OptumG2

Verification of slope stability

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1 Introduction

The following document contains a number of common slope stability problems. These are solved using the Strength Reduction analysis in OptumG2. The results are compared to results from the literature, mostly obtained using limit equilibrium methods.

A unique feature to OptumG2 is the ability to compute rigorous upper and lower bounds on the factor of safety. This allows the user to bracket the exact solution from above and below. More precisely, if we denote the exact solution by E and the lower and upper bounds by L and U respectively, the following inequalities hold:

$$L \leq E \leq U$$

Moreover, if we denote the mean value of the upper and lower bounds by $M = (L + U)/2$, we may define an absolute error by

$$\varepsilon_{abs} = (M - L) = (U - M)$$

In this way, the exact solution may be expressed as:

$$E = M \pm \varepsilon_{abs}$$

Alternatively, we may define a relative error:

$$\varepsilon_{abs} = (M - L)/M = (U - M)/M = (U - L)/(U + L)$$

So that the exact solution may be expressed as:

$$E = M \pm \varepsilon_{abs}\ [\%]$$

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.

In the following sections, these problems are solved using OptumG2.

2.1 Simple slope

Project file: Slope01.g2x

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.

Geometry and material properties:

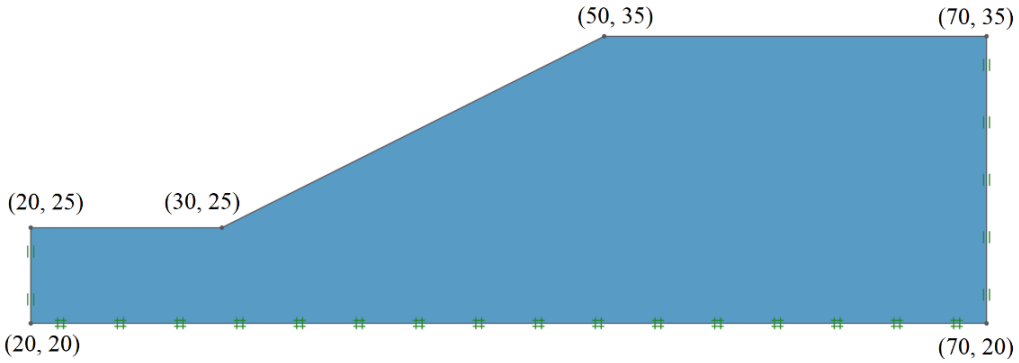

Figure **1: Geometry**

c (kN/m^2)	ϕ (°)	γ (kN/m^3)
3.0	19.6	20.0

Table **1: Material properties**

Results:

Upper and Lower bound Strength Reduction Finite Element Limit Analysis (SR-FELA) was used with 10,000 elements and 3 mesh adaptivity iterations. The results are shown in the table below along with various Limit Equilibrium (LE) results from the Slide and SVSLOPE verification manuals. The Optum results are generally in good agreement with the limit equilibrium results.

Program	Method	Factor of Safety	Deviation (%)
Slide	LE (Ordinary)	0.947	-3.47
	LE (Bishop Simplified)	0.987	+0.61
	LE (Janbu Simplified)	0.939	-4.28
	LE (Spencer)	0.986	+0.51
	LE (GLE)	0.986	+0.51
SVSLOPE	LE (Ordinary)	0.945	-3.67
	LE (Bishop Simplified)	0.989	+0.82
	LE (Janbu Simplified)	0.94	-4.18
	LE (Spencer)	0.988	+0.71
	LE (GLE)	0.988	+0.71
	Reference (Giam & Donald)	1.000	+1.94
OptumG2	SR-FELA (Lower)	0.978	-0.31
	SR-FELA (Upper)	0.984	+0.31
	Exact	0.981 ± 0.003	-

Table **2: Factors of Safety**

The collapse mechanism is indicated in the figure below.

