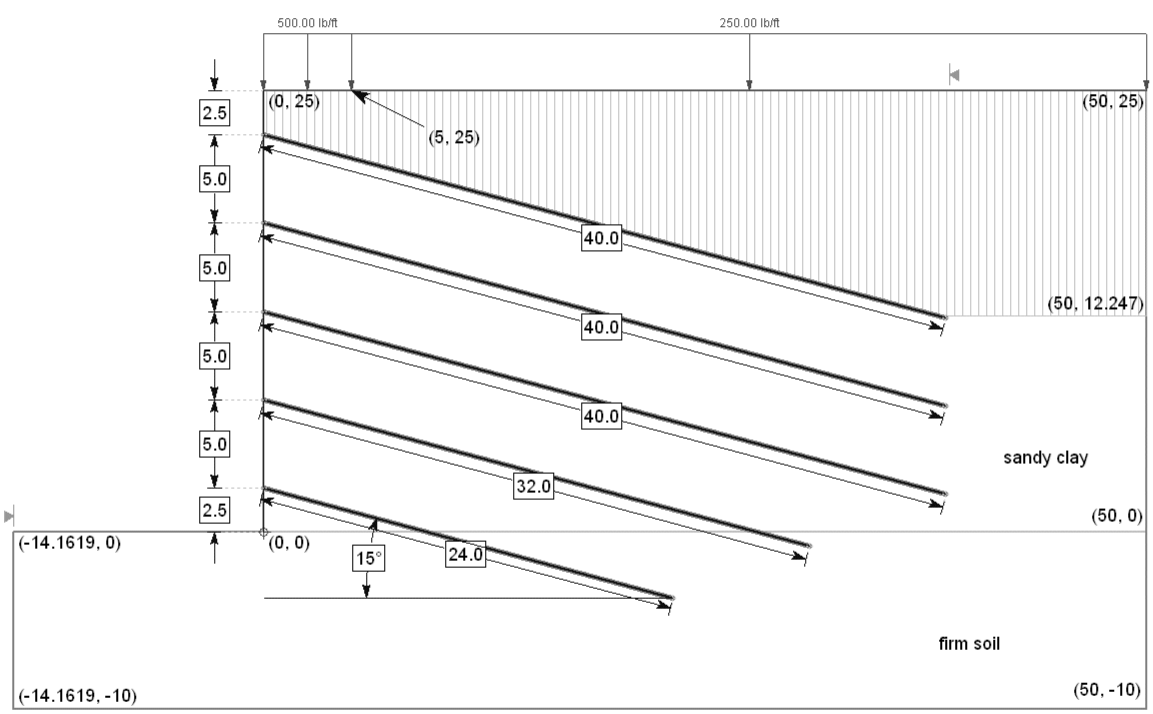


Figure 60.1 – Geometry

60.4 Results - Circular

Method	SLIDE	UTEXAS4	SLOPE/W	WINSTABL
Spencer	1.01	1.02	1.02	0.99
Bishop simplified	1.00	1.00	1.01	1.06
Janbu simplified	1.04	1.08	1.07	1.10
Lowe-Karafiath	1.02	1.00	-	-
Ordinary	0.99	-	1.00	-

GOLD-NAIL FS = 0.91 (Circular method)

