Slide

2D limit equilibrium slope stability
for soil and rock slopes

Slope Stability (Sarma Method)
Verification Manual

Table of Contents

Introduction 1

Slide Verification Problem #1 2
Slope, (2) materials, weak layer

Slide Verification Problem #2 4
Slope, homogeneous

Slide Verification Problem #3 6
Slope, (4) materials, water table

Slide Verification Problem #4 8
Pile, (2) materials, weak layer, water table

Slide Verification Problem #5 10
Slope, homogeneous material, water table

Slide Verification Problem #6 13
Slope, homogeneous material, water table

Slide Verification Problem #7 16
Slope, (3) materials

Slide Verification Problem #8 18
Slope, (3) materials, water table

Slide Verification Problem #9 20
Slope, (2) materials, Weak Layer, Water table

References 22

Introduction

This document contains a series of verification slope stability problems that have been analyzed using the **Sarma** analysis method in *Slide* version 7.0. These verification tests come from published examples found in reference material such as research papers, journals and conference proceedings.

The Sarma method allows for non-vertical slices (wedges) in order to determine factor of safety for non-circular failure modes. A vertical slice version of the Sarma method is also used for some problems.

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

The *Slide* slope stability verification files (Sarma method) can be accessed by selecting File → Recent Folders → Examples Folder → Slope Stability Verification Wedge. The file names are **slope stability sarma #001.slim**, **slope stability sarma #002.slim** etc., corresponding to the verification problem numbers in this document.

1.1 Introduction

This model is taken from Baker (1980) based on a problem of Fredlund and Krahn (1977). It consists of a slope with a weak layer and dry water conditions. Quite a few other authors, such as Kim and Salgado (2002), and Zhu, Lee, and Jiang (2003) have also analyzed this slope. Unfortunately, the location of the weak layer is slightly different in all the above references. Since the results are quite sensitive to this location, results routinely vary in the second decimal place.

1.2 Problem Description

The example consists searching for the failure surface that minimizes the factor of safety of the slope. The example finds the optimum failure mechanism using Sarma non-vertical analysis method with three slices and seven slices. The search method used is the block search option and a polyline was created in the bottom weak layer to find the critical failure surface.
Verification problem #1 is shown in Figure 1.1. The material properties are given in Table 1.1.

1.3 Geometry and Material Properties

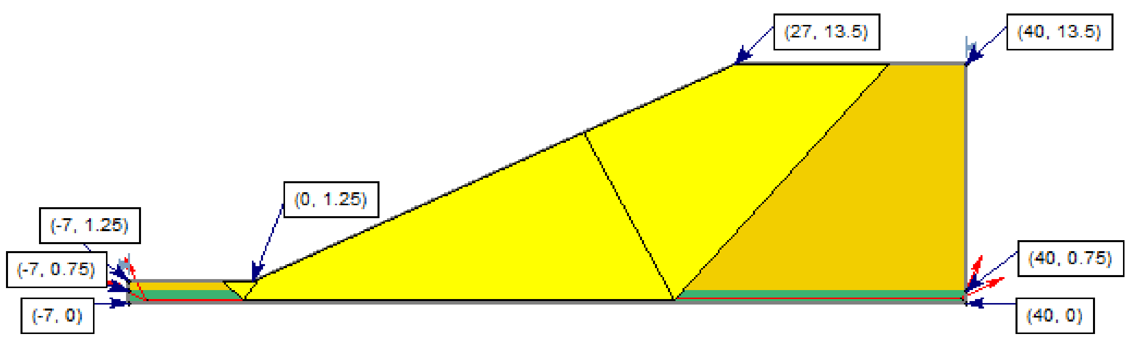

Figure 1.1 – Geometry Setup in *Slide*

Table 1.1: Soil Properties

	c' (kN/m^2)	ϕ' (deg.)	γ (kN/m^3)
Upper soil	28.45	20	18.84
Weak layer	0	10	18.84

3.1 Results

Using the Sarma method with three and seven slices, the figures below shows the failure surface that gives the lowest factor of safety using block search tool. The failure mechanism computed using *Slide* matches the results of the generalized wedges method used by Donald I. B.. The factor of safety for the failure surface is 1.382 for three slices and 1.324 for seven slices. The reference factor of safety values for this verification example are shown in Table 1.2.

Table 1.2: Results Comparison

	Slide Factor of Safety	Reference Factor of Safety
Three Slices	1.382	1.29
Seven Slices	1.324	1.27

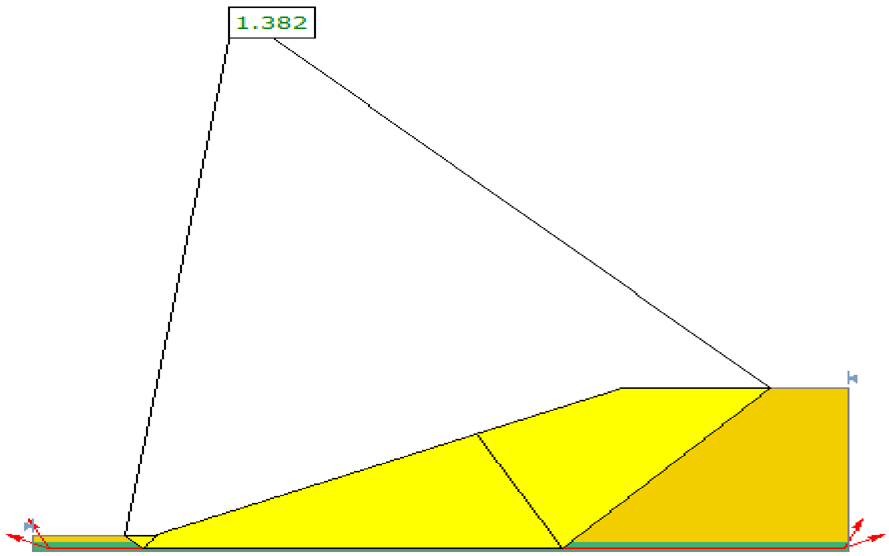

Figure 1.2 - Optimized Failure Surface for three slices

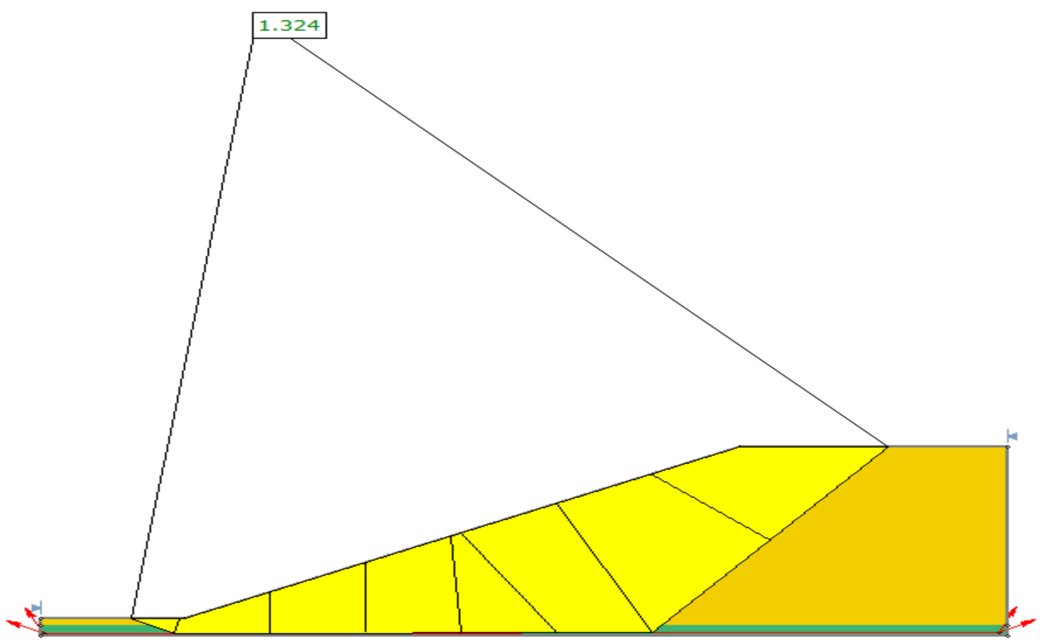

Figure 1.3 - Optimized Failure Surface for seven slices

Slope, homogeneous

2.1 Introduction

Example 2 is a simple homogeneous slope studied in detail by Zienkiewicz et al (1975) and Donald and Giam (1975).