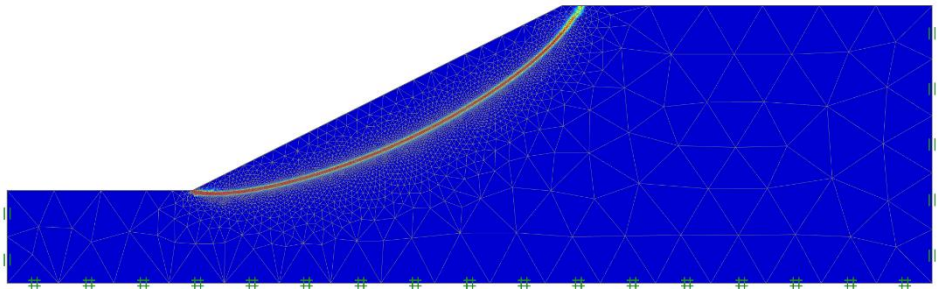

Figure **2: Shear strain distribution**

2.2 Non-homogenous slope

Project file: Slope02.g2x

In 1988 a set of 5 basic slope stability problems, together with 5 variants, was distributed both in the Australian Geomechanics profession and overseas as part of a survey sponsored by ACADS (Giam & Donald, 1989). This model is a non-homogenous three-layer slope with material properties shown in Table 3.

Geometry and material properties:

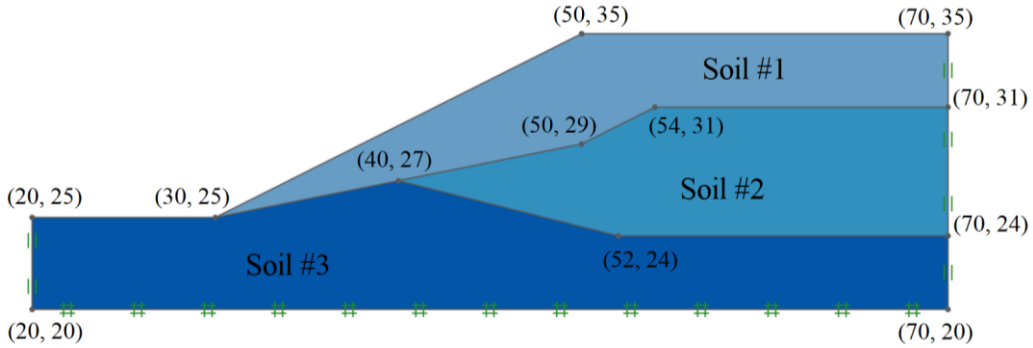

Figure **3: Geometry**

	c (kN/m^2)	ϕ (°)	γ (kN/m^3)
Soil #1	0.0	38.0	19.5
Soil #2	5.3	23.0	19.5
Soil #3	3.0	19.6	20.0

Table **3: Material properties**

Results:

Upper and Lower bound Strength Reduction Finite Element Limit Analysis (SR-FELA) was used with 10,000 elements and 3 mesh adaptivity iterations. The results are shown in the table below along with various Limit Equilibrium (LE) results from the Slide and SVSLOPE verification manuals. The Optum results are generally in good agreement with the limit equilibrium results.

Program	Method	Factor of Safety	Deviation (%)
Slide	LE (Ordinary)	1.232	-9.31
	LE (Bishop Simplified)	1.405	+3.42
	LE (Spencer)	1.375	+1.21
	LE (GLE)	1.374	+1.14
SVSLOPE	LE (Ordinary)	1.231	-9.39
	LE (Bishop Simplified)	1.405	+3.42
	LE (Spencer)	1.374	+1.14
	LE (GLE)	1.375	+1.21
OptumG2	SR-FELA (Lower)	1.352	-0.48
	SR-FELA (Upper)	1.365	+0.48
	Exact	1.359 ± 0.006	-

Table **4: Factors of safety**

The collapse mechanism is indicated in the figure below.