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

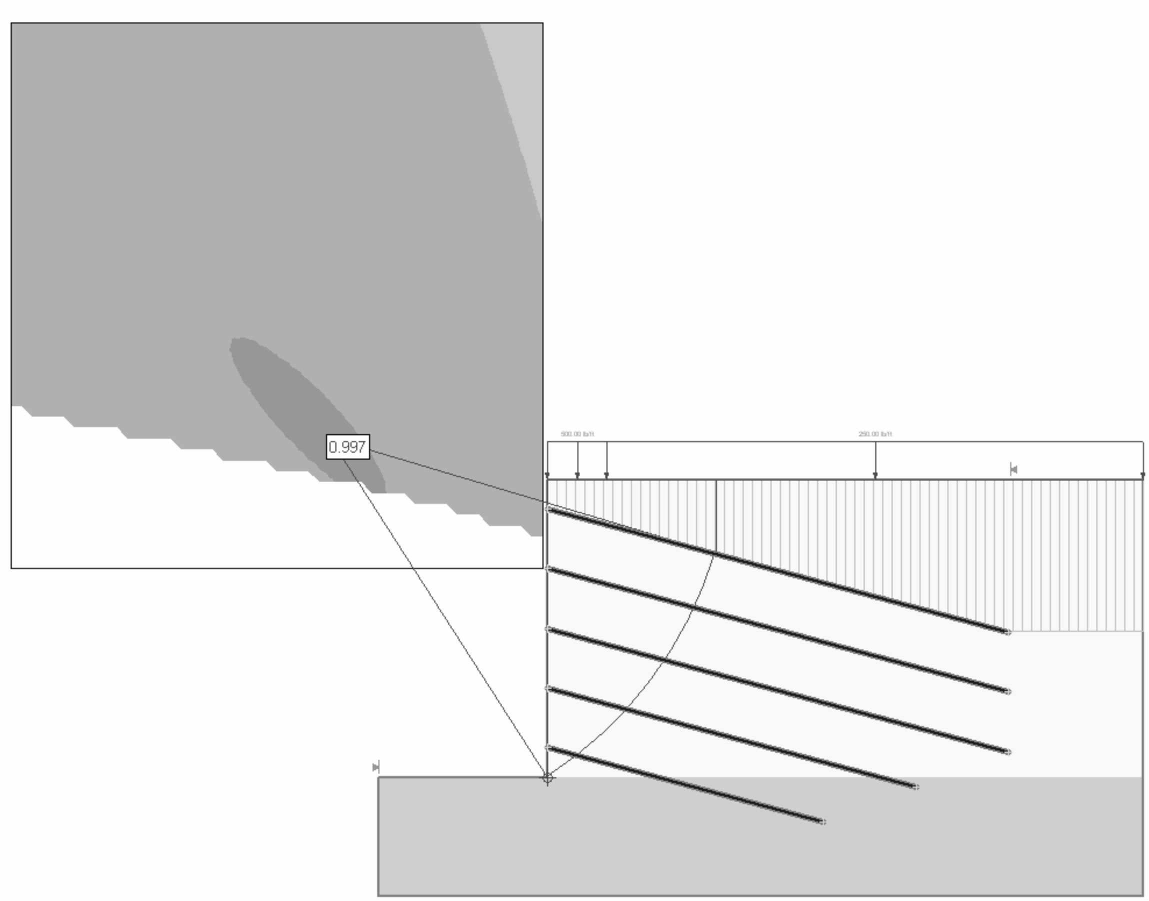


Figure 60.2 – Critical failure surface using Bishop's simplified method.

61.1 Introduction

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

61.2 Description

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

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

The power curve variables are in the form:

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

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

61.3 Geometry and Properties

Table 61.1 Material Properties – Power Curve criterion

	Baker's Parameters			SLIDE Parameters			
Material	A	n	T	a	b	c	d
Clay	0.535	0.6	0.0015	3.39344	0.6	0	0.1520

