



**SVSLOPE<sup>TM</sup>**

**Slope Stability Modeling Software**

## Verification Manual

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## 1 INTRODUCTION

The word "Verification", when used in connection with computer software can be defined as "the ability of the computer code to provide a solution consistent with the physics of the problem. There are also other factors such as initial conditions, boundary conditions, and control variables that may affect the accuracy of the code to perform as stated.

"Verification" is generally achieved by solving a series of so-called "benchmark" problems. "Benchmark" problems are problems for which there is a closed-form solution or for which the solution has become "reasonably certain" as a result of longhand calculations that have been performed. Publication of the "benchmark" solutions in research journals or textbooks also lends credibility to the solution.

There are also example problems that have been solved and published in User Manual documentation associated with other comparable software packages. While these are valuable checks to perform, it must be realized that it is possible that errors can be transferred from one's software solution to another. Consequently, care must be taken in performing the "verification" process on a particular software package. It must also be remembered there is never such a thing as complete software verification for "all" possible problems. Rather, it is an ongoing process that establishes credibility with time.

SoilVision Systems takes the process of "verification" most seriously and has undertaken a wide range of steps to ensure that the SVSLOPE software will perform as intended by the theory of limit equilibrium slope stability.

The following models represent comparisons made to textbook solutions, hand calculations, and other software packages. We at SoilVision Systems Ltd., are dedicated to providing our clients with reliable and tested software. While the following list of example models is comprehensive, it does not reflect the entirety of models, which may be posed to the SVSLOPE software.

It is our recommendation that checks be performed on all model runs prior to presentation of results. It is also our recommendation that the modeling process move from simple to complex models with simpler models being verified through the use of hand calculations or simple spreadsheet calculations.

## 2 ACADS MODELS

The following group of models represent a series of models originally presented in the Australian ACADS study (Giam & Donald, 1989). The study presented a series of benchmark examples and allowed a variety of consultants using differing software packages to solve the models.

The results were then reviewed by an expert review panel and a “most correct” answer was established. The SVSLOPE software package was compared to these models in the following sections.

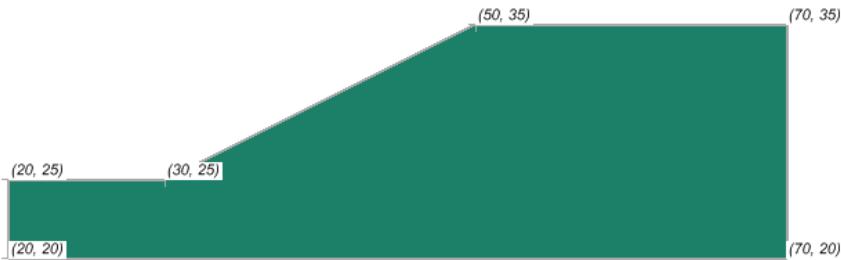
### 2.1 1(A) SIMPLE SLOPE

Project: Verification\_SVSlope\_Group1  
Model: VS\_1

This model contains a simple case a total stress analysis without considering pore-water pressures. It is a simple analysis that represents a homogenous slope with given soil properties. This model is originally published by the ACADS study (Giam & Donald, 1989).

The slope properties that are in use for this model are presented in Table 1. The requirements for this problem are the factor of safety and its corresponding critical circular failure surface.

#### 2.1.1 Geometry and Material Properties



**Figure 1 Geometry of the Simple Slope model**

**Table 1 Material Properties of the Simple Slope model**

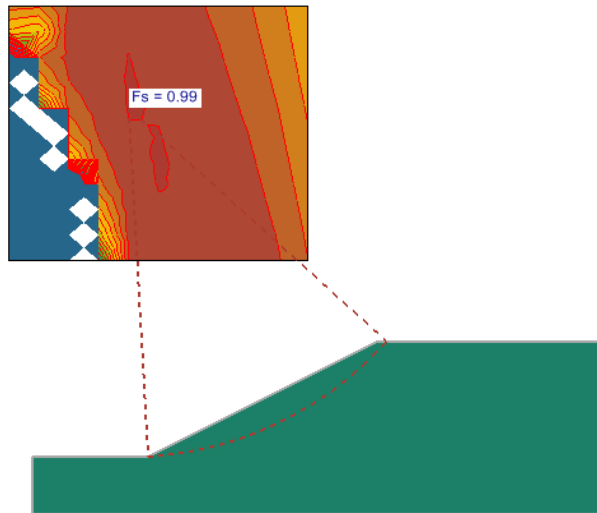
$c$ (kN/m <sup>2</sup> )	$\phi$ (degrees)	$\gamma$ (kN/m <sup>3</sup> )
3.0	19.6	20.0

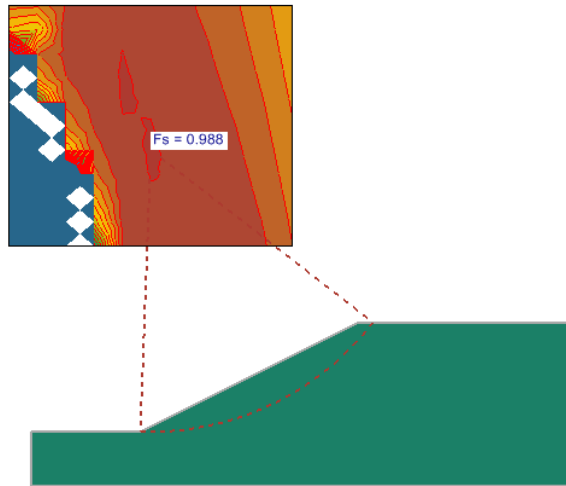
#### 2.1.2 Results and Discussions

The grid and radius method was used to identify a critical slip surface location. A grid of centers of 20 x 20 was used along with 11 tangent points. This period of a total of 4851 circular slip surfaces. The results of the analysis for each different analysis method are presented in Table 2. The referee Factor of Safety published by the ACADS study was 1.00.

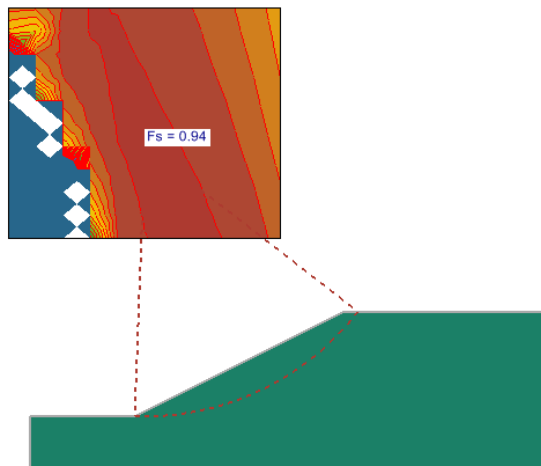
**Table 2 Results of the Simple Slope model**

Method	Factor of Safety		Difference (%)
	Slide	SVSLOPE	
Ordinary	0.947	0.945	-0.211
Bishop Simplified	0.987	0.989	0.203
Janbu Simplified	0.939	0.94	0.106
Spencer	0.986	0.988	0.203
GLE	0.986	0.988	0.203

**Figure 2 Solution of the Simple Slope model using the Spencer Method**



**Figure 3 Solution of the Simple Slope model using the GLE Method**



**Figure 4 Solution of the Simple Slope model using the Janbu Simplified Method**

## 2.2 1(B) TENSION CRACK

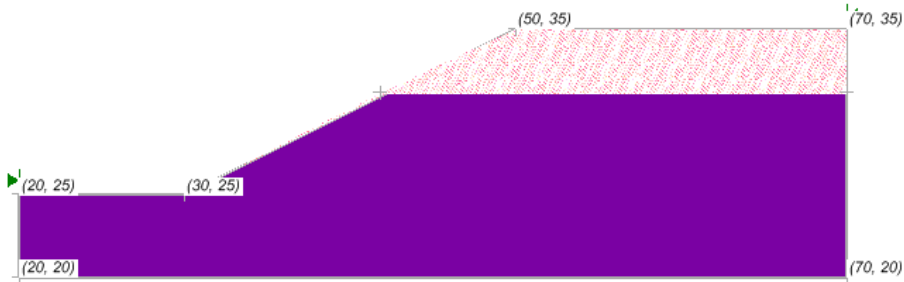
Project: Verification\_SVSlope\_Group1  
 Model: VS\_2

This model has the same slope geometry as verification problem #1, with the exception that a tension crack zone has been added as shown in Figure 5. For this problem, a suitable tension crack depth is required. Water is assumed to fill the tension crack.

The calculations the equation used to calculate the tension crack depth is shown below (Craig 1997).

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

### 2.2.1 Geometry and Material Properties



**Figure 5 Geometry of the Tension Crack model**

**Table 3 Material Properties of the Tension Crack model**

c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
32.0	10.0	20.0

### 2.2.2 Results and Discussions

The grid and radius search technique was used to locate the most critical slip surface. A grid 20 x 20 grid of centers was used along with 11 tangents points.

A total of 4851 slip surface was generated. The values of the critical factor of safety are shown in Table 4. The Bishop, Spencer, GLE and Janbu’s corrected, solutions are shown along with the location of the critical slip surface. The referee Factor of Safety published by the ACADS study is 1.65 to 1.70.

**Table 4 Results of the Tension Crack model**

Method	Slide	Factor of Safety				Difference (with Slide) (%)	Difference (with SLOPE/W) (%)
		Slope/W		SVSLOPE			
		Moment	Force	Moment	Force		
Ordinary	1.521	1.52		1.521		0.00	0.07
Bishop Simplified	1.596	1.592		1.593		0.19	0.06
Janbu Simplified	1.382		1.377		1.381	0.07	0.29
Spencer	1.592	1.594	1.599	1.589	1.589	0.19	0.31
M-P	1.592	1.588	1.594	1.59	1.59	0.13	0.13
GLE	1.592	1.588	1.588	1.59	1.59	0.13	0.13

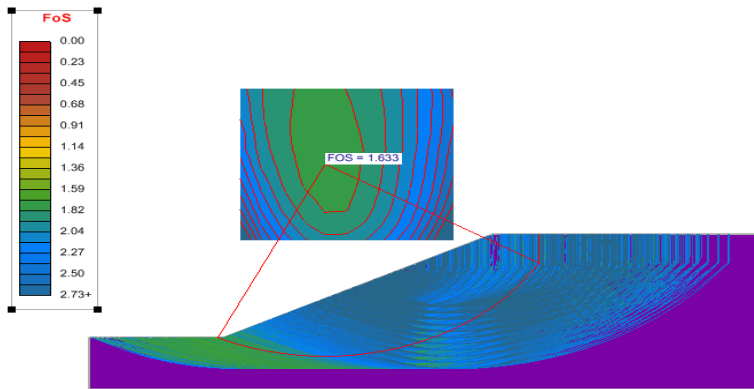


Figure 6 Solution of the Tension Crack model using the Bishop Method

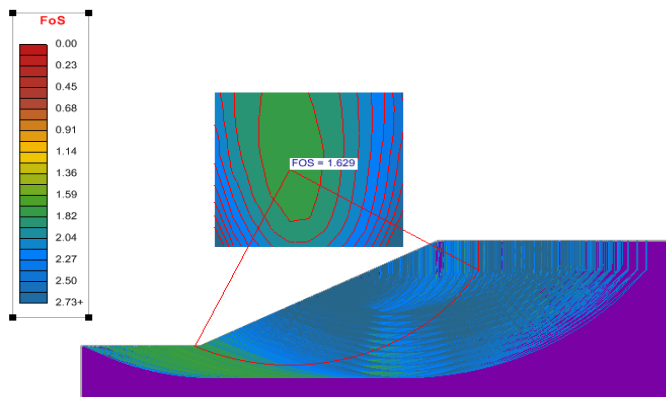


Figure 7 Solution of the Tension Crack model using the Spencer Method

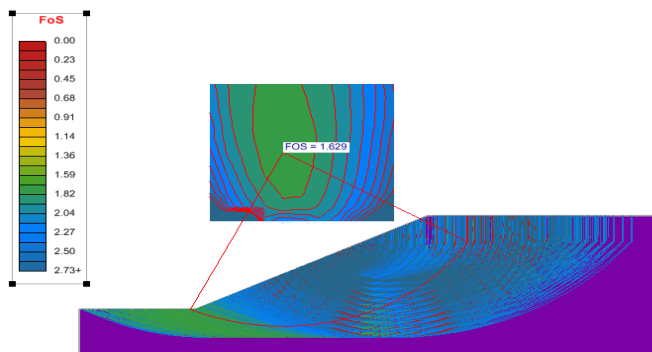
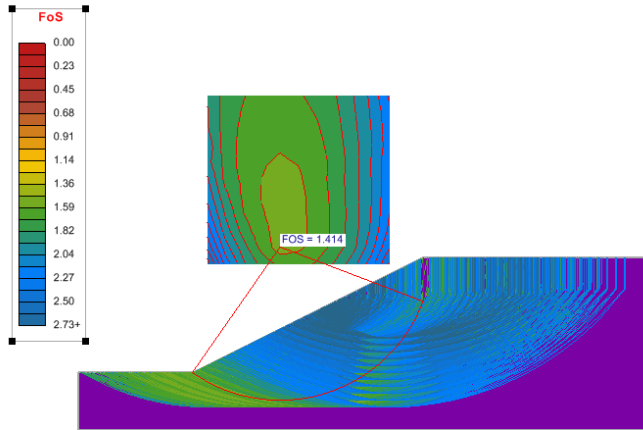


Figure 8 Solution of the Tension Crack model using the GLE Method



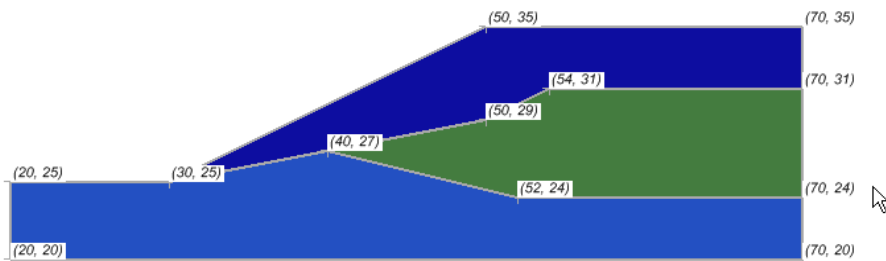
**Figure 9 Solution of the Tension Crack model using the Janbu Corrected Method**

### 2.3 1(C) NON-HOMOGENOUS

Project: Verification\_SVSlope\_Group1  
 Model: VS\_3

This model is a non-homogenous three-layer slope with material properties shown in Table 5. The calculation of the factor of safety and its corresponding critical slip surface is shown.

#### 2.3.1 Geometry and Material Properties



**Figure 10 Geometry of the Non-Homogenous model**

**Table 5 Material Properties of the Non-Homogenous model**

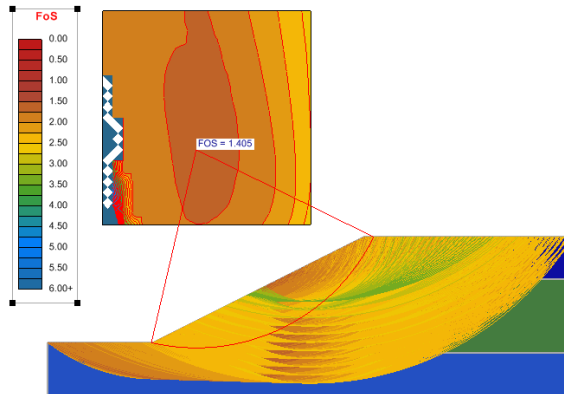
	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Soil #1	0.0	38.0	19.5
Soil #2	5.3	23.0	19.5
Soil #3	7.2	20.0	19.5

### 2.3.2 Results and Discussions

The grid and radius technique was used to determine the location of the critical slip surface. A slip surface centers search grid of 20 x 20 was used for the grid of centers and 11 tangents points were used at each grid center. This resulted in total of 4851 trial slip surfaces. The results of the factor of safety calculations are shown in Table 6. The referee Factor of Safety published by the ACADS study was 1.39.

**Table 6 Results of the Non-Homogenous model**

Method	Factor of Safety			Difference (%)
	Slide	SVSLOPE		
		Moment	Force	
Ordinary	1.232	1.231		-0.08
Bishop Simplified	1.405	1.405		0.00
Spencer	1.375	1.374	1.374	-0.07
GLE	1.374	1.375	1.375	0.07



**Figure 11 Solution of the Non-Homogenous model using the Bishop Method**

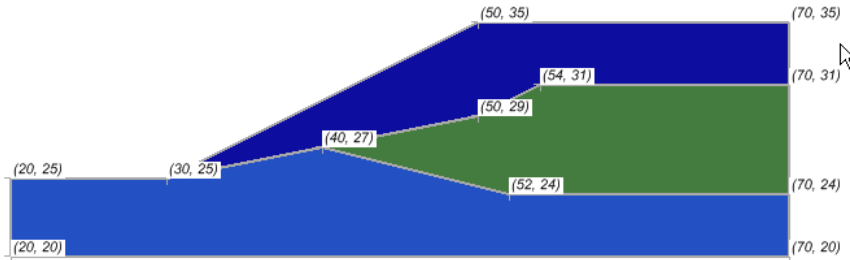
### 2.4 1(D) NON-HOMOGENOUS WITH SEISMIC LOAD

Project: Verification\_SVSlope\_Group1  
 Model: VS\_4

This model is identical to the previous model with the exception that a horizontal seismically induced acceleration of 0.15g was included in the analysis. The intent of this model is to test the ability of the software to analyze seismic conditions.

The model requires the calculations of the factor of safety and the corresponding location of the critical slip surface. No pore-water pressures are designated and therefore a total stress analysis is performed.

### 2.4.1 Geometry and Material Properties



**Figure 12 Geometry of the Non-Homogeneous with Seismic Load model**

**Table 7 Material Properties of the Non-Homogenous with Seismic Load**

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Soil #1	0.0	38.0	19.5
Soil #2	5.3	23.0	19.5
Soil #3	7.2	20.00	19.5

### 2.4.2 Results and Discussions

The results of the analysis produce the following table of factors of safety for the Bishop, Spencer, GLE, Janbu corrected methods. The referee Factor of Safety published by the ACADS study was 1.00.

**Table 8 Results of the Non-Homogenous with Seismic Load model**

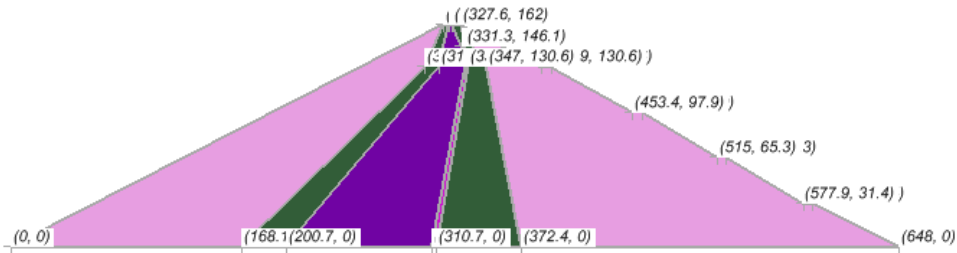
Method	Factor of Safety			Difference (%)
	Slide	SVSLOPE		
		Moment	Force	
Ordinary	0.884	0.884		0.00
Bishop Simplified	1.015	1.014		0.10
Janbu Simplified	0.897		0.897	0.00
Spencer	0.991	0.991	0.991	0.00
GLE	0.989	0.991	0.991	0.20

## 2.5 2(A) TALBINGO DAM, DRY

Project: Verification\_SV Slope\_Group1  
 Model: VS\_5 with Weak Layer

This model is the Talbingo Dam (Giam & Donald, 1989) for the end-of-construction stage. Soil properties are given in Table 9 and the geometrical data is given in Table 10. The model requirements are that a factor of safety and a corresponding location of the critical failure surface must be calculated.

### 2.5.1 Geometry and Material Properties



**Figure 13 Geometry of the Talbingo Dam model**

**Table 9 Material Properties of the Talbingo Dam model**

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Rock fill	0	45	20.4
Transitions	0	45	20.4
Filter	0	45	20.4
Core	85	23	18.1

**Table 10 Geometry Data of Talbingo Dam, with weak layer**

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	-	-	-

### 2.5.2 Results and Discussions

Resulting Factor of Safety are calculated that are shown in Table 11. The referee Factor of Safety published by the ACADS study is (1.95)/1.90.

**Table 11 Results of the Talbingo Dam model**

Method	Factor of Safety (Neglect PWP, with no cracks)			Difference (%)
	Slide	SVSLOPE		
		Moment	Force	
Ordinary	1.948	1.949		0.05
Bishop Simplified	1.948	1.95		0.10
Janbu Simplified	1.919		1.919	0.00
Spencer	1.948	1.95	1.95	0.10
GLE	1.948	1.95	1.95	0.10

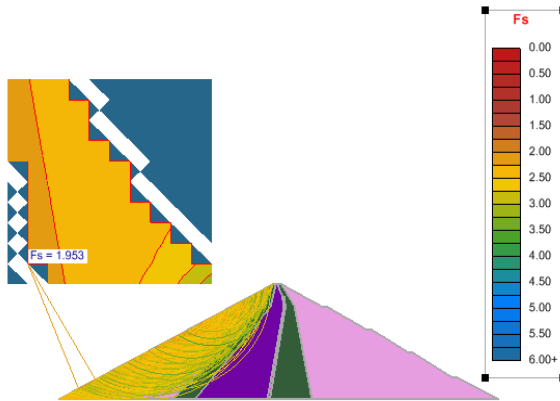


Figure 14 Solution of the Talbingo Dam model using the Bishop Simplified Method

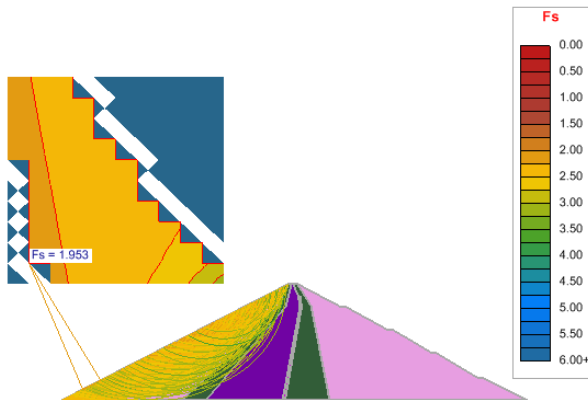


Figure 15 Solution of the Talbingo Dam using the Spencer Method

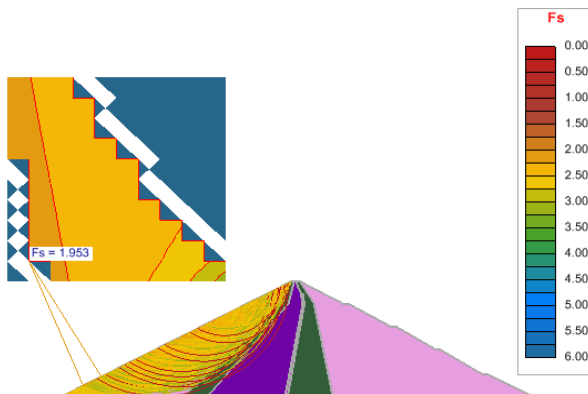


Figure 16 Solution of the Talbingo Dam model using the GLE Method

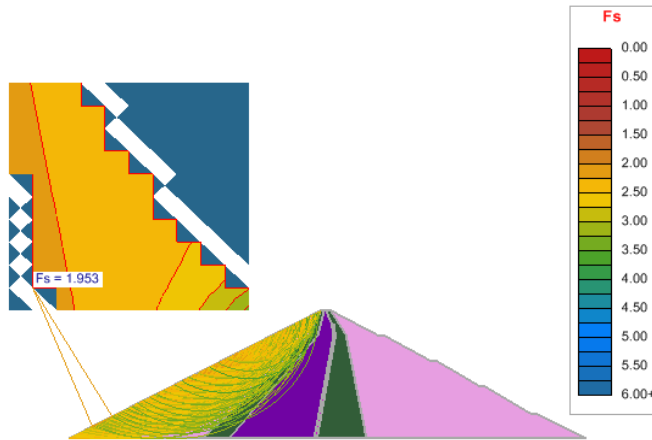


Figure 17 Solution of the Talbingo Dam model using the Janbu Corrected Method

## 2.6 2(B) TALBINGO DAM, DRY PREDEFINED SLIP SURFACE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_6

Model#6 is identical to model #5 with the exception is that a singular slip surface of known center and radius is analyzed in this particular problem.

### 2.6.1 Geometry and Material Properties

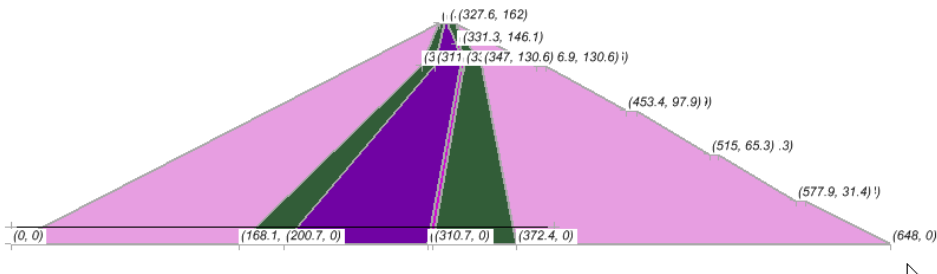


Figure 18 Geometry of the Talbingo Dam, Dry Predefined Slip Surface model

**Table 12 - Data for slip circle**

Xc	Yc (m)	Radium (m)
100.3	291	278.8

**Table 13 - Material Properties of the Talbingo Dam**

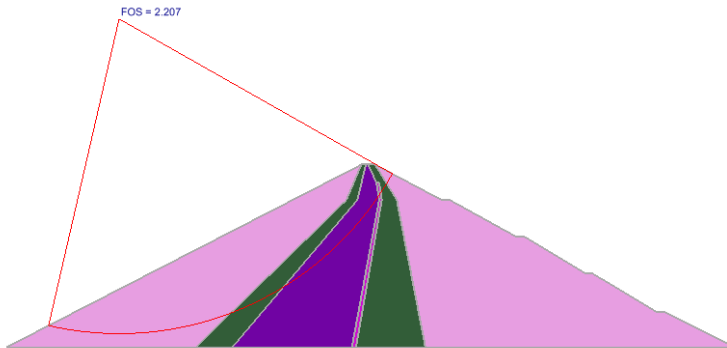
	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Rock fill	0	45	20.4
Transitions	0	45	20.4
Filter	0	45	20.4
Core	85	23	18.1

## 2.6.2 Results and Discussions

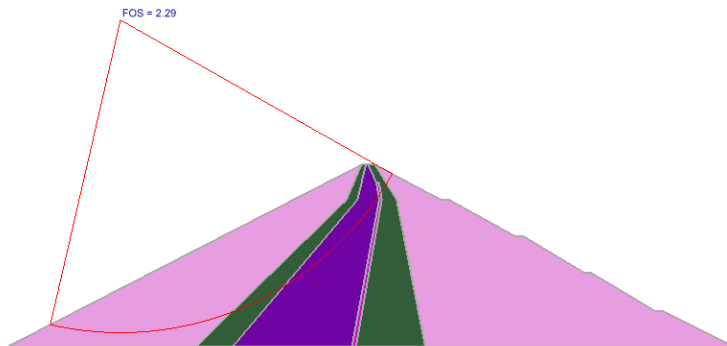
The following table illustrates the factor of safety and the methodology used for analyzing these conditions. The results are presented in Table 14. The referee Factor of Safety published by the ACADS study was 2.29.

**Table 14 Results of the Talbingo Dam**

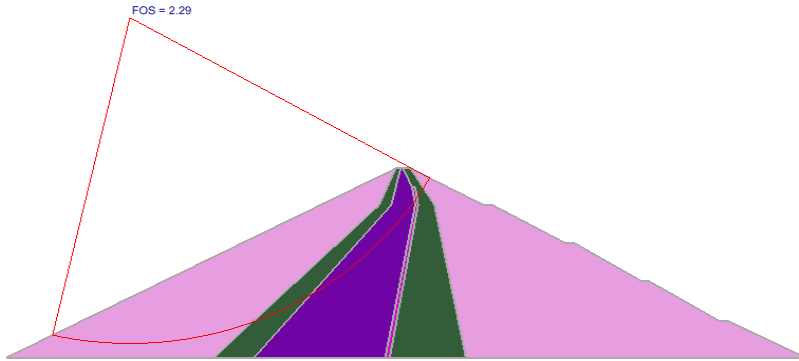
Method	Factor of Safety (Neglect PWP, with no cracks)				Difference (%)
	Slide		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	2.208		2.207		0.05
Spencer	2.292		2.29	2.29	0.09
GLE	2.301		2.298	2.298	0.13



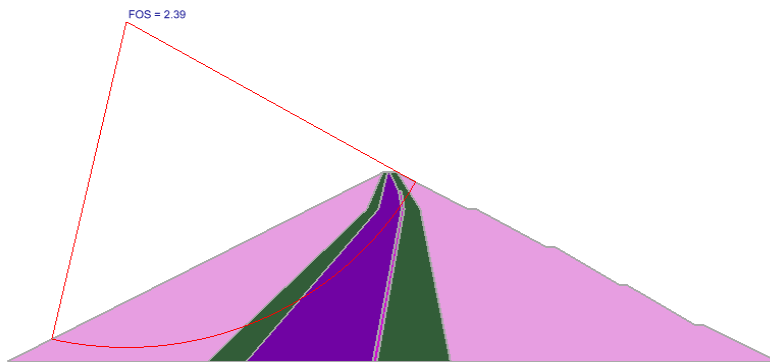
**Figure 19 Solution using the Bishop Simplified Method**



**Figure 20 Solution using the Spencer Method**



**Figure 21 Solution using the GLE Method**



**Figure 22 Solution using the Janbu Corrected**

## 2.7 3(A) WATER TABLE MODELED WITH WEAK SEAM

Project: Verification\_SVSlope\_Group1  
Model: VS\_7

This particular model illustrates the analysis of a slope containing a both a water table and a weak layer. The water table is assumed to coincide with the base of the weak layer. In this case, the affects of negative pore-water pressure above the water tables were ignored. The tension crack zone is also ignored in this model. The requirement is to calculation of the Factor of Safety and the corresponding noncircular failure surface.

### 2.7.1 Geometry and Material Properties

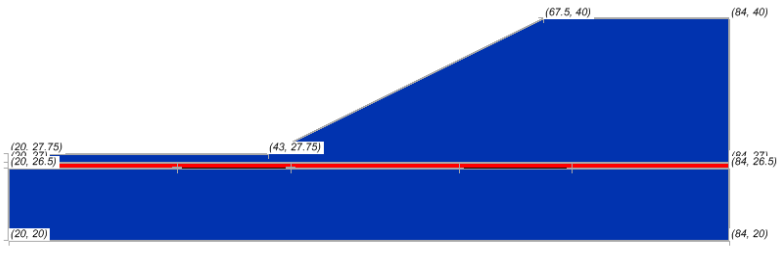


Figure 23 Geometry of the Water Table Modeled with the Weak Seam model

Table 15 - Material Properties of the Water Table

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Soil #1	28.5	20.0	18.84
Soil #2	0	10.0	18.84

### 2.7.2 Results and Discussions

The results of the analysis can be seen in Table 16. The referee Factor of Safety published by the ACADS study was 1.26.