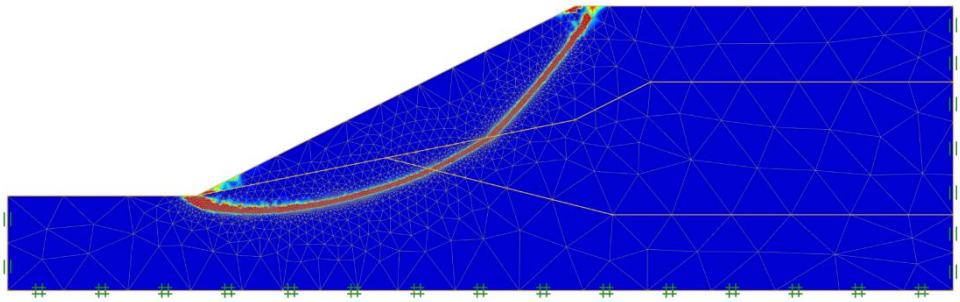

Figure **4: Shear strain distribution**

2.3 Non-homogenous with seismic load

Project file: Slope03.g2x

This problem is identical to #2, but with a horizontal seismically induced acceleration of 0.15g included in the analysis. The factor of safety and its corresponding critical circular failure surface is required.

Geometry and material properties:

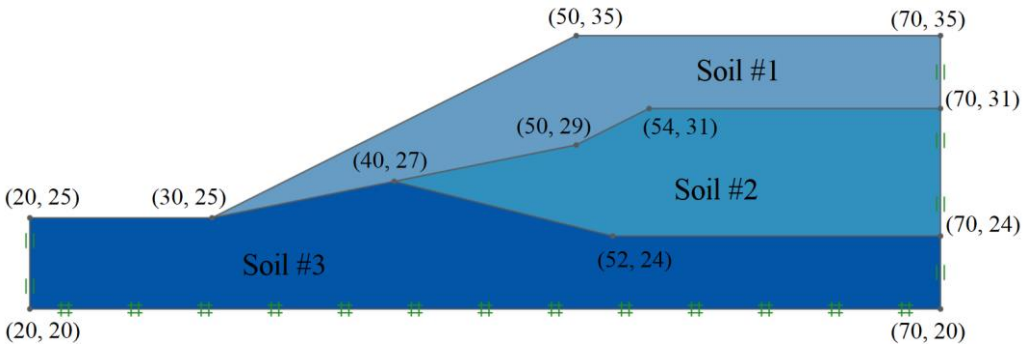

Figure **5: Geometry**

	c (kN/m^2)	ϕ (°)	γ (kN/m^3)
Soil #1	0.0	38.0	19.5
Soil #2	5.3	23.0	19.5
Soil #3	3.0	19.6	20.0

Table **5: Material properties**

Results:

Upper and Lower bound Strength Reduction Finite Element Limit Analysis (SR-FELA) was used with 10,000 elements and 3 mesh adaptivity iterations. The results are shown in the table below along with various Limit Equilibrium (LE) results from the Slide and SVSLOPE verification manuals. The Optum results are generally in good agreement with the limit equilibrium results, though generally slightly higher.

Program	Method	Factor of Safety	Deviation (%)
Slide	LE (Ordinary)	0.884	-14.9
	LE (Bishop Simplified)	1.015	-2.26
	LE (Spencer)	0.897	-13.6
	LE (GLE)	0.991	-4.57
SVSLOPE	LE (Ordinary)	0.989	-4.77
	LE (Bishop Simplified)	0.884	-14.9
	LE (Spencer)	1.014	-2.36
	LE (GLE)	0.897	-13.6
OptumG2	SR-FELA (Lower)	1.034	-0.43
	SR-FELA (Upper)	1.043	+0.43
	Exact	1.039 ± 0.004	-

Table **6: Factors of safety**

The collapse mechanism is indicated in the figure below.