Table 61.2: Material Properties – Mohr-Coulomb criterion

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

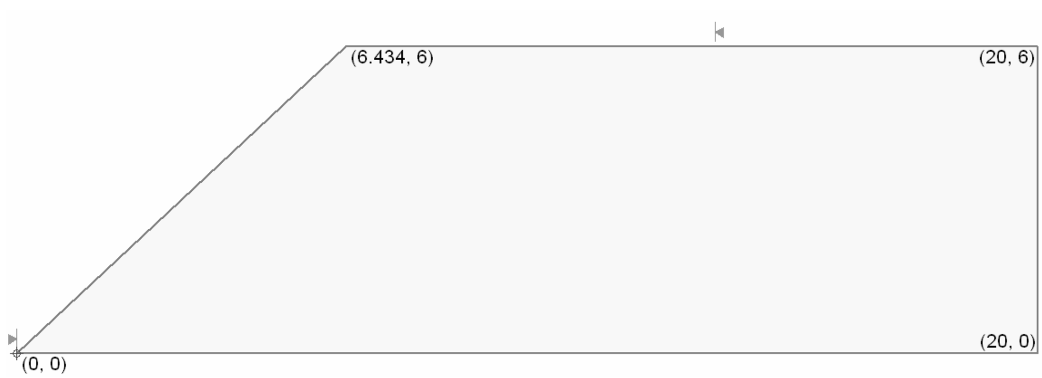


Figure 61.1 - Geometry

61.4 Results

Strength Type	Method	Factor of Safety	Maximum effective normal stress (kPa)
Power Curve	Janbu Simplified	1.35	36.33
	Spencer	1.47	31.21
Mohr-Coulomb	Janbu Simplifed	1.29	30.05
	Spencer	1.37	26.44

Baker (2003) non-linear results: FS = 1.48, $\sigma_{max} = 21.4$

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

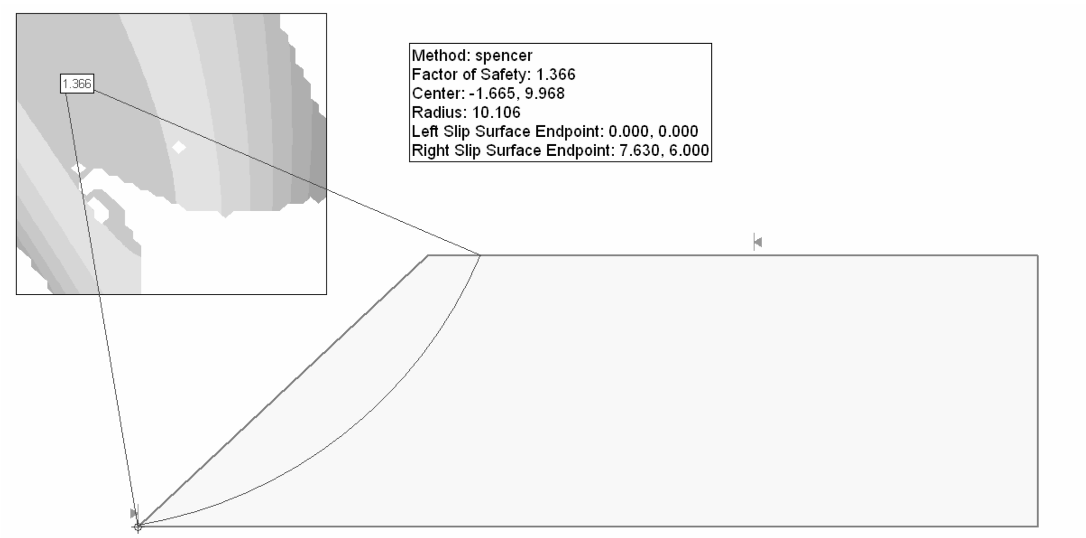


Figure 61.2 – Circular critical surface with Mohr-Coulomb criteria, Spencer method