Table 16 – Results of the Water Table

Method	Factor of Safety		Difference (%)
	Slide	SVSLOPE	
Spencer	1.258	1.256	0.16
GLE	1.246	1.247	0.08

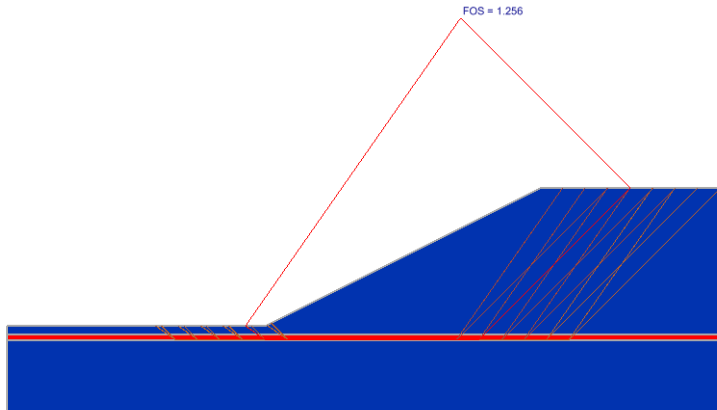


Figure 24 Solution using the Spencer Method

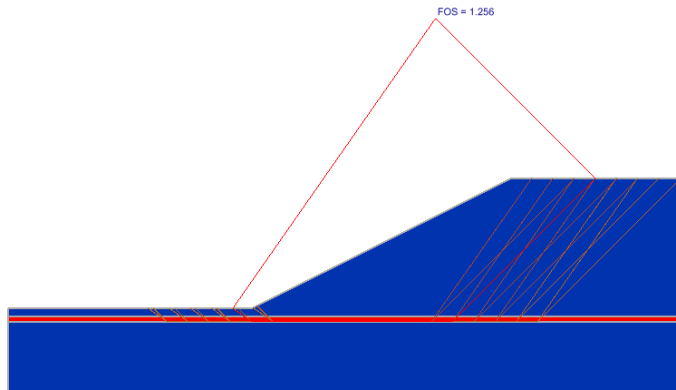


Figure 25 Solution using the GLE Method

### 2.8 3(B) WATER TABLE MODELED WITH WEAK SEAM WITH PREDEFINED SLIP SURFACE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_8

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

**NOTE :**

The referee values for each model can be viewed in the ACADS document publication and presented along side the SVSLOPE solutions.

#### 2.8.1 Geometry and Material Properties

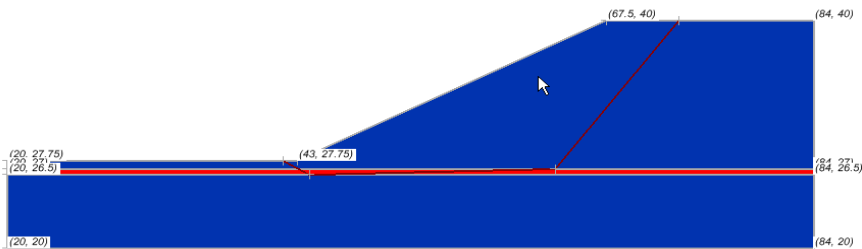


Figure 26 Geometry of the Water Table Modeled with Weak Seam with Predefined Slip Surface model

Table 17 Failure Surface Coordinates

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

**Table 18 Material Properties of the Water Table Modeled with Weak Seam**

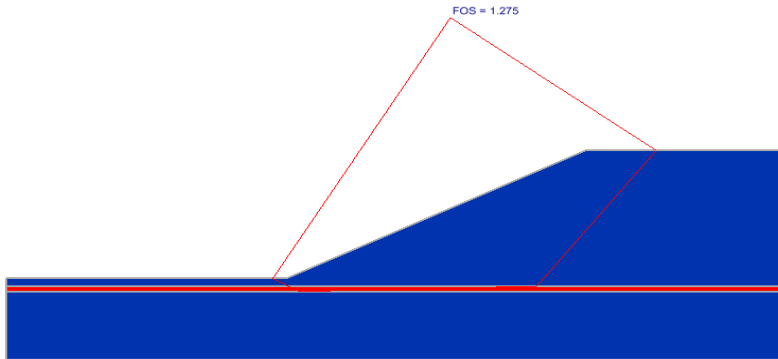
	<b>c (kN/m<sup>2</sup>)</b>	<b>φ (degrees)</b>	<b>γ (kN/m<sup>3</sup>)</b>
Soil #1	28.5	20.0	18.84
Soil #2	0	10.0	18.84

2.8.2 Results and Discussions

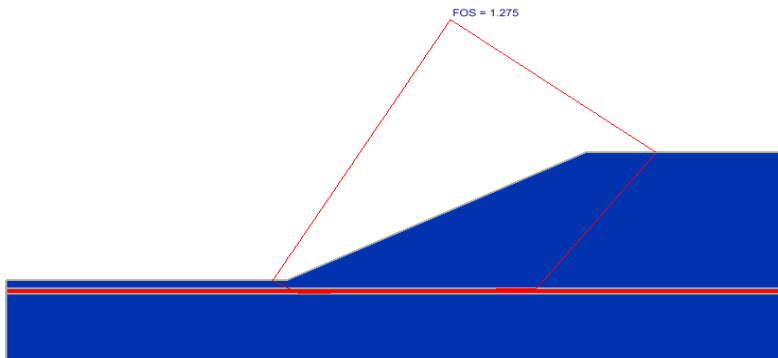
**Table 19 Results of pre-defined slip surface model**

Method	Slide	Factor of Safety		Difference (%)
		SVSLOPE		
		Moment	Force	
Spencer	1.277	1.276	1.276	0.08
GLE	1.262	1.259	1.258	0.24

The referee Factor of Safety published by the ACADS study was 1.34.



**Figure 27 Solution using the Spencer Method**



**Figure 28 Solution using the GLE Method**

## 2.9 4 EXTERNAL LOADING, PORE-PRESSURE DEFINED BY WATER TABLE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_9

This is a more complex example involving a weak layer, pore-water pressures and surcharges. The ACADS verification program received a wide range of answers for this model and fully expected this during the program. The soil parameters, external loadings and piezometric surface are shown in the following diagram. Tension cracks are ignored in this example. The model requirement is that the noncircular slip surface and the corresponding factor of safety are required.

### 2.9.1 Geometry and Material Properties

A block search for the critical noncircular failure surface is carried out by defining two line searches to block search squares within the weak layer. A number of different random surfaces were generated by the search and the results compared well with the actual results.

**Table 20 External Loadings**

X (m)	Y (m)	Normal Stress (kN/m <sup>2</sup> )
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 21 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 29

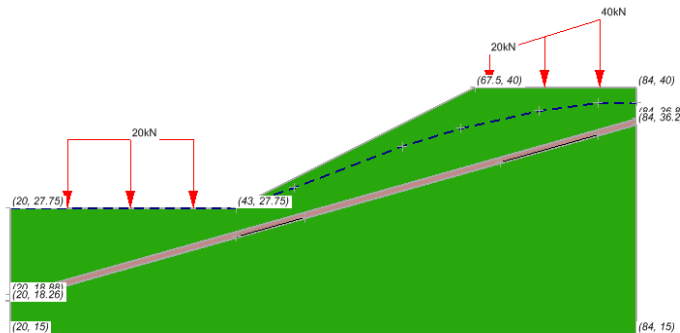


Figure 29 Geometry of the External Loading, Pore-Pressure defined by Water Table model

Table 22 Material Properties of the External Loading

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Soil #1	28.5	20.0	18.84
Soil #2	0	10.0	18.84

### 2.9.2 Results and Discussions

The results of this model illustrate the difference between a model with no optimization and a model where optimization methods are used. What is interesting in this case is that the optimized methods yield a lower Factor of Safety than the non-optimization techniques.

Table 23 – Optimization (Greco in SVSlope)

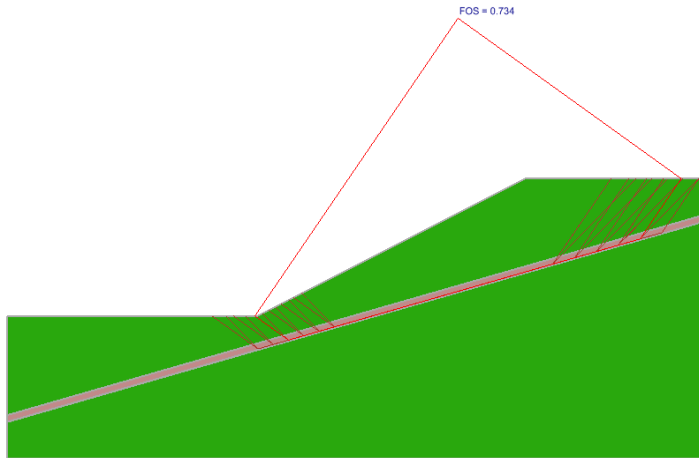
Method	Slide	Factor of Safety (Optimization-Greco)		Difference (%)
		SVSLOPE		
		Moment	Force	
Spencer	0.71	0.634	0.634	-10.70
GLE	0.685	0.665	0.665	-2.92

Table 24 - No optimization

Method	Slide	Factor of Safety		Difference (%)
		SVSLOPE		
		Moment	Force	
Spencer	0.760	0.739	0.739	-2.76
GLE	0.721	0.708	0.708	-1.80



Figure 30 Solution using the Spencer Method



**Figure 31 Solution using the GLE Method**

### 3 MISCELLANEOUS GROUP #1

The following examples compare the results of SVSLOPE against published solutions presented in textbooks or journal papers.

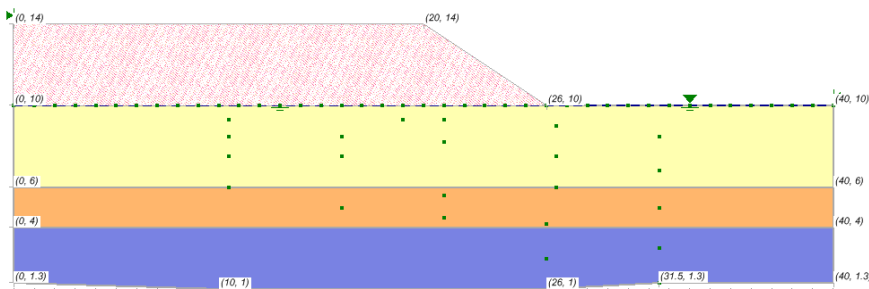
#### 3.1 LANESTER EMBANKMENT VERIFICATION

Project: Verification\_SVSLope\_Group1  
 Model: VS\_12

This problem is the Lanester embankment (in France) which was built with an induced failure for testing and research purposes in 1969 (Pilot et al, 1982). A dry tension crack zone is assumed to spread over the entire embankment for this model. Pore-water pressures are derived from Table data, from raw data presented for this model, and interpolated data across the model domain using the bilinear interpolation method.

The location of the critical slip surface and the corresponding factor of safety are required for this model.

##### 3.1.1 Geometry and Material Properties



**Figure 32 Geometry of the Lanester Embankment model**

**Table 25 Material Properties of the Lanester Embankment**

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Embankment	30	31.0	18.2
Soft Clay	4	37.0	14.0
Silty Clay	7.5	33.0	13.2
Sandy Clay	8.5	35.0	13.7

**Table 26 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	10.58	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	-	-	-

### 3.1.2 Results and Discussions

The results of the analysis are presented in Table 27.

**Table 27 Results of the Lanester Embankment model**

Method	Factor of Safety			Difference (%)
	Slide	SVSLOPE		
		Moment	Force	
Spencer	1.079	1.068	1.068	1.02
M-P	1.077	1.068	1.068	0.84
GLE	1.077	1.068	1.068	0.84

Note: No solution in **Slide** for the critical slip surface (SVSlope) in Bishop

**Table 28 Results of the Lanester Embankment model**

Method	Factor of Safety (Water Table)			Difference (%)
	Slide	SVSLOPE		
		Moment	Force	
Spencer	2.645	2.647	2.647	0.08
M-P	2.644	2.647	2.647	0.11
GLE	2.644	2.647	2.647	0.11

## 3.2 CUBZAC-LES-PONTS EMBANKMENT

Project: Verification\_SVSlope\_Group1  
 Model: VS\_13

In 1974, the Cubzac-les-Ponts embankment (in France) was built and a failure induced for testing and research purposes. This model represents an analysis of that particular problem.

### 3.2.1 Geometry and Material Properties

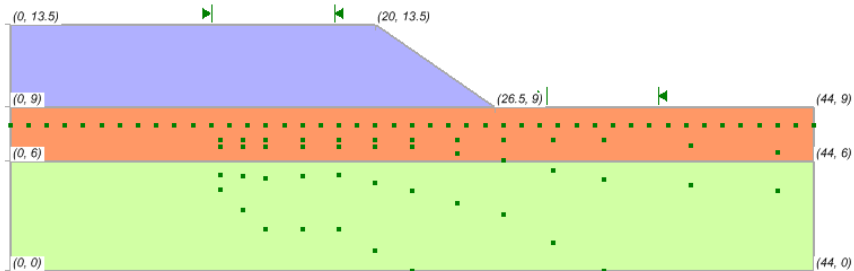


Figure 33 Geometry of the Cubzac-les-Ponts Embankment model

**Table 29 Water Pressure Points, u**

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	-	-	-

Table 30 presents the pore-water pressures at designated points. The pore-water pressures at the case of the slice were interpolation from the given data using a bio interpolation method. The location of the critical slip surface and the corresponding factor of safety are to be determined.

**Table 30 Material Properties of the Cubzac-les-Ponts Embankment model**

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Embankment	0	35.0	21.2
Upper Clay	10	24.0	15.5
Lower Clay	10	28.4	15.5

### 3.2.2 Results and Discussions

The resulting factors of safety from the SVSLOPE software are shown in Table 31.

**Table 31 Results of the Cubzac-les-Ponts Embankment model**

Method	Factor of Safety		Difference (%)
	Slide	SVSLOPE	
Moment Force			
Ordinary	0.662	0.656	0.91
Bishop Simplified	1.314	1.317	0.23
Janbu Simplified	1.199	1.206	0.58
Spencer	1.334	1.334	0.00
M-P	1.336	1.338	0.15
GLE	1.336	1.336	0.00

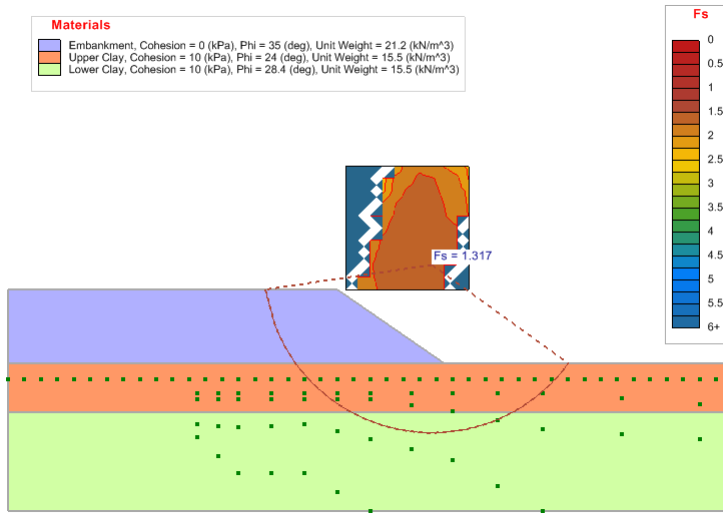


Figure 34 Results of the Cubzac-les-Ponts model using the Bishop Simplified method

### 3.3 ARAI AND TAGYO HOMOGENEOUS SLOPE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_14

Arai and Tagyo (1985) presented simple homogeneous soil slope with zero pore-water pressure. This model represents analysis of this particular problem and the results are provided in Table 33. There are no pore-water pressures input for this problem. The position of the critical slip surface, as well the calculated factor of safety is required in this analysis.

#### 3.3.1 Geometry and Material Properties

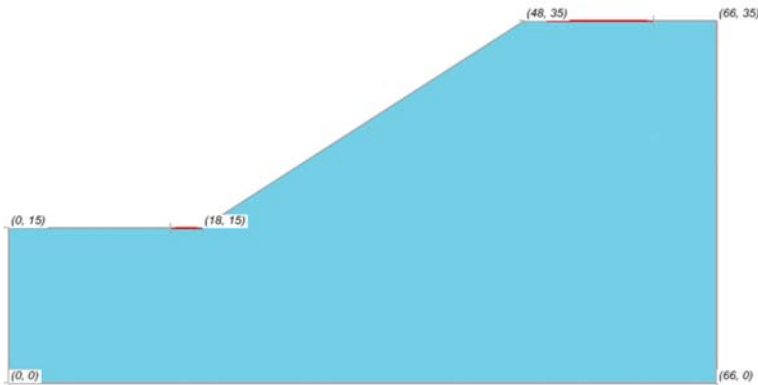


Figure 35 Geometry of the Arai and Tagyo Homogenous Slope Circular model

**Table 32 Material Properties of the Arai and Taygo Homogenous Slope Circular model**

	$c$ (kN/m <sup>2</sup> )	$\phi$ (degrees)	$\gamma$ (kN/m <sup>3</sup> )
Soil	41.65	15.0	18.82

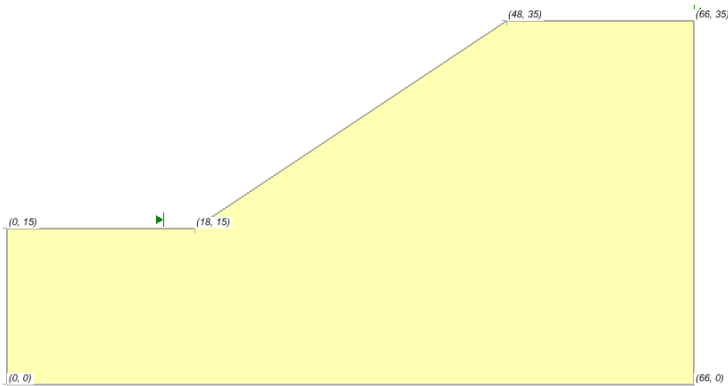
### 3.3.2 Results and Discussions

#### 3.3.2.1 Part 1 Circular Slip Surface Results: using grid and radius method.

The following results were obtained using the grid and radius search technique.

**Table 33 Circular Results – using auto refine search**

Method	Factor of Safety		Difference (%)
	Slide	SVSLOPE	
Ordinary		1.353	
Bishop Simplified	1.409	1.411	0.14
Janbu Simplified	1.319	1.326	0.53
Spencer	1.406	1.408	0.14



**Figure 36 Geometry of the Arai and Taygo Homogenous Non-circular model**

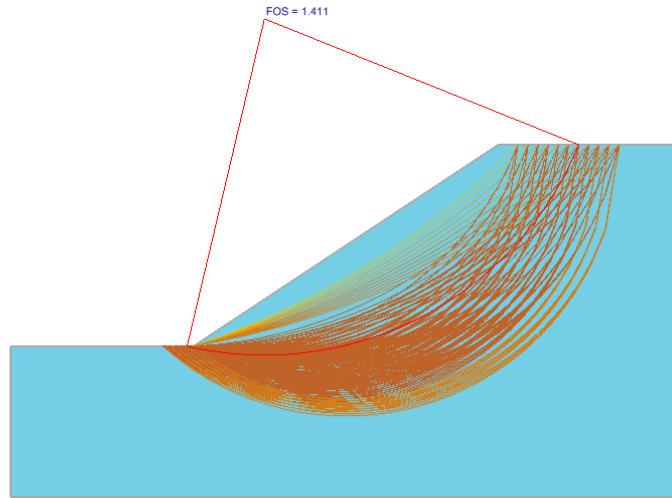


Figure 37 Circular Failure Surface Using Bishop Simplified Method

### 3.4 ARAI AND TAGYO LAYERED SLOPE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_15

Arai and Tagyo (1985) present an example, which consists of a layered slope, where a layer of low shear strength is located between two high strength layers. The results of this analysis have also been presented by Kim, et al. (2002), Malkawi et al. (2001) and Greco (1996). There are no pore-water pressures in this example. The corresponding model and set up data are presented in the following section. The position of the most critical slip surface as well as the calculated factor of safety is required for this analysis.

#### 3.4.1 Geometry and Material Properties

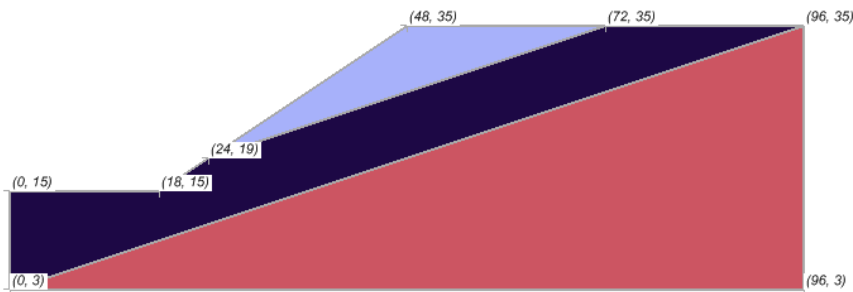


Figure 38 Geometry of the Arai and Tagyo Layered Slope model

Table 34 Material Properties of the Arai and Tagyo Layered Slope

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Upper Layer	29.4	12.0	18.82
Middle Layer	9.8	5.0	18.82
Lower Layer	294	40.0	18.82

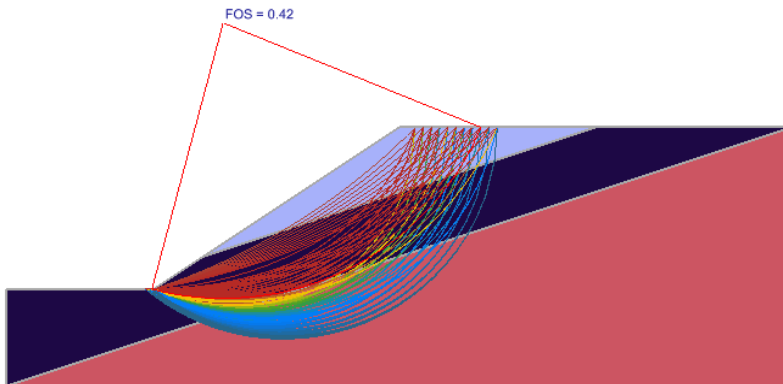
### 3.4.2 Results and Discussions

#### 3.4.2.1 Circular results

The entry and exist point search method are used to determine the location of the critical slip surface. The results are shown in Table 35.

**Table 35 Circular Results – using auto refine search**

Method	Factor of Safety		Difference (%)
	Slide	SVSLOPE	
Bishop Simplified	0.421	0.423	0.48
Janbu Simplified	0.410	0.415	1.22
Spencer	0.424	0.426	0.47



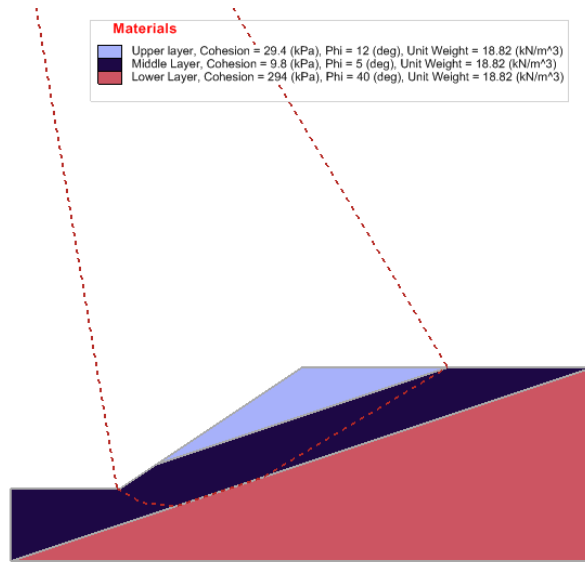
**Figure 39 Circular Failure Surface Using Bishop Simplified Method**

#### 3.4.2.2 Noncircular results

The noncircular slip surface analyses were performed using the Spencer method, and the Greco searching technique. The results of the Greco technique are presented in Table 36.

**Table 36 Noncircular Results using Random search with Optimization (1000 surfaces)**

Method	Factor of Safety				Difference (%)
	Slide		SVSLOPE		
	Moment	Force	Moment	Force	
Janbu Simplified		0.394		0.397	0.76
Spencer	0.412	0.412	0.414	0.414	0.49



**Figure 40 Noncircular Failure Surface Using Spencer Method and Random Search**

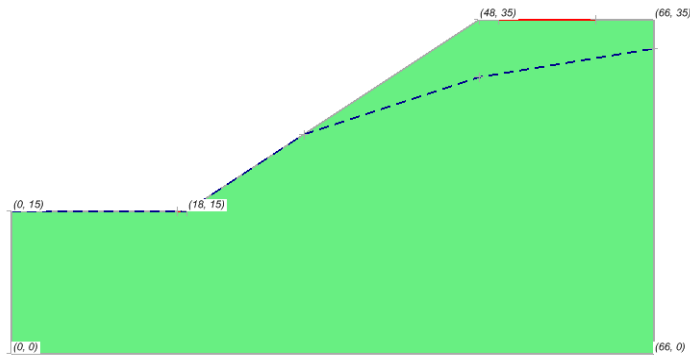
### 3.5 ARAI AND TAGYO PORE-WATER PRESSURE SLOPE

Project: Verification\_SVSlope\_Group1

Model: VS\_16

This example 3 is from Arai and Tagyo, (1985). The model is a simple homogeneous soil slope with pore-water pressures. The model contains a high water table with a daylight facing water table existing along the slope. The location of the water table is shown in Figure 41.

#### 3.5.1 Geometry and Material Properties



**Figure 41 Geometry of the Arai and Tagyo Pore-Water Pressure Slope model**

The pore-water pressures are calculated assuming hydrostatic conditions. Specific the pore-water pressures at point below the water table are calculated from the vertical distance to the water table and multiplying by the unit weight of water.

It is assumed that there is no affect of suction above the water table. The location of the vertical slip surface and the value of the factor of safety were required for this analysis.

**Table 37 Material Properties of the Arai and Tagyo Pore-Water Pressure Slope model**

	$c$ (kN/m <sup>2</sup> )	$\phi$ (degrees)	$\gamma$ (kN/m <sup>3</sup> )
Soil	41.65	15.0	18.82

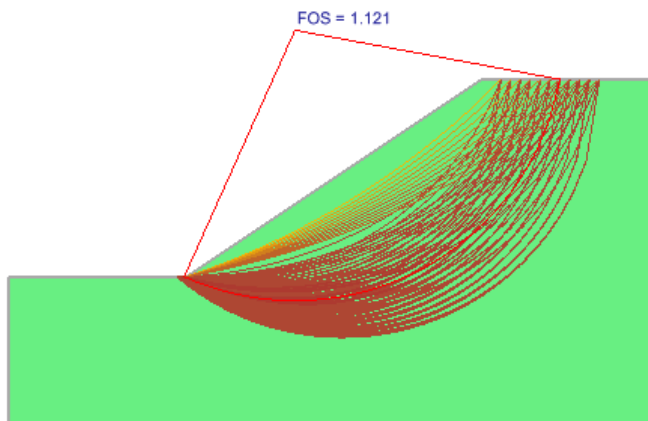
### 3.5.2 Results and Discussions

#### 3.5.2.1 Circular results

The grid and radius search technique was used to determine the location of the critical slip surface. The results are shown in Table 38.

**Table 38 Circular Results using Auto Refine Search**

Method	Factor of Safety		Difference (%)
	Slide	SVSLOPE	
Bishop Simplified	1.117	1.120	0.27
Janbu Simplified	1.046	1.050	0.38
Spencer	1.118	1.122	0.36



**Figure 42 Failure Surface using Bishop Simplified Method**

#### 3.5.2.2 Noncircular results

A noncircular analysis was also performed using the Greco search technique. The Greco search technique was applied with the Spencer and Janbu Simplified methods to yield the following factor of safety.

**Table 39 Noncircular Results using Random Search with Monte Carlo Optimization**

Method	Factor of Safety				Difference (%)
	Arai & Tagyo 1985	Slide		SVSLOPE	
		Moment	Force	Moment	
Janbu Simplified	0.995	0.968	0.967	0.10	
Spencer	1.094	1.094	1.099	0.46	

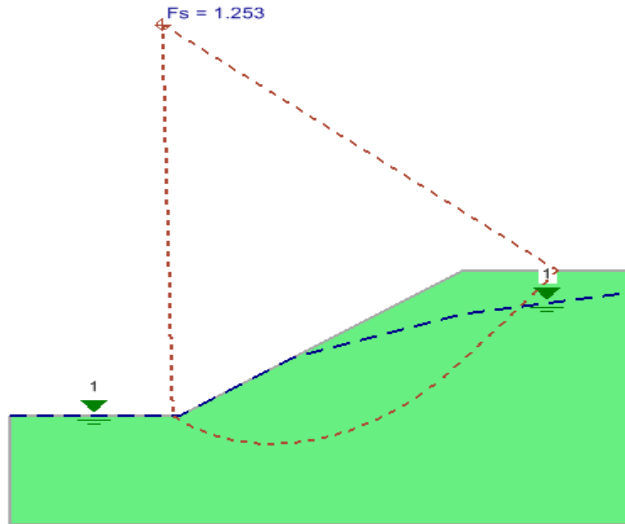


Figure 43 Noncircular Failure using Janbu Simplified Method

### 3.6 YAMAGAMI AND UETA SIMPLE SLOPE

Project: Verification\_SVSlope\_Group1

Model: VS\_17

This model was originally presented by Yamagami and Ueta (1988). The model consists of a simple homogeneous soil slope and zero pore-water pressures. The model was also analyzed by Greco in 1996. The location of the critical slip surface and the corresponding factor of safety are to be calculated.

#### 3.6.1 Geometry and Material Properties

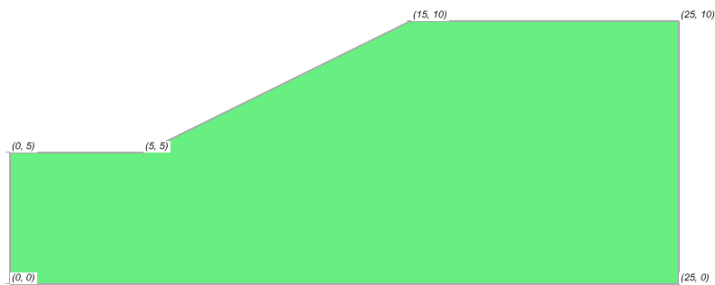


Figure 44 Geometry of the Yamagami and Ueta Simple Slope model

Table 40 Material Properties of the Yamagami and Ueta Simple Slope model

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Soil	9.8	10.0	17.64

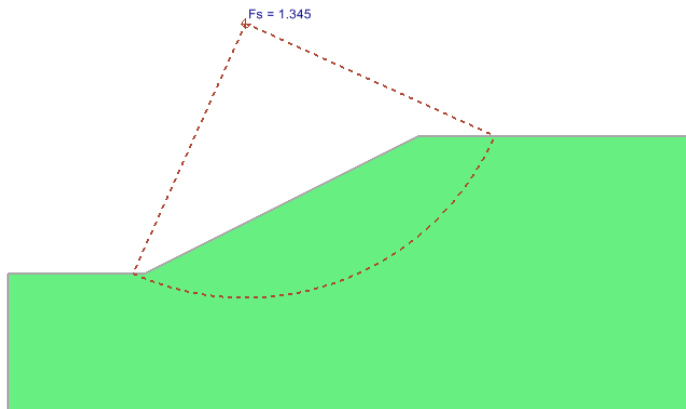
### 3.6.2 Results and Discussions

#### 3.6.2.1 Circular results

The analysis was performed using a specified range of entry and exit points. The calculated factors of safety for the Bishop's and Ordinary method are tabulated in Table 41.