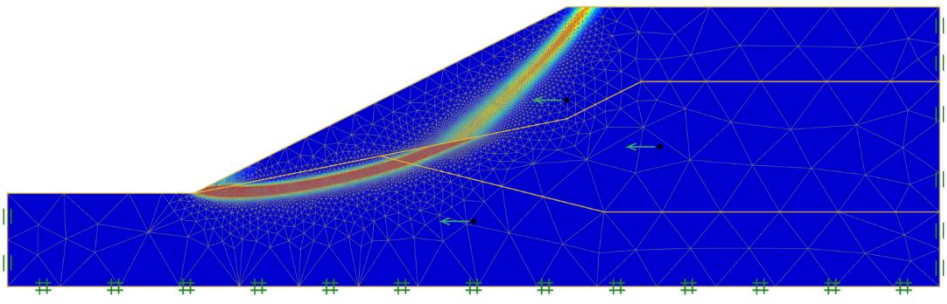

Figure **6: Shear strain distribution**

2.4 Slope with water table and weak seam

Project file: Slope04.g2x

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 effects

of negative pore-water pressure above the water tables were ignored. Geometry and Material Properties

Geometry and material properties:

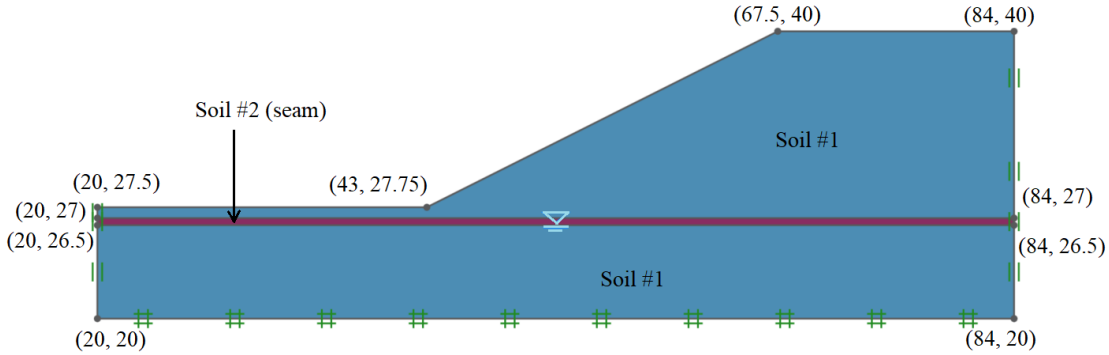

Figure **7: Geometry**

	c (kN/m^2)	ϕ (°)	γ (kN/m^3)
Soil #1	0.0	38.0	19.5
Soil #1	5.3	23.0	19.5

Table **7: Material properties**

Results:

Upper and Lower bound Strength Reduction Finite Element Limit Analysis (SR-FELA) was used with 10,000 elements and 3 mesh adaptivity iterations. The results are shown in the table below along with various Limit Equilibrium (LE) results from the Slide and SVSLOPE verification manuals. The Optum results are in very good agreement with the limit equilibrium results.

Program	Method	Factor of Safety	Deviation (%)
Slide	LE (Spencer)	1.258	-0.51
	LE (GLE)	1.246	-1.46
SVSLOPE	LE (Spencer)	1.256	-0.67
	LE (GLE)	1.247	-1.38
OptumG2	SR-FELA (Lower)	1.257	-0.59
	SR-FELA (Upper)	1.272	+0.59
	Exact	1.265 ± 0.008	-

Table **8: Factors of safety**

The collapse mechanism is indicated in the figure below.

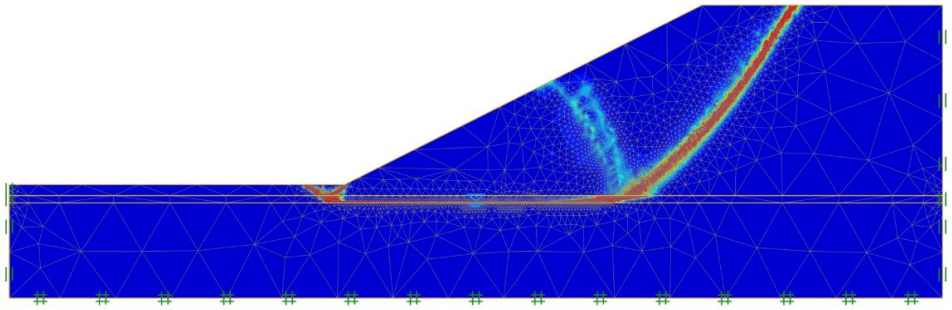

Figure **8: Shear strain distribution**

2.5 Slope subjected to external loading and pore-pressure defined by water table

Project file: Slope05.g2x

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.