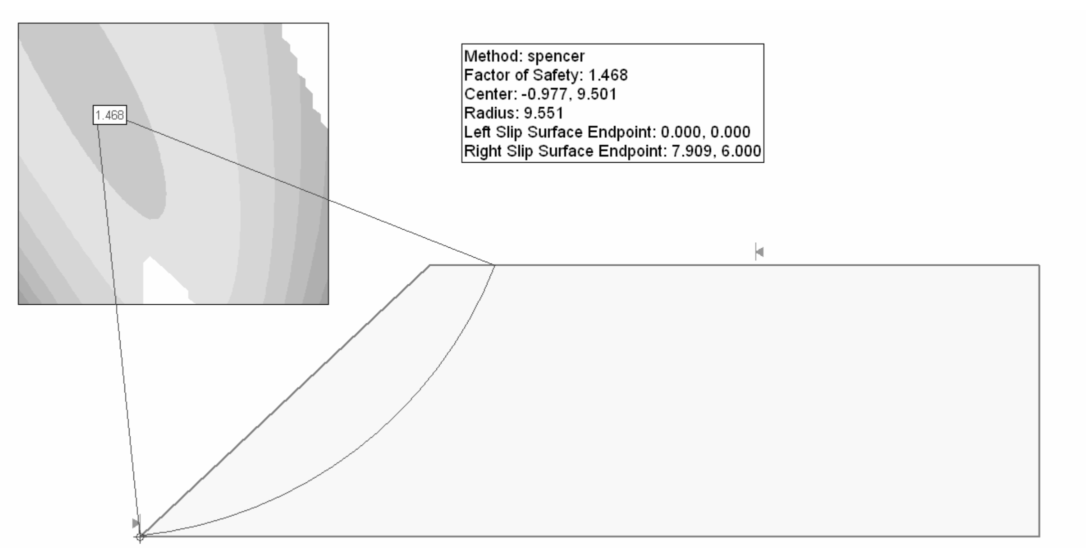


Figure 61.3 – Circular critical surface with power curve criteria, Spencer method

62.1 Introduction

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

62.2 Description

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

*Loukidis examines a log-spiral surface. In order to model this type of noncircular surface with SLIDE, a path search with Monte-Carlo optimization must be performed.