**Table 41 Circular Results using auto refine search**

Method	Factor of Safety		Difference (%)
	Slide	SVSLOPE	
Ordinary	1.278	1.28	0.16
Bishop Simplified	1.344	1.345	0.07



**Figure 45 Failure surface using Bishop Simplified Method**

#### 3.6.2.2 Noncircular results

The critical noncircular slip surface was obtained using the Greco search method. The Greco search method results as well as the SVSLOPE results are presented in Table 42. In this particular case, the results of SVSLOPE are believed to be more optimal.

**Table 42 Noncircular Results using Random search with Monte Carlo optimization**

Method	Factor of Safety				Difference (%)
	Slide		SVSLOPE		
	Moment	Force	Moment	Force	
Janbu Simplified		1.178		1.178	0.00
Spencer	1.324	1.324	1.216	1.212	-8.13

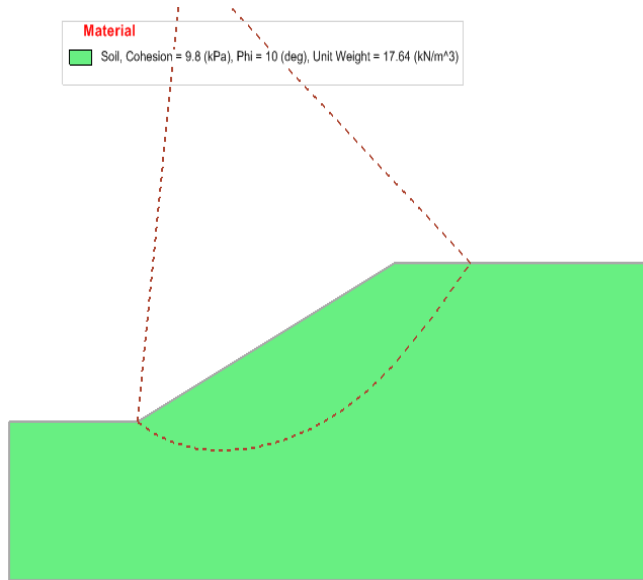


Figure 46 Noncircular failure using Spencer Method

### 3.7 BAKER SIMPLE SLOPE

Project: Verification\_SVSlope\_Group1  
Model: VS\_18

Baker (1980) published the results of this model, which was originally published by Spencer, (1969). It consists of a simple homogeneous soil slope with a pore-water pressure distribution defined by a pore pressure coefficient,  $r_u$  of 0.5.

#### 3.7.1 Geometry and Material Properties



Figure 47 Geometry of the Baker Simple Slope model

**Table 43 Material Properties of the Baker Simple Slope model**

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )	r <sub>u</sub>
Soil	10.8	40.0	17.64	0.5

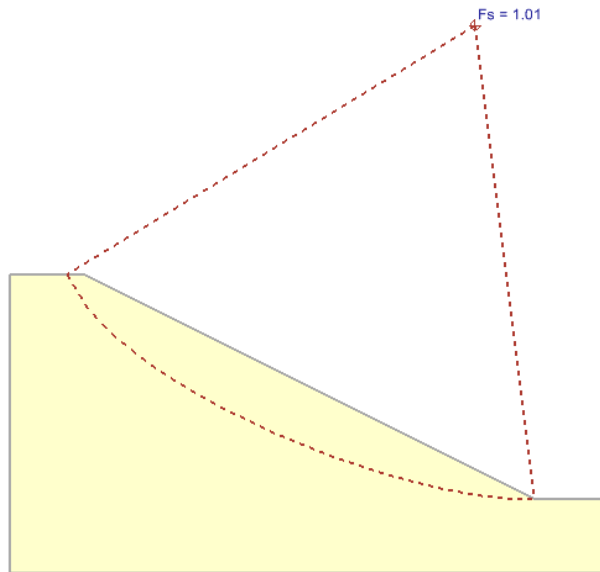
### 3.7.2 Results and Discussions

#### 3.7.2.1 Noncircular results

This model is solved using the Greco search technique along with Spencer’s method of calculating the factor of safety. The results may for the critical slip surfaces are shown in Figure 48.

**Table 44 Noncircular Results using Random Search with Monte Carlo optimization**

Method	Factor of Safety				Difference (%)
	Baker (1980)	Spencer (1969)	Slide	SVSLOPE	
			Moment Force	Moment Force	
Spencer	1.02	1.08	1.01	1.016	0.59



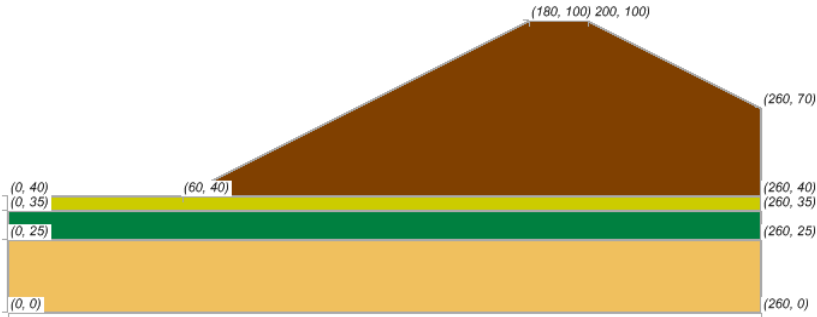
**Figure 48 Noncircular Failure Surface using Spencer Method along with the Greco search technique**

### 3.8 GRECO LAYERED SLOPE

Project: Verification\_SVSLope\_Group1  
 Model: VS\_19

This model was taken from Greco, 1996, Example # 4. It consists of a layered slope without pore-water pressures. It was originally published by Yamagami and Ueta (1988). The model consists of an earth dam type structure with three underlying soil layers.

### 3.8.1 Geometry and Material Properties



**Figure 49 Geometry of the Greco Layered Structure model**

**Table 45 Material Properties of the Greco Layered Structure model**

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Upper Layer	49	29.0	20.38
Layer 2	0	30.0	17.64
Layer 3	7.84	20.0	20.38
Bottom Layer	0	30.0	17.64

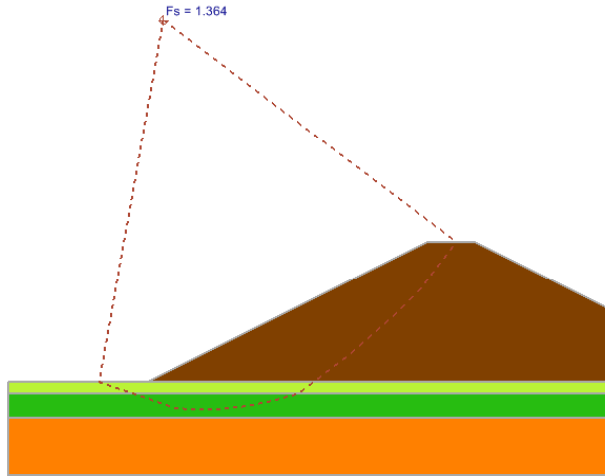
### 3.8.2 Results and Discussions

#### 3.8.2.1 Noncircular results

Using the Greco method, the following factors of safety were calculated for the Spencer method. The results are displayed in the Table 46 for the critical slip surface.

**Table 46 Noncircular Results using random search with Monte Carlo technique with convex surfaces**

Method	Factor of Safety						Difference (%)
	Greco 1996	Spencer 1969	Slide		SVSLOPE		
			Moment	Force	Moment	Force	
Spencer	1.40-1.42	1.40-1.42	1.398	1.398	1.4	1.4	0.14
GLE			1.398	1.398	1.39	1.39	0.57



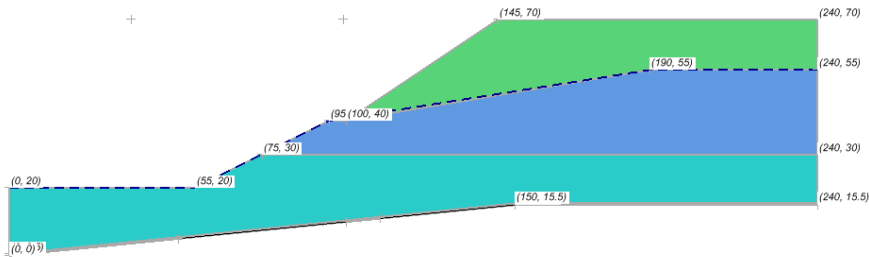
**Figure 50 Noncircular Failure Surface using the Spencer Method**

### 3.9 GRECO WEAK LAYER SLOPE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_20

This model is taken from Greco’s paper (1986) (Example #5). The model was originally published by Chen and Shao (1988). It consists of a layered slope with pore-water pressures and designated by a phreatic line. The geometry also has a weak seam. The weak seam is modeled as a 0.5m thick material layer at the base of the model. The critical slip surface and the corresponding factor of safety are to be calculated for a circular and noncircular slip surface.

#### 3.9.1 Geometry and Material Properties



**Figure 51 Geometry of the Greco Weak Layer Slope model**

**Table 47 Material Properties of the Greco Weak Layer Slope model**

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Layer 1	9.8	35.0	20.0
Layer 2	58.8	25.0	19.0
Layer 3	19.8	30.0	21.5
Layer 4	9.8	16.0	21.5

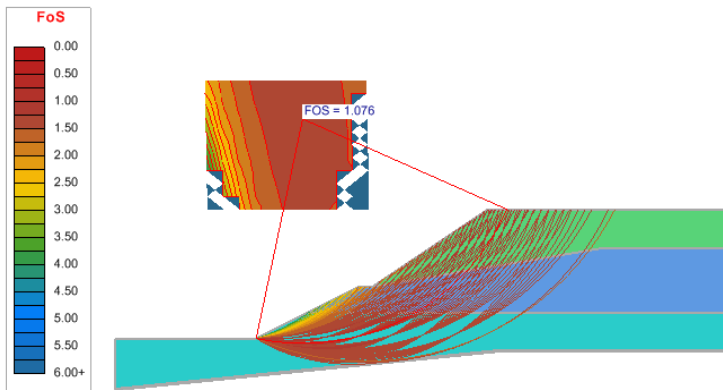
### 3.9.2 Results and Discussions

#### 3.9.2.1 Circular Results

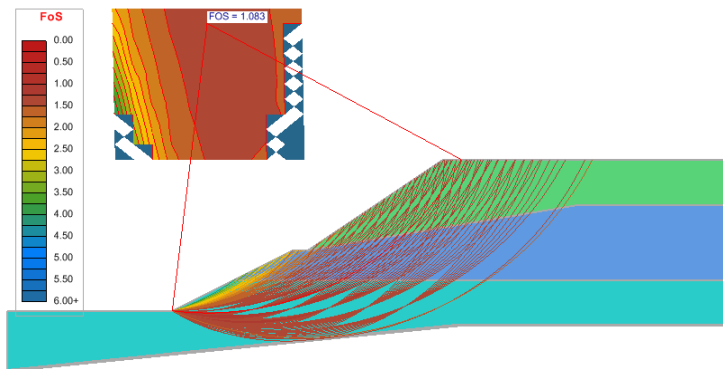
The results of the circular analysis are shown in Table 48.

**Table 48 Circular Results using a grid search and a focus object at the toe (40x40 grid)**

Method	Factor of Safety		Difference (%)
	Greco (1996)	Slide SVSLOPE	
Bishop Simplified	1.087	1.073	-1.29
Janbu Simplified	0.995	0.984	-1.11
Spencer	1.08	1.093	-1.10



**Figure 52 Circular Failure Surface using Bishop's Simplified Method**



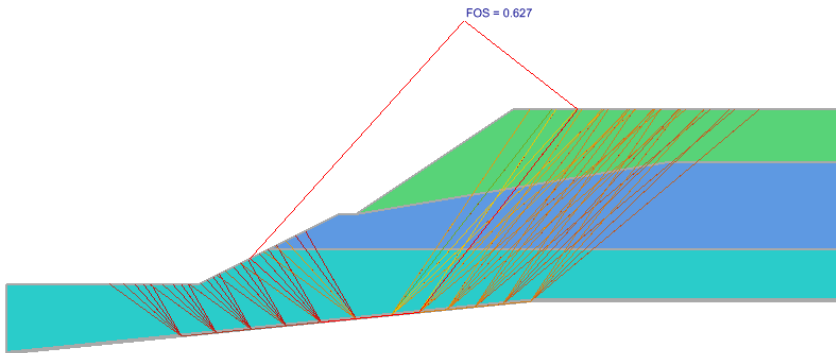
**Figure 53 Circular Failure Surface using Spencer's Method**

#### 3.9.2.2 Noncircular results

The results were obtained using the block search method. The block search method produced the following factor of safety.

**Table 49 Noncircular Results using block search polyline in the weak seam and Monte Carlo optimization**

Method	Factor of Safety (Greco)		Difference (%)
	Slide	SVSLOPE	
Spencer	1.007	0.987	-1.99



**Figure 54 Noncircular Failure Surface using Spencer Method and Block Search**

### 3.10 FREDLUND AND KRAHN HOMOGENEOUS SLOPE

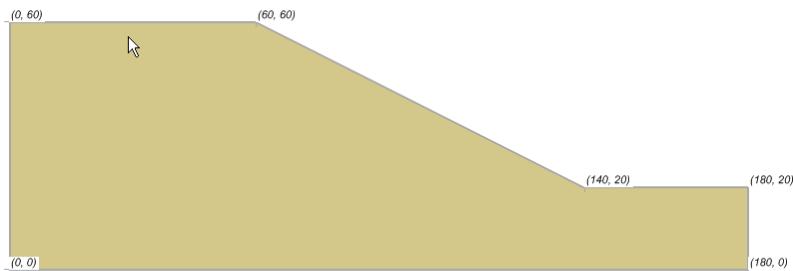
Project: Verification\_SVSlope\_Group1  
 Model: VS\_21

Fredlund and Krahn (1977) originally published this model. The intent of this model was to study the affect of various pore-water pressures and the resulting factor of safety. The model consists of a homogeneous slope consisting of three separate water conditions; namely:

1. Dry soil,
2.  $r_u$  defined pore-water pressures, and
3. Pore pressures defined using a water table, WT.

The calculations for this mode are performed in imperial units to be consistent with the original paper. Other authors such as Baker, (1980), Greco (1986) and Malkawi (2001) have also analyzed this slope.

#### 3.10.1 Geometry and Material Properties



**Figure 55 Geometry of the Fredlund and Krahn Homogenous Slope model**

**Table 50 Material Properties of the Fredlund and Krahn Homogenous Slope model**

	<b>c (psf)</b>	<b>φ (degrees)</b>	<b>γ (pcf)</b>	<b>r<sub>u</sub> (case2)</b>
Soil	10.8	40.0	17.64	0.5

### 3.10.2 Results and Discussions

The results of the defined circular analysis are presented in Table 51.

**Table 51 Results of the Circular slip surface analysis**

<b>Case</b>	<b>Ordinary (F &amp; K)</b>	<b>Ordinary</b>	<b>Bishop (F &amp; K)</b>	<b>Bishop Simplified</b>	<b>Spencer (F &amp; K)</b>	<b>Spencer</b>	<b>M-P (F &amp; K)</b>	<b>M-P</b>
1-Dry	1.928	1.930	2.080	2.079	2.073	2.075	2.076	2.075
2-Ru	1.607	1.609	1.766	1.762	1.761	1.760	1.764	1.760
3-WT	1.693	1.696	1.834	1.832	1.830	1.831	1.832	1.831

**Table 52 Results–Dry**

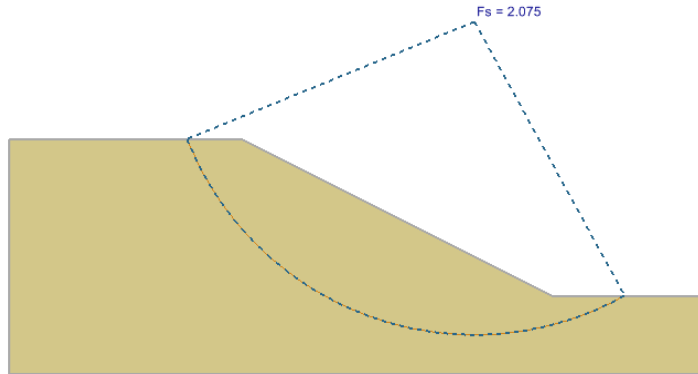
<b>Method</b>	<b>Factor of Safety</b>				<b>Difference (%)</b>
	<b>Fredlund &amp; Krahn (1977)</b>	<b>Slide</b>	<b>SVSLOPE</b>		
			<b>Moment</b>	<b>Force</b>	
Ordinary	1.928	1.931	1.93		-0.05
Bishop Simplified	2.08	2.079	2.079		0.00
Spencer	2.073	2.075	2.075	2.075	0.00
M-P	2.076	2.075	2.075	2.075	0.00

**Table 53 Results of the analysis with ru pore-water pressures**

<b>Method</b>	<b>Factor of Safety</b>				<b>Difference (%)</b>
	<b>Fredlund &amp; Krahn (1977)</b>	<b>Slide</b>	<b>SVSLOPE</b>		
			<b>Moment</b>	<b>Force</b>	
Ordinary	1.607	1.609	1.609		0.00
Bishop Simplified	1.766	1.763	1.762		-0.06
Spencer	1.761	1.76	1.76	1.76	0.00
M-P	1.764	1.76	1.76	1.76	0.00

**Table 54 Results of the analysis with a designated water table, WT**

<b>Method</b>	<b>Factor of Safety</b>				<b>Difference (%)</b>
	<b>Fredlund &amp; Krahn (1977)</b>	<b>Slide</b>	<b>SVSLOPE</b>		
			<b>Moment</b>	<b>Force</b>	
Ordinary	1.693	1.697	1.696		-0.06
Bishop Simplified	1.834	1.833	1.832		-0.05
Spencer	1.83	1.831	1.831	1.831	0.00
M-P	1.832	1.831	1.83	1.83	-0.05



**Figure 56 Location of the Circular slip surface for the Fredlund & Krahn (1977), Dry slope analysis with the Spencer method.**

### 3.11 FREDLUND AND KRAHN WEAK LAYER SLOPE

Project: Verification\_SVSlope\_Group1  
Model: VS\_22

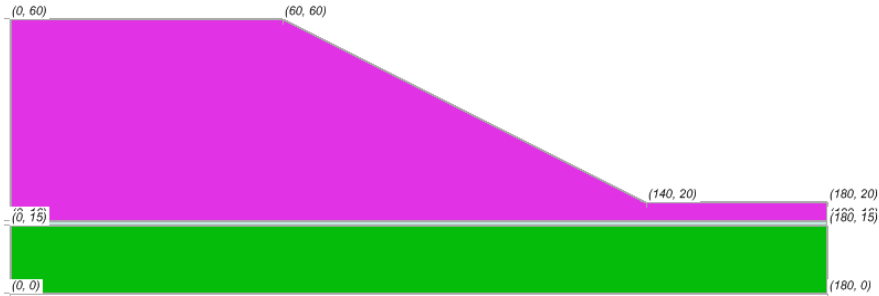
In 1977, Fredlund and Krahn published a paper, which contained a verification model consisting of a slope with a weak layer and three different designations of water pressure conditions. A number of different authors, such as Kim and Salgado (2002), Baker (1980), and Zhu, Lee and Jiang (2003), have also analyzed this slope. The model consists of a slope with a weak layer, which is sandwiched between soil strata. The water conditions are defined as follows:

1. Dry soil,
2.  $R_u$  defined pore-water pressures, and
3. Pore pressures defined using a water table, WT.

The model is set up in imperial units to be consistent with the original paper. The location of the weak layer appears to be slightly different in some of the mentioned references above. The results for this example model are sensitive to the location of the weak layer, therefore, the results may vary in the second decimal place. The geometry is shown in the following figure.

The location of the composite slip surface provided in the original paper was shown as having coordinates,  $x_c = 120$ ,  $y_c = 90$  and radius = 80. The GLE method was run with a half sign interslice force function for calculating the factor of safety.

### 3.11.1 Geometry and Material Properties



**Figure 57 Geometry of the Fredlund and Krahn (1977) Weak Layer Slope model**

**Table 55 Material Properties of the Fredlund and Krahn (1977) Weak Layer Slope model**

	c (psf)	$\phi$ (degrees)	$\gamma$ (pcf)	Ru (case2)
Upper Soil	600	20	120	0.25
Weak Layer	0	10.0	120	0.25

### 3.11.2 Results and Discussions

The computer results for three cases are presented in Tables 56, 57 and 58 for SVSLOPE, Fredlund and Krahn and Zhu et al, respectively.

**Table 56 Composite Circular Results SVSLOPE**

Method	Case 1: Dry	Case 2: Ru	Case 3: WT
Ordinary	1.299	1.039	1.174
Bishop Simplified	1.382	1.123	1.242
Spencer	1.382	1.124	1.244
GLE/M-P	1.382	1.124	1.244

**Table 57 Composite Circular Slip Surface Results Fredlund & Krahn (1977)**

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/M-P	1.370	1.118	1.245

**Table 58 Composite Circular Slip Surface Results Zhu, Lee, and Jiang (2003)**

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/M-P	1.371	1.109	1.254

The computer results are also presented for each of the pore-water pressure conditions in Tables 59 to 61. In this case, a comparison of 4 computer software package results is compared.

**Table 59 Comparison of computed factors of safety for the Case of a Dry slope**

Method	Factor of Safety					Difference (%)
	Fredlund & Krahn	Zhu, Lee & Jiang	Slide	SVSLOPE		
				Moment	Force	
Ordinary	1.288	1.300	1.300	1.299		-0.08
Bishop Simplified	1.377	1.380	1.382	1.382		0.00
Spencer	1.373	1.381	1.382	1.382	1.382	0.00
M-P	1.370	1.371	1.372	1.372	1.372	0.00

**Table 60 Comparison of computed factors of safety for the Case of a designated Ru value**

Method	Factor of Safety					Difference (%)
	Fredlund & Krahn	Zhu, Lee & Jiang	Slide	SVSLOPE		
				Moment	Force	
Ordinary	1.029	1.038	1.039	1.039		0.00
Bishop Simplified	1.124	1.118	1.124	1.123		-0.09
Spencer	1.118	1.119	1.118	1.124	1.124	0.54
M-P	1.118	1.109	1.118	1.114	1.114	-0.36

**Table 61 Comparison of computed factors of safety for the Case of a designated water table, WT**

Method	Factor of Safety					Difference (%)
	Fredlund & Krahn	Zhu, Lee & Jiang	Slide	SVSLOPE		
				Moment	Force	
Ordinary	1.171	1.192	1.174	1.174		0.00
Bishop Simplified	1.248	1.260	1.243	1.242		-0.08
Spencer	1.245	1.261	1.244	1.244	1.244	0.00
M-P	1.245	1.254	1.237	1.237	1.237	0.00

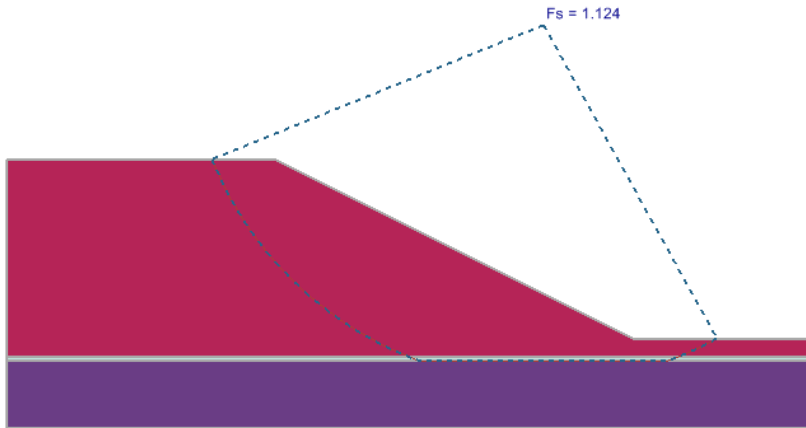


Figure 58 Solution when using SVSLOPE and Ru value for the M-P method

### 3.12 LOW TWO LAYER SLOPE

Project: Verification\_SVSSlope\_Group1  
 Model: VS\_23

This model was originally published by Low (1989). The model consisted of a slope overlaying two soil layers. The soil properties defined are shown in Table 62. The middle and lower soils have constant and linear by varying undrained shear strengths. The position of the critical slip surface and the corresponding factor of safety were calculated for a critical slip surface using both the Bishop and Ordinary/Fellenius methods.

#### 3.12.1 Geometry and Material Properties

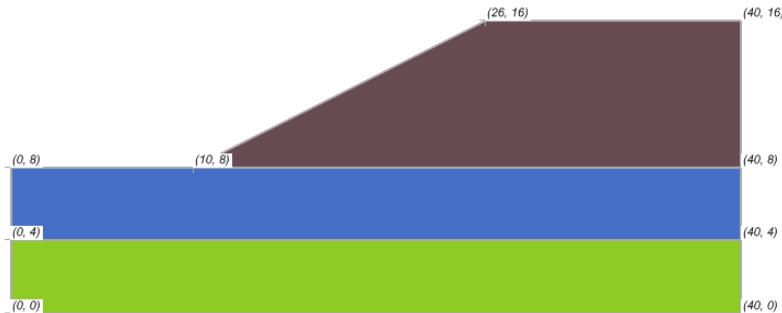


Figure 59 Geometry of the Low Two Layer Slope model

Table 62 - Material Properties of the Low Two Layer Slope model

	$Cu_{top}$ (kN/m <sup>2</sup> )	$Cu_{bottom}$ (kN/m <sup>2</sup> )	$\phi$ (degrees)	$\gamma$ (kN/m <sup>3</sup> )
Upper Soil	95	95	15	20
Middle Soil	15	15	0	20
Lower Soil	15	30	0	20

### 3.12.2 Results and Discussions

The results of a circular slip surface analysis are presented in Table 63, showing a comparison with published results.

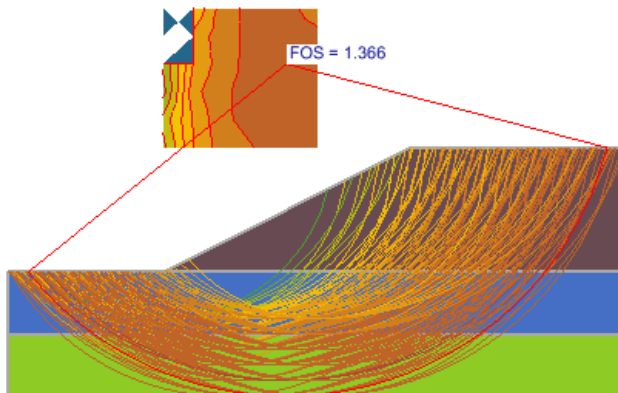
#### 3.12.2.1 Circular Results

**Table 63 Circular Results of the Low Two Layer Slope model**

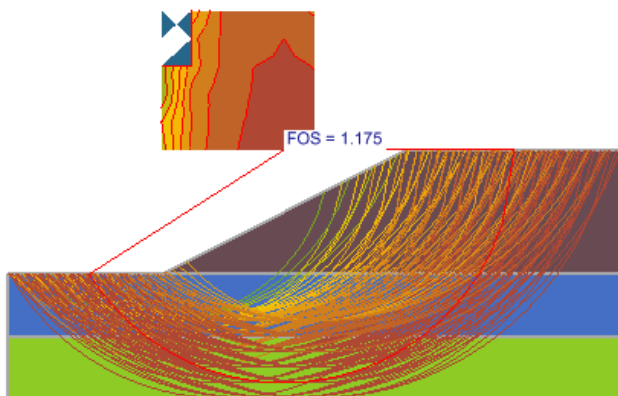
Method	Factor of Safety				Difference (%)	
	Kim (2002)	Low (1989)	Slide	SVSLOPE		
				Moment		Force
Ordinary		1.36	1.37	1.366	-0.29	
Bishop Simplified	1.17	1.14	1.192	1.175	-1.43	

#### 3.12.2.2 Grid and radius search method

The results of the grid and radius search method can be seen in the following figures.



**Figure 60 Circular Slip Surfaces using Ordinary/Fellenius Method**



**Figure 61 Circular Slip Surfaces using Bishop's Simplified Method**

### 3.13 LOW THREE LAYER SLOPE

Project: Verification\_SVSlope\_Group2  
Model: VS\_24

This model is also taken from Low (1989) and it consists of a slope with three layers with three different undrained shear strength values.

The geometry for a verification problem #24 is shown in Figure 62. 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. The material properties are shown in Table 64.

#### 3.13.1 Geometry and Material Properties

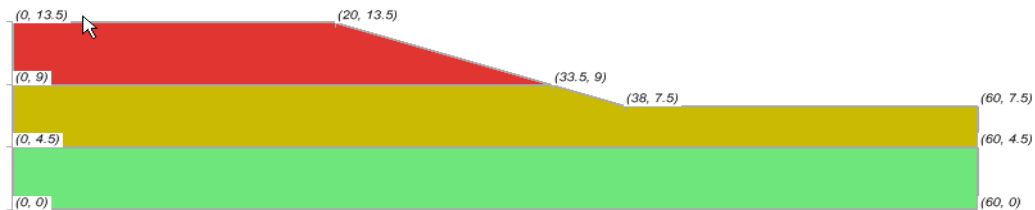


Figure 62 Geometry of the Low Three Layer Slope model

Table 64 Material Properties of the Low Three Layer Slope model

	Cu (kN/m <sup>2</sup> )	(kN/m <sup>3</sup> )
Upper Layer	30	18
Middle Layer	20	18
Bottom Layer	150	18

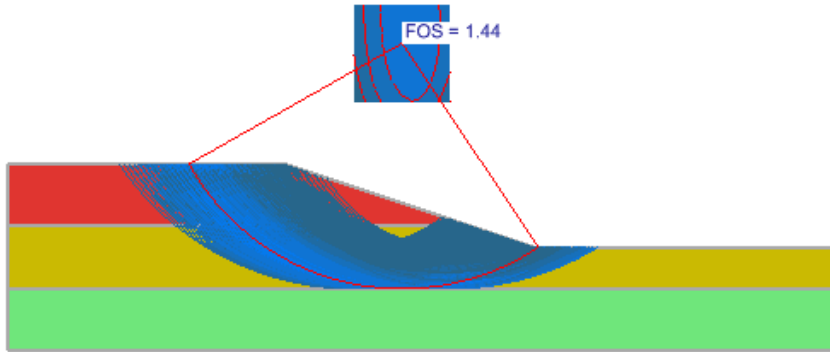
#### 3.13.2 Results and Discussions

##### 3.13.2.1 Circular Results

The following results were calculated using the auto refine search technique in SVSLOPE.

Table 65 Circular Results–auto refine search technique

Method	Factor of Safety			Difference (%)
	Low (1989)	Slide	SVSLOPE	
Ordinary	1.44	1.439	1.44	0.07
Bishop Simplified	1.44	1.439	1.44	0.07



**Figure 63 Circular Failure Surfaces using Bishop’s Simplified Method**

### 3.14 CHEN AND SHAO FRICTIONLESS SLOPE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_25

Chen and Shao (1988) presented the problem to illustrate a plasticity solution for a weightless frictionless slope subjected to a vertical load. This problem was first solved by Prandtl (1921).