2.1 Problem Description

The problem consists of finding the optimal failure surface that minimizes the factor of safety of the slope. This example finds the critical failure mechanism using Sarma non-vertical analysis method and Cuckoo search method for six slices mechanisms and seven slices mechanisms.

Verification problem # 2 is shown in Figure 2.1. The material properties are given in Table 2.1.

2.2 Geometry and Material Properties

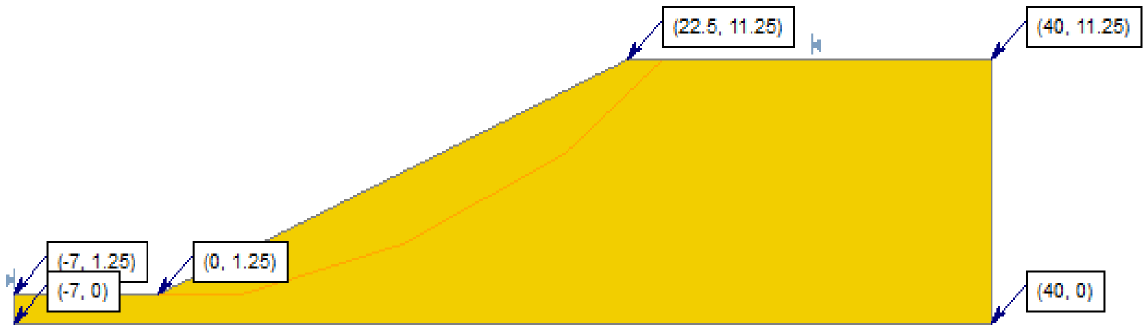

Figure 2.1 – Geometry Setup in *Slide*

Table 2.1: Soil Properties

	C (kN/m^2)	ϕ (deg.)	γ (kN/m^3)
Soil Layer	3	20	20

2.3 Results

Figures 2.2 and 2.3 below show the results of the Cuckoo search using Sarma non-vertical methods with six slices and seven slices. The optimal failure surface for six slices has a factor of safety of 1.115 while the optimal failure surface for seven slices has a factor of safety of 1.109. The reference factor of safety values for this verification example are shown in Table 2.2.

Table 2.2: Results Comparison

	Slide Factor of Safety	**Reference Factor of Safety**
Six Slices	1.115	1.05
Seven Slices	1.109	1.01

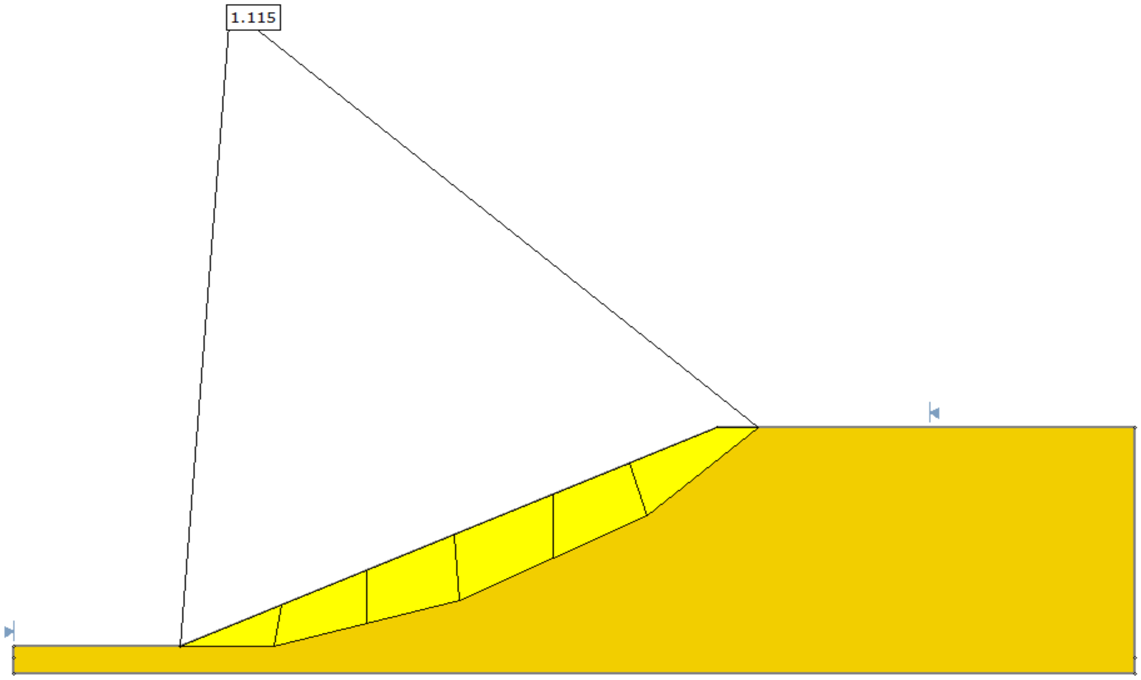

Figure 2.2 – Optimized failure surface using 6 slices

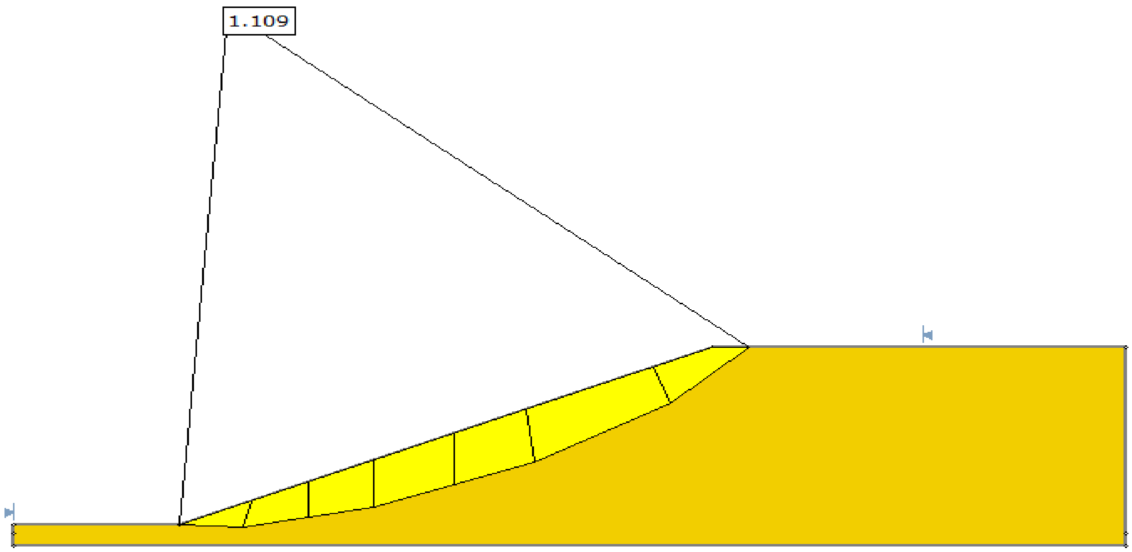

Figure 2.3 – Optimized failure surface using 7 slices

Slope, (4) materials, water table

3.1 Introduction

Verification Problem #3 is a model of an open pit coal mine in the Bowen Basin coking and thermal coal resource of Central Queensland, Australia. During Strip mining, very large volumes of dumped spoil material are generated; such spoil material must be as steep as possible while maintaining acceptable stability. The Sarma method is used to evaluate the stability of the spoil material.

3.2 Problem Description

The model mainly consists of rock and spoil material. In order to assess the reliability of the spoil material, a slope stability analysis is conducted. Two failure surfaces are analyzed using the Sarma method; they are seen in figures 3.2 and 3.3.
Verification problem # 3 and its material properties are shown in Figure 3.1 and Table 3.1.