62.3 Geometry and Properties

Table 62.1: Seismic Coefficients

Dry Slope	0.432
R_u = 0.5	0.132

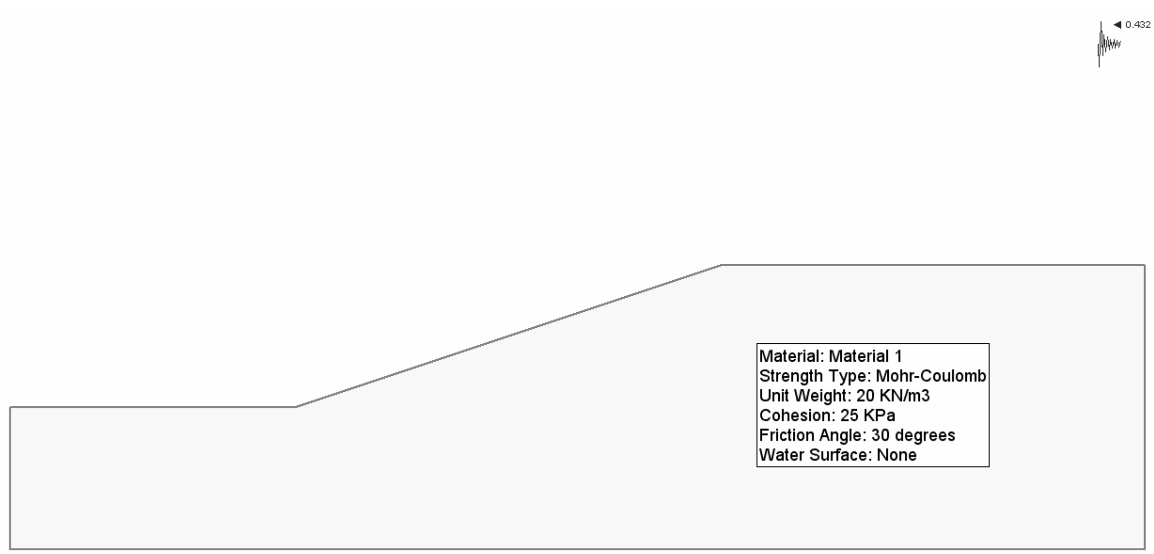


Figure 62.1 – Geometry and Material Properties

62.4.1 Results – Dry slope (k_c = 0.432)

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

Loukidis factor of safety (Spencer) = 1.000

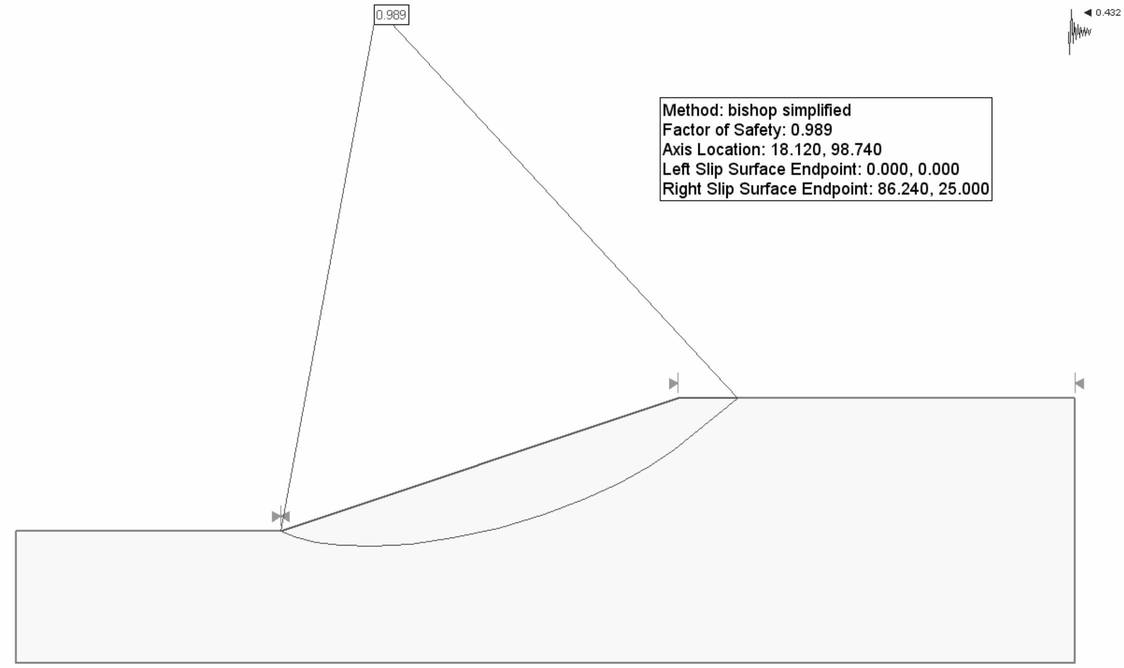