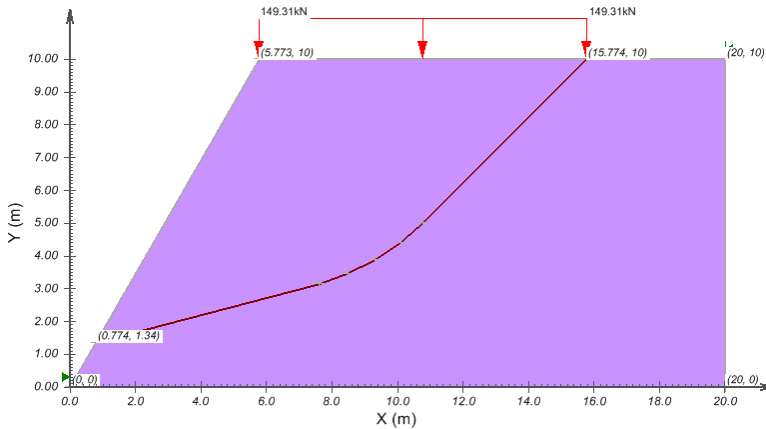
The critical load position for the critical slip surface was defined by Prandtl and is shown in Figure 64. The critical failure surface has a theoretical factor of safety of 1.0. The critical uniformly distributed load for failure is presented in the paper as 149.31 kN/m, with a length equal to the slope height of 10m.

**NOTE :**

A “custom” interslice shear force function was used with GLE and Morgenstern-Price methods as shown in Chen and Shao (1988).

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

### 3.14.1 Geometry and Material Properties



**Figure 64 Geometry of the Chen and Shao Frictionless Slope model**

**Table 66 Material Properties of the Chen and Shao Frictionless Slope model**

	c (kN/m <sup>2</sup> )	ϕ' (degrees)	γ (kN/m <sup>3</sup> )
Soil	49	0.0	1e-06

### 3.14.2 Results and Discussions

**Table 67 Results of the Chen and Shao Frictionless Slope**

Method	Factor of Safety		SVSLOPE		Difference (%)
	Theoretical F <sub>s</sub>	Slide	Moment	Force	
Spencer	1	1.051	1.049	1.049	0.19
M-P	1	1.009	1.000	1.000	0.89
GLE	1	1.009	0.996	0.996	1.29

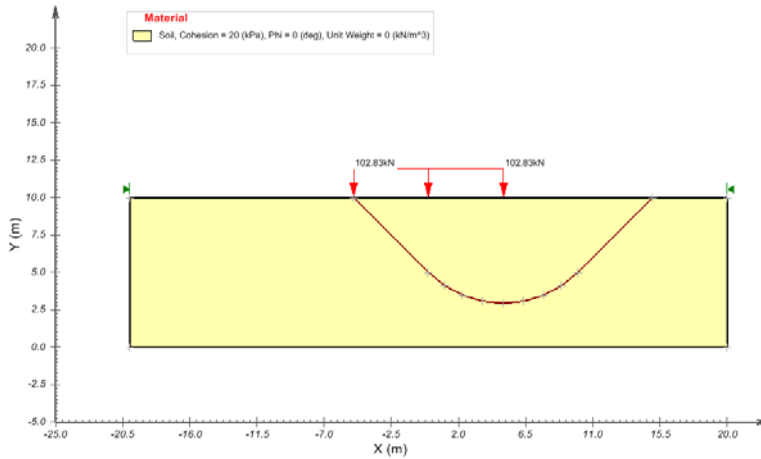
### 3.15 PRANDTL BEARING CAPACITY

Project: Verification\_SVSLope\_Group1  
 Model: VS\_26

This verification test models the well-known Prandtl solution for bearing capacity; namely,

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

### 3.15.1 Geometry and Material Properties



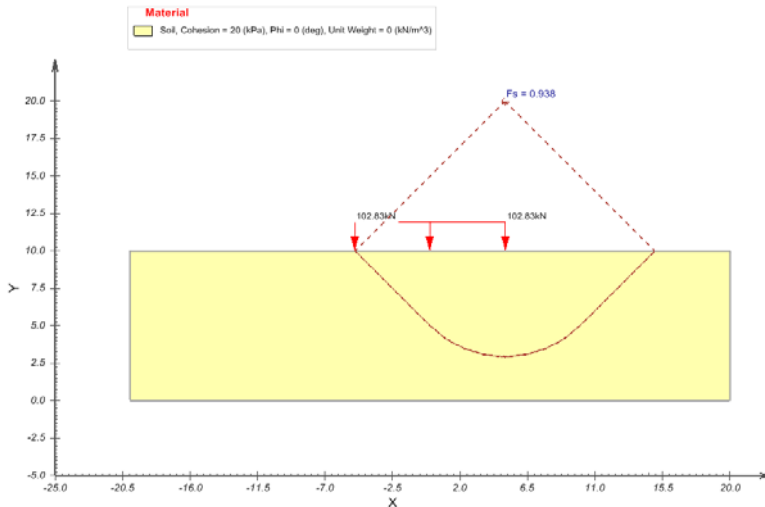
**Figure 65 Geometry of the Bearing Failure model**

The material properties are given in Table 68. For an cohesion of 20kN/m<sup>2</sup>, q<sub>c</sub> 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 Figure 66. The theoretical critical failure surface was used for the analysis.

**Table 68 Material Properties of the Bearing Failure model**

	c (kN/m <sup>2</sup> )	φ' (degrees)	γ (kN/m <sup>3</sup> )
Soil	20	0	1e-06

### 3.15.2 Results and Discussions



**Figure 66 Presentation of the resulting factor of safety for the Prandtl bearing capacity problem**

**Table 69 Results of the Prandtl Bearing Capacity**

Method	Factor of Safety				Difference (%)
	Theoretical F <sub>s</sub>	Slide	SVSLOPE		
			Moment	Force	
Spencer	1.000	0.941	0.938	0.938	0.32

### 3.16 CHOWDHURY AND XU (1995)

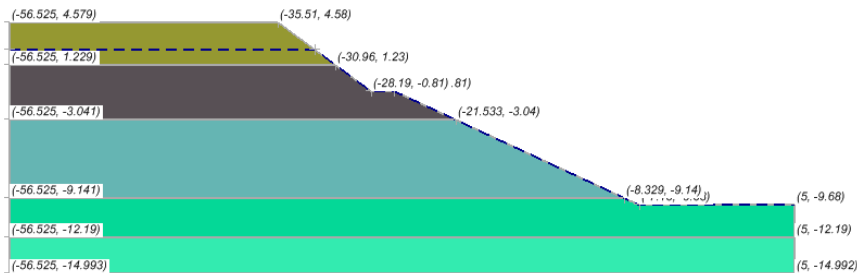
Project: Verification\_SVSlope\_Group1  
 Model: Chowdhury\_Xu VS\_28

This set of verification problems were originally published by Chowdhury and Xu (1995). The Congress St. Cut model, which was first analyzed by Ireland (1954), contained the geometry for the first four examples.

The purpose of these models is to perform a statistic analysis in which the probability of failure is calculated when the input parameters are represented in terms of means and standard deviations.

#### 3.16.1 Geometry and Material Properties

#### 3.16.2 Example #1



**Figure 67 Geometry for Example 1 - 4**

In each of these examples 1 to 4, two sets of circular slip surfaces are considered. One set places the failure surface tangential to the lower boundary of Clay 2 layer and the second considers the slip surface tangential to the lower boundary of Clay 3. The soil models used for both clays are constant undrained shear strength.

**NOTE :**

Chowdhury and Xu do not consider the strength of the upper sand layer in the examples 1 to 4. As well, they use the Bishop simplified method for all their analysis.

Unit weights for soil materials are not provided in the original paper by Chowdhury and Xu. Information also is not provided regarding the geometry of the critical slip surface. In this particular example, material unit weights that enable SVSLOPE to obtain factor of safety values, similar to those in addicted in the paper are used.

**Table 70 Example 1 Input Data**

	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
$\gamma$ (kN/m <sup>3</sup> )	21	22	22

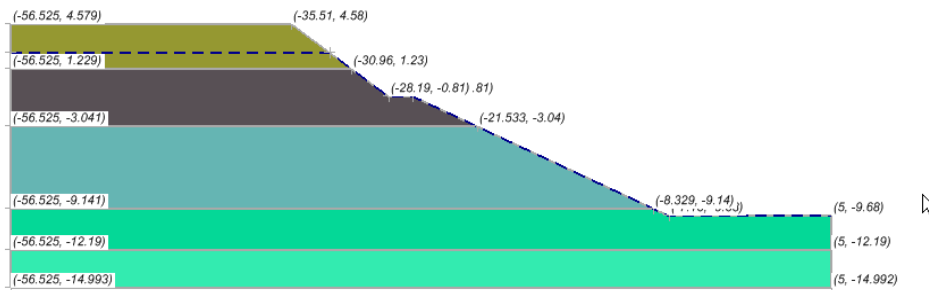
**Table 71 Results of Example 1 with Layer 2**

Method	Factor of Safety						Difference (%)
	Chowdhury and Xu		Slide		SVSLOPE		
	$F_s$	PF(%)	$F_s$	PF(%)	$F_s$	PF(%)	
Bishop Simplified	1.128	26.592	1.128	24.61	1.127	25.340	0.09

**Table 72 Results Example 1 with Layer 3**

Method	Factor of Safety						Difference (%)
	Chowdhury and Xu		Slide		SVSLOPE		
	$F_s$	PF(%)	$F_s$	PF(%)	$F_s$	PF(%)	
Bishop Simplified	1.109	27.389	1.109	27.89	1.111	28.030	0.18

3.16.3 Example #2



**Figure 68 Geometry of Example #2**

**Table 73 Example 2 Input Data**

	Soil Layer		
	Clay 1	Clay 2	Clay 3
	$c_1$	$c_2$	$c_3$
<b>Mean (kPa)</b>	68.1	39.3	50.8
<b>Standard Deviation (kPa)</b>	6.6	1.4	1.5
<b><math>\gamma</math> (kN/m<sup>3</sup>)</b>	21	22	22

**Table 74 Results of Example 2 with Layer 2**

Method	Factor of Safety						Difference (%)
	Chowdhury and Xu		Slide		SVSLOPE		
	$F_s$	PF(%)	$F_s$	PF(%)	$F_s$	PF(%)	
Bishop Simplified	1.1096	0.48	1.108	0.37	1.108	0.440	0.00

3.16.4 Example #3

**Table 75 Example 3 Input Soil Data**

	Soil Layer		
	Clay 1	Clay 2	Clay 3
	$c_1$	$c_2$	$c_3$
<b>Mean (kPa)</b>	136	80	102
<b>Standard Deviation (kPa)</b>	50	15	24
<b><math>\gamma</math> (kN/m<sup>3</sup>)</b>	21	22	22

Failure Mode (Layer)	Chowdhury and Xu		SVSLOPE	
	Factor of Safety (Bishop Simplified)	Probability of Failure	Factor of Safety (Bishop Simplified)	Probability of Failure
Layer 2 (Clay 1)	2.2343	0.1151		
Layer 3 (Clay 2)	2.1396	0.00242		

3.16.5 Example #4

**Table 76 Example 4 Input Data**

	Soil Layer					
	Clay 1		Clay 2		Clay 3	
	$c_1$ (kPa)	$\phi_1$ (°)	$c_2$ (kPa)	$\phi_2$ (°)	$c_3$ (kPa)	$\phi_3$ (°)
<b>Mean (kPa)</b>	55	5	43	7	56	8
<b>Standard Deviation (kPa)</b>	20.4	1	8.7	1.5	13.2	1.7
<b><math>\gamma</math> (kN/m<sup>3</sup>)</b>	17		22		22	

Failure Mode (Layer)	Chowdhury and Xu		SVSLOPE	
	Factor of Safety (Bishop Simplified)	Probability of Failure	Factor of Safety (Bishop Simplified)	Probability of Failure
Layer 2 (Clay 1)	1.4239	0.01559		
Layer 3 (Clay 2)	1.5075	0.00468		

### 3.16.6 Example #5

This example illustrates the stability of an embankment on a soft clay foundation. Two circular slip surface failure conditions are again considered. First slip surface one is tangent to the interface of the embankment and the foundation and second slip surface one is tangent to the lower boundary of the soft clay foundation.

Probabilities of failure are presented in the original paper by Chowdhury and Xu (1995), which are calculated using a commonly used definition of reliability index. As well, as assumption that all factor of safety distributed.

SVSLOPE makes use of the Monte Carlo technique in calculating the probability of failure. It is assumed that all input variables used in SVSLOPE are normally distributed.

**Table 77 Example 5 Input Data**

	Soil Layer			
	Layer 1		Layer 2	
	$c_1$ (kPa)	$\phi_1$ ( $^\circ$ )	$c_2$ (kPa)	$\phi_2$ ( $^\circ$ )
Mean (kPa)	10	12	40	0
Standard Deviation (kPa)	2	3	8	0
$\gamma$ (kN/m <sup>3</sup> )	20		18	

Failure Mode (Layer)	Chowdhury and Xu		SVSLOPE	
	Factor of Safety (Bishop Simplified)	Probability of Failure	Factor of Safety (Bishop Simplified)	Probability of Failure
Layer 1	1.1625	0.20225		
Layer 2	1.1479	0.19733		

**Table 78 Material Properties**

	$c$ (kN/m <sup>2</sup> )	$\phi$ (degrees)	$\gamma$ (kN/m <sup>3</sup> )
Sand	0	0	21

### 3.17 DUNCAN - LASH TERMINAL

Project: Verification\_SVSLope\_Group1  
 Model: Duncan\_2000 VS\_29

Duncan (2000) published a model that examines the failure of the 100ft high underwater slope at the lighter Abroad Ship (LASH) terminal at the Port of San Francisco, U.S.A.

The values that are used in this analysis were published by Duncan (2000). It was assumed that the cohesion was 100 psf at a deviation of -20ft and increases linearly with depth at the rate of 9.8psf per ft.

The Latin-HyperCube simulation technique was performed using 10000 samples to compute both the probability failure and the reliability index of the estimated failure surface, as defined with Duncan, (2000). Janbu, Spencer, and GLE methods were used to compute the factors of safety.

### 3.17.1 Geometry and Material Properties

The model geometry is illustrated in Figure 69.

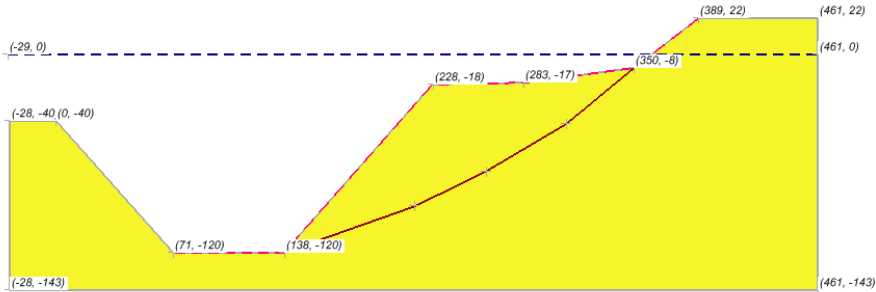


Figure 69 Geometry of the Duncan (2000) model

### 3.17.2 Results and Discussions

Table 79 Results of the Duncan (2000) model

Method	Factor of Safety		Difference (%)
	Slide	SVSLOPE	
Janbu Simplified	1.127	1.138	0.98
Spencer	1.150	1.160	0.87
GLE	1.161	1.163	0.17

Note: Probability analysis cannot be performed at this time, because the cohesion change with depth is not included in SVSLOPE

## 3.18 BORGES AND CARDOSO - GEOSYNTHETIC EMBANKMENT

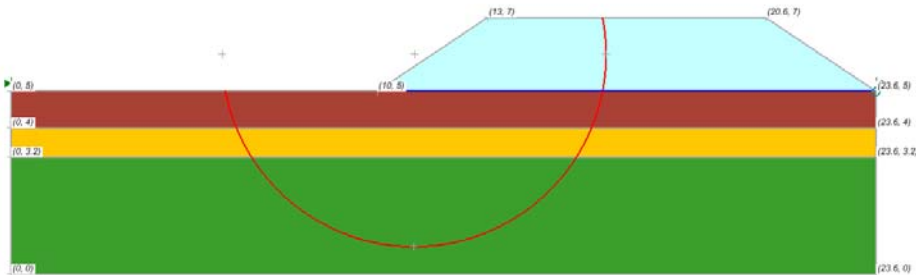
Project: Verification\_SVSlope\_Group1  
 Model: VS\_30

This example considers the stability of a geosynthetic-reinforced embankment on soft soil. The problem was originally published by Borges and Cardoso (2002).

The sand embankment region is represented by Mohr-Coulomb strength model and the foundation material is a soft clay which contains a varied undrained shear strength. The geosynthetic has a tensile strength of 200 KN/m, is not anchored, and has no adhesion.

It also has a frictional resistance against slip of 33.7 degrees. The reinforcement force for this example is assumed to be parallel to the reinforcement. This model is analyzed using the Bishop Simplified method. Since the original authors used the moment based limit equilibrium method for this model, the reinforcement is modeled as a passive force. This procedure is consistent with how the authors implemented reinforcement forces in the limit equilibrium methods in SVSLOPE.

### 3.18.1 Geometry and Material Properties



**Figure 30 Geometry of the Borges and Cardoso Geosynthetic Embankment Case 1**

**Table 80 Material Properties of Borges and Cardoso-Embankment**

	$c$ (kN/m <sup>2</sup> )	$\phi$ (degrees)	$\gamma$ (kN/m <sup>3</sup> )
Embankment	0	35	20
	$c_u$ top (kN/m <sup>2</sup> )	$c_u$ bottom (kN/m <sup>2</sup> )	$\gamma$ (kN/m <sup>3</sup> )
Upper Clay	8.490	8.490	17
Middle Clay	8.490	4.725	17
Lower Clay	4.725	13.125	17

### 3.18.2 Results and Discussions

**Table 81 Results for Case 1**

Method	Factor of Safety (Case 1-single circular)			Difference (%)
	Borges & Cardoso	Slide Moment	SVSLOPE Force	
Bishop Simplified	1.74	1.659	1.663	0.24

**Table 82 Results for Case 2**

Method	Factor of Safety (Case 2-single circular)			Difference (%)
	Borges & Cardoso	Slide Moment	SVSLOPE Force	
Bishop Simplified	1.77	1.692	1.695	0.18

## 3.19 BORGES AND CARDOSO - GEOSYNTHETIC EMBANKMENT #2

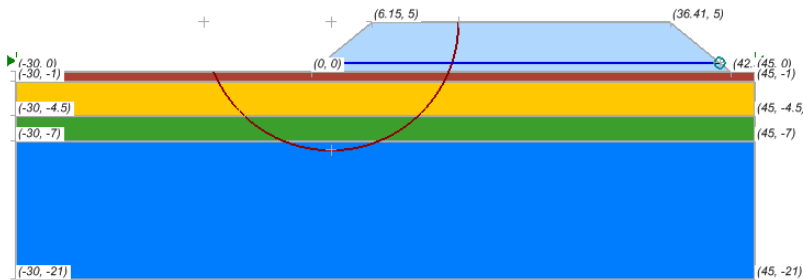
Project: Verification\_SVSlope\_Group1  
 Model: VS\_31

This model looks at the stability of a geosynthetic-reinforced embankment placed over a soft soil. This model was original published by Borges and Cardoso (2002). This is their Case 2 example.

The model is set up as a more competent material overlaying soft clay with varying undrained shear strength. The geosynthetic has a tensile strength of 200 KN/m and a frictional resistance of 33.7 degrees. The geosynthetic is not anchored and has no adhesion.

In this case, the reinforcement force is parallel to the reinforcement. Bishop's Simplified method is used to analyze this model. The reinforcement is modeled as a passive force. This corresponds to the manner in which the authors implemented the reinforcement force in their original papers.

### 3.19.1 Geometry and Material Properties



**Figure 70 Geometry of the Case 1 example by Borges and Cardoso (2002)**

**Table 83 Material Properties of Borges and Cardoso – Embankment #2**

	$c$ (kN/m <sup>2</sup> )	$\phi$ (degrees)	$\gamma$ (kN/m <sup>3</sup> )
Embankment	0	35	20
	$c_u$ top (kN/m <sup>2</sup> )	$c_u$ bottom (kN/m <sup>2</sup> )	$\gamma$ (kN/m <sup>3</sup> )
Clay 1	33	33	17
Clay 2	16	16	17
Clay 3	16	18.4	17
Clay 4	18.4	55.1	17

### 3.19.2 Results and Discussions

**Table 84 Results for the Case 1 example by Borges and Cardoso (2002)**

Method	Factor of Safety (Case 1 - single circular slip surface)					Difference (%)
	Borges & Cardoso	Slide			SVSLOPE (Slice = 30)	
		Slices = 25 (on Manual)	Slices = 30	Slices = 40	Moment	Force
Ordinary		1.346	1.346	1.323	1.323	0
Bishop Simplified	1.19	1.176	1.176	1.166	1.165	0.09
Janbu Simplified		1.208	1.208	1.205	1.204	0.08

**Table 85 Results of Case 2 example by Borges and Cardoso (2002)**

Method	Factor of Safety (Case 2 - single circular slip surface)					Difference (%)
	Borges	Slide		SVSLOPE		
	& Cardoso	Slices = 25 (on Manual)	Slices = 30	Slices = 40	Moment Force	
Ordinary		1.282	1.282	1.277	1	0.08
Bishop Simplified	1.15	1.163	1.162	1.16	1	0.09
Janbu Simplified		1.17	1.17	1.169		1.17 -0.09

### 3.20 BORGES AND CARDOSO - GEOSYNTHETIC EMBANKMENT #3

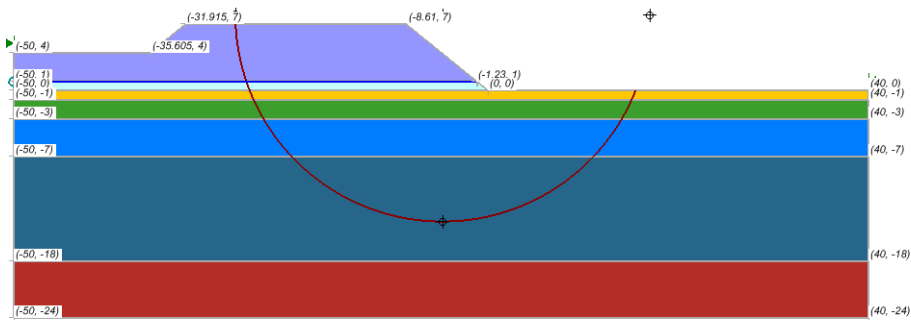
Project: Verification\_SVSlope\_Group1  
 Model: VS\_32

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

The material properties are the same as the previous two examples. The geosynthetic in this case has the tensile strength of 200 KN/m as well as a frictional resistance of 39.6 degrees. The Bishop Simplified analysis method is used for consistency with the method used by the authors.

The two embankment materials are implemented in the model. The lower embankment material is 0 to 1 m and the upper embankment material is from 1 to 7 m (Case 1) or 1 to 8.75m (Case 2). The geosynthetic is placed at the elevation 0.9 m, just inside on the lower embankment material.

#### 3.20.1 Geometry and Material Properties



**Figure 71 Geometry of Case 1**

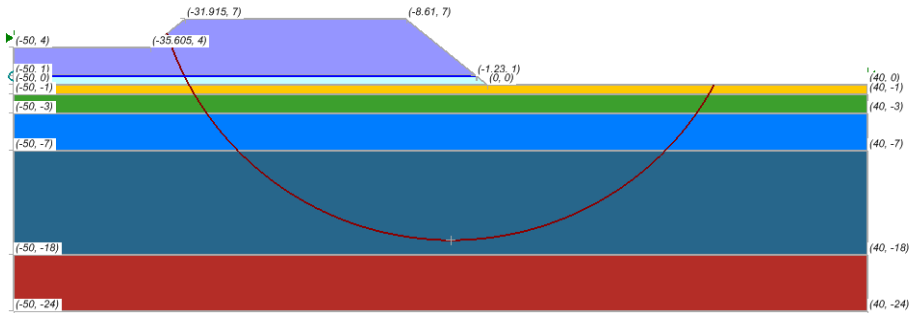


Figure 72 Geometry of Case 2

Table 86 Material Properties

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Upper Embankment	0	35	21.9
Lower Embankment	0	33	17.2

	c <sub>u</sub> (kN/m <sup>2</sup> )	γ (kN/m <sup>3</sup> )
Clay 1	43	18
Clay 2	31	16.6
Clay 3	30	13.5
Clay 4	32	17
Clay 5	32	17.5

### 3.20.2 Results and Discussions

Table 87 Results Case 1-Embankment Height = 7m

	SVSLOPE Factor of Safety	Overturing Moment (kN/m/m)	Resisting Moment (kN/m/m)
Circle A (SVSLOPE)			
Circle A (Borges & Cardoso)		34166	42695
Circle B (SVSLOPE)			
Circle (Borges & Cardoso)		63870	75754

Table 88 Results Case 2-Embankment Height = 8.75m

	SVSLOPE Factor of Safety	Overturing Moment (kN/m/m)	Resisting Moment (kN/m/m)
Circle C (SVSLOPE)		64873	63846
Circle C (Borges & Cardoso)		65116	64784

**Table 89 Results**

Method	Factor of Safety (Case 1)			Difference (%)
	Borges	Slide	SVSLOPE	
	& Cardoso		Moment Force	
Bishop Simplified	1.25	1.225	1.226	0.08

**Table 90 Results**

Method	Factor of Safety (Case 2)			Difference (%)
	Borges	Slide	SVSLOPE	
	& Cardoso		Moment Force	
Bishop Simplified	1.19	1.219	1.218	0.08

**Table 91 Results**

Method	Factor of Safety (Case 3)			Difference (%)
	Borges	Slide	SVSLOPE	
	& Cardoso		Moment Force	
Bishop Simplified	0.99	0.984	0.982	0.2

### 3.21 SYNCRUDE PROBABILISTIC TAILINGS DYKE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_33

This example model was published by El-Ramly et al (2003). This model is designed for the calculation of the factor of safety for a Syncrude tailings dyke in Alberta, Canada. In this case, a probabilistic analysis is performed.

This paper does not consider spaciouly variation of soil properties, and is therefore described as a simplified probabilistic analysis. The original geometry from the El-Ramly et al (2003) paper is shown in Figure 73.

The material parameters are input into SVSLOPE as shown in Table 92. The soil parameters were considered probabilistic by El-Ramly et al. They varied 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 in the middle and the toe of the dyke.

In the SVSLOPE model we consider the variation of the friction angles of the Kca clay-shale and Pgs sandy till. The phreatic surface indicated in Figure 74 was used in place of the pore pressure ratios. In order in to be consistent the El-Ramly paper the Bishop Simplified analysis method was used.

A Monte Carlo analysis was used to calculate the probability of failure. It is worth noting that it is assumed that all probabilistic input parameters are normally distributed.

### 3.21.1 Geometry and Material Properties

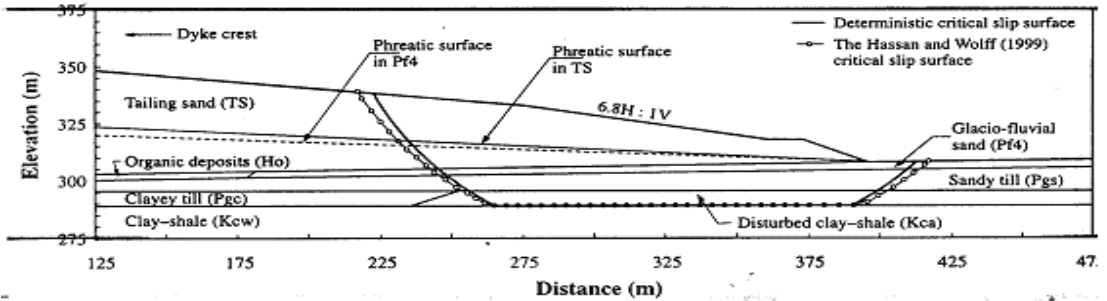


Figure 73 Original Geometry of the Syncrude Tailings Dyke model

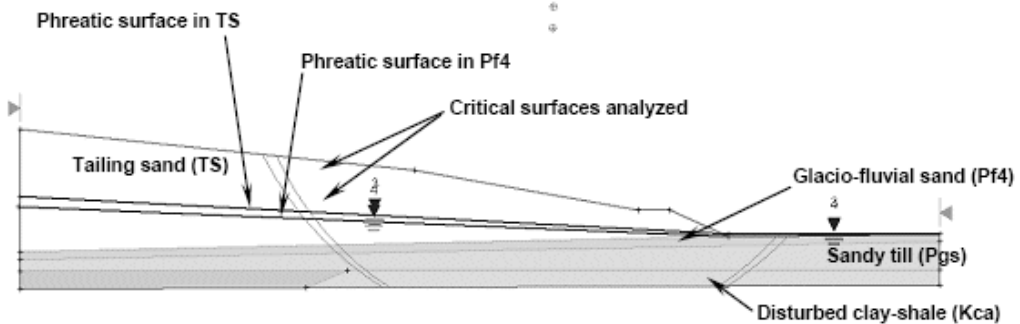


Figure 74 Phreatic Surface

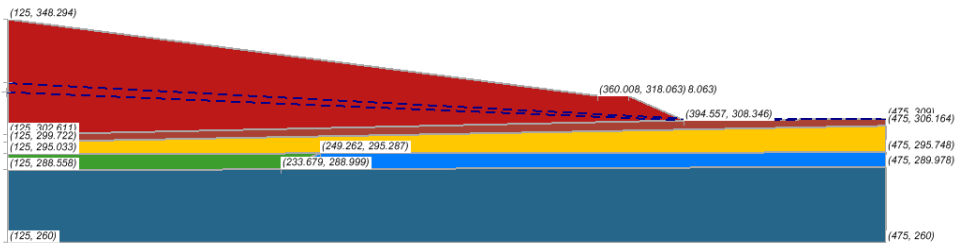


Figure 75 Geometry of the Syncrude Tailing Dyke model

Table 92 Material Properties of the Syncrude Tailing Dyke model

	c (kN/m <sup>2</sup> )	φ (degrees)	Standard Deviation of φ (degrees)	γ (kN/m <sup>3</sup> )
Tailings sand	0	34	-	20
Glacio-fluvial sand	0	34	-	17
Sandy till	0	34	-	17
Clayey Till	0	7.5	-	17
Distributed clay-shale	0	7.5	-	17

### 3.21.2 Results and Discussions

**Table 93 Results of the Syncrude Tailing Dyke model**

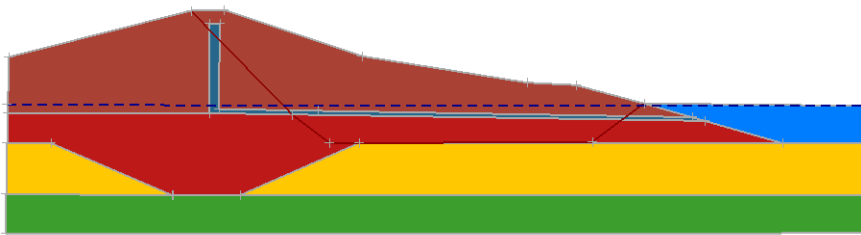
Method	Factor of Safety								Difference (%)
	EI-Ramly		Slide			SVSLOPE			
	Determ	PF(%)	Determ	Probabilistic		Determ	Probabilistic		
			Mean	PF(%)		Mean	PF(%)		
Bishop Simplified	1.31	0.16	1.305	1.327	0.154	1.302	1.304	3.65	0.23

### 3.22 CANNON DAM

Project: Verification\_SVSlope\_Group1  
 Model: VS\_34

The Cannon Dam Model was published from Wolff and Harr (1987). The probabilistic analysis results from SVSLOPE are compared to the results published in the paper by Wolff and Harr for a noncircular slip surfaces. Wolff and Harr (1987) used the point-estimate method for their probability analysis failure for the Cannon Dam. The location of critical slip surface was taken from their paper. The input parameters; namely, friction angle for the Phase I and Phase II fills was calculated. The unit weights of the fills were back-calculated in order to match the factor of safety computed by Wolff and Harr. Wolff and Harr (1987) based on the stochastic properties provided in the paper originally published results that only satisfied force equilibrium. The results were compared to those obtained by GLE and the Spencer methods. It is assumed in the SVSLOPE model that all the probabilistic input variables are normally distributed.