3.3 Geometry and Material Properties

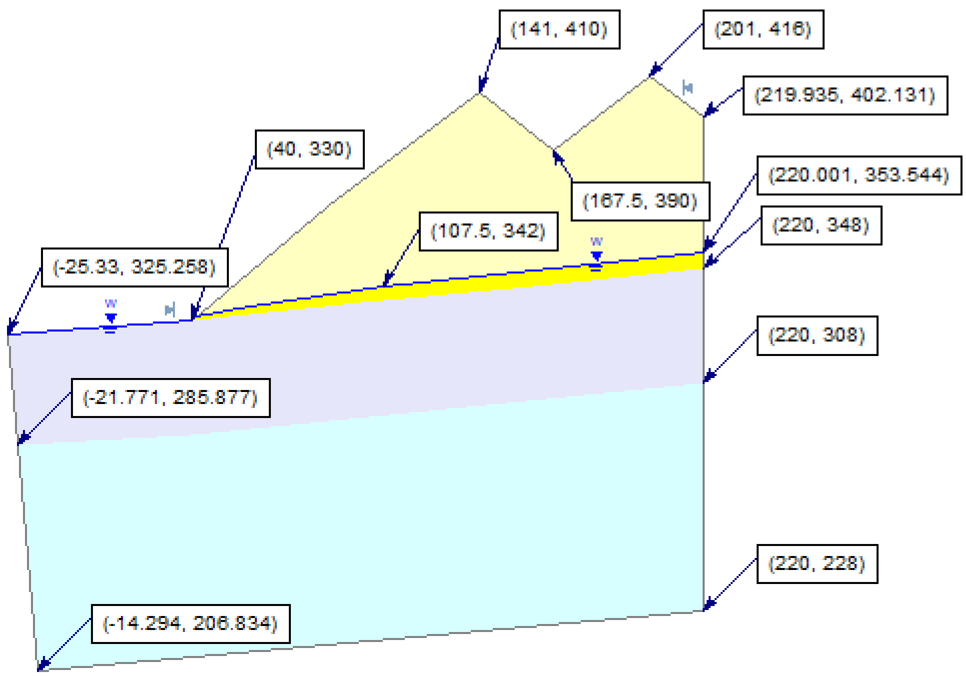

Figure 3.1 – Geometry and Material Properties inputted in Slide

Table 3.1: Soil Properties

	C (kN/m^2)	ϕ (deg.)	γ (kN/m^3)
Spoil Cat.2U	30	28	18
Spoil Cat.2S	15	23	20
FR GCM Rock	450	42	24
Tight Basal Rock	500	45	24

3.4 Results

The factors of safety for the surfaces 1 and 2 seen in Figures 3.2 and 3.3 are respectively 1.149 and 1.508. The reference factor of safety values for this verification example are shown in Table 3.2.

Table 3.2: Results Comparison

	Slide Factor of Safety	Reference Factor of Safety
Failure Surface 1	1.149	1.19
Failure Surface 2	1.508	1.68

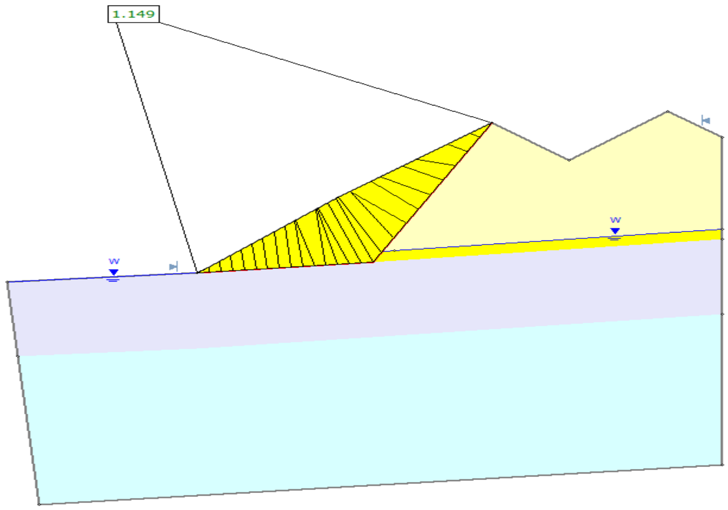

Figure 3.2 – Proposed failure surface 1

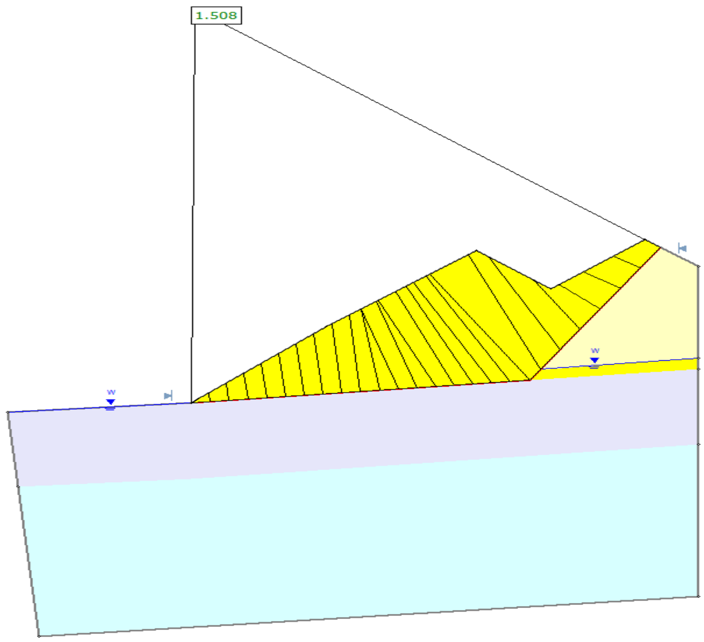

Figure 3.3 – Proposed failure surface 2

4.1 Introduction

Verification Problem #4 is a model of a spoil pile on a weak foundation. A common problem which occurs in the strip mining of coal involves failure of spoil piles on weak inclined foundations. This problem has been studied by coulthard (1979) and Hoek (1987).

4.2 Problem Description

The stability of spoil pile lying on a weak inclined surface is evaluated using Sarma non-vertical slice method. The analysis conducted by Hoek in 1987 to find the factor of safety of the spoil pile failure surface is reproduced in Slide using the Sarma method with two slices. The example was analyzed for a drained spoil pile as well as a saturated spoil pile.
Verification problem # 4 and its material properties are shown in Figure 4.1 and Table 4.1.

4.3 Geometry and Material Properties

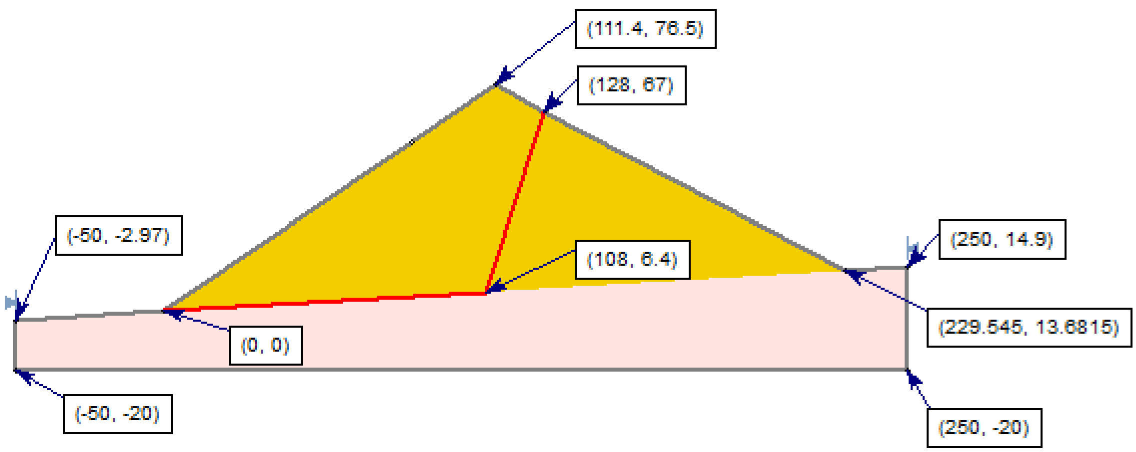

Figure 4.1 – Geometry Setup in *Slide*

Table 4.1: Soil Properties

	C (kN/m^2)	ϕ (deg.)	γ (kN/m^3)
Spoil	100	42	15.7
Sheared Floor	10	6	15.7

4.4 Results

The factors of safety of the chosen failure surface is 1.198 for a drained spoil pile and 0.434 for a saturated soil pile; as can be seen in Figures 4.2 and 4.3. The reference factor of safety values for this verification example are shown in Table 4.2.