Figure 62.2 – Critical slip surface using Bishop's method, path search

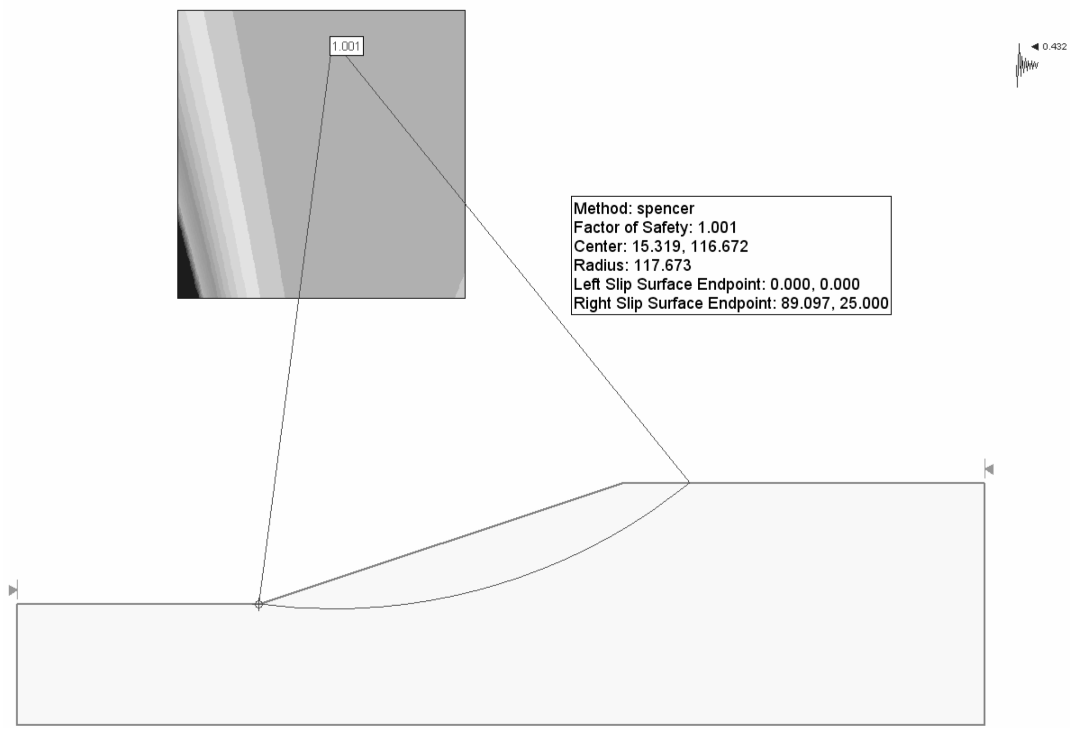


Figure 62.3 – Critical slip surface using Spencer's method, grid search

62.4.2 Results – R_u = 0.5 (k_c = 0.132)

Type	Spencer	Bishop Simplified
Circular (Grid search)	1.001	0.987
Noncircular (Path search with optimization)	0.998	0.966