#### 3.22.1 Geometry and Material Properties



**Figure 76 Geometry of the Cannon Dam model**

**Table 94 Material Properties of the Cannon Dam**

Material	c (lb/ft <sup>2</sup> )	Standard Deviation of c (lb/ft <sup>2</sup> )	φ (degrees)	Standard deviation of φ (degrees)	Correlation coefficient for c and φ	γ (lb/ft <sup>3</sup> )
Phase I fill	2,230		6.33			150
Phase II fill	2,901.6		14.8			150
Material 3	1		50			150
Material 4	1		35			150
Spoil Fill	3,000		60			150
Filter	-		35			120

### 3.2.2.2 Results and Discussions

Table 95 Results of the Cannon Dam

Method	Factor of Safety							Difference (%)
	Wolff and Harr		Slide			SVSLOPE		
	Deterministic	PF(%)	Deterministic	Probabilistic		Probabilistic		
				Mean	PF(%)	Deterministic	Mean PF(%)	
Spencer	2.36	4.55	2.383	2.401	0.355	2.383	2.378	0
GLE			2.333	2.358	0.355	2.338	2.337	0.21

### 3.2.3 CANNON DAM #2

Project: Verification\_SVSlope\_Group1  
 Model: VS\_35

This model of the Cannon Dam in Missouri was presented by Hassan and Wolff (1999). The purpose of this verification model is to look at duplicating reliability index results for several circular failure surfaces as specified in the original paper. Hassan and Wolff (1999) presented a new reliability based approach in their paper. The cross-section of the Cannon Dam is shown below. The Bishop Simplified method of slices was used to analyze this verification problem. The present set of slip circles are those shown in Figure 77 of the Hassan and Wolff paper and Figure 78 shows the model input parameters.

The Hassan and Wolff (1999) paper does not provided all the required input parameters. Therefore we selected values for the missing parameters that allowed to us to match the factors of safety for some of the circles slip surfaces shown in Figure 77. The assumption is made in this analysis that all the probabilistic input variables are normally distributed for performing the Monte Carlo simulations. The reliability indices calculated in SVSLOPE are based on the mean and standard deviations of the factor of safety values calculated in the simulations. The reliability indices shown in the results section are calculated using the assumption that the factors of safety values are log-normally (Hassan and Wolff, 1999). The results obtained from SVSLOPE and the results from Hassan and Wolff are shown in Table 97.

#### 3.2.3.1 Geometry and Material Properties

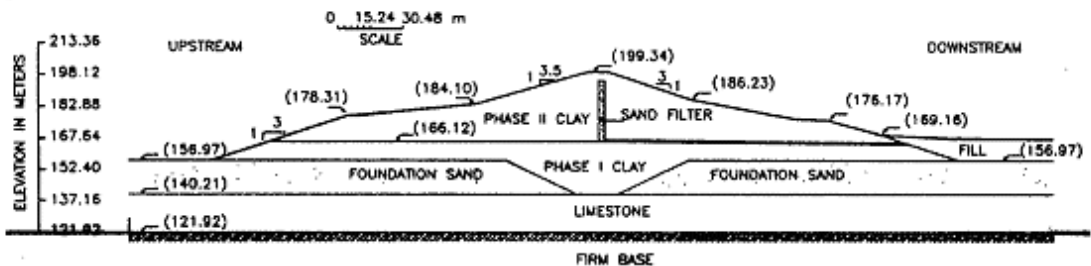


Figure 77 Hassan and Wolff's Geometry

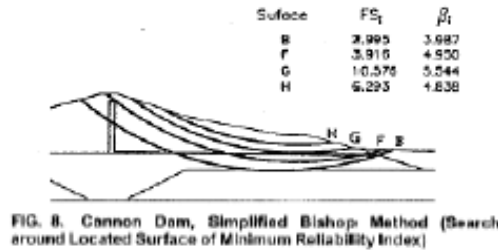
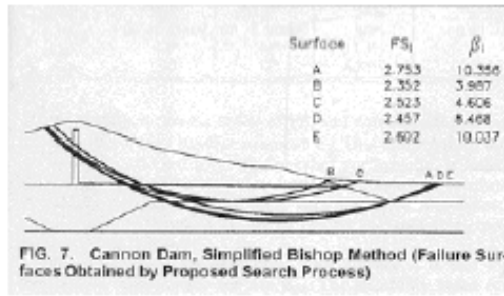


Figure 78 Hassan and Wolff (1999) paper

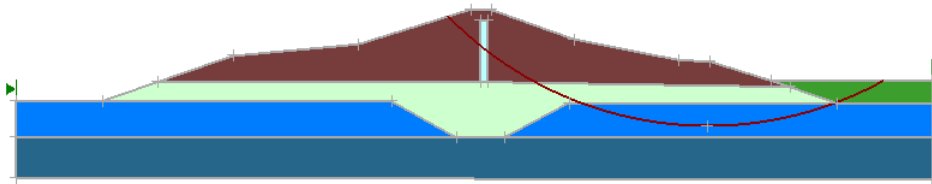


Figure 79 Surface A Cannon Dam #2

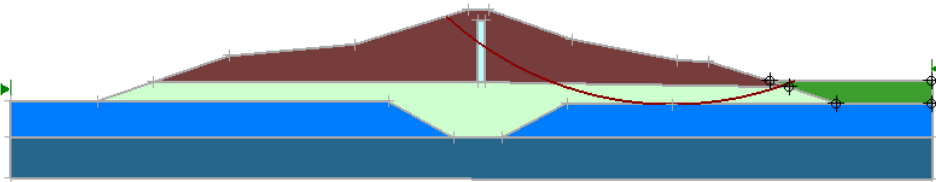


Figure 80 Surface B Cannon Dam #2

Table 96 Material Properties of the Cannon Dam #2

Material	$c$ (lb/ft <sup>2</sup> )	Standard Deviation of $c$ (lb/ft <sup>2</sup> )	$\phi$ (degrees)	Standard deviation of $\phi$ (degrees)	Correlation coefficient for $c$ and $\phi$	$\gamma$ (lb/ft <sup>3</sup> )
Phase I clay fill						
Phase II clay fill						
Sand Filter						
Foundation sand						
Spoil fill						

3.23.2 Results and Discussions

Table 97 Results of the Cannon Dam #2

Surfaces	Method	Factor of Safety										Difference (%)	
		Hanssan and Wolff		Slide				SVSLOPE					
		Reliability Index-		Probabilistic				Probabilistic					
		Determ	lognormal	Determ	Mean	Lognormal	PF(%)	Determ	Mean	RI	PF(%)		
Figure 7			4.55										
Surface A	Bishop	2.8		2.551	2.6	10.95	0	2.55	2.635	8.76	0	0.04	
Figure 7			3.987										
Surface B	Bishop	2.4		2.82	3.1	4.351	0.1	2.817	3.099	4.11	0	0.11	
Figure 7			4.606										
Surface C	Bishop	2.5		2.777	3.1	4.263	1.2	2.779	3.052	4.06	0	0.07	
Figure 7			8.468										
Surface D	Bishop	2.5		2.583	2.6	11.09	0	2.581	2.667	8.83	0	0.08	
Figure 7			10.04										
Surface E	Bishop	2.6		2.692	2.8	10.28	0	2.691	2.79	8.19	0	0.04	
Figure 8			3.987										
Surface B	Bishop	3		2.676	2.9	4.858	0	2.674	2.893	4.5	0	0.07	
Figure 8			4.95										
Surface F	Bishop	3.9		3.598	3.8	5.485	0	3.594	3.894	4.82	0	0.11	
Figure 8			5.544										
Surface G	Bishop	11		6.074	6.1	5.563	0	6.068	6.473	4.62	0	0.1	
Figure 8			4.838										
Surface H	Bishop	6.3		11.23	11	6.394	0	11.228	11.95	5.75	0	0.02	

3.24 LI AND LUMB - RELIABILITY INDEX

Project: Verification\_SVSSlope\_Group1  
 Model: VS\_36

This model is original presented in Li and Lumb (1987) and Hassan and Wolff (1999). The purpose of this model is to analyze the reliability indices of a simple homogenous slope. The verification compares of the reliability index of the deterministic global circular surface and the minimum reliability index value obtained from an analysis of multiple slip surfaces.

The geometry is presented in Figure 81 and the material properties are presented in Table 98. In this analysis the Bishop Simplified method of analysis was used. A Monte Carlo analysis was used which assumes that all input probability variables are normally distributed.

The reliability indices are calculated on the assumption that the factors of safety values are distributed log normal. This interpretation is consisted with the original analysis presented by Hassan and Wolff (1999).

Separate reliability indices are calculated for the minimum deterministic critical slip surface, as well as the critical probabilistic slip surface. The overall reliability indices of the slope are compared with reliability calculated by Hassan and Wolff (1999). The results are shown in the following figures:

### 3.24.1 Geometry and Material Properties

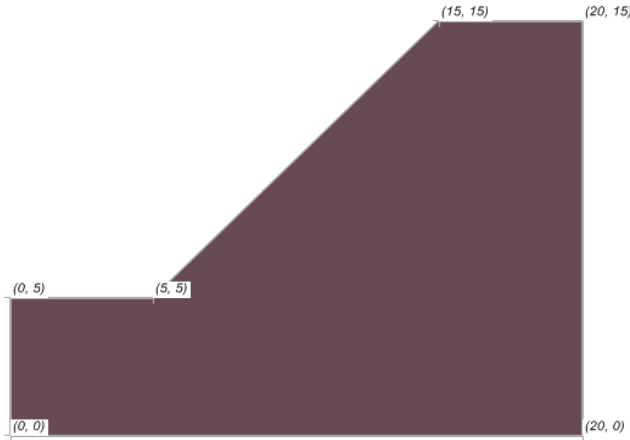


Figure 81 Geometry of the Li and Lumb – Reliability Index model

Table 98 Material Properties of the Li and Lumb (1987) reliability index

Property	Mean Value	Standard deviation
c (kN/m <sup>2</sup> )	18	3.6
φ (degrees)	30	3
γ (kN/m <sup>3</sup> )	18	0.9
R <sub>u</sub>	0.2	0.02

### 3.24.2 Results and Discussions

Table 99 Results of the Li and Lumb (1987) reliability index

Method	Factor of Safety				Difference (%)
	Hassan and Wolf (1999)	Slide		SVSLOPE	
	Reliability Index Log normal	Reliability Index Log normal	Probability of Failure (%)	Reliability Index Log normal	Probability of Failure (%)
	F <sub>s</sub>	F <sub>s</sub>		F <sub>s</sub>	
Bishop Simplified	1.339			1.338	0.07
Janbu Simplified	1.261			1.257	0.32

### 3.25 REINFORCEMENT BACK ANALYSIS

Project: Verification\_SVSlope\_Group1  
 Model: VS\_37

This model is original presented in the reference manual of slope stability program XSTABL (1999). A back analysis is used to determine the amount of reinforcement required to stabilize a slope.

Relatively simple geometry and slope conditions are used along with one non-cohesive soil material. The analysis proceeds in two steps:

- Determining the reinforcement needed to stabilize a slope to predetermine a factor of safety value of 1.5, and
- Establishing the minimum required length of reinforcement.

Figure 82 describes the slope model and the solution. In XSTABL the slip surfaces past only through the toe of the slope. This type of restriction has been duplicated in SVSLOPE by placing an exist point near the toe of the slope. It should also be noted that when there is no cohesive, the slip surface would tend to rise to the ground surface. Therefore, a minimum depth was imposed on considered slip surfaces. The next step involved changing the slope and including a reinforced zone with a higher friction angle calculated from the formula presented in the XSTABL Reference Manual, (1999).

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

$$where F_r = \frac{F_{min}}{F_{crit}}$$

The length of the reinforced zone was varied manually until the factor of safety value very close to 1.5 was obtained. The results may be seen in Table 100.

#### 3.25.1 Geometry and Material Properties

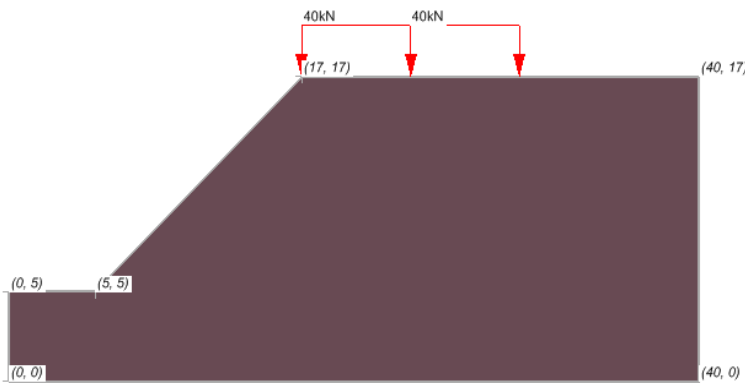


Figure 82 Geometry of the Reinforcement Back Analysis model

### 3.25.2 Results and Discussions

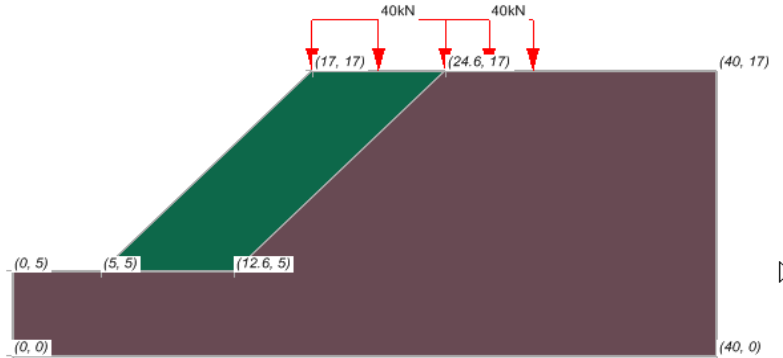


Figure 83 Results of the Reinforcement Back Analysis model

Table 100 Results Back Analysis – Reinforcement

Method	Factor of Safety		Difference (%)
	Slide	SVSLOPE	
Ordinary		0.756	
Bishop Simplified	0.765	0.76	0.71
Janbu Simplified	0.739	0.756	2.30

Table 101 No Reinforcement

Method	Factor of Safety		Difference (%)
	Slide	SVSLOPE	
Bishop Simplified	0.765	0.73	-4.58
Janbu Simplified	0.739	0.728	-1.49

Table 102 Reinforced Zone, neglect pore-water pressures and no cracks

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary					
Bishop Simplified	1.504		1.427		-5.12
Janbu Simplified		1.247		1.279	2.57

### 3.26 TANDJIRIA - GEOSYNTHETIC REINFORCED EMBANKMENT

Project: Verification\_SVSSlope\_Group1  
 Model: VS\_39

This model was originally presented by Tandjiria (2002) as their example #1 problem. The stability of a geosynthetic-reinforced embankment on soft soil was examined. This problem examines the stability of the embankment when it consists of sand or an undrained clay fill. The objective of this example is to compute the required reinforcement force to yield a factor of safety of 1.35.

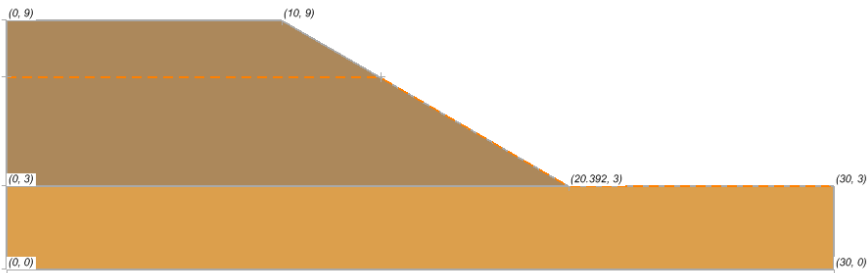
Circular and noncircular critical slip surfaces were examined. In each case presented, the embankment was first modeled without reinforcement and the critical slip surfaces determined. Then the determined critical slip surface was used in the reinforcement model to determine the reinforcement force to achieve a factor of safety of 1.35.

The above approach was used for both the clay embankment with a circular and noncircular slip surface. All cases incorporate a tension crack in the embankment. Water is allowed to fill the tension cracks in the case of the clay embankment. In this case the reinforcement was located at the base of the embankment. Both Spencer and GLE methods were used to analyze the slope. The GLE method used a half sine interslice function.

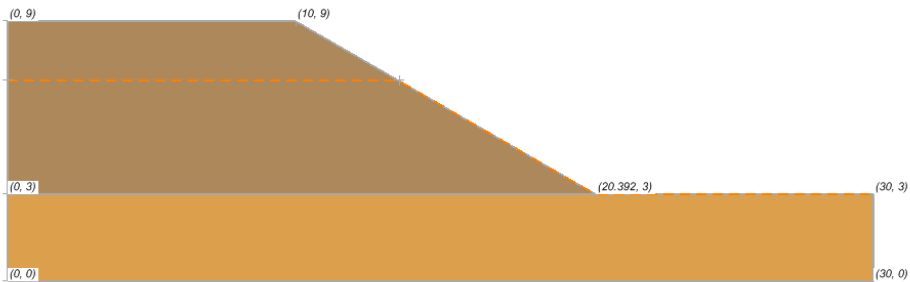
**NOTE :**

The reinforcement is modeled as an active force since Tadjiria (2002) modeled the force in this manner.

3.26.1 Geometry and Material Properties



**Figure 84 Clay Fill Embankment (circular) non reinforcement**



**Figure 85 Clay Fill Embankment (non circular) non reinforcement**

**Table 103 Material Properties of the clay fill embankment**

	$c_u/c$ (kN/m <sup>2</sup> )	$\phi$ (degrees)	$\gamma$ (kN/m <sup>3</sup> )
Clay Fill Embankment	20	0	19.4
Sand Fill Embankment	0	37	17.0
Soft Clay Foundation	20	0	19.4

## 3.26.2 Results and Discussions

**Table 104 Circular Results clay embankment with no reinforcement**

Method	Factor of Safety				Difference (%)	
	Tandjiria (2002)	Slide		SVSLOPE		
		Moment	Force	Moment		Force
Spencer	0.981	0.975	0.975	0.975	0.975	0.00
GLE		0.975	0.975	0.975	0.975	0.00

**Table 105 Noncircular Results-clay embankment with no reinforcement**

Method	Factor of Safety				Difference (%)
	Slide		SVSLOPE		
	Moment	Force	Moment	Force	
Spencer	0.932	0.932	0.838	0.838	-10.09
GLE	0.937	0.937	0.936	0.936	-0.11

**Table 106 Circular Results-sand embankment with no reinforcement**

Method	Factor of Safety				Difference (%)
	Slide		SVSLOPE		
	Moment	Force	Moment	Force	
Spencer	1.209	1.209	1.211	1.211	0.17
M-P	1.218	1.218	1.218	1.219	0.08

**Table 107 Noncircular Results sand embankment with no reinforcement**

Method	Factor of Safety				Difference (%)
	Slide		SVSLOPE		
	Moment	Force	Moment	Force	
Spencer	1.188	1.188	1.181	1.181	-0.59
GLE	1.196	1.196	1.184	1.184	-1.00

**Table 108 Circular Results clay embankment with reinforcement**

Method	Factor of Safety						Difference (%)	
	Tandjiria (2002)	Slide			SVSLOPE			
		Rein Force kN/m	Moment	Force	Rein Force kN/m	Moment		Force
Spencer	170	1.35	1.35	169	1.349	1.349	169	-0.07
GLE	170	1.35	1.35	169	1.349	1.349	169	-0.07

**Table 109 Noncircular Results clay embankment with reinforcement**

Method	Factor of Safety							Difference (%)
	Tandjiria (2002)			Slide SVSLOPE				
	Rein Force	Moment	Force	Rein Force	Moment	Force	Rein Force	
	kN/m			kN/m			kN/m	
Spencer	190	1.351	1.351	184	1.349	1.349	184	-0.15
GLE	190	1.366	1.366	184	1.365	1.365	184	-0.07

**Table 110 Circular Results sand embankment with reinforcement**

Method	Factor of Safety							Difference (%)
	Tandjiria (2002)			Slide SVSLOPE				
	Rein Force	Moment	Force	Rein Force	Moment	Force	Rein Force	
	kN/m			kN/m			kN/m	
Spencer	45	1.35	1.35	44	1.347	1.347	44	-0.22
GLE	45	1.357	1.357	44	1.353	1.353	44	-0.29

**Table 111 Noncircular Results sand embankment with reinforcement**

Method	Factor of Safety							Difference (%)
	Tandjiria (2002)			Slide SVSLOPE				
	Rein Force	Moment	Force	Rein Force	Moment	Force	Rein Force	
	kN/m			kN/m			kN/m	
Spencer	56	1.35	1.35	56	1.353	1.353	53	0.22
GLE	56	1.359	1.359	56	1.359	1.359	53	0.00

### 3.27 BAKER AND LESHCHINSKY - EARTH DAM

Project: Verification\_SVSSlope\_Group1  
 Model: VS\_42

This model was original published by Baker and Leshchinsky (2001). It was presented to illustrate the use of safety maps as a practical tools for slope stability analysis.

The geometry of the model can be seen in Figure 86. The model consists of a clay core with granular fill surrounding the core. The model has a solid base. A dry tension crack is placed at the top of the model to stimulate a 5m thick crack layer. All trial slip surfaces must be plotted on the dam to obtain a safety map of regional safety factors of safety. Noncircular slip surfaces and corresponding factor of safety are also required in this analysis.

### 3.27.1 Geometry and Material Properties

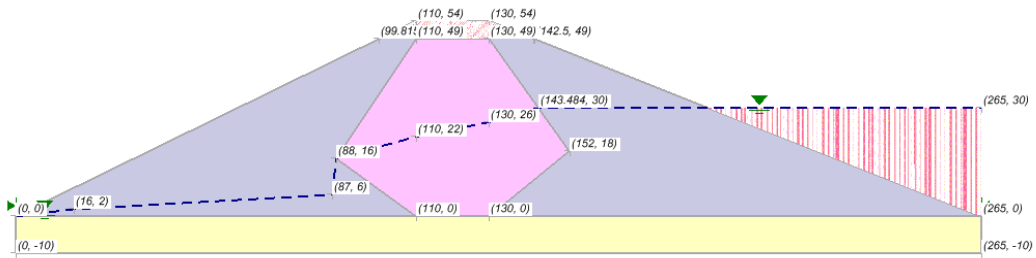


Figure 86 Geometry of the Baker and Leshchinsky Earth Dam Circular model

Table 112 Material Properties of the Earth Dam Circular model

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Clay core	0	20	20
Granular Fill	0	40	21.5
Hard Base	200	45	24

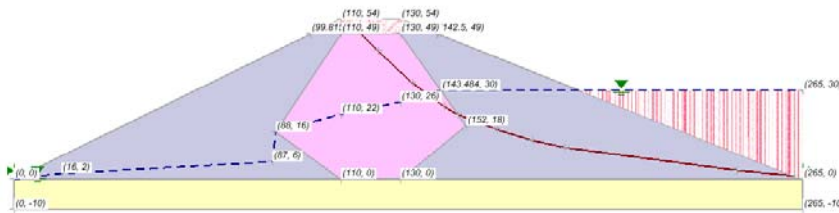


Figure 87 Geometry of the Noncircular model

### 3.27.2 Results and Discussions

Table 113 Results - Circular failure surface, 80 x 80 grid

Method	Factor of Safety (VS 42 Circular Slip Surfaces)				Difference (%)
	Baker & Leshchinsky	Slide	SVSLOPE Moment	SVSLOPE Force	
Spencer	1.91	1.923	1.921	1.921	0.10

Table 114 Results Noncircular using Random Search with Optimization (zero faces)

Method	Factor of Safety (VS 42 Non-Circular Slip Surfaces)				Difference (%)
	Baker & Leshchinsky	Slide	SVSLOPE Moment	SVSLOPE Force	
Spencer	1.91	1.857	1.855	1.855	0.11

### 3.28 BAKER - PLANAR HOMOGENEOUS

Project: Verification\_SVSlope\_Group1  
 Model: VS\_43

This model is original published by Baker (2001), and looks at the factor of safety of planar slip surfaces. The results are compared at various failure plane angles. The slope presented is homogenous and dry. The geometry can be seen in Figure 88. In this case, there are two tests that must be run on this slope. The first test is that the plot of factors of safety versus x-coordinate are required for all critical failure planes passing through the toe of the slope. Subsequently, the critical circular slip surfaces in Zone A must determined at which point the safety factors versus x-coordinate for Zone A must be plotted. A method of locating the factor of safety as a function of the failure plane angle is presented.

#### 3.28.1 Geometry and Material Properties

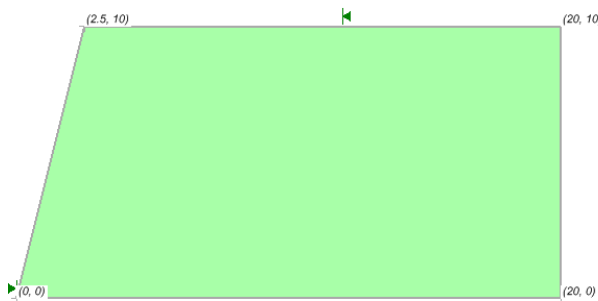


Figure 88 Geometry of the Baker (2001) - Planar Homogeneous Slope

Table 115 Material Properties of the Baker (2001) - Planar Homogeneous Slope

	$c$ (kN/m <sup>2</sup> )	$\phi$ (degrees)	$\gamma$ (kN/m <sup>3</sup> )
Material	30	30	20

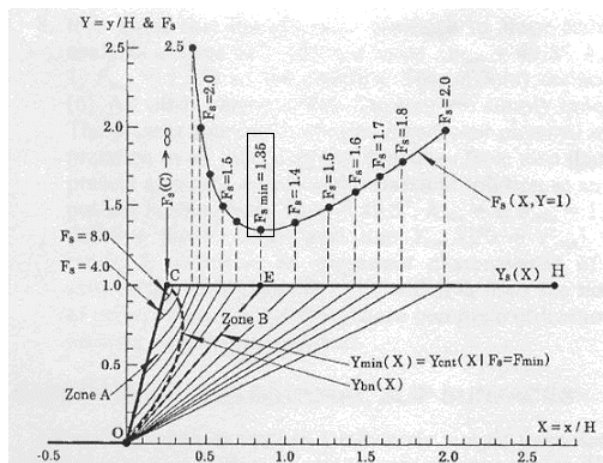


Figure 89 Baker's (2001) Distribution (Referee plot)

### 3.28.2 Results and Discussions

**Table 116 Results non-circular Baker (2001)**

Method	Factory of Safety						Difference (%)
	Baker	RocPlane 2.0		Slide		SVSLOPE	
	(2001)	F <sub>s</sub>	Angle	F <sub>s</sub>	Angle	F <sub>s</sub> Angle	
Janbu Simplified	1.35	1.351	49.5	1.352	49.5	1.352 49.5	0

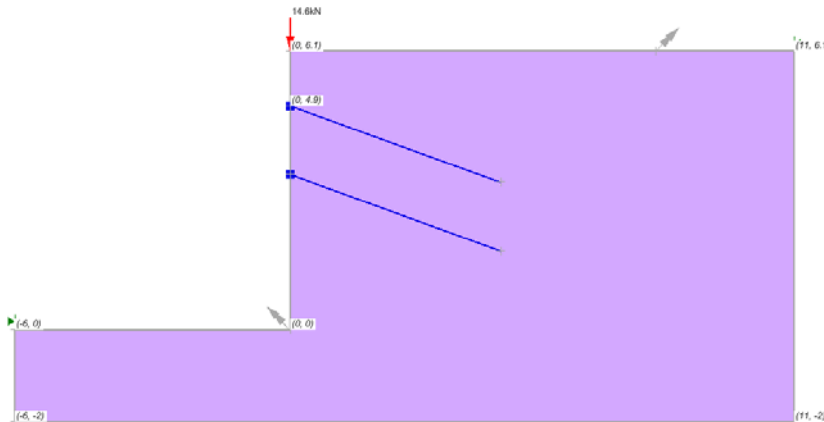
### 3.29 SHEAHAN - AMHEARST SOIL NAILS

Project: Verification\_SV Slope\_Group1  
 Model: VS\_47

This problem was published by Sheahan (2003). It examines the Amhearst test wall, which was a soil nailed wall in clay that failed due to over excavation.

This particular analysis involves a planar failure through a soil nailed wall. The factor of safety is calculated for the undrained, homogeneous slope. In this case the slope is reinforced by two rows of nails. The shotcrete plate on the soil nails has a weight of 14.6 kN/m. This weight is modeled as a point load at the top of the wall face. The purpose of the analysis is to determine the location of the critical planar slip surface and associated factor of safety.

#### 3.29.1 Geometry and Material Properties



**Figure 90 Geometry of the Sheahan Amhearst Soil Nails Model**

**Table 117 Material Properties of the Sheaham Amhearst Soil Nails model**

Material	c (kN/m <sup>2</sup> )	γ (kN/m <sup>3</sup> )
Amherst Clay	25	18.9

**Table 118 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

### 3.29.2 Results and Discussions

**Table 119 Results – Sheahan-Amhearst Soil Nails**

Method	Factor of Safety			Difference (%)	
	Sheahan (2003)	Slide	SVSLOPE		
			Moment		Force
Janbu Simplified	0.887	0.888		0.89	0.23

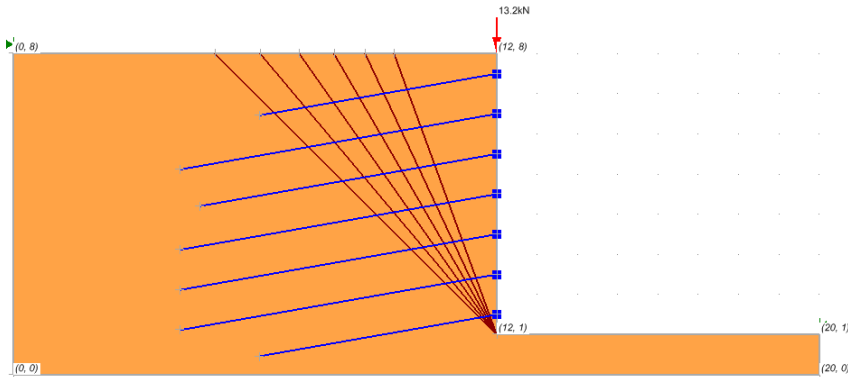
### 3.30 SHEAHAN - CLOUTERRE TEST WALL

Project: Verification\_SV Slope\_Group1  
 Model: VS\_48

This problem was presented by Sheahan (2003) and it examines the Clouterre Test Wall. The test wall was constructed using Fontainebleau sand and failed by backfill saturation. The test was carried out as part of the French national project on soil nailing.