Table 4.2: Results Comparison

	Slide Factor of Safety	Reference Factor of Safety
Without water table	1.198	1.2
With water table	0.434	0.48

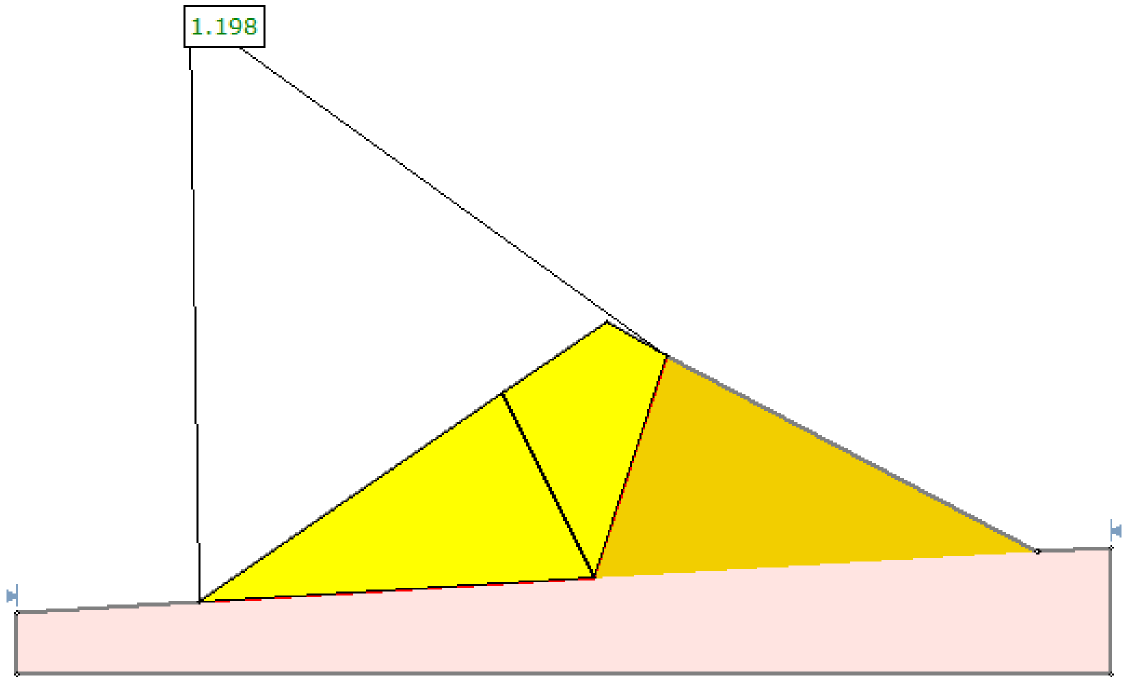

Figure 4.2 – Factor of Safety of Failure Surface in Drained Spoil Pile

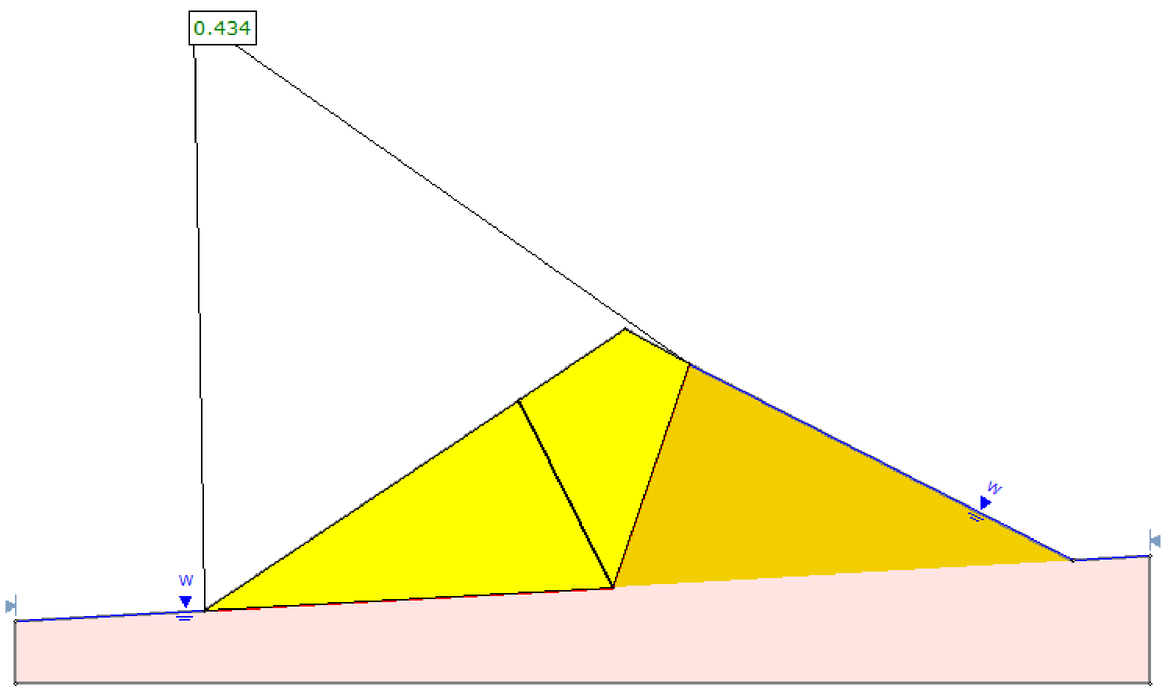

Figure 4.3 – Factor of Safety of Failure Surface in Spoil Pile with Water

Slope, homogeneous material, water table

5.1 Introduction

Verification Problem #5 represents a model of a slope problem in a large open pit coal mine. A thin coal seam is overlain by soft tuff. An existing failure in the slope shows that sliding occurs along the coal seam. A reservoir close to the crest of the slope recharges the slope with water and results in the high groundwater surface illustrated in Figure 5.1. This problem is analyzed by Hoek (1987).

5.2 Problem Description

The failure surface created along the coal seam in the open pit coal mine slope was analyzed by Hoek (1987) using the Sarma method with 9 non-vertical slices to find the factor of safety of the failure surface. The model developed by Hoek was reproduced is Slide.

Verification problem # 5 geometry is shown in Figure 5.1 and its material properties are shown in Tables 5.1 and 5.2.