Loukidis factor of safety (Spencer) = 1.000

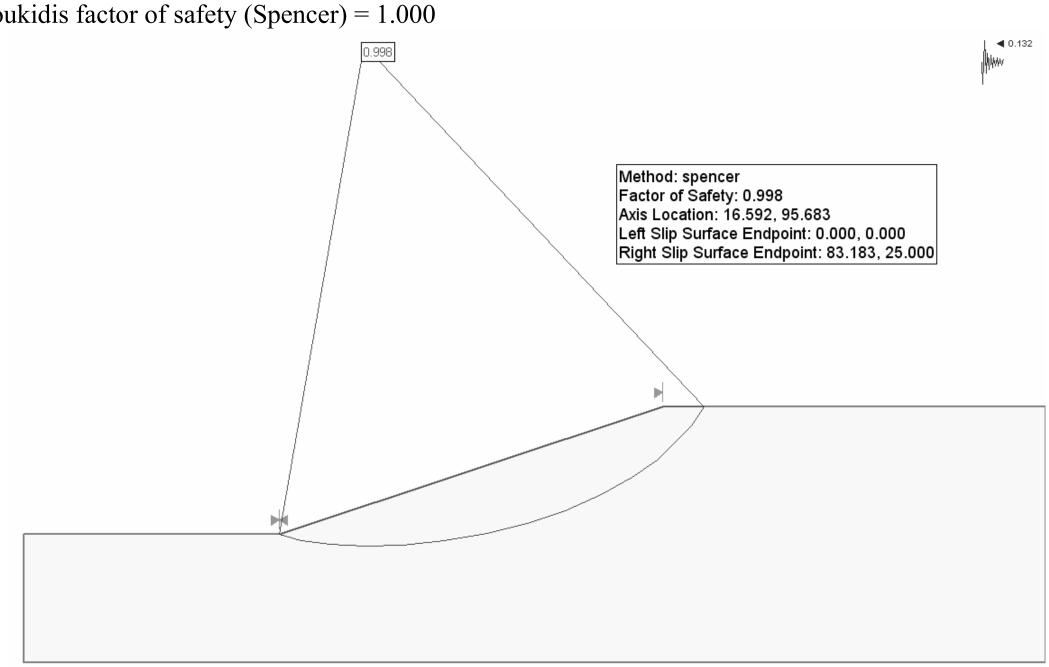


Figure 62.4 – Critical slip surface using Spencer's method, path search

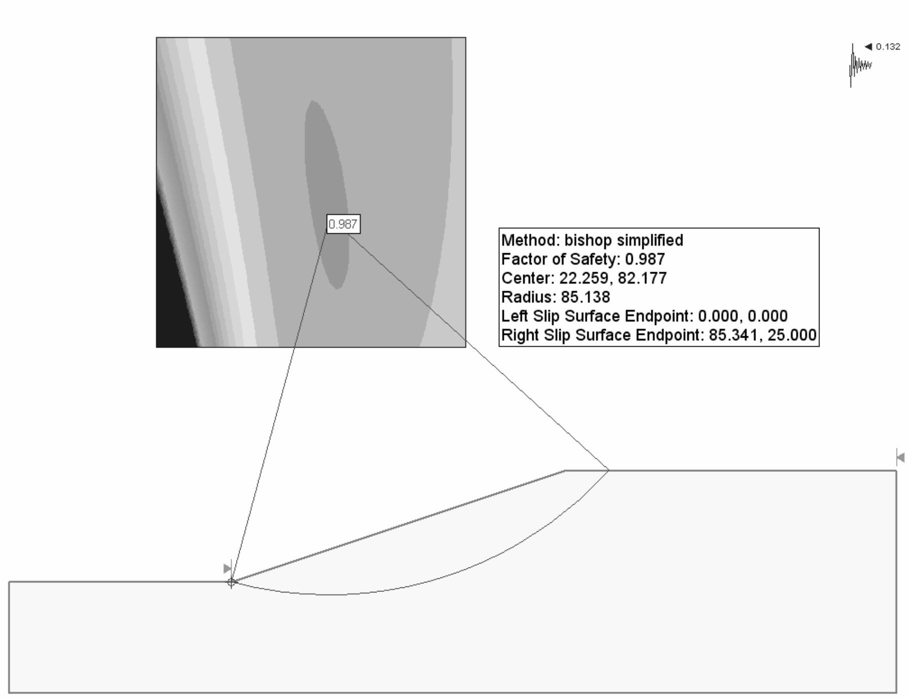


Figure 62.5 – Critical slip surface suing Bishop's method, grid search

63.1 Introduction

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

63.2 Description

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