The relationship between the failure slope angle and the factor of safety of a homogeneous slope is examined in this case. The primary resistance against failure is friction generated by the soil weight. The test wall was reinforced using seven rows of soil nails and a shotcrete plate weighting 13.2 kN/m. The shotcrete plate weighting was modeled as point load acting on the wall face. The purpose of this analysis is to determine the factor of safety for six different plane angles ranging from 45 to 70 degrees.

#### 3.30.1 Geometry and Material Properties



**Figure 91 Geometry of the Sheahan Clouterre Test Wall model**

**Table 120 Material Properties of the Sheahan Clouterre Test Wall model**

Material	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Fontainebleau Sand	3	38	20

**Table 121 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

### 3.30.2 Results and Discussions

**Table 122 Results Janbu Simplified (Sheahan, 2003)**

Method	Factory of Safety		Difference (%)
	Slide	SVSLOPE	
		Moment	Force
Janbu Simplified	0.921	0.923	0.22

**Table 123 Results for different slope angles of the failure surface**

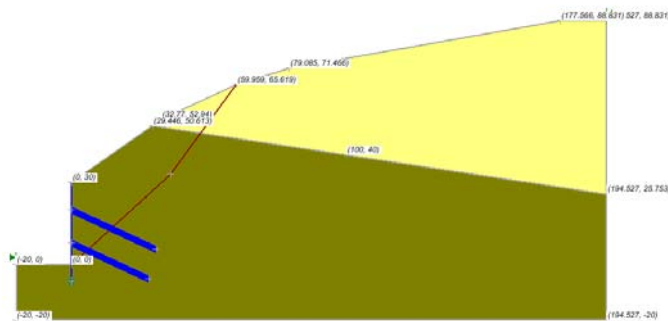
Slope Angle	Factor of Safety			Difference (%)
	Sheahan	Slide Janbu Simplified	SVSLOPE Janbu Simplified	
45	1.176	1.124	1.124	0.00
50	1.070	1.043	1.043	0.00
55	0.989	0.989	0.989	0.00
60	0.929	0.946	0.946	0.00
65	0.893	0.921	0.923	0.22
70	0.887	0.922	0.924	0.22

### 3.31 SNAILZ - REINFORCED SLOPE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_49

This model was taken from the SNAILZ reference manual (<http://www.dot.ca.gov/hq/esc/geotech>). The model has two materials and is a slope reinforced with a soldier pile tieback wall. Imperial units are used for this particular model. There are two different types of reinforcements in this model. Each of the two rows of soil nails has different bar diameters, which results in different tension capabilities. The soldier piles are modeled using a micro-pile in SVSLOPE. The purpose of this model is to determine the factor of safety for a given slip surface.

#### 3.31.1 Geometry and Material Properties



**Figure 92 Geometry of the Snailz Reinforced Slope model**

**Table 124 Material Properties of the Snailz Reinforced Slope**

Material	c (psf)	$\phi$ (degrees)	$\gamma$ (pcf)
Layer 1	600	24	120
Layer 2	300	34	130

**Table 125 Soil Nail Properties (Active)**

	Out-of-plane Spacing (m)	Tensile Strength (lb)	Plate Strength (kN)	Bond Strength (kN)
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.		

### 3.31.2 Results and Discussions

**Table 126 Results of the Snailz Reinforced Slope**

Method	Factor of Safety			Difference (%)
	SNAILZ	Slide	SVSLOPE	
			Moment Force	
Janbu Simplified	1.52	1.446	1.446	0.00

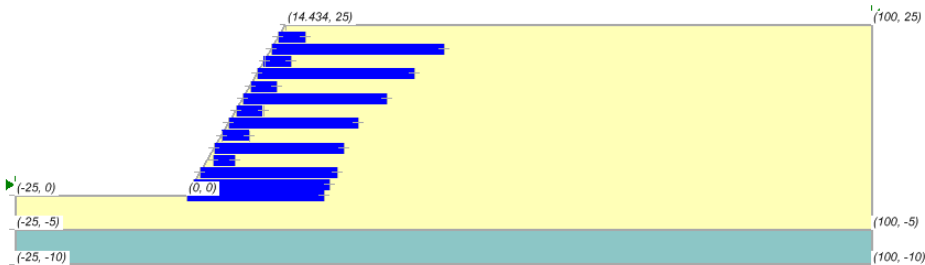
### 3.32 SNAILZ - GEOTEXTILE LAYERS

Project: Verification\_SVSlope\_Group1  
 Model: VS\_50

This problem is taken from the SNAILZ reference manual. It examines a slope, which has been reinforced with geotextile layers extending to different depths into the slope. It should be noted that SNAILZ models the geotechnical characteristics with soil nails as having the same parameters as it would have if it were not equipped with a geotextile reinforcement.

The problem at hand involves two layers with multiple reinforcement parameters. In this model, each horizontal reinforcement consists of parallel rows varying in length, tensile capacity and bond strength. The rows are all evenly spaced at 1.8 ft, except for row 14, which is spaced 1.8 ft. The problem at hand considers rows that are evenly spaced. The rows are numbered starting at the crest. The factor of safety is required for the two failure surfaces given in Figure 93.

#### 3.32.1 Geometry and Material Properties



**Figure 93 Geometry of the Snailz Geotextile Layers model**

**Table 127 Material Properties of the Snailz Geotextile Layers**

Material	c (psf)	$\phi$ (degrees)	$\gamma$ (pcf)		
Layer 1	600	24	120		
Layer 2	300	34	130		

	Out-of-plane Spacing (ft)	Tensile Strength (lb)	Plate Strength (lb)	Bond Strength (lb/ft)	Length (ft)
Rows: 1,3,4,7, 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

### 3.32.2 Results and Discussions

**Table 128 Results for Case 1**

Method	Factor of Safety			Difference (%)
	Slide	SVSLOPE		
		Moment	Force	
Janbu Simplified	1.354		1.354	0.00
Spencer	1.618	1.616	1.616	0.12
GLE	1.621	1.631	1.631	0.62

Note: "Corrected" Janbu method is not available in SVSlope, so the results were compared to the Janbu Simplified method

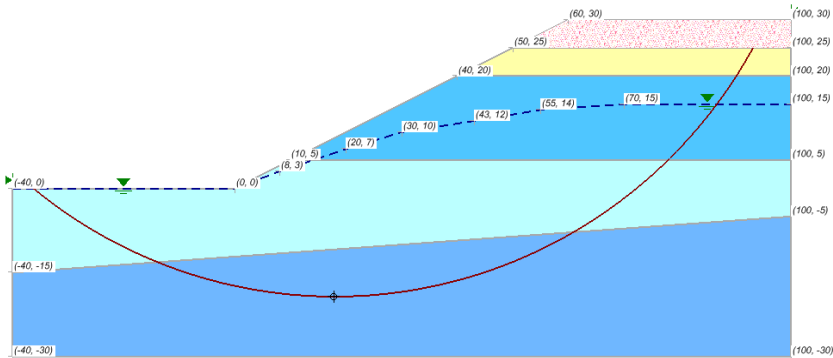
### 3.33 ZHU - FOUR LAYER SLOPE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_51

This model was presented by Zhu (2003). The problem consists of four soil layers with a designated slip surface, using a number of different methods. The multiple layer slope is analyzed using circular slip surfaces.

Tension cracks are placed through the top layer and the slope is assumed to be subjected to earthquake conditions with a seismic coefficient of 0.1. In this case, the factor of safety for the surface with 100 slices is required using all methods of analysis. The tolerance level is set at 0.001.

### 3.33.1 Geometry and Material Properties



**Figure 94 Geometry of the Zhu Four Layer Slope model**

**Table 129 Material Properties of the Zhu Four Layer Slope**

Material	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Layer 1 (top)	20	32	18.2
Layer 2	25	30	18.0
Layer 3	40	18	18.5
Layer 4 (bottom)	40	28	18.8

### 3.33.2 Results and Discussions

**Table 130 Results for Case 1**

Method	Factor of Safety				Difference (%)
	Zhu	Slide	SVSLOPE		
			Moment	Force	
Ordinary	1.066	1.075	1.072		0.28
Bishop Simplified	1.278	1.288	1.284		0.31
Janbu Simplified	1.112	1.121		1.115	0.54
Corps of Engineers #2	1.377	1.420		1.375	-3.17
Lowe-Karafiath	1.290	1.288		1.256	-2.48
Spencer	1.293	1.302	1.298	1.298	0.31
M-P	1.313	1.313	1.309	1.309	0.30
GLE	1.313	1.313	1.308	1.308	0.38

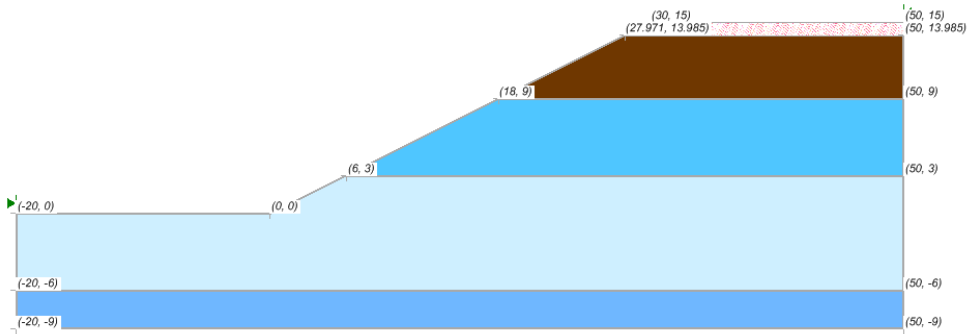
### 3.34 ZHU AND LEE - HETEROGENEOUS SLOPE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_52

Zhu and Lee (2002) presented this model to analyze a heterogeneous slope under wet and dry conditions. Four different slip surfaces were analyzed for each of these conditions. A dry tension crack was placed at the top of the slope and the factor of safety was required for eight separate cases, four distinct slip surfaces under dry conditions, and four distinct slip surfaces when a water

table was included (Table 2). In this case surfaces 1 and 3 were circular, while surfaces 2 and 4 are noncircular. Critical slip surfaces 1 and 2 are shallow, and critical slip surfaces 3 and 4 are deep.

### 3.34.1 Geometry and Material Properties



**Figure 95 Geometry of the Zhu and Lee Heterogenous Slope model**

**Table 131 Material Properties of the Zhu and Lee Heterogenous Slope model**

Material	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Layer 1 (top)	20	18	18.8
Layer 2	40	22	18.5
Layer 3	25	26	18.4
Layer 4 (bottom)	10	12	18.0

**Table 132 Water Table Geometry wet condition**

Coordinates	Arc
(0, -20)	
(0,0)	
(6,3)	
	(100568, 5.284)
	(25.314, 9.002)
	(39.149, 10.269)
(50,10.269)	

### 3.34.2 Results and Discussions

**Table 133 Surface 1 Circular, shallow**

Method	Factor of Safety (1-dry-single circular)				Difference (%)
	Zhu	Slide	SVSLOPE		
	& Lee		Moment	Force	
Ordinary	1.935	1.934	1.933		0.05
Bishop Simplified	2.011	2.010	2.010		0.00
Spencer	2.035	2.017	2.017	2.017	0.00
M-P	2.035	2.017	2.017	2.017	0.00

**Table 134 Results - Surface 2 Circular, deep Grid search**

Method	Factor of Safety (1-wet single circular)				Difference (%)
	Zhu	Slide	SVSLOPE		
	& Lee		Moment	Force	
Ordinary	1.496	1.460	1.460		0.00
Bishop Simplified	1.534	1.526	1.526		0.00
Spencer	1.559	1.533	1.533	1.533	0.00
M-P	1.559	1.533	1.533	1.533	0.00

**Table 135 Results Surface 3 Circular, deep Grid search**

Method	Factor of Safety (3-dry Grid tangent)				Difference (%)
	Zhu	Slide	SVSLOPE		
	& Lee		Moment	Force	
Ordinary	1.229	1.495	1.490		-0.33
Bishop Simplified	1.429	1.804	1.799		-0.28
Spencer	1.836	1.804	1.801	1.801	-0.17
M-P	1.823	1.790	1.790	1.790	0.00

**Table 136 Results Surface 3 Wet Grid Tangent**

Method	Factor of Safety (3-wet Grid Tangent)				Difference (%)
	Zhu	Slide	SVSLOPE		
	& Lee		Moment	Force	
Ordinary	0.922	0.812	0.820		0.99
Bishop Simplified	1.079	1.176	1.170		-0.51
Spencer	1.211	1.189	1.183	1.183	-0.50
M-P	1.197	1.174	1.172	1.172	-0.17

**Table 137 Results Surface 4 Noncircular, deep dry Path search**

Method	Factor of Safety (4-dry Path Search)				Difference (%)
	Zhu	Slide	SVSLOPE		
	& Lee		Moment	Force	
Spencer	1.772	1.797	1.765	1.765	-1.78
M-P	1.765	1.776	1.767	1.767	0.51

**Table 138 Results Surface 5 Non-circular wet path search**

Method	Factor of Safety (4-wet-Path Search)				Difference (%)
	Zhu	Slide	SVSLOPE		
	& Lee		Moment	Force	
Spencer	1.150	1.176	1.148	1.148	-2.38
M-P	1.141	1.162	1.148	1.148	-1.20



### 3.36 YAMAGAMI - STABILIZING PILES

Project: Verification\_SVSlope\_Group1  
 Model: VS\_54

This model was taken from Yamagami (2000) and it examines the reinforcement of an unstable slope. The slope is reinforced using stabilizing piles.

The homogeneous slope can be seen in Figure 97. The model is analyzed using a circular slip surface. The single row of micro-piles, act as passive reinforcement. The piles are spaced 1m apart horizontally and have an shear strength of 10.7 kN. The purpose of this analysis is to determine factor of safety for the slope with or without reinforcement.

#### 3.36.1 Geometry and Material Properties

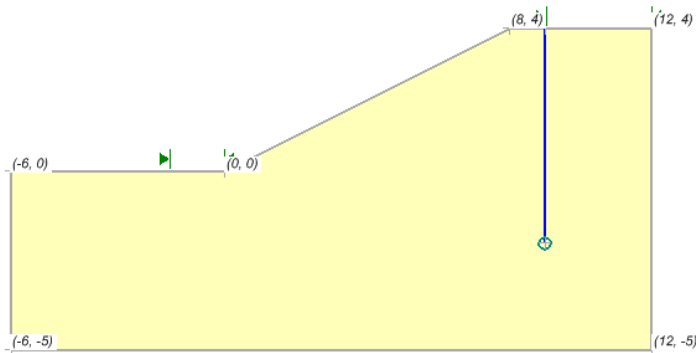


Figure 97 Geometry of the Yamagami example with Pile

Table 141 Material Properties of the Yamagami example

Material	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Material 1	4.9	10	15.68

#### 3.36.2 Results and Discussions

Table 142 No Pile Results

Method	Factor of Safety (no pile)			Difference (%)
	Yamagami Slide (2000)	SVSLOPE Moment	SVSLOPE Force	
	Bishop Simplified	1.1	1.102	

Table 143 With Pile Results

Method	Factor of Safety (with pile)			Difference (%)
	Yamagami (2000)	Slide	SVSLOPE Moment	
	Bishop Simplified	1.2	1.193	

### 3.37 POCKOSKI AND DUNCAN - REINFORCED SLOPE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_55

Pockoski and Duncan (2000) presented this model. The model compares eight different computer programs for analysis for reinforced slopes. The purpose of this analysis is to confirm the ability of SVSLOPE to analysis reinforce slopes.

The analysis of a homogeneous, un-reinforced slope is first presented. A water table is present and the slip surfaces are circular. The purpose of this problem is to calculate critical slip surface and the factor of safety.

#### 3.37.1 Geometry and Material Properties

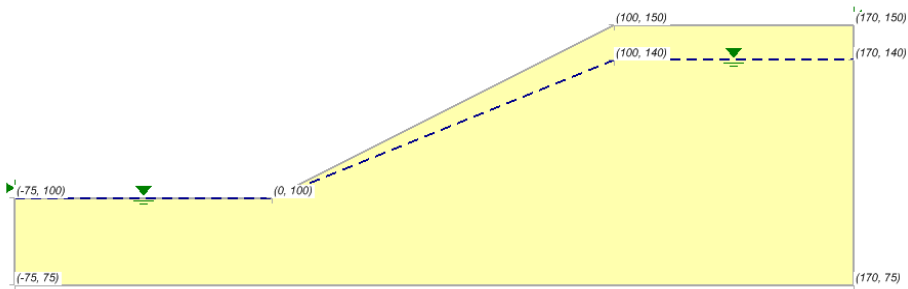


Figure 98 Geometry of the Pockoski and Duncan Reinforced Slope model

Table 144 Material Properties of the Pockoski and Duncan Reinforced Slope

Material	c (psf)	$\phi$ (degrees)	$\gamma$ (pcf)
Sandy Clay	300	30	120

#### 3.37.2 Results and Discussions

Table 145 Results of the Pockoski and Duncan Reinforced Slope model

Method	Factor of Safety						Difference		
	UTEXAS4	Slope/W	WINSTABL	XSTABL	RSS	Slide	SVSLOPE		Difference (%)
							Moment	Force	
Ordinary Bishop	-	1.04	-	-	-	1.052	1.058	0.57	
Simplified Janbu	1.29	1.29	1.29	1.29	1.29	1.293	1.292	0.08	
Simplified Lowe-Karafiath	1.15	1.15	1.2	1.24	1.15	1.151	1.151	0.00	
Spencer	1.32	-	-	-	-	1.318	1.307	-0.83	
	1.3	1.3	1.34	-	-	1.3	1.298	1.298	0.15

SNAIL  $F_s = 1.22$  (Wedge method)

GOLD-NAIL  $F_s = 1.32$  (Circular method)

### 3.38 POCKOSKI AND DUNCAN - TENSION CRACKS

Project: Verification\_SVSlope\_Group1  
 Model: VS\_56

This is second test slope presented by Pockoski and Duncan (2000). This model is similar to the previous model with the exception that a dry tension crack is included.

#### 3.38.1 Geometry and Material Properties

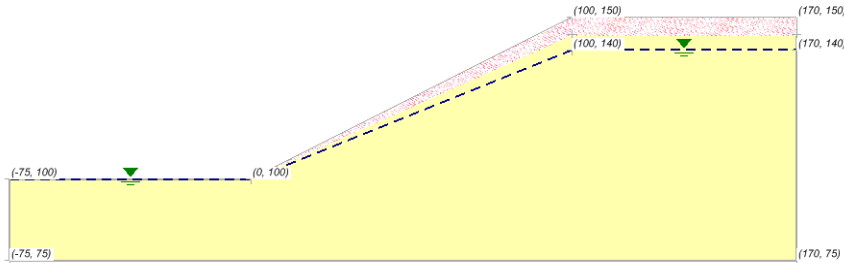


Figure 99 Geometry of the Pockoski and Duncan model

Table 146 Material Properties of the Pockoski and Duncan model

Material	c (psf)	$\phi$ (degrees)	$\gamma$ (pcf)
Sandy Clay	300	30	120

#### 3.38.2 Results and Discussions

Table 147 Results of the Pockoski and Duncan model

Method	Factor of Safety						Difference		
	UTEXAS4 Slope/W		XSTABL	RSS	Slide	SVSLOPE	Moment	Force	(%)
Ordinary	-	1.02	-	-	-	1.03	1.027		0.29
Bishop Simplified	1.28	1.28	1.31	1.28	1.28	1.285	1.284		0.08
Janbu Simplified	1.14	1.14	1.18	1.23	1.13	1.142		1.142	0.00
Lowe-Karafiath	1.31	-	-	-	-	1.305		1.314	0.69
Spencer	1.29	1.29	1.32	-	-	1.289	1.29	1.29	0.08

SNAIL  $F_s = 1.18$  (Wedge method)

GOLD-NAIL  $F_s = 1.30$  (Circular method)

### 3.39 POCKOSKI AND DUNCAN - REINFORCED SLOPE

Project: Verification\_SVSlope\_Group1  
 Model: VS\_57

This is a continuation of the Pockoski and Duncan (2000), comparison of eight different computer programs for the analysis of reinforced slopes. This is the third test slope. In this case, a water table is also included. The slope is analyzed with and without composite slip surfaces in order to compare results with programs that have this option as well as those that do not have this option.

### 3.39.1 Geometry and Material Properties

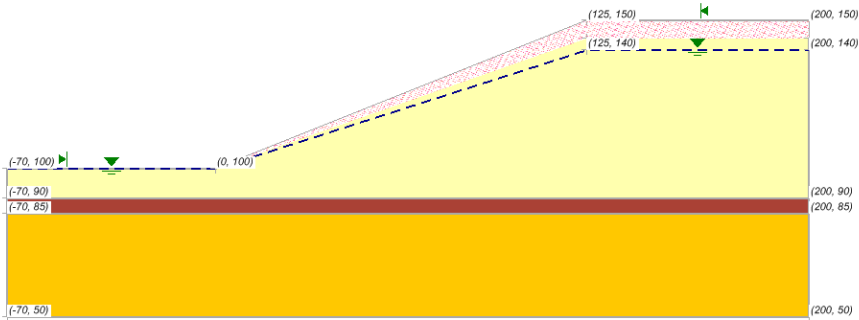


Figure 100 Geometry of the composite/non circular

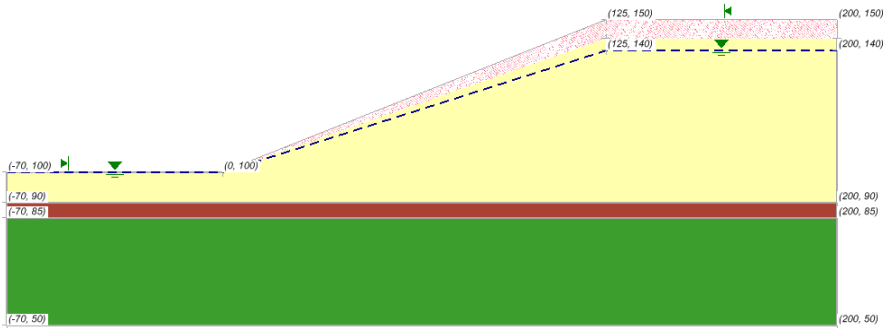


Figure 101 Geometry of the no composite/circular

Table 148 Material Properties

Material	c (psf)	$\phi$ (degrees)	$\gamma$ (pcf)
Sandy Clay	300	35	130
Highly Plastic Clay	0	25	130

### 3.39.2 Results and Discussions

Table 149 Composite Surface Non Circular

Method	Factor of Safety Composite surfaces/NonCircular				Difference (%)	
	Slope/W	XSTABL	Slide	SVSLOPE		
				Moment		Force
Ordinary	0.85		0.944	0.928	1.69	
Bishop Simplified	1.39	1.41	1.392	1.392	0.00	
Janbu Simplified	1.21	1.34	1.222	1.221	0.08	
Lowe-Karafiath			1.385	1.41	1.81	
Spencer	1.4		1.4	1.401	1.401	0.07

SNAIL  $F_s = 1.39$  (Wedge method)

**Table 150 No Composite Surfaces Circular**

Method	Factor of Safety –No composite surfaces/Circular					Difference (%)	
	UTEXES4	WINSTABL	RSS	Slide	SVSLOPE		
					Moment		Force
Ordinary				1.11	1.102	0.72	
Bishop	1.41	1.39	1.41	1.417	1.413	0.28	
Janbu Simplified	1.2	1.23	1.24	1.263		1.259	0.32
Lowe-Karafiath	1.12			1.414		1.428	0.99
Spencer	1.42	1.45		1.422	1.419	1.419	0.21

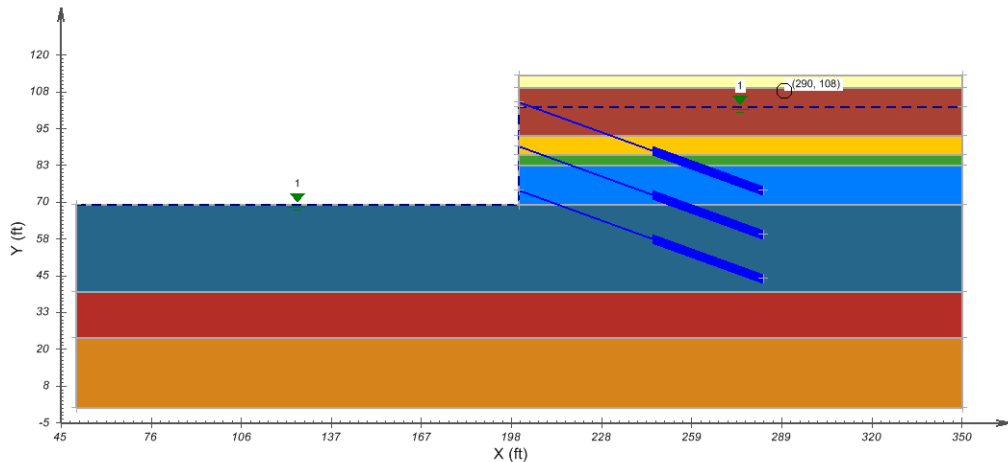
GOLD-NAIL  $F_s = 1.40$  (Circular method)

### 3.40 POCKOSKI AND DUNCAN - TIE-BACK WALL

Project: Verification\_SVSSlope\_Group1  
 Model: VS\_58

This is the fourth test slope analysis provided by Pockoski and Duncan (2000). This model analyzes a tie-back wall in a layered soil. A water table is presented and each layer is horizontal. Three identical rows of active grouted tie back reinforcement are modeled in this tie back wall. The purpose of the model is to determine the location of critical failure surface and the factor of safety.

#### 3.40.1 Geometry and Material Properties



**Figure 102 Geometry of the Pockoski and Duncan Tie Back Wall model**

**Table 151 Material Properties of the Pockoski and Duncan Tie Back Wall model**

Layer	c (psf)	φ (degrees)	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 152 Grouted Tieback Properties all rows**

Tensile Cap. (lbs)	Plate Cap. (lbs)	Bond Strength (lb/ft)	Bond Length (ft)	Out-of-Plane Spacing (ft)
247343	247343	4000	40	4

### 3.40.2 Results and Discussions

**Table 153 Results**

Method	Factor of Safety					Difference (%)
	UTEXAS4	Slope/W	WINSTABL	Slide	SVSLOPE	
					Moment Force	
Ordinary		1.12		1.125	1.126	0.09
Bishop Simplified	1.14	1.14	1.16	1.147	1.15	0.26
Janbu Simplified	1.13	1.05	1.12	1.061	1.065	0.38
Lowe-Karafiath	1.20			1.175	1.284	9.28
Spencer	1.14	1.14	1.20	1.145	1.148	0.26

GOLD-NAIL  $F_s = 1.19$  (Circular)  
 SNAIL  $F_s = 1.03$  (Wedge method-noncircular)

### 3.41 POCKOSKI AND DUNCAN - REINFORCEMENT

Project: Verification\_SVSlope\_Group1  
 Model: VS\_59

This is the fifth test slope provided by Pockoski and Duncan, (2000). This scenario varies the effect of the reinforcement. The analysis represents a tie back wall and homogeneous sand. A single row of active grouted tieback support is installed for this problem. A water table is present, circular critical slip surfaces are considered and the resulting factor of safety is required.

### 3.41.1 Geometry and Material Properties

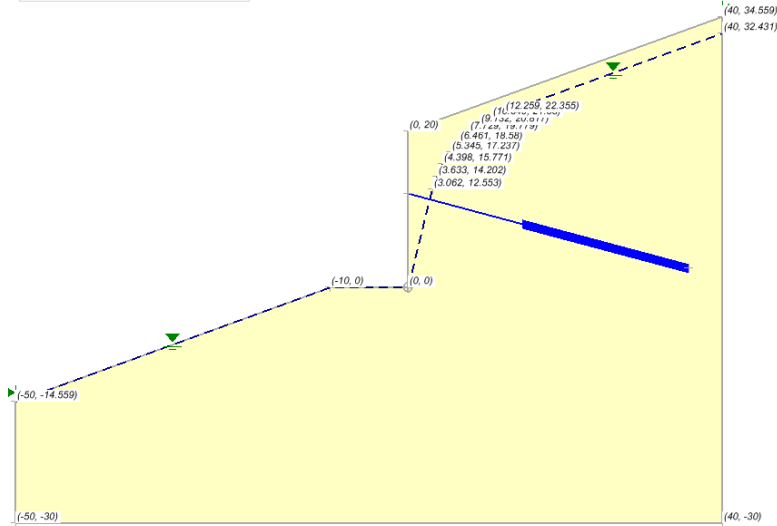


Figure 103 Geometry of the Reinforcement model

Table 154 - Material Properties of the Pockoski and Duncan Reinforcement model

Material	c (psf)	$\phi$ (degrees)	$\gamma$ (pcf)
Sand	0	30	120

Table 155 Soil Nail Properties

Tensile Cap. (lbs)	Plate Cap. (lbs)	Bond Strength (lb/ft)	Bond Length (ft)	Out-of-Plane Spacing (ft)
184077	184077	5000	22	8

### 3.41.2 Results and Discussions

Table 156 Results Circular

Method	Factor of Safety						Difference (%)
	UTEXAS4	Slope/W	WINSTABL	Slide	SVSLOPE		
					Moment	Force	
Ordinary	-	0.62	-	0.626	0.59	-	-5.75
Bishop Simplified	0.56	0.60	0.74	0.583	0.584	-	0.17
Janbu Simplified	0.64	0.61	0.76	0.583	-	0.584	0.17
Lowe-Karafiath	0.76			0.588	-	0.588	0.00
Spencer	0.65	0.60	0.59	0.594	0.591	0.591	0.51

GOLD-NAIL  $F_s = 0.62$  Circular

SNAIL  $F_s = 0.62$  Wedge method noncircular

### 3.42 POCKOSKI AND DUNCAN - SOIL NAILS

Project: Verification\_SVSlope\_Group1  
 Model: VS\_60

This is the seventh test slope providing by Pockoski and Duncan (2000). This model analyzes a soil nailed wall in homogenous 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 on the high bench.

There are also five parallel rows passive soil nails that reinforce the wall. In this case, each row has identical strength characteristics. The purpose of the model is to calculate the critical slip surface (through the toe) as well as the factor of the safety.

#### 3.42.1 Geometry and Material Properties

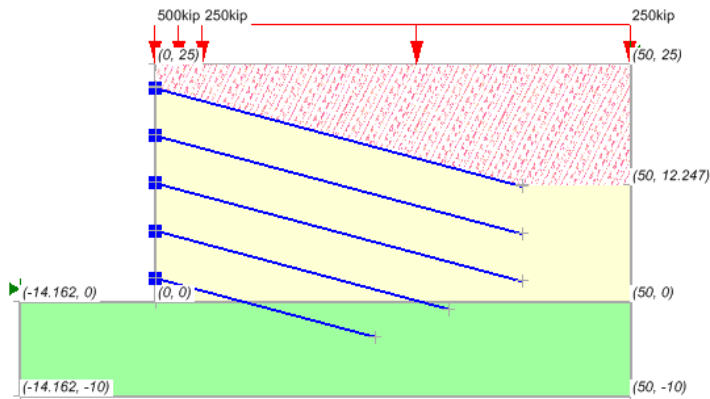


Figure 104 Geometry of the Pockoski and Duncan Soil Nails model

Table 157 Material Properties of the Pockoski and Duncan Soil Nails model

Material	c (psf)	$\phi$ (degrees)	$\gamma$ (pcf)
Sand	800	0	120

Table 158 Soil Nail Properties

Tensile Cap. (lbs)	Plate Cap. (lbs)	Bond Strength (lb/ft)	Out-of-Plane Spacing (ft)
25918	25918	1508	5

### 3.42.2 Results and Discussions

**Table 159 Results Dry Circular**

Method	Factor of Safety (Dry Circular)					Difference (%)
	UTEXAS4	SLOPE/W	WINSTABL	Slide	SVSLOPE Moment Force	
Ordinary	-	1.00	-	0.99	0.998	0.81
Bishop Simplified	1.00	1.01	1.06	0.997	0.998	0.10
Janbu Simplified	1.08	1.07	1.10	1.041	1.042	0.10
Lowe-Karafiath	1.00			1.021	1.036	1.47
Spencer	1.02	1.02	0.99	1.01	1.022	1.19
GOLD-NAIL $F_s = 0.91$						
Circular Method						
SNAIL $F_s = 0.84$ Wedge						
Method						

### 3.43 LOUKIDIS - SEISMIC COEFFICIENT

Project: Verification\_SVSlope\_Group1  
 Model: VS\_62

This model was published by Loukidis et al. (2003) and provides a method for determining the critical seismic coefficient  $k_c$ . The seismic coefficient determined corresponds a factor of safety of 1.0. This is their first example.