5.3 Geometry and Material Properties

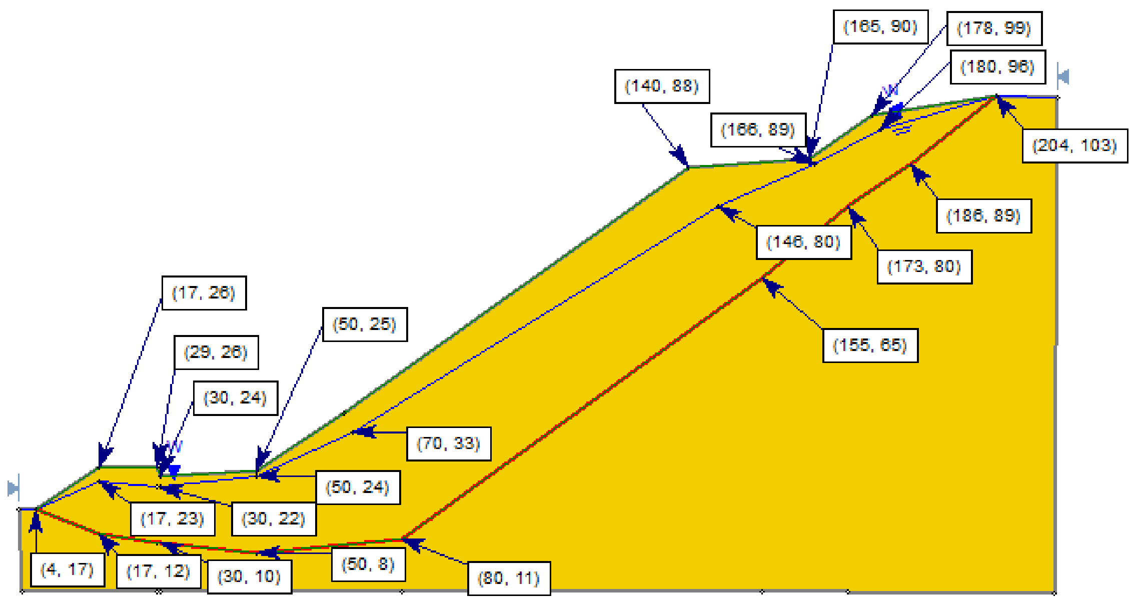

Figure 5.1 – Geometry Setup in *Slide*

Table 5.1: Soil Properties

	C (kN/m^2)	ϕ (deg.)	γ (kN/m^3)
Material 1	2	30	2.1

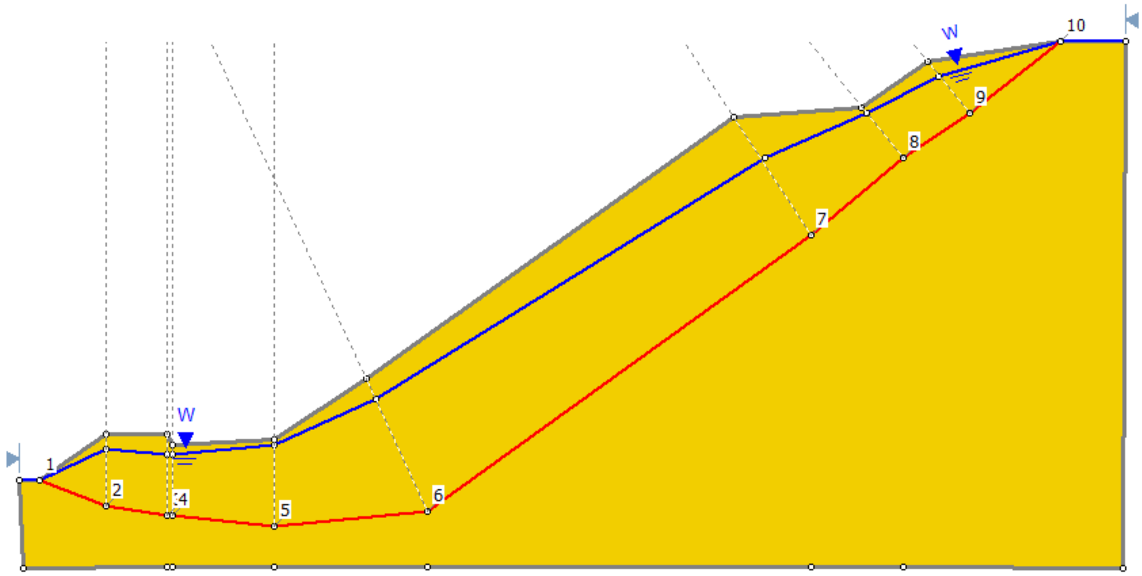

Figure 5.2 – Slope Slices Indexing

Table 5.2: Slice Properties

Vertex	Slice Angle (deg)	Cohesion (kPa)	ϕ (deg.)
2	90	2	30
3	90	2	30
4	90	2	30
5	90	2	30
6	114.775	0	18
7	123.111	0	18
8	128.66	0	18
9	128.66	0	18

5.4 Results

The factor of safety of the failure surface is 1.091 as seen in Figure 5.3. The reference factor of safety values for this verification example are shown in Table 5.2.

Table 5.2: Results Comparison

Slide Factor of Safety	Reference Factor of Safety
1.091	1.17

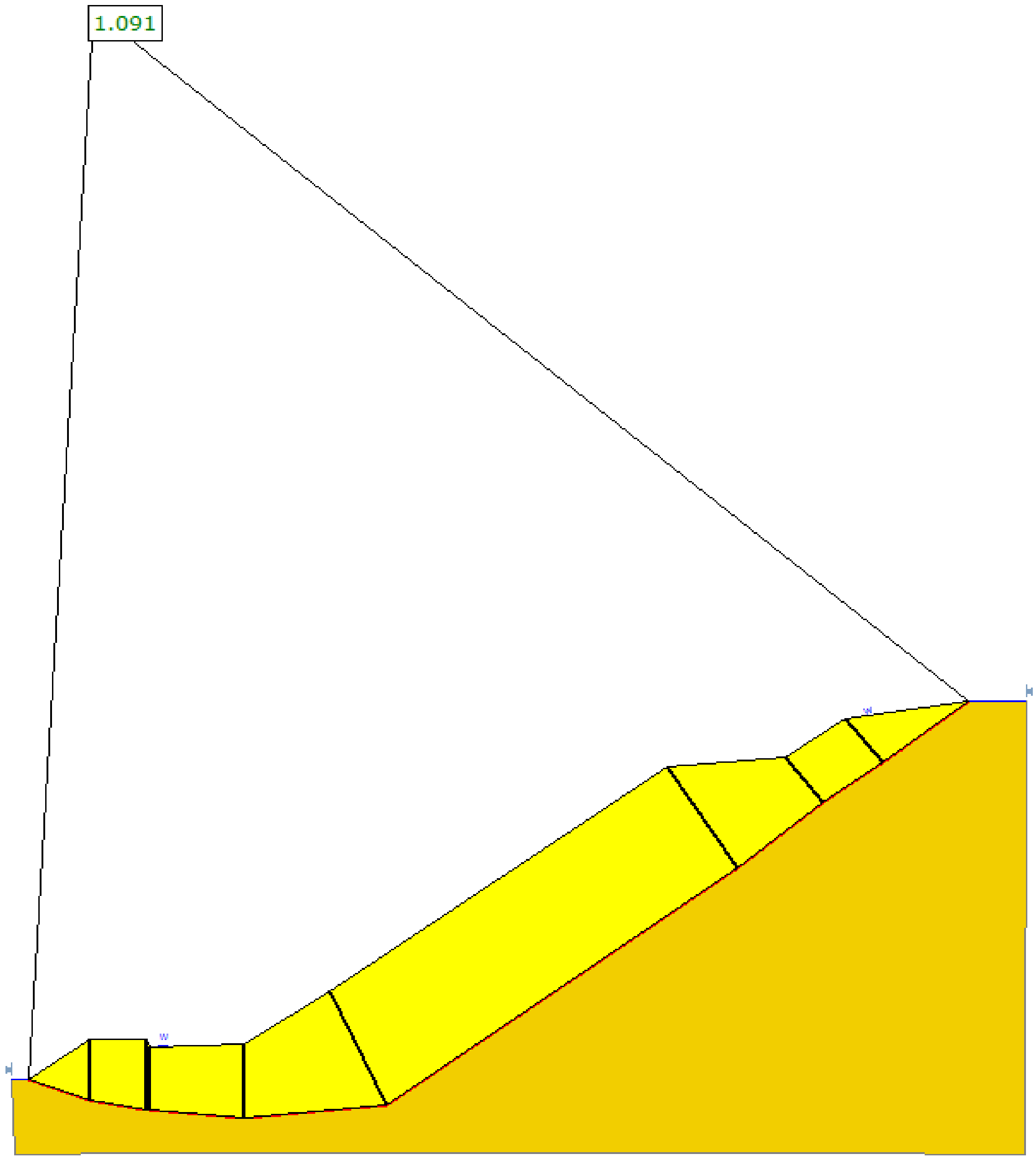

Figure 5.3 – Factor of Safety for Defined Failure Surface in Slide Using Sarma

6.1 Introduction

Verification Problem #6 is a model of a partially submerged rockfill slope. This problem is analyzed using Sarma's vertical slice method by Hoek (1987).

