SLOPE STABILITY ANALYSIS BY FINITE ELEMENTS

A guide to the use of Program **slope1**

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Downloading the **slope1** program

The source code for **slope1** is written in Fortran 95, but users are provided with the executable file **slope1.exe** and the example data files **ex1.dat** thru **ex7.dat** as described in this report. The slope stability software is in folder

4th_ed/executable/slope_stab/slope1

The files needed to run the slope program with one of the examples are as follows:

slope1.exe	An executable file of the slope1 program
ex?.dat	A typical example data file as described in this report

Running an example problem

In order to run **slope1** with an example data file, e.g. **ex4.dat**, use Windows Explorer to navigate to the folder **4th_ed/executable/slope_stab/slope1,** double click on the executable icon **slope1.exe**, and when prompted type the base-name of the data file, namely **ex4**

If the program runs properly, you should see evidence of iterations being reported back to the screen. When the job is complete you should see the following additional files in the **slope1** folder:

ex4.res	Output file giving the estimated Factor of Safety.
ex4.msh	PostScript file showing the finite element mesh.
ex4.vec	PostScript file showing nodal displacement vectors at failure.
ex4.dis	PostScript file showing the deformed mesh at failure.

<u>Running your own problem</u>

Create your own data file. This report explains the layout of data for use with **`slope1.`** It may help to make a copy of one of the example data files closest to your own problem and edit that as needed. Let us assume your data file is called **`fred.dat`**. Note that the extension <u>must</u> be of type **`.dat`**.

In order to run your own data file **`fred.dat`**, once more double- click on the executable icon **`slope1.exe`**, and when prompted type the basename of the data file, namely **`fred`**

If all goes well, the following additional files will appear in your folder: **`fred.res, fred.msh, fred.vec`** and **`fred.dat`**

Note: Program **`slope1.f95`** is based closely on **`p63.f95`** in the textbook, "Programming the Finite Element Method" by I.M. Smith and D.V. Griffiths. 4th ed., 2004. The main difference lies in the mesh generation and the automatic search for the critical strength reduction factor. Users of **`slope1`** are encouraged to refer to this text and the companion paper, "Slope stability analysis by finite elements", by D.V. Griffiths and P.A. Lane, *Géotechnique* 49, no.3, pp.387-403, (1999).

Explanation of data for Program `slope1.exe`

A typical configuration is shown in Figure 1.

Slope geometry data:

`w1`	=	Width of top of embankment
`s1`	=	Width of sloping portion of embankment
`w2`	=	Distance foundation extends to right of embankment toe
`h1`	=	Height of embankment
`h2`	=	Thickness of foundation layer

Element discretization data:

`nx1`	=	Number of x-elements in embankment
`nx2`	=	Number of x-elements to right of embankment toe
`ny1`	=	Number of y-elements in embankment
`ny2`	=	Number of y-elements in foundation

Soil property data: [1]

`np_types`	=	Number of different property groups
`phi,c,psi,gamma,e,v`	=	Material properties $\phi', c', \psi, \gamma, E, \nu$ (`np_types` times)
`etype`	=	Property group assigned to each element (`nels` times) (data not needed if `np_types=1`)

Pseudo-static analysis: [2]

`k_h`	=	Horizontal acceleration factor

Free surface data: [3]

`nosurf`	=	Number of free surface coordinates
`x,y`	=	$x-$ and $y-$ coordinates of free-surface (`nosurf` times), or the r_u value
`gam_w`	=	Unit weight of water, γ_w

Iteration ceiling:

`limit`	=	Iteration ceiling (suggested value, 500)

Factor of Safety Tolerance:

`fos_tol`	=	Factor of safety tolerance (suggested value, 0.05)

[1] ϕ' is the effective friction angle; c' is the effective cohesion; ψ is the dilation angle and can usually be set to zero; γ is the total unit weight; E is Young's modulus and is often set to a nominal value (e.g. 10^5); ν is Poisson's ratio and is often set to a nominal value (e.g. 0.3), `nels` is the total number of elements in the mesh and is computed internally by the program

[2] k_h is the horizontal pseudo-static acceleration factor, e.g. for a horizontal acceleration of $0.2g$, set $k_h = 0.2$

[3] If `nosurf=1`, then instead of `x,y` data, read a single value of r_u.