A simple homogenous earth slope is subjected to seismic loading. Both circular and noncircular slip surfaces are considered in the analysis and all slip surfaces must pass through the toe of the slope.

Two independent pore-water pressures conditions are given consideration:

- Dry slope, and
- $R_u$  of 0.05.

The purpose of this verification problem is to reproduce a safety factor of 1 using Spencer's method and the seismic coefficients presented in the Loukidis et al. paper (2003).

### 3.43.1 Geometry and Material Properties

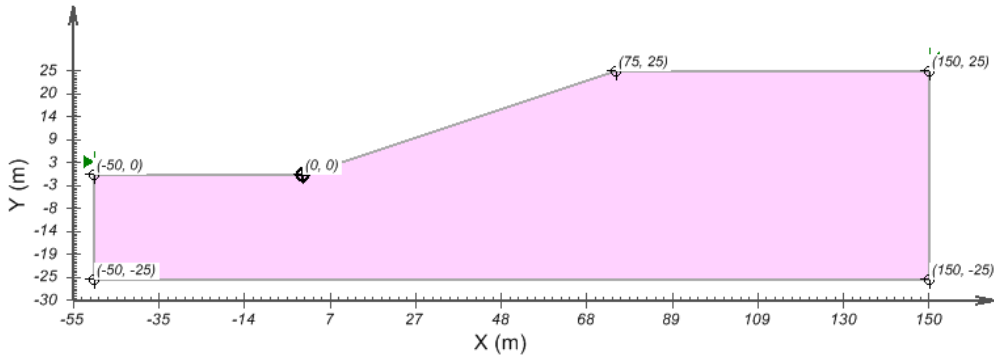


Figure 105 Geometry of the Loukidis Seismic Coefficient model

Table 160 Seismic Coefficients

Dry Slope	0.432
$R_u = 0.5$	0.132

### 3.43.2 Results and Discussions

Table 161 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

Table 162 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

Table 163 Results Wet Circular

Method	Factor of Safety (Wet Circular)			Difference (%)
	Slide	SVSLOPE		
		Moment	Force	
Bishop Simplified	0.987	0.991		0.41
Janbu Simplified	0.899		0.901	0.22
Corp Engineers#1	0.984		0.988	0.41
Corp Engineers#2	0.994		0.996	0.20
Lowe-Karafiath	0.976		0.982	0.61
Spencer	1.001	1.003	1.003	0.20
M-P	1.00	1.003	1.003	0.30
GLE	1.00	1.003	1.003	0.30

Loukidis  $F_s = 1.00$  (Spencer)

**Table 164 Results Wet No-Circular**

Method	Factor of Safety (Wet Non-Circular)			Difference (%)
	Slide	SVSLOPE		
		Moment	Force	
Bishop Simplified	0.966	0.958		0.83
Spencer	0.998	0.999	0.999	0.10

Loukidis  $F_s = 1.00$  (Spencer)

### 3.44 LOUKIDIS - SEISMIC COEFFICIENT #2

Project: Verification\_SVSlope\_Group1

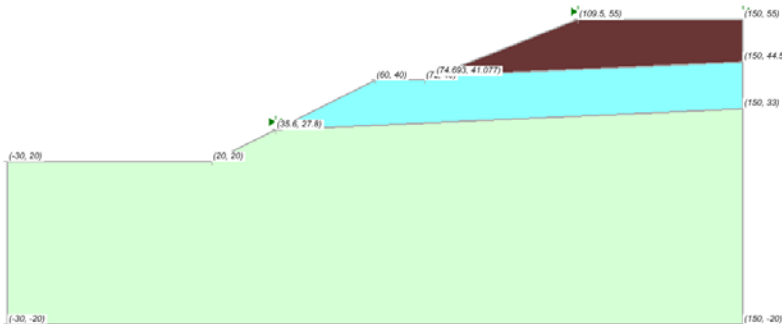
Model: VS\_63

This is the second example problem presented by Loukidis et al., 2003. The effect of the critical seismic coefficient is examined in this example.

This model analyzes a layered dry slope under seismic loading conditions. The purpose of the model is to bring the Spencer's factor of safety to 1.0 using the author's presented seismic coefficient of 0.115. The Loukidis analysis was for the case of a log-spiral surface.

This problem is analyzed in SVSLOPE by using a Greco search technique with a Monte Carlo optimization. The critical slip surface in this case passes through the material boundary on the slope between the middle and lower layers.

#### 3.44.1 Geometry and Material Properties



**Figure 106 Geometry of the Loukidis Seismic Coefficient model**

**Table 165 - Material Properties of the Loukidis Seismic Coefficient model**

Layer	$c$ (kN/m <sup>2</sup> )	$\phi$ (degrees)	$\gamma$ (kN/m <sup>3</sup> )
Top	4	30	17
Middle	25	15	19
Bottom	15	45	19

## 3.44.2 Results and Discussions

Table 166 Results of the Dry Circular

Method	Factor of Safety (Dry Circular)				Difference (%)
	Loukidis et al (2003)	Slide	SVSLOPE		
			Moment	Force	
Spencer	1.00	0.991	0.993	0.993	0.20

## 4 MISCELLANEOUS GROUP #2

This chapter represents the second set of examples problems used to verify the SVSLOPE software. The chapter represents a collection of classic examples, which verify the calculation of the factor of safety in various cases including variations in material properties, water table locations, circular and non-circular slip surfaces and anchors.

### 4.1 SIMPLE MULTI - LAYER SLOPE

Project: Verification\_SV Slope\_Group2  
 Model: VW\_1

This example creates a simple multi-layer slope in which the potential slip surfaces crosses three or four different material and there is a water table in the example. The primary purpose of this model is to analyze a typical case with circular slip surfaces. The Bishop's Simplified method is used to calculate the factor of safety.

In this model approximately 20 points were used in the grid and radius search method. The pore-water pressures were specified using a piezometric line. The model consists of silty clay over layering sandy clay tills.

#### 4.1.1 Geometry and Material Properties

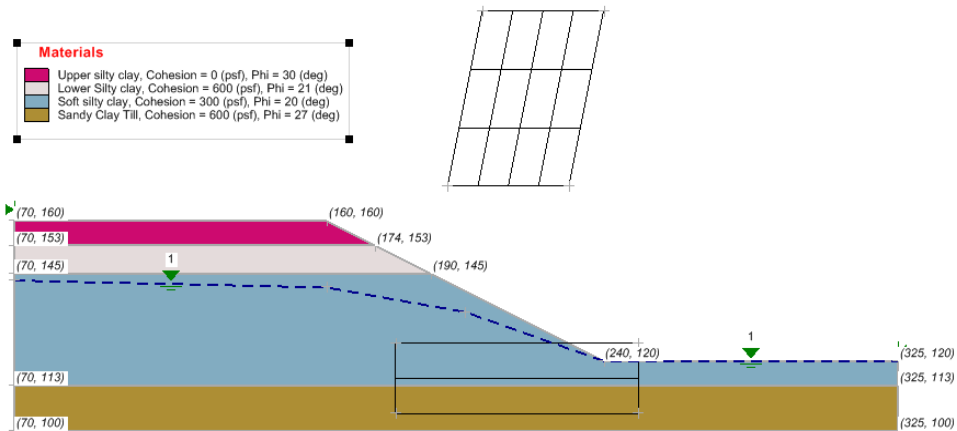


Figure 107 Geometry of the Simple Multi-Layer Slope Model

### 4.1.2 Results and Discussions

Table 167 illustrates the location of the critical slip surface. The analysis resulted in a factor of safety of approximately 1.2.

**Table 167 Results of the Simple Multi-Layer Slope model**

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.101		1.104		0.27
Bishop Simplified	1.211		1.213		0.18
Janbu Simplified		1.090		1.113	0.37
Corps. of Engineers #1		1.255		1.257	0.18
Corps. of Engineers #2		1.290		1.293	0.25
Lowe-Karafiath		1.249		1.245	-0.32
Spencer	1.210	1.210		1.213	0.25
M-P	1.211	1.214	1.213	1.213	0.25
GLE	1.211	1.211	1.213	1.213	0.25

## 4.2 MULTI - LAYER MODEL WITH NO ANCHORS

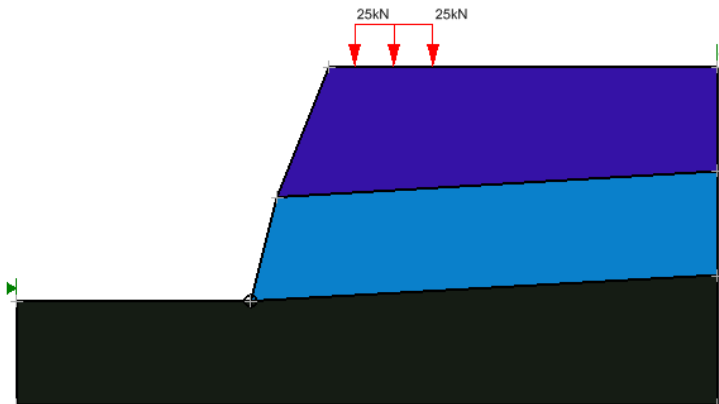
Project: Verification\_SVSlope\_Group2  
 Model: VW\_2

This example problem presents a multi-layer model. The analysis method used in this case is the Morgenstern-Price method.

### 4.2.1 Geometry and Material Properties

**Materials**

- Fine Sand, Cohesion = 12.5 (kPa), Phi = 35 (deg), Unit Weight = 16 (kN/m<sup>3</sup>)
- Clayey Till, Cohesion = 20 (kPa), Phi = 30 (deg), Unit Weight = 15 (kN/m<sup>3</sup>)
- Sandy Clay, Cohesion = 12 (kPa), Phi = 25 (deg), Unit Weight = 16 (kN/m<sup>3</sup>)



**Figure 108 Geometry of the Multi-Layer Model with No Anchors**

### 4.2.2 Results and Discussions

The results of the calculation factor of safety may be seen in Table 168. At the end of calculation the factor of safety is a result approximately 1.2.

**Table 168 No Anchor Results**

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	0.726		0.727		0.13
Bishop Simplified	0.760		0.754		-0.75
Janbu Simplified		0.728		0.730	0.24
Corps of Engineers #1		0.753		0.754	0.08
Corps of Engineers #2		0.766		0.758	-1.06
Lowe-Karafiath		0.746		0.750	0.54
Spencer	0.750	0.743	0.749	0.750	-0.14
M-P	0.750	0.741	0.749	0.750	-0.14
GLE	0.749	0.749	0.749	0.749	0.00

### 4.3 BLOCK SEARCH MODEL

Project: Verification\_SVSlope\_Group2  
 Model: VW\_3

The purpose of this example is to illustrate the use of the block search technique to generate a series of potential slip surfaces.

The Morgenstern-Price method of calculations will be used in this case. Tension cracks are also applied in the upper zone as well as downstream water bonded. The minimum block slip surface is selected given the contribution of a number of trial slip surfaces and the influence of the associated tension crack zone.

#### 4.3.1 Geometry and Material Properties

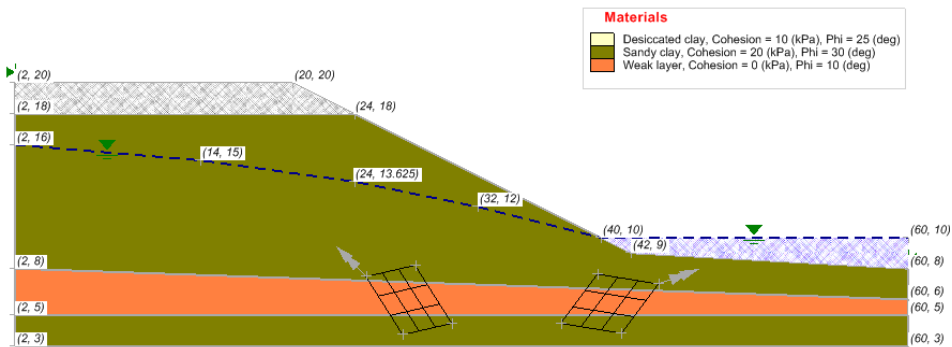


Figure 109 Geometry of the Block Search Model

### 4.3.2 Results and Discussions

The following figure illustrates the identification of the most critical slip surfaces with the calculated factor of safety approximately equal to 1.0.

**Table 169 Results of the Block Search model**

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	0.974		0.974		0.00
Bishop Simplified	1.065		1.064		-0.09
Janbu Simplified		1.035		1.033	0.19
Corps of Engineers #1		1.218		1.222	0.33
Corps of Engineers #2		1.268		1.163	-8.28
Lowe-Karafiath		1.303		1.201	-7.83
Spencer	1.078	1.071	1.073	1.073	0.46
M-P	1.076	1.072	1.073	1.073	-0.28
GLE	1.074	1.074	1.073	1.073	0.09

Note: The difference between Slope/W and SVSLOPE for the Lowe-Karafiath and the Corps of Engineers #2 method is due to different assumptions made regarding the interslice force functions in Slope/W. Slope/W uses positive values when the base angle is negative. This difference has been extensively studied and we believe the SVSLOPE implementation to be reasonable.

## 4.4 COMPOSITE SLIP SURFACES

Project: Verification\_SVSSlope\_Group2  
 Model: VW\_4

The purpose of this model is to illustrate the use of composite slip surfaces. The analysis method in this case is the Morgenstern-Price method of analysis. This model is characterized by tension crack zones, pore-water pressures specified by piezometric lines and downstream water ponding.

### 4.4.1 Geometry and Material Properties

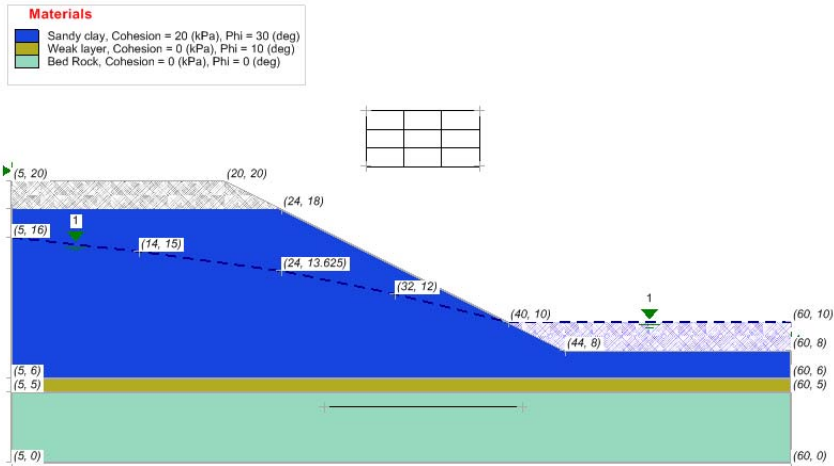


Figure 110 Geometry of the Composite Slip Surfaces model

### 4.4.2 Results and Discussions

The following figure indicates the identified location of the critical slip surface. The resulting factor of safety is approximately equal to 1.14.

The base of the slip surfaces is truncated at the bedrock layer as necessary. Also, the upper portion of the slip surface goes vertical once it encounters the tension crack zone.

Table 170 Results of the Composite Slip Surfaces model

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	0.855		0.825		-3.51
Bishop Simplified	1.125		1.055		-6.22
Janbu Simplified		1.062		1.045	-1.60
Corps of Engineers #1		1.333		1.142	-14.33
Corps of Engineers #2		1.221		1.086	-11.06
Lowe-Karafiath		1.299		1.086	-16.40
Spencer	1.140	1.139	1.058	1.058	-7.19
M-P	1.113	1.11	1.054	1.054	-5.30
GLE	1.112	1.112	1.054	1.054	-5.22

### 4.5 RETAINING WALL

Project: Verification\_SVSlope\_Group2  
 Model: VW\_5

The primary purpose of this model is to illustrate the analysis of the stability of a gravity retaining wall using a fully specified slip surface. The Spencer Method is used to calculate the factor of safety.

This model illustrates the use of fully specified slip surfaces, a single search center and a retaining wall in order to calculate the location of the critical slip surface.

#### 4.5.1 Geometry and Material Properties

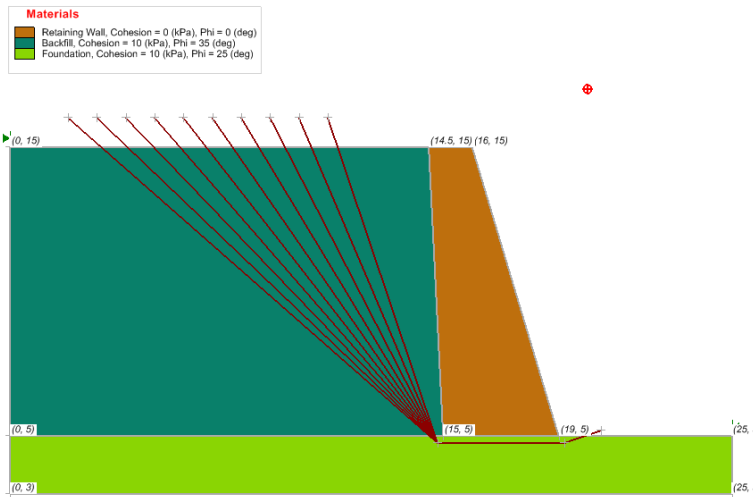


Figure 111 Geometry of the Retaining Wall model

#### 4.5.2 Results and Discussions

The following figure shows the calculations for the factor of safety on specified slip surfaces. A final factor of safety of 1.677 was calculated.

Table 171 Results of the Retaining Wall model

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.368		1.369		0.07
Bishop Simplified	1.479		1.488		0.61
Janbu Simplified		1.320		1.323	0.23
Corps of Engineers #1		1.697		1.700	0.18
Spencer	1.677	1.669	1.685	1.685	0.48
M-P	1.678	1.672	1.686	1.686	0.48
GLE	1.680	1.680	1.687	1.687	0.42

### 4.6 FABRIC MODEL

Project: Verification\_SVSlope\_Group2  
 Model: VW\_6

The purpose of this example is to show how geo-fabric reinforcement can be represented in a slope stability analysis. In this case, the GLE method is used to calculate the factor of safety. This model has contained no pore-water pressures and represents a single specified circular slip surface. A single applied line load is applied to the crest of the slope. Geo-fabric reinforcements are entered as anchor loads with full bond length and variable applied loads.

#### 4.6.1 Geometry and Material Properties

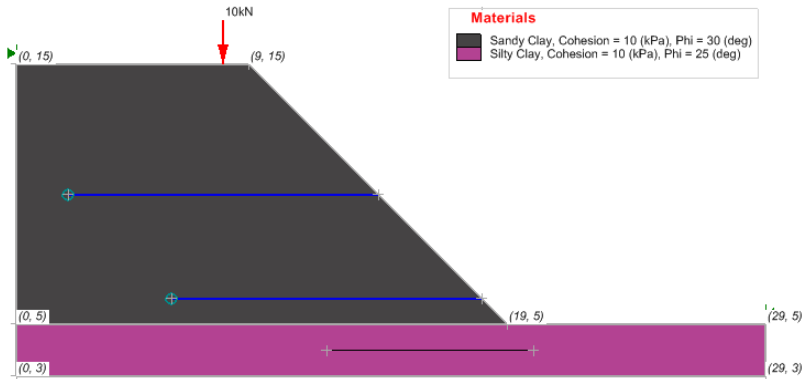


Figure 112 Geometry of the Fabric Model

#### 4.6.2 Results and Discussions

The calculation of the factor of safety is shown in the following figure. A factor of safety of 1.502 was calculated using SVSLOPE. Of particular interest is the free bond diagram for slices 5 and 10, which are shown on the following figures. In this case, the line load applied at crest of the slope is specified as 10KN/m and is shown in the free body diagram of slice no. 5. A force mobilization load of 21.165 KN/m was calculated as the force in the anchor. The calculation of this force can be seen in free body diagram for slice 10.

Table 172 Fabric model Results

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.518		1.525		0.46
Bishop Simplified	1.663		1.667		0.24
Janbu Simplified		1.496		1.510	0.94
Corps of Engineers #1		1.703		1.712	0.53
Corps of Engineers #2		1.783		1.792	0.50
Spencer	1.643	1.646	1.650	1.634	0.73
M-P	1.641	1.637	1.646	1.646	0.55
GLE	1.640	1.640	1.646	1.646	0.37

Note: Reinforcement constant = 50 KN

**Table 173 Fabric No rein/no line load**

Method	Factor of Safety (No reinforcement / no line load)				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
	Ordinary	1.291		1.297	
Bishop Simplified	1.444		1.447	0.21	
Janbu Simplified		1.292		1.300	0.62
Corps of Engineers #1				1.484	
Corps of Engineers #2				1.572	
Lowe-Karafiath				NA	
Spencer	1.426	1.429	1.43	1.430	0.07
M-P			1.427	1.427	
GLE	1.423	1.423	1.427	1.427	0.28

**Table 174 Fabric no reinforcement/with line load**

Method	Factor of Safety (No reinforcement with line load)				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
	Ordinary	1.281		1.287	
Bishop Simplified	1.434		1.436	0.14	
Janbu Simplified		1.283		1.291	0.62
Spencer	1.416	1.418	1.421	1.407	0.78
GLE	1.413	1.413	1.417	1.417	0.28

**Table 175 Fabric with rein and no line load**

Method	Factor of Safety (with rein but no line load)				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
	Ordinary	1.386		1.392	
Bishop Simplified	1.535		1.538	0.20	
Janbu Simplified		1.397		1.387	0.72
Spencer	1.517	1.512	1.523	1.508	0.26
GLE	1.514	1.514	1.518	1.518	0.26

## 4.7 BISHOP AND MORGENSTERN - HOMOGENEOUS

Project: Verification\_SV Slope\_Group2  
 Model: VW\_7

This example problem is based on an example problem original published by Bishop and Morgenstern, (1960). The solutions presented in the original work developed a series of stability charts that could then be used to estimate the factor of safety for simple, homogenous earth slopes.

The purpose of this model is to illustrate agreement between the SVSLOPE software and the original slope stability charts. The slope of this particular model is at a ratio to 4 horizontal to 1 vertical. The grid and radius search technique was used to identify the location of the critical slip surface.

### 4.7.1 Geometry and Material Properties

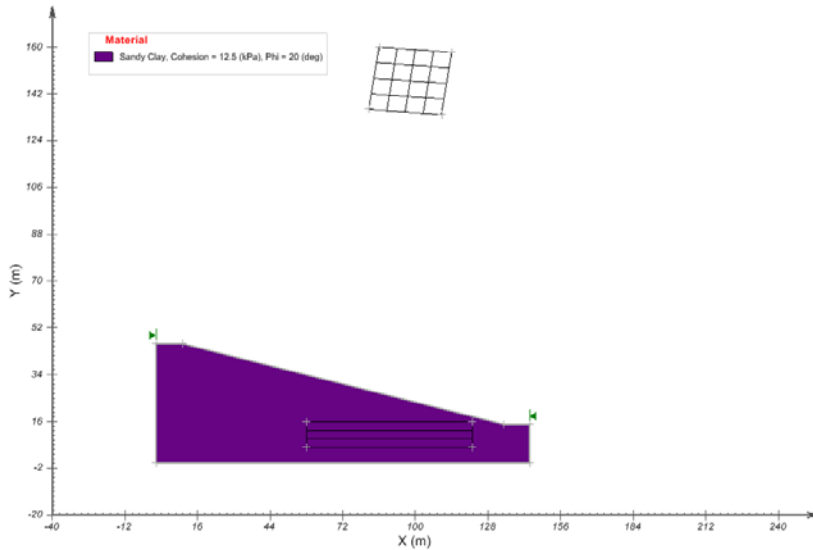


Figure 113 Geometry of the Bishop and Morgenstern Homogenous Model

### 4.7.2 Results and Discussions

The location of the critical slip surface and the calculation of the factor of safety can be seen in the following figure. A factor of safety of 1.35 was calculated which agrees well with stability chart calculations.

In this case, the Bishop's Simplified method and the Morgenstern-Price method yields similar results.

Table 176 Chart results Bishop and Morgenstern Homogenous model

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.231		1.232		0.10
Bishop Simplified	1.337		1.338		0.04
Janbu Simplified		1.261	1.262		
Corps of Engineers #1		1.344		1.345	0.07
Corps of Engineers #2		1.351		1.352	0.07
Lowe-Karafiath		1.347		1.346	0.10
Spencer	1.338	1.339	1.339	1.339	0.08
M-P	1.338	1.34	1.339	1.339	0.06
GLE	1.338	1.338	1.339	1.339	0.06

### 4.8 FREDLUND AND KRAHN (1977)

Project: Verification\_SVSlope\_Group2  
 Model: VW\_8

This example model was originally presented by Fredlund and Krahn (1977). It represented a comparison study of various slope stability methods. In this example the slope is comprised of three layers. The upper layer contains a weak layer at its base. The weak layer subsequently overlays a bedrock layer.

The critical slip surface will potentially come down and follow along the weak layer but will not extend into the strong bedrock.

#### 4.8.1 Geometry and Material Properties

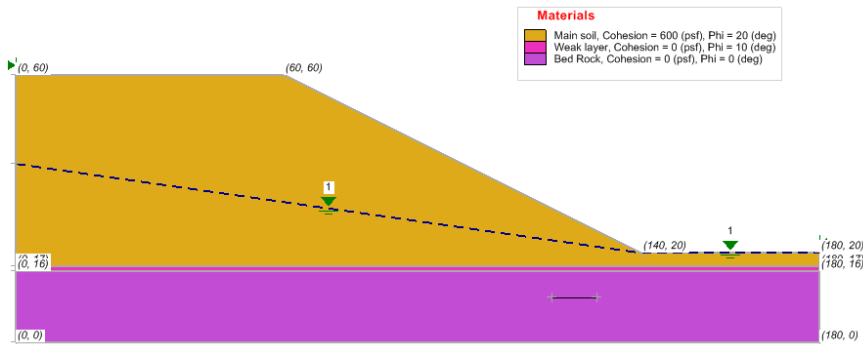


Figure 114 Geometry of the Fredlund and Krahn (1977) Model

#### 4.8.2 Results and Discussions

The following figure shows the results of the calculations for this model. The results compare reasonably to the results calculated by Fredlund and Krahn (1977).

Table 177 Results of the Fredlund and Krahn (1977)

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.147		1.151		0.33
Bishop Simplified	1.210		1.213		0.22
Janbu Simplified		1.186		1.191	0.39
Corps of Engineers #1		1.272		1.273	0.08
Corps of Engineers #2		1.259		1.264	0.40
Spencer	1.212	1.212	1.214	1.214	0.17
M-P	1.205	1.205	1.209	1.209	0.33
GLE	1.205	1.205	1.209	1.209	0.34

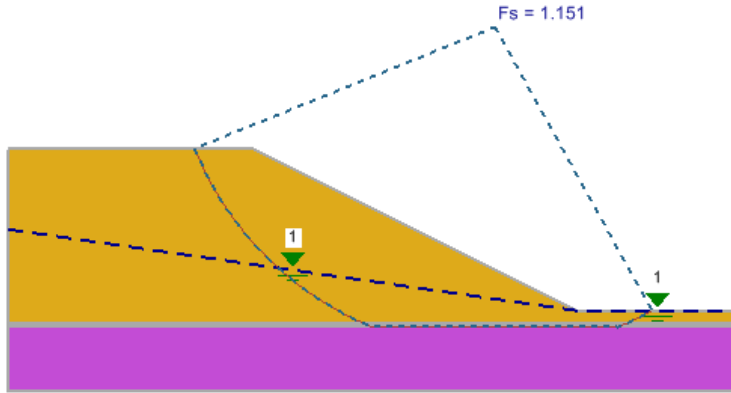


Figure 115 Critical slip surface calculated for the Fredlund and Krahn model (Ordinary method)

### 4.9 SIMPLE TWO MATERIAL MODEL

Project: Verification\_SVSlope\_Group2  
 Model: VW\_9

This example consists of a simple two layers slope with a water table. The problem is analyzed using the Bishop Simplified method as well as the Morgenstern Price method. The purpose of this example is to illustrate the calculation of the factor of safety for a simple slope example.

#### 4.9.1 Geometry and Material Properties

**Materials**

- Upper Soil, Cohesion = 5 (kPa), Phi = 20 (deg)
- Lower Soil, Cohesion = 10 (kPa), Phi = 25 (deg)

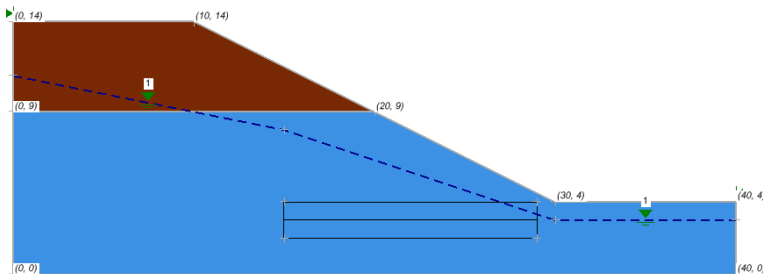
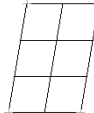


Figure 116 Geometry of the Simple Two Material Model

	c (kN/m <sup>2</sup> )	φ (degrees)	γ (kN/m <sup>3</sup> )
Upper Soil	5.0	20.0	15.00
Lower Soil	10.0	25.0	18.00

### 4.9.2 Results and Discussions

The factors of safety calculated for this example are shown in Table 178. The results agree well with those calculated using the Slope/W software.

**Table 178 Results of the Simple Two Material model**

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.279		1.283		
Bishop Simplified	1.464		1.466		0.12
Janbu Simplified		1.286		1.290	
Corps of Engineers #1		1.502		1.505	0.20
Corps of Engineers #2		1.534		1.536	0.13
Lowe-Karafiath		1.498		1.505	0.46
Spencer	1.467	1.469	1.469	1.469	0.15
M-P	1.466	1.471	1.468	1.468	0.14
GLE	1.466	1.466	1.468	1.468	0.14

### 4.10 INFINITE SLOPE MODEL

Project: Verification\_SVSlope\_Group2  
 Model: VW\_11

This example illustrates the use of the software to calculate the stability of a semi-infinite slope. In this case the Morgenstern-price method was used to calculate the factor of safety.