Geometry and material properties:

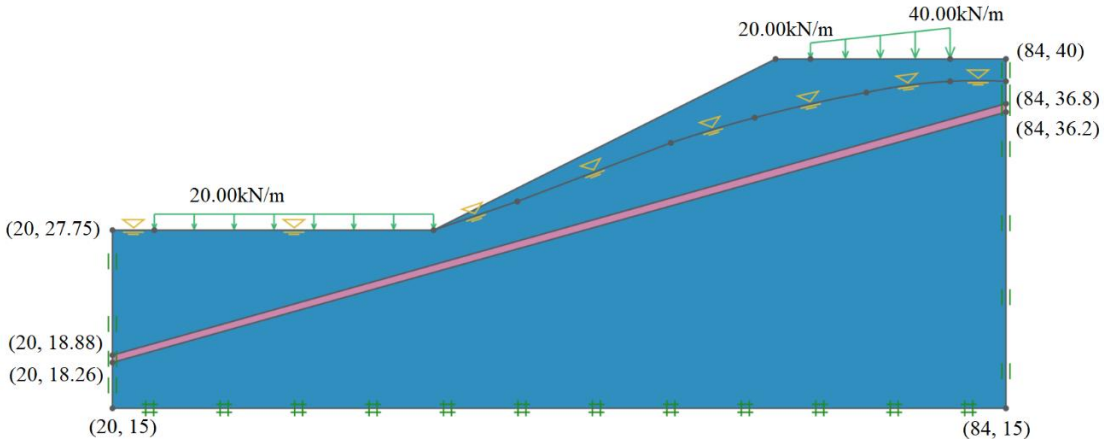

Figure **9: Geometry**

	X (m)	Y (m)	Normal Stress (kN/m^2)
Load #1	23.00	27.75	20.00
	43.00	27.75	20.00
Load #2	70.00	40.00	20.00
	80.00	40.00	40.00

Table **9: External Loadings**

Point #	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

Table **10: Data for Piezometric Surface**

	c (kN/m^2)	ϕ (°)	γ (kN/m^3)
Soil #1	28.5	20	18.84
Soil #1	0	10.0	18.84

Table **11: Material properties**

Results:

Upper and Lower bound Strength Reduction Finite Element Limit Analysis (SR-FELA) was used with 10,000 elements and 3 mesh adaptivity iterations. The results are shown in the table below along with various Limit Equilibrium (LE) results from the Slide and SVSLOPE verification manuals. The Optum results are generally in reasonable agreement with the limit equilibrium results, though the deviation is greater than for the previous examples.

It should be noted that the water table as defined above implies a seepage that may or may not have been taken into account in previous solutions, but is taken into account in OptumG2.

Program	Method	Factor of Safety	Deviation (%)
Slide	LE (Spencer)	0.71	-12.3
	LE (GLE)	0.685	-15.4
SVSLOPE	LE (Spencer)	0.634	-21.7
	LE (GLE)	0.665	-17.9
OptumG2	SR-FELA (Lower)	0.802	-0.99
	SR-FELA (Upper)	0.818	+0.99
	Exact	0.81 ± 0.008	-

Table **12: Factors of safety**

The collapse mechanism is indicated in the figure below.