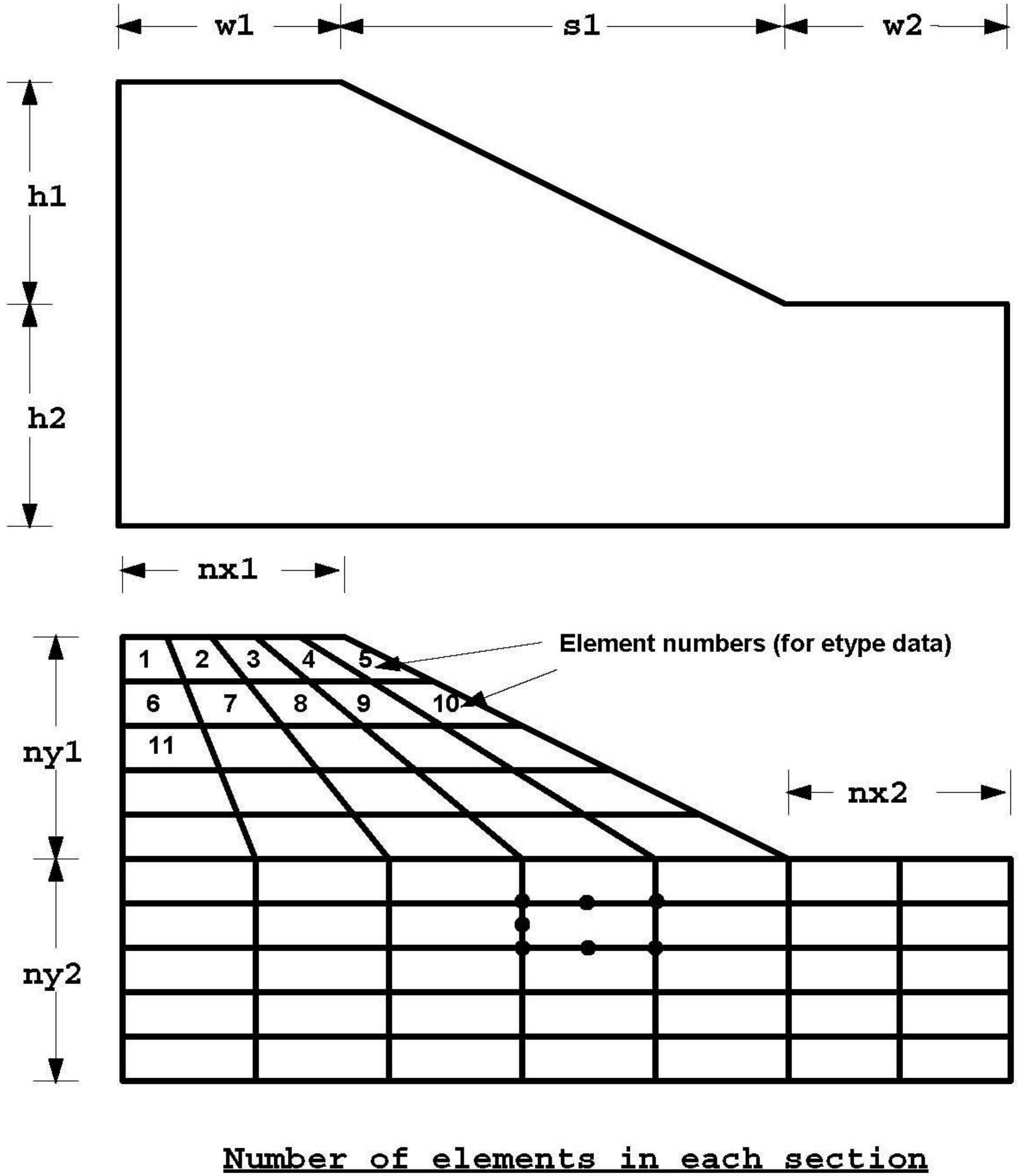


Fig. 1 Layout and dimensions of embankment geometry

Example 1: A homogeneous slope

The stability analysis is of the homogeneous c'-ϕ' slope shown in Figure 1.1

Data for Example 1 (`ex1.dat`)

```
"Example 1: A homogeneous slope"

"Width of top of embankment (w1)"
1.2

"Width of sloping portion of embankment (s1)"
2.0

"Distance foundation extends to right of
 embankment toe (w2)"
1.2

"Height of embankment (h1)"
1.0

"Thickness of foundation layer (h2)"
1.0

"Number of x-elements in embankment (nx1)"
32

"Number of x-elements to right of embankment toe (nx2)"
12

"Number of y-elements in embankment (ny1)"
10

"Number of y-elements in foundation (ny2)"
10
```