6.2 Problem Description

The critical failure surface of the slope found by Hoek is reproduced in Slide using the Sarma method and 8 slices previously established in Hoek's model.
Verification problem # 6 geometry is shown in Figure 6.1 and its material properties are shown in Tables 6.1 and 6.2.

6.3 Geometry and Material Properties

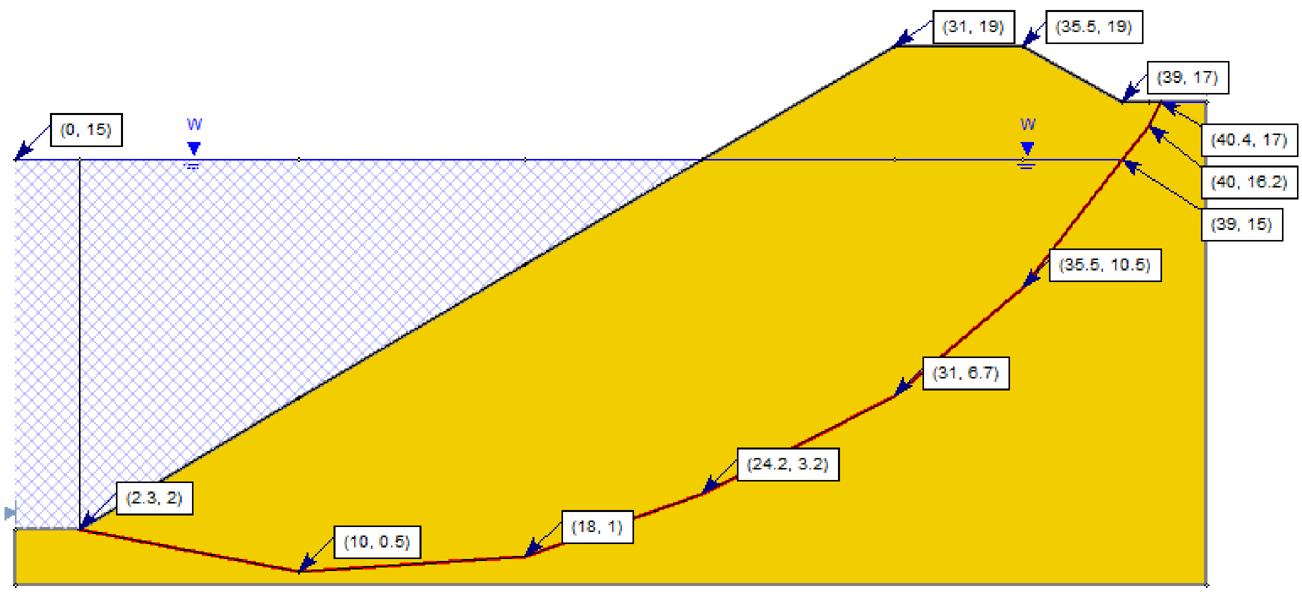

Figure 6.1 – Geometry Setup in *Slide*

Table 6.1: Soil Properties

	C (kN/m^2)	ϕ (deg.)	γ (kN/m^3)
Material 1	0	40	19.7

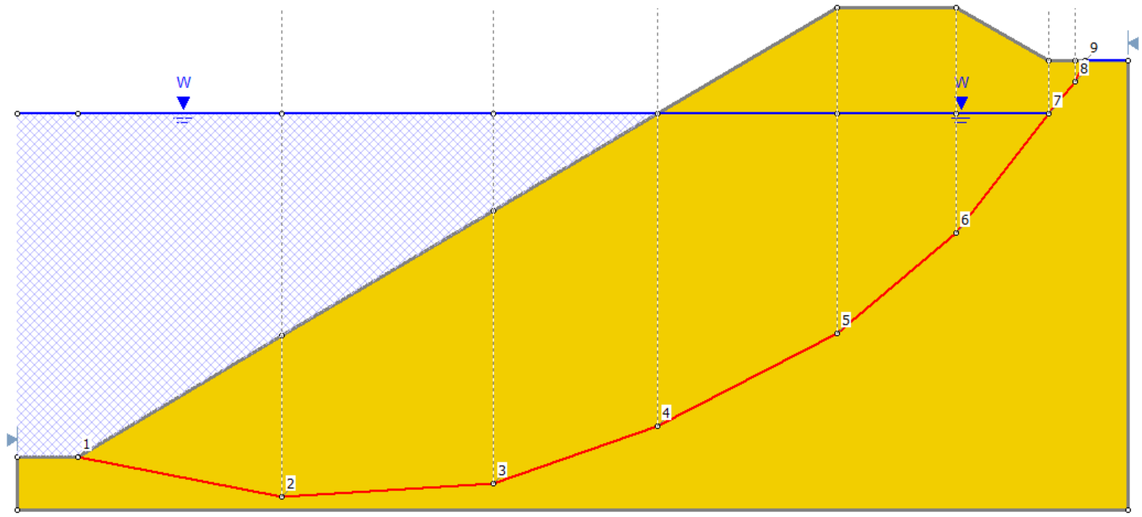

Figure 6.2 – Slope Slices Indexing

Table 6.2: Slice Properties

Vertex	Slice Angle (deg)	Cohesion (kPa)	ϕ (deg.)
2	90	0	35
3	90	0	40
4	90	0	40
5	90	0	40
6	90	0	40
7	90	0	40
8	90	0	33

6.4 Results

The factor of safety of the failure surface is 2.164 as seen in Figure 6.3. The reference factor of safety values for this verification example are shown in Table 6.2.

Table 6.2: Results Comparison

Slide Factor of Safety	Reference Factor of Safety
2.164	1.91

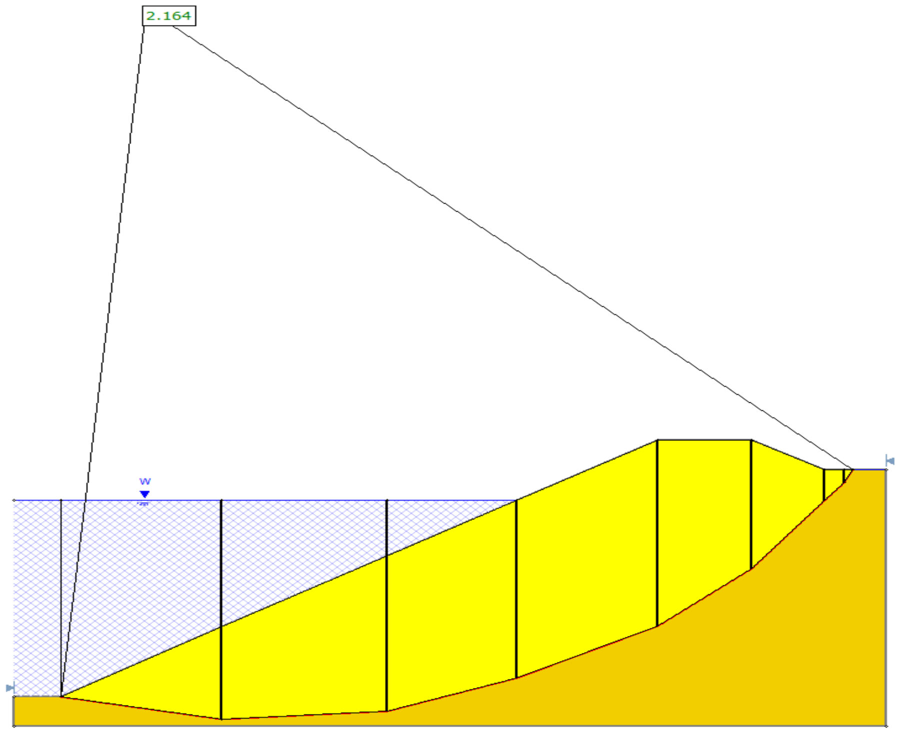

Figure 6.3 – Factor of Safety for Defined Failure Surface in Slide Using Sarma vertical slice method

Slope, (3) materials

7.1 Introduction

Verification problem #7 is taken from a technical paper written by Matthews Carol, Farook Zeena and Helm Peter in order to compare limit equilibrium and finite element methods for slope stability analysis.

7.2 Problem Description

The problem consists of a slope consisting of two different clay layers and a sand layer on top. The purpose of the exercise is to find the critical circular slip surface of the slope. A model of the slope was set up in Slide as can be seen in Figure 7.1, the Sarma non-vertical method was used to find the critical circular failure surface and its factor of safety.
Verification problem # 7 and its material properties are shown in Figure 7.1 and Table 7.1.

7.3 Geometry and Material Properties

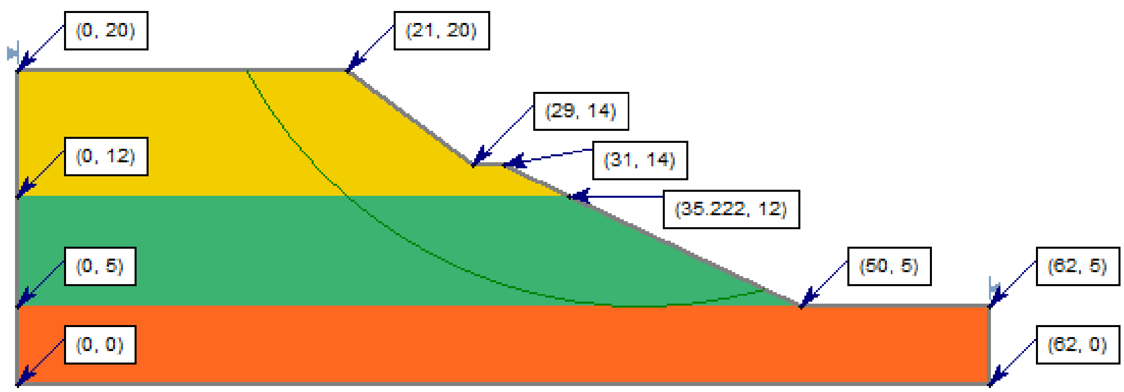

Figure 7.1 – Geometry Setup in *Slide*

Table 7.1: Soil Properties

	C (kN/m^2)	ϕ (deg.)	γ (kN/m^3)
Soil 1 (Sand)	3	30	21
Soil 2 (Clay)	22	11	21
Soil 3 (Clay)	25	20	21

7.4 Results

The factor of safety of the critical circular failure surface is 1.175 and the centre of the circular surface is located at (39.88, 33.63). The reference factor of safety values for this verification example are shown in Table 7.2.

Table 7.2: Results Comparison

Slide Factor of Safety	Reference Factor of Safety
1.175	1.136

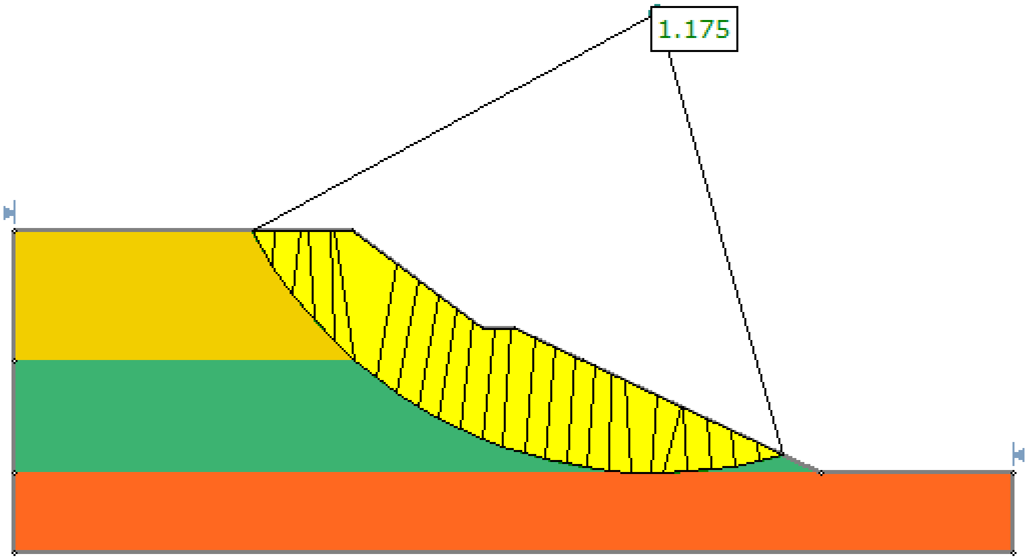

Figure 7.2 – Factor of Safety for Critical Failure Surface in Slide Using Sarma

Slide Verification Problem #8

Slope, (3) materials, water table

8.1 Introduction

Verification problem #8 represents an analysis of a dam site slope during the wet season. The problem is taken from a case study conducted by Krishna Prasad as a part of his doctoral thesis in 2006.

8.2 Problem Description

The dam site slope was modelled with two soil layers and bedrock. The groundwater table for the wet season was also added to the slope profile. Slide was used to find the critical circular failure surface and the factor of safety of the slope. The method used for the analysis is the Sarma method with vertical slices.
Verification problem #8 and its material properties are shown in Figure 8.1 and Table 8.1.

8.3 Geometry and Material Properties

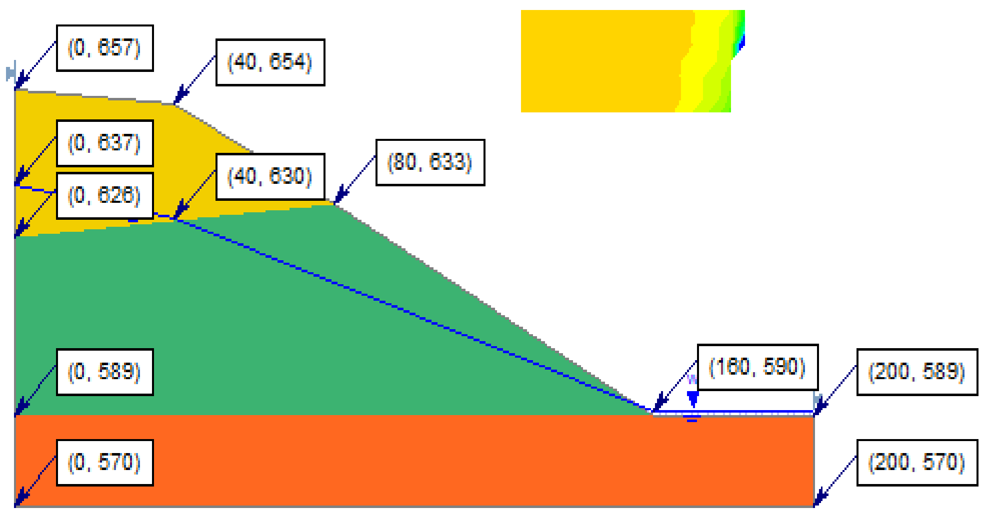

Figure 8.1 – Geometry Setup in *Slide*

Table 8.1: Soil Properties

	C (kN/m^2)	ϕ (deg.)	γ (kN/m^3)
D1	12.6	32.3	22
D2	13.5	34	22
Bedrock	5	40	23

8.4 Results

The factor of safety of the critical circular failure surface is 1.263 as can be seen in Figure 8.2 below. The reference factor of safety values for this verification example are shown in Table 8.2.