63.3 Properties and Geometry

Table 63.1: Material Properties

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

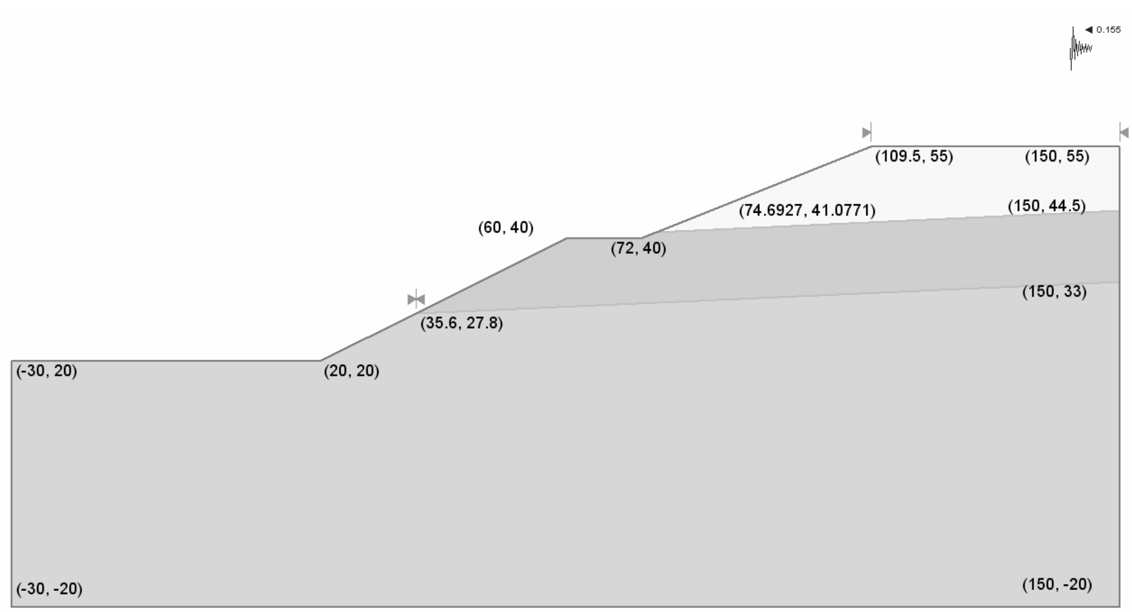


Figure 63.1 - Geometry

63.4 Results

SLIDE Spencer Factor of Safety = 0.991

Loukidis Spencer Factor of Safety = 1.000

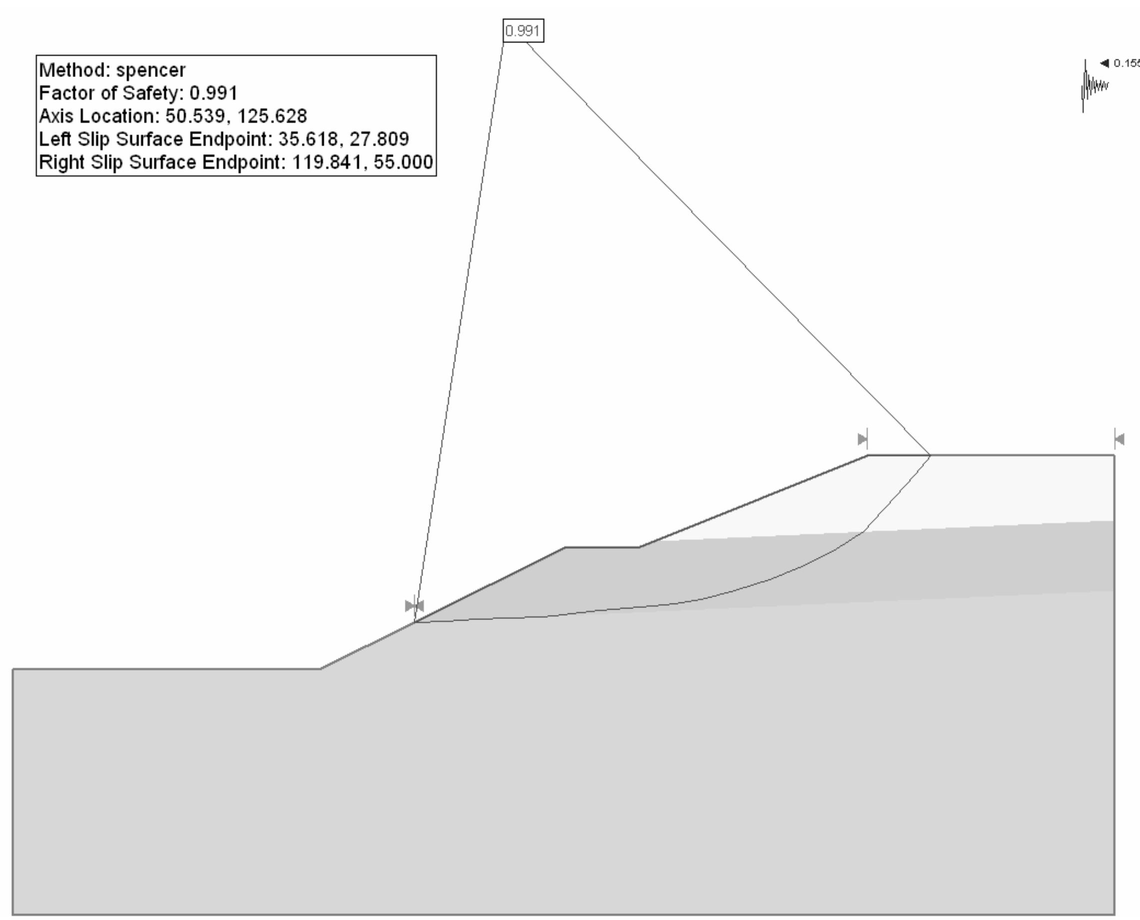


Figure 63.2 – Critical slip surface using the Spencer method

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