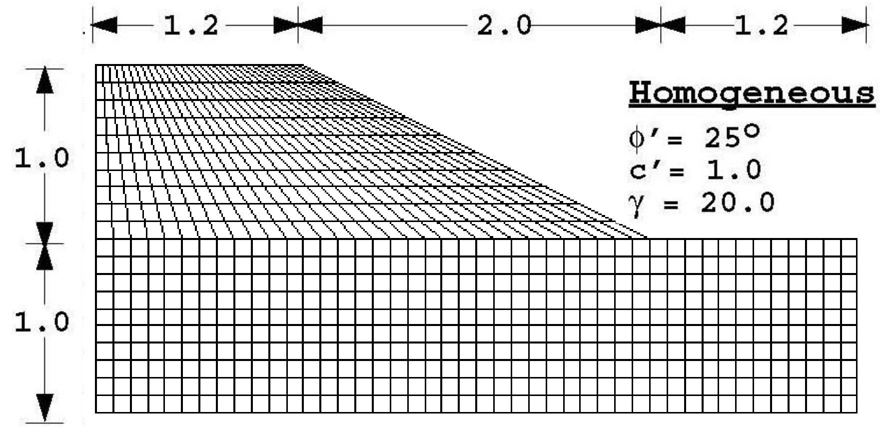


Fig 1.1 Finite element mesh for Example 1

```
"Number of different property groups (np_types)"
1

"Material properties (phi,c,psi,gamma,e,v) for each group"
25.0  1.0  0.0  20.0  1.e5  0.3

"Property group assigned to each element (etype, data not needed if np_types=1)"

"Pseudo-static analysis: Horizontal acceleration factor (k_h)"
0.0

"Number of free surface points and their coordinates (nosurf, surf(2,nosurf))"
0

"Unit weight of water (gam_w)"
0.0

"Iteration ceiling (limit)"
1000

"Factor of Safety accuracy tolerance (fos_tol)"
0.05
```

Output for Example 1 (`ex1.res`)

```
trial factor      max displ          iterations
    0.5000       0.3050E-03               2
    1.0000       0.3074E-03               8
    1.5000       0.3890E-03              42
    1.5625       0.4039E-03             250
    1.5781       0.4076E-03             428
    1.5938       0.4511E-03            1000

Estimated Factor of Safety =       1.59
```

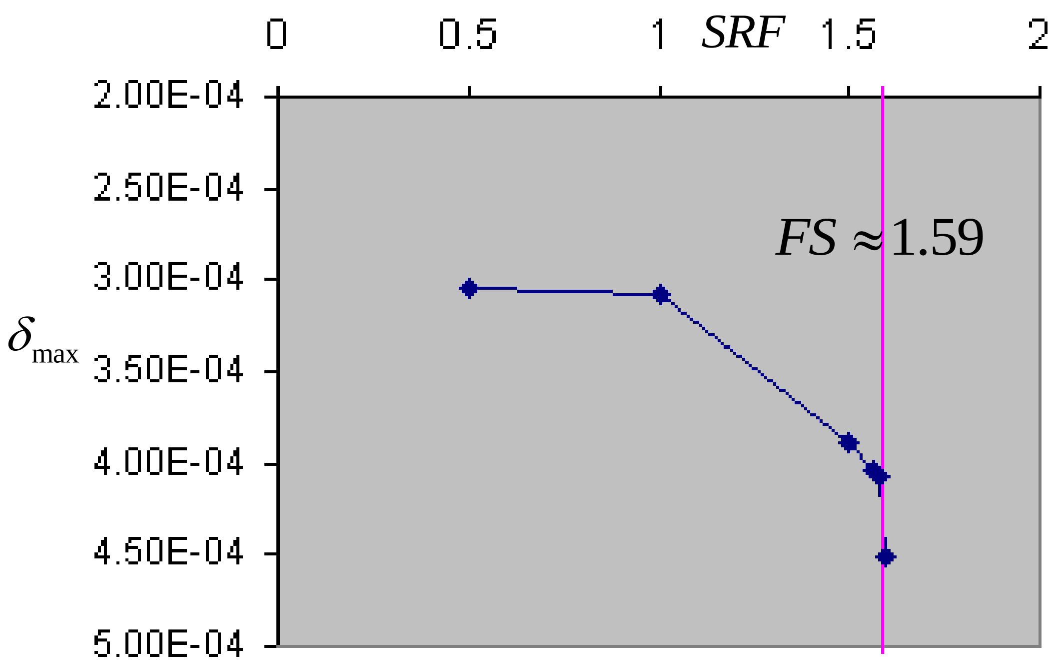


Fig 1.2 SRF vs. d_{max} for Example 1