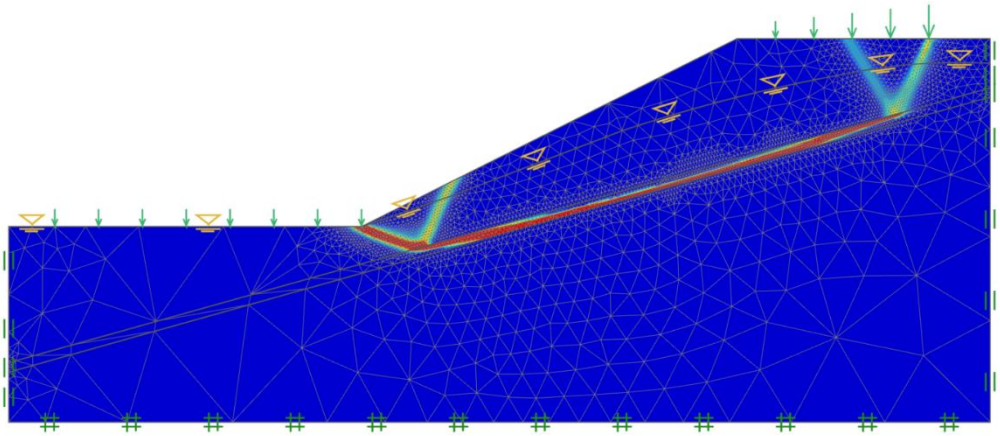

Figure **10: Shear strain distribution**

3 James Bay Dike

Project file: Duncan.g2x

This problem is taken from Duncan et al. (2014) where it was solved using both limit equilibrium and conventional finite element strength reduction (c-tanϕ reduction).

Geometry and material properties:

The geometry and material properties are shown in the figure below.

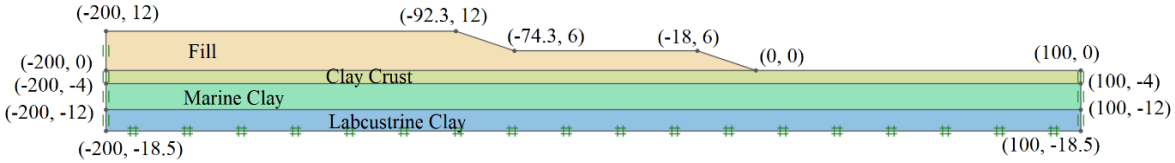

Figure **11: Geometry**

	c (kN/m^2)	ϕ (°)	γ (kN/m^3)
Fill	0.0	30	20
Clay Crust	41	0	20
Marine Clay	34.5	0	18.8
Lacustrine Clay	31.2	0	20.3

Table **13: Material properties**

Results:

Upper and Lower bound Strength Reduction Finite Element Limit Analysis (SR-FELA) was used with 10,000 elements and 3 mesh adaptivity iterations. The results are shown in the table below along with various Limit Equilibrium (LE) and FE results. The Optum results are in reasonable agreement with the FE results whereas the LE results overestimate the factor of safety considerably.

Program	Method	Factor of Safety	Deviation (%)
UTEXAS4 SLOPE/W SLIDE	LE, Circular	1.45	+19.1
Phase^2	FE	1.16	-4.69
OptumG2	SR-FELA (Lower)	1.212	-0.37
	SR-FELA (Upper)	1.221	+0.37
	Exact	1.217 ± 0.005	-

Table **14: Factors of safety**

The collapse mechanism is indicated in the figure below.

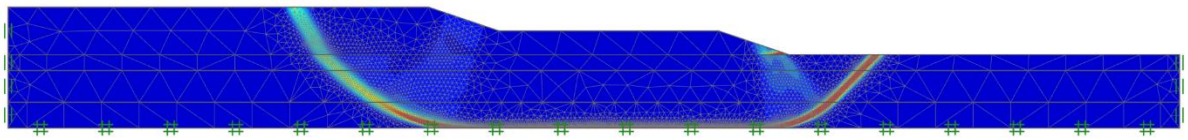

Figure **12: Shear strain distribution**

Reference:

Duncan MJ, Wright SJ, Brandon TL (2014). Soil Strength and Slope Stability, Elsevier.

Anon (2010). Slide - Slope Stability Verification Manual Part I, Rocscience

Fredlund M, Fredlund D (Eds) (2009). SVSLOPE Verification Manual, SoilVision Systems Ltd.

Giam, P.S.K. and I.B. Donald (1989), Example problems for testing soil slope stability programs, Civil Engineering Research Report No. 8/1989, Monash University.

Giam, P.S.K. (1989). Improved methods and computational approaches to geotechnical stability analysis", Ph.D., Thesis, Department. of Civil Engineering, Monash University, Australia.