Table 8.2: Results Comparison

Slide Factor of Safety	Reference Factor of Safety
1.263	1.35

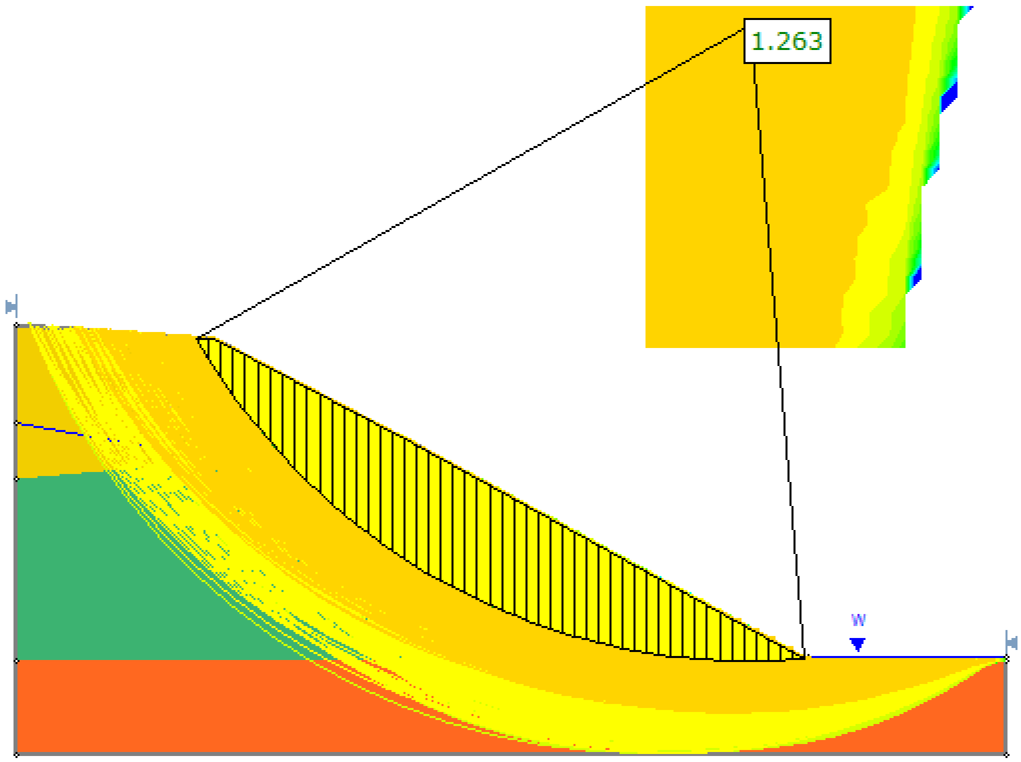

Figure 8.2 – Factor of Safety for Critical Failure Surface in Slide Using Sarma vertical slice method

Slope, (2) materials, Weak Layer, Water table

9.1 Introduction

Verification problem #9 is taken from Fredlund and Krahn (1977). It consists of a homogeneous slope with a water table. The model is done in imperial units to be consistent with the original paper. Quite a few other authors, such as Baker (1980), Greco (1996), and Malkawi (2001) have also analyzed this slope.

9.2 Problem Description

Verification problem #9 and its material properties are shown in Figure 9.1 and Table 9.1. The position of the circular slip surface is given in Fredlund and Krahn as being xc=120, yc=90, radius=80. In this example, the Sarma vertical slice method is used to find the optimal circular failure surface.

9.3 Geometry and Material Properties

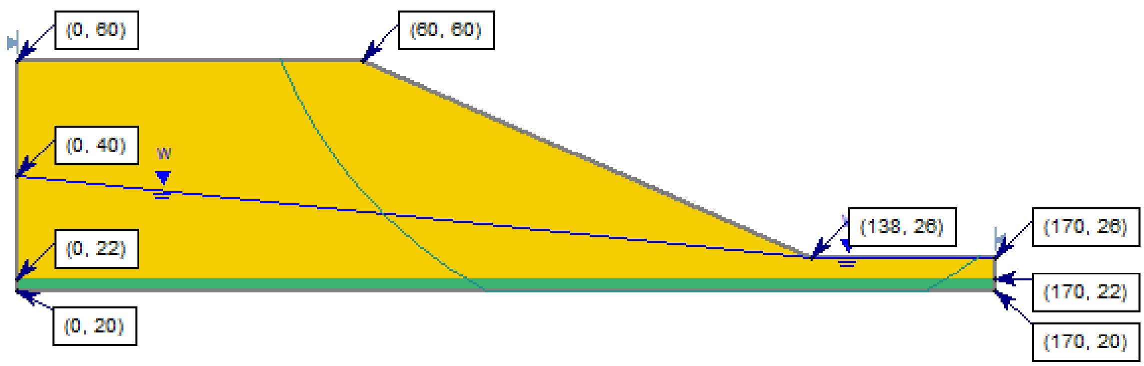

Figure 9.1 – Geometry Setup in *Slide*

Table 9.1: Soil Properties

	C (psf)	ϕ (deg.)	γ (lbs/ft^3)
Material 1	600	20	120
Weak Material	0	10	120

9.4 Results

The factor of safety of the critical circular failure surface is 1.438 as can be seen in Figure 9.2 below which closely matches Fredlund and Kahn's results. The reference factor of safety values for this verification example are shown in Table 9.2.

Table 9.2: Results Comparison

Slide Factor of Safety	Reference Factor of Safety
1.438	1.432

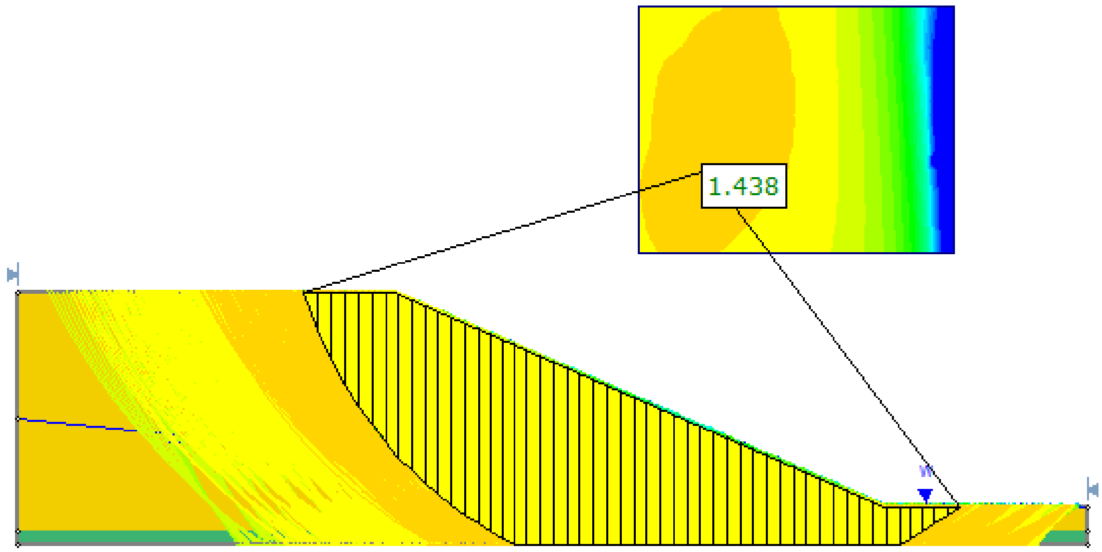

Figure 9.2 – Factor of Safety for Critical Failure Surface in Slide Using Sarma vertical slice method

References

1. Giam, P.S.K. & I.B. Donald (1989), "Example problems for testing soil slope stability programs." Civil Engineering Research Report No. 8/1989, Monash University, ISBN 0867469218, ISSN 01556282.

2. Fredlund, D.G. & Krahn, J. (1977), "Comparison of slope stability methods of analysis." Canadian Geotechnical Journal Vol. 14, No. 3, pp 429-439.

3. Hoek, E. and Grabinsky, M. and Diederichs, M. (1989), "Numerical Modelling in Rock Engineering", Dept. of Civil Engineering, University of Toronto.

4. Simmons, J. and McManus, D. (2004), "Shear Strength Framework for Design of Dumped Spoil Slopes for Open Pit Coal Mines". Advances in Geotechnical Engineering: The Skempton Conference, 2004, Thomas Telford, London.

5. Matthews, C. and Farook, Z. and Helm, P. "Slope stability analysis – limit equilibrium or the finite element method?" Ground Engineering, May 2014.

6. Prasad, K. (2006) "Slope Stability Evaluations by Limit Equilibrium and Finite Element Methods". Dept. of Civil Engineering, Norwegian University of Science and Technology.