#### 4.10.1 Geometry and Material Properties

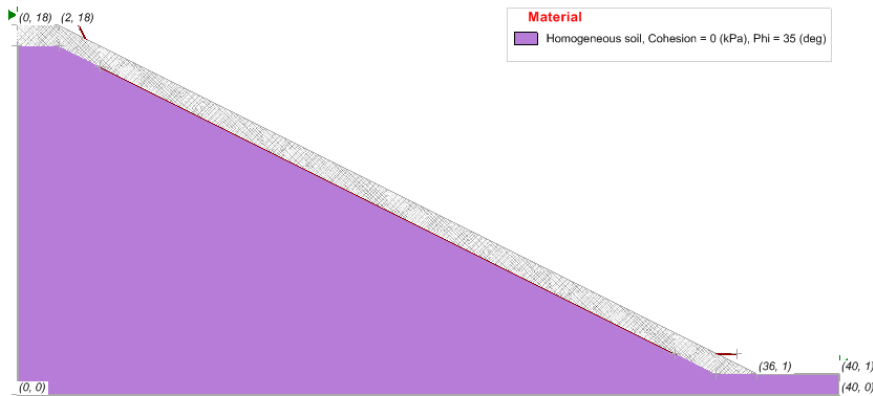


Figure 117 Geometry of Infinite Slope Model

#### 4.10.2 Results and Discussions

The results of the analysis are shown in Table 179. The results can be compared to the calculated closed-form solutions.

**Table 179 Infinite slope model**

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.400		1.400		0.03
Bishop Simplified	1.402		1.400		0.12
Janbu Simplified		1.400		1.400	0.03
Janbu Generalized				1.400	
Corps of Engineers #1		1.400		1.400	0.03
Corps of Engineers #2		1.400		1.400	0.03
Lowe-Karafiath		1.400		1.400	0.03
Spencer	1.400	1.400	1.400	1.400	0.03
M-P	1.400	1.400	1.400	1.400	0.03
GLE	1.400	1.400	1.400	1.400	0.03

**Table 180 Slope/w results of infinite slope calculations**

Case	$\phi'$	c'	$r_u$	Closed Form Solution	Factor of Safety	
					SLOPE/W Bishop Simplified	SLOPE/W Morgenstern-Price
1	35	0.0	0.0	1.400	1.402	1.400
2	35	0.0	0.25	0.963	0.965	0.963
3	35	5.0	0.25	1.600	1.601	1.600

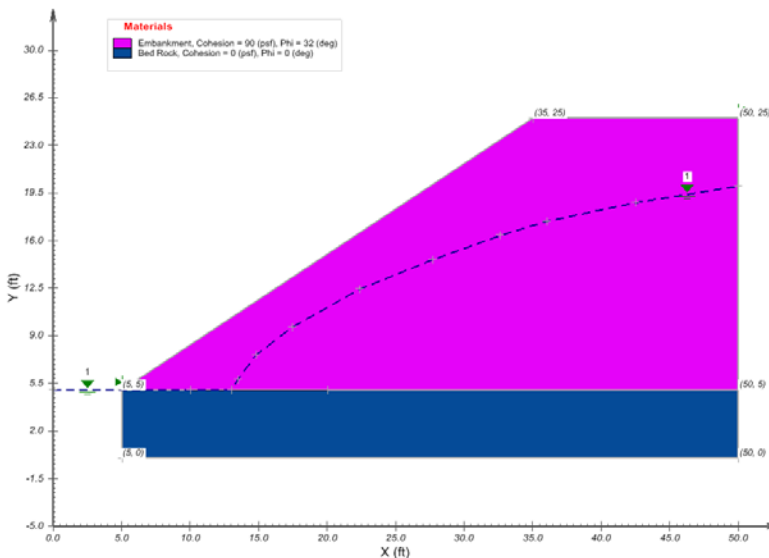
#### 4.11 LAMBE AND WHITMAN - DRAINED SLOPE

Project: Verification\_SVSlope\_Group2  
 Model: VW\_12

This model was originally presented by Lambe and Whitman (1969). In the original solution Lambe and Whitman presented a hand-calculated factor of safety for a simple slope with under drain.

The slope is 20 feet high and has a slope of 1 horizontal to 1.5 vertical. The slope consists of a single homogenous material. The slip surface is assumed to be circular with the radius of 30 feet. In the original calculations, the pore-water pressures conditions in the slope were characterized by a flow net.

### 4.11.1 Geometry and Material Properties



**Figure 118 Geometry of the Lambe and Whitman – Drained Slope model**

### 4.11.2 Results and Discussions

The results of the SVSLOPE software package are compared to the original Lambe and Whitman calculations.

**Table 181 Lambe and Whitman – Drained Slope model**

Method	Factor of Safety				Difference (%)
	Slope/W (30 slices)		SVSLOPE (30 slices)		
	Moment	Force	Moment	Force	
Ordinary	1.198		1.200		0.18
Bishop	1.332		1.332		0.01
Janbu Simplified		1.207		1.210	0.24
Corps of Engineers #1		1.376		1.380	0.29
Corps of Engineers #2		1.397		1.401	0.29
Lowe-Karafiath		1.346		NS	
Spencer	1.332	1.338	1.333	1.333	0.07
M-P	1.332	1.339	1.334	1.334	0.11
GLE	1.332	1.332	1.334	1.334	0.11

### 4.12 PORE-WATER PRESSURES AT DISCRETE POINTS

Project: Verification\_SVSlope\_Group2  
 Model: VW\_13

The purpose of this model is to illustrate the use of specified pore-water pressures at discrete points in the model. The GLE method is used to analyze this case. A single circular slip surface was used in this case and a tension crack zone was specified through the use of a limiting angle designation.

A spline interpolation was used between the pore-water pressures points in order to determine the pore-water pressures at the base of each slice.

#### 4.12.1 Geometry and Material Properties

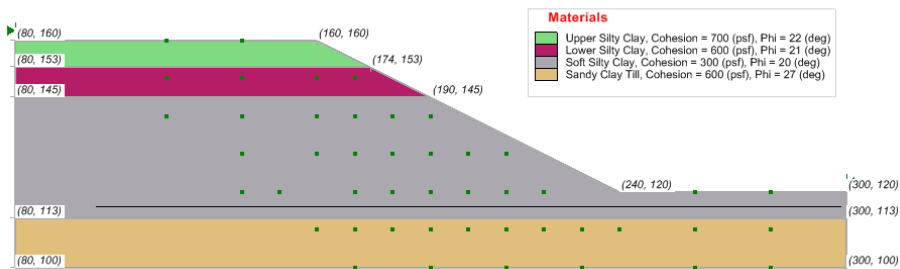


Figure 119 Geometry of the Pore-Water Pressures at Discrete Points model

#### 4.12.2 Results and Discussions

The resulting critical slip surfaces and the factors of safety are presented in the following figures. A calculated factor of safety of 1.252 was calculated, which agrees well with the original publication.

Table 182 Discrete points model results

Method	Factor of Safety				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.181		1.180		0.09
Bishop	1.252		1.253		0.07
Janbu Simplified		1.187		1.184	0.26
Corps of Engineers #1		1.284		1.284	0.00
Corps of Engineers #2		1.321		1.323	0.15
Lowe-Karafathi		1.283		1.284	0.08
Spencer	1.253	1.247	1.254	1.254	0.08
M-P	1.252	1.253	1.253	1.253	0.08
GLE	1.252	1.252	1.253	1.253	0.08

**Table 183 Discrete points results with no crack and no pore-water pressures**

Method	Factor of Safety (Neglect pore-water pressures and no cracks)				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.541		1.544		0.19
Bishop	1.621		1.623		0.12
Janbu Simplified		1.528		1.531	0.20
Corps of Engineers #1				1.670	
Corps of Engineers #2				1.710	
Spencer			1.622	1.622	
M-P			1.621	1.621	
GLE	1.619	1.619	1.621	1.621	0.12

**Table 184 pore-water pressures and no tension crack**

Method	Factor of Safety (with pore-water pressures and no tension cracks)				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.225		1.222		0.22
Bishop Simplified	1.285		1.285		0.01
Janbu Simplified		1.241		1.238	0.28
GLE	1.286	1.286	1.286	1.286	0.02

**Table 185 pnt pore-water pressures with crack**

Method	Factor of Safety (Neglect pore-water pressures with tension cracks)				Difference (%)
	Slope/W		SVSLOPE		
	Moment	Force	Moment	Force	
Ordinary	1.499		1.498		100.00
Bishop Simplified	1.587		1.587		100.00
Janbu Simplified		1.473		1.471	
GLE	1.584	1.584	1.584	1.584	0.00



**Table 188 Results Figure 5.9 (Pham)**

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.686		1.684		0.12
M-P	1.691		1.687		0.24
SAFE (SVDynamic)		1.671		1.603	4.07

**Table 189 Results Figure 5.10 (Pham)**

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.167		1.166		-0.09
M-P	1.168		1.165	1.165	-0.26
SAFE (SVDynamic)		1.187		1.143	-3.71

**Table 190 Results Figure 5.11 (Pham)**

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.520		1.514		0.39
M-P	1.519		1.514	1.514	0.33
SAFE (SVDynamic)		1.520		1.485	2.30

**Table 191 Results Figure 5.12 (Pham)**

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.686		1.684		-0.12
M-P	1.691		1.687		-0.24
SAFE (SVDynamic)		1.895		1.666	-12.08

## 5.2 PHAM CHAPTER 5 FIGURES 5.28 TO 5.33

Project: Verification\_SVSLope\_SAFE  
 Model: Pham\_Ch5\_Figure5\_28 to Pham\_Ch5\_Figure5\_33

Figures 5.28 to 5.33 show locations of the critical slip surfaces obtained both by Pham (2002) as well as by other methods of slices, such as the Morgenstern-Price (1965) method, the Bishop's Simplified (1955) method, and the Enhanced (Stress-Based) method (Scoular, 1997).

The Poisson's ratio value used in Figures 5.28 to 5.30 was 0.33. The Poisson's ratio used in Figures 5.31 to 5.33 was 0.48.

### 5.2.1 Geometry and Material Properties

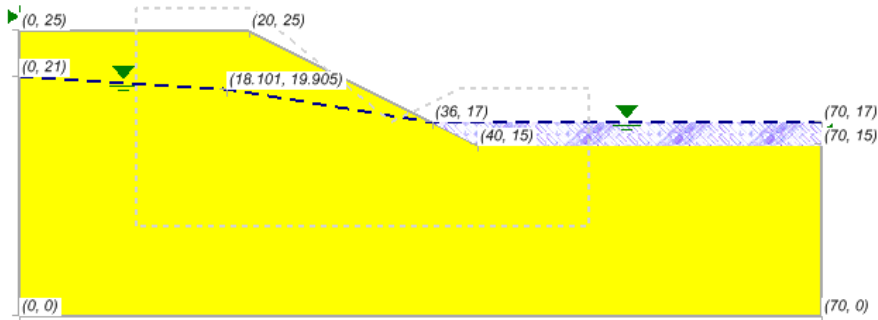


Figure 121 Chapter 5 Figures 5.28 to 5.33 from Pham (2002)

### 5.2.2 Results and Discussions

Table 192 Results Ch5 Figure 5.28 (Pham)

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.248		1.226		-1.76
M-P	1.247		1.225	1.225	-1.76
SAFE (SVDynamic)	1.162				

Table 193 Results Ch5 Figure 5.29 (Pham)

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	2.526		2.481		-1.78
M-P	2.523		2.479	2.479	-1.74
SAFE (SVDynamic)	2.353				

Table 194 Results Ch5 Figure 5.30 (Pham)

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.800		1.730		-3.89
M-P	1.801		1.734		-3.72
SAFE (SVDynamic)	1.807				

**Table 195 Results Ch5 Figure 5.31 (Pham)**

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.248		1.226		-1.76
M-P	1.247		1.225	1.225	1.76
SAFE (SVDynamic)	1.269				

**Table 196 Results Ch5 Figure 5.32**

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	2.526		2.481		-1.78
M-P	2.523		2.479	2.479	-1.74
SAFE (SVDynamic)	2.571				

**Table 197 Results Ch5 Figure 5.33**

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.800		1.730		-3.89
M-P	1.801	1.801	1.734	1.734	-3.72
SAFE (SVDynamic)	1.968				

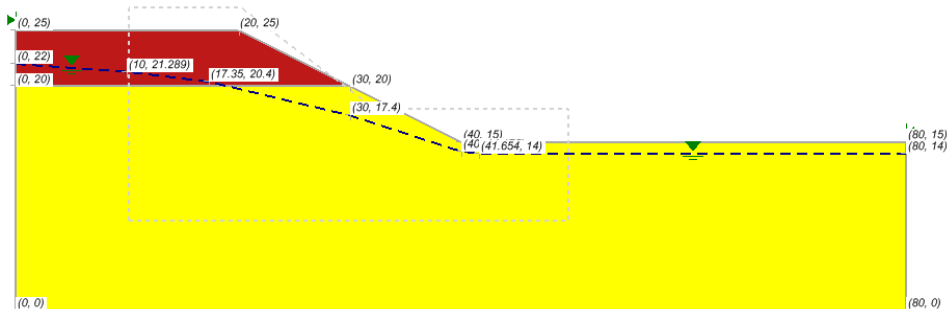
### 5.3 PHAM CHAPTER 5 FIGURE 5.44 (2002)

Project: Verification\_SVSLope\_SAFE  
 Model: Pham\_Ch5\_Figure5\_44

This example problem contains two soil layers with shear strength parameters as shown in the following figures. Poisson's ratio was selected assuming the soil was normally consolidated. A reasonable value of Young's modulus was also assumed.

#### 5.3.1 Geometry and Material Properties

The geometry of the slope is shown in the following figure:



**Figure 122 Geometry of the Pham Ch5 Figure 5.44**

### 5.3.2 Results and Discussions

The published solutions presented by Pham (2002) is shown in Figure 123.

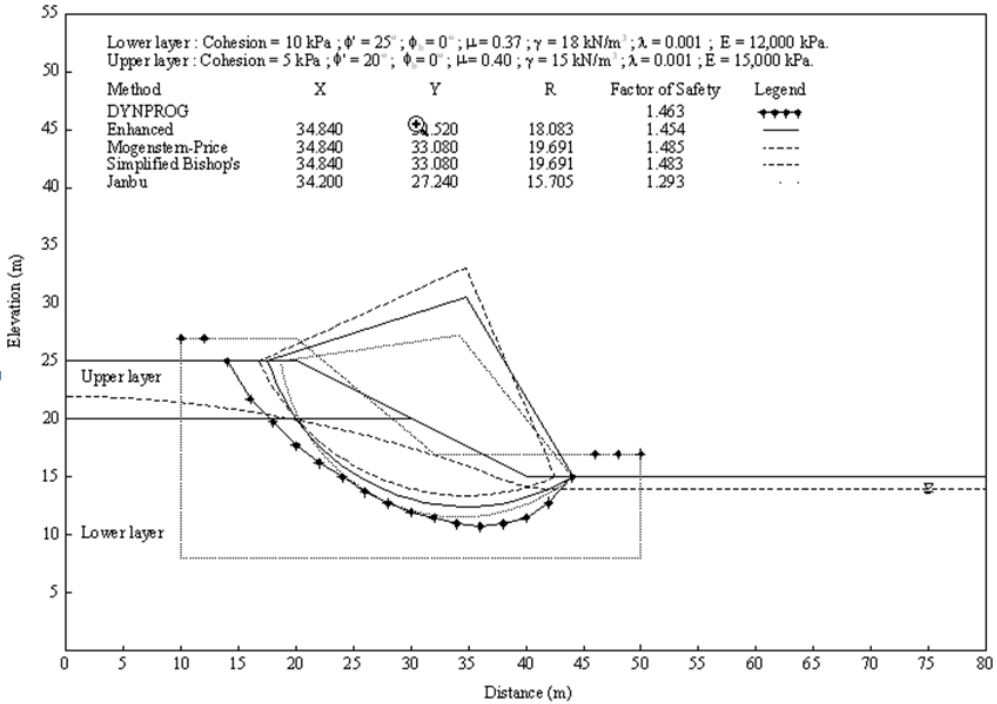


Figure 123 Locations of the critical slip surfaces in the 2-layer slope (Pham, 2002)

Fs = 1.434

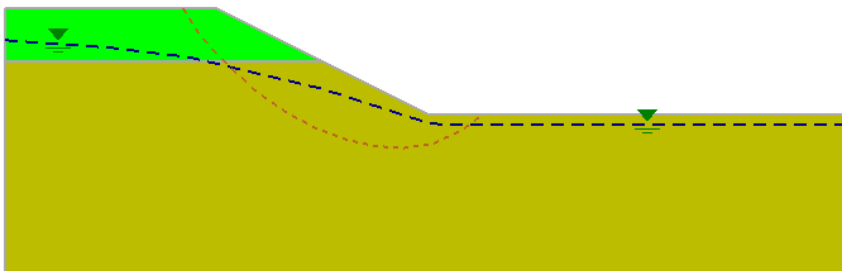


Figure 124 Results of the SAFE analysis for the two-layer slope

Table 198 Results Figure Ch5 figure 5.44

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.483		1.482		-0.07
Janbu Simplified		1.293		1.300	0.54
M-P	1.485	1.485	1.484	1.484	-0.07
SAFE (SVDynamic)		1.463		1.434	-1.98

### 5.4 3-LAYER SLOPE RESTING ON A HARD SURFACE

Project: Verification\_SVSLope\_SAFE  
 Model: Pham\_Ch5\_Figure5\_48

The slope stability studies by Pham (2002) contain three layers of soil with the base layers considerable harder than the above layers. The soil is described using a linear elastic. The Poisson's ratio was approximated using the procedure suggested by Pham (2002).

#### 5.4.1 Geometry and Material Properties

The geometry of the problem and the groundwater conditions are shown in Figure 125.

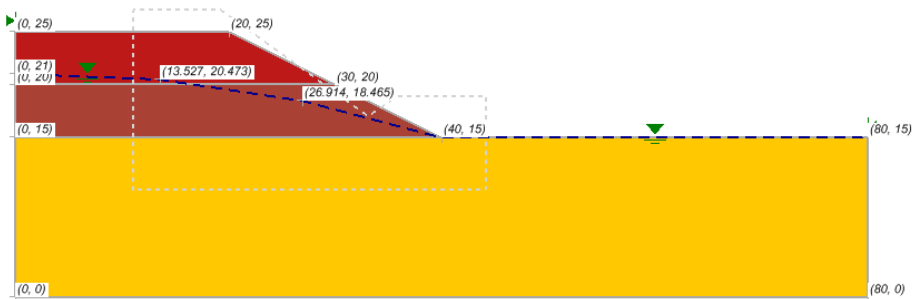


Figure 125 Geometry of the 3-Layer Slope Resting on a Hard Surface model

#### 5.4.2 Results and Discussions

The published solution by Pham (2002) for the 3-soil layer system is shown in Figure 126

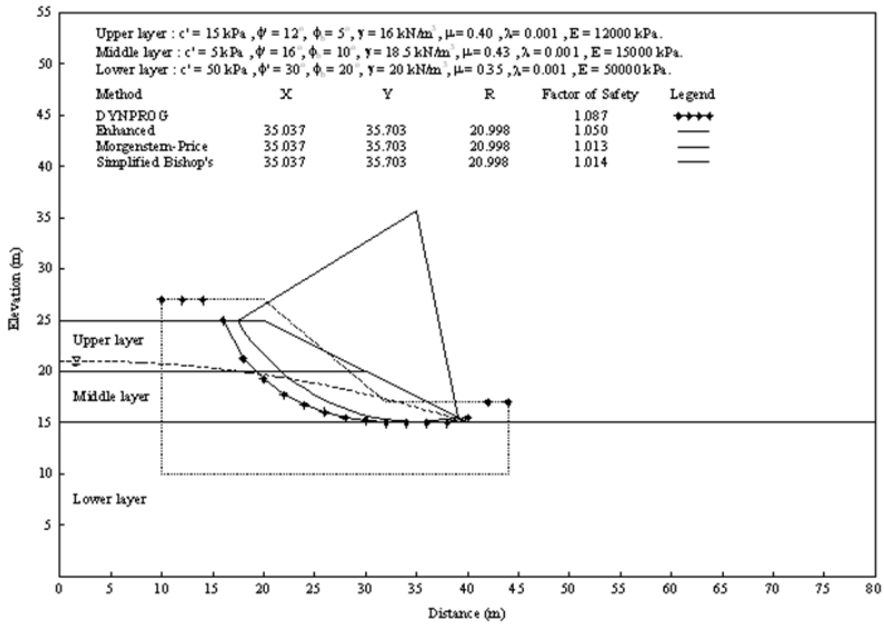


Figure 126 Locations of the critical slip surface in 3-layer slope resting on a hard foundation (Pham, 2002)

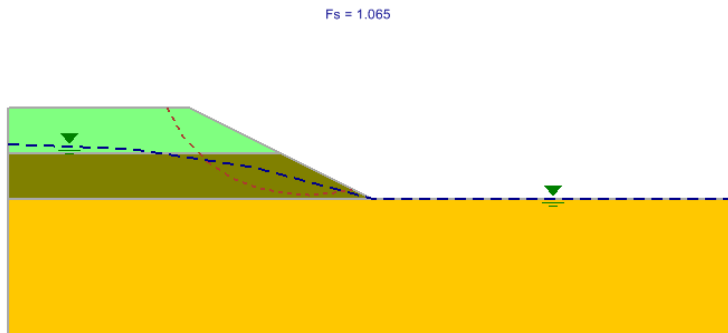


Figure 127 Calculation of the Factor of Safety by the SAFE method

Table 199 Comparison between Pham (2002) and SVSLOPE

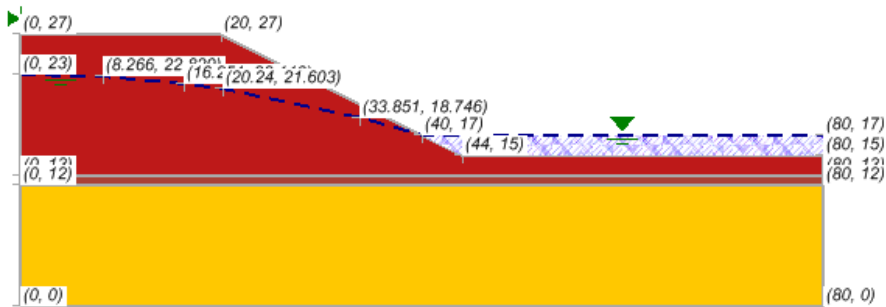
Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.014		1.025		1.08
M-P	1.014	1.014	1.025	1.025	1.08
SAFE (SVDynamic)		1.087		1.065	-2.02

## 5.5 THIN AND A WEAK LAYER RESTING A BEDROCK

Project: Verification\_SVSlope\_SAFE  
Model: Pham\_Ch5\_Figure5\_52

The bedrock layer was modeled as a relatively hard soil layer with high shear strength parameters. The slope is partly submerged with water. This example is typical of the case where the anticipated block movement is the most likely mode of failure.

### 5.5.1 Geometry and Material Properties



**Figure 128 Geometry of the Thin and a Weak Layer Resting a Bedrock model**

### 5.5.2 Results and Discussions

The published solution by Pham (2002) for the 3-soil layer with bedrock is shown in Figure 129.

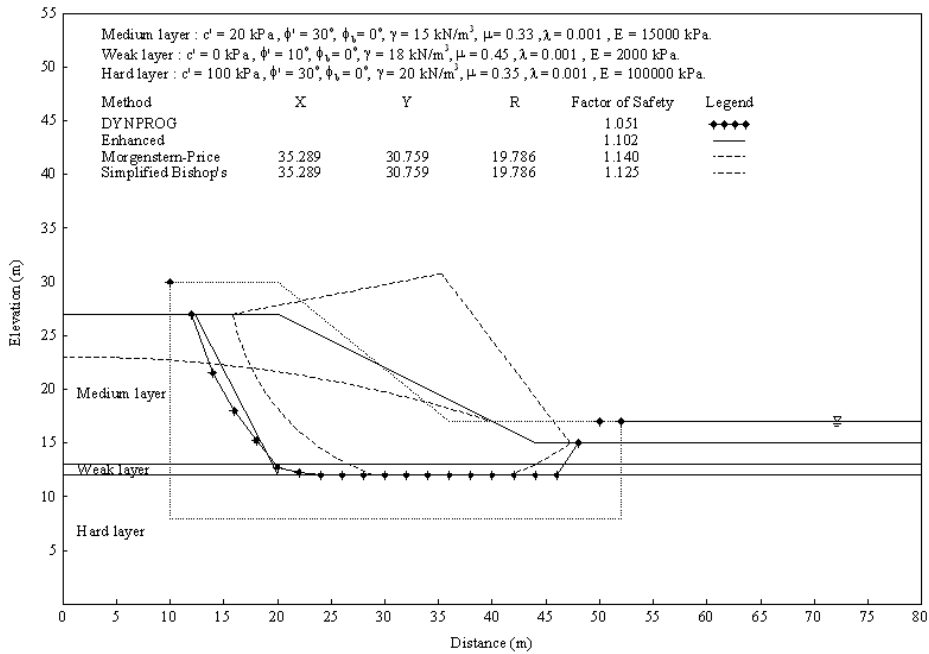


Figure 129 Results of chapter 5 figure 5.52 (Pham, 2002)

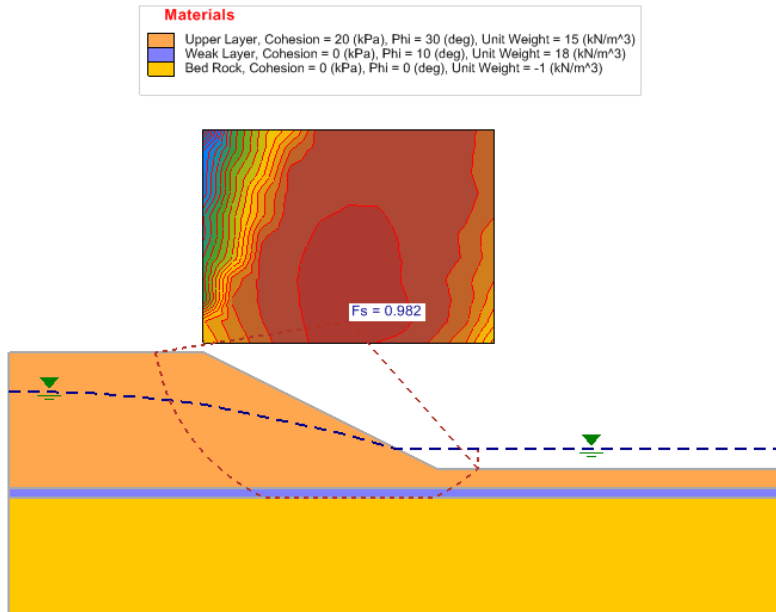


Figure 130 Results of Figure 5.52 model calculated by SVSLOPE using Bishop's Simplified method for a non circular slip surface

Table 200 Results for the example with a bedrock layer					
Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
					-12.71
					-12.72
SAFE (SVDynamic)	1.051				

### 5.6 LODALEN CASE HISTORY

Project: Verification\_SVSlope\_SAFE  
 Model: Pham\_Ch5\_Figure5\_56

This example is considered as a homogenous slope with shear strength parameters equal to the average published values.

#### 5.6.1 Geometry and Material Properties

The geometry of the problem was published by Sevaldson (1956). According to data reported by Sevaldson, 1956, the groundwater table passed through the toe of the slope. The slide was analyzed by Pham (2002) and is shown as Slide No. 2 in Figure 131, Sevaldson (1956).

There were three slides investigated in the Lodalen site, however, only the results of Slide No. 2 were published. The geometry and the groundwater conditions of the Slide No. 2 at Lodalen are presented in Figure 131.

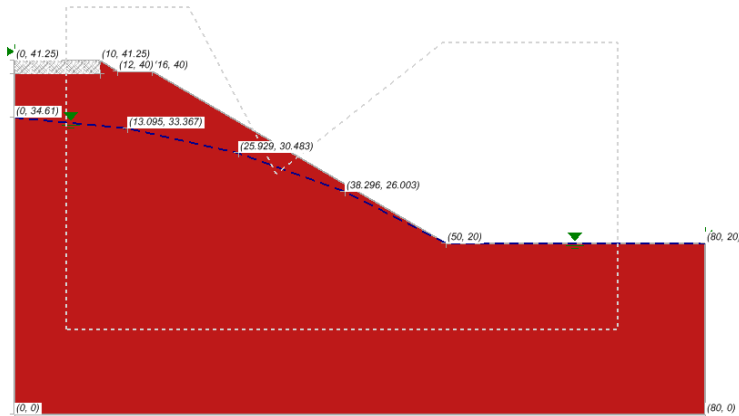


Figure 131 Geometry of the Lodalen Case History model

#### 5.6.2 Results and Discussions

The published results by Pham (2002) for the Lodalen Slide No. 2 are shown in Figure 132.

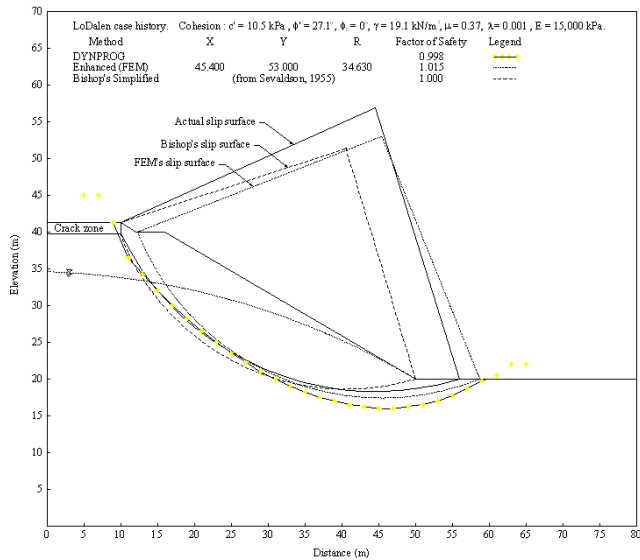


Figure 132 Pham (2002) thesis Chapter 5, Figure 5.56

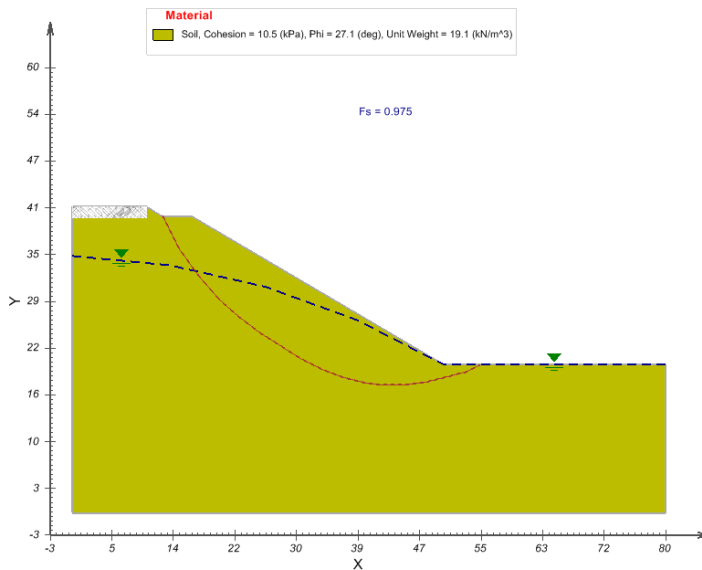


Figure 133 SVSLOPE results of model Chapter 5, Figure 5.56

Table 201 Results of calculations

Method	Factor of Safety				Difference (%)
	Pham		SVSLOPE		
	Moment	Force	Moment	Force	
Bishop Simplified	1.000		0.951		-4.90
SAFE (SVDynamic)		0.998		1.257	25.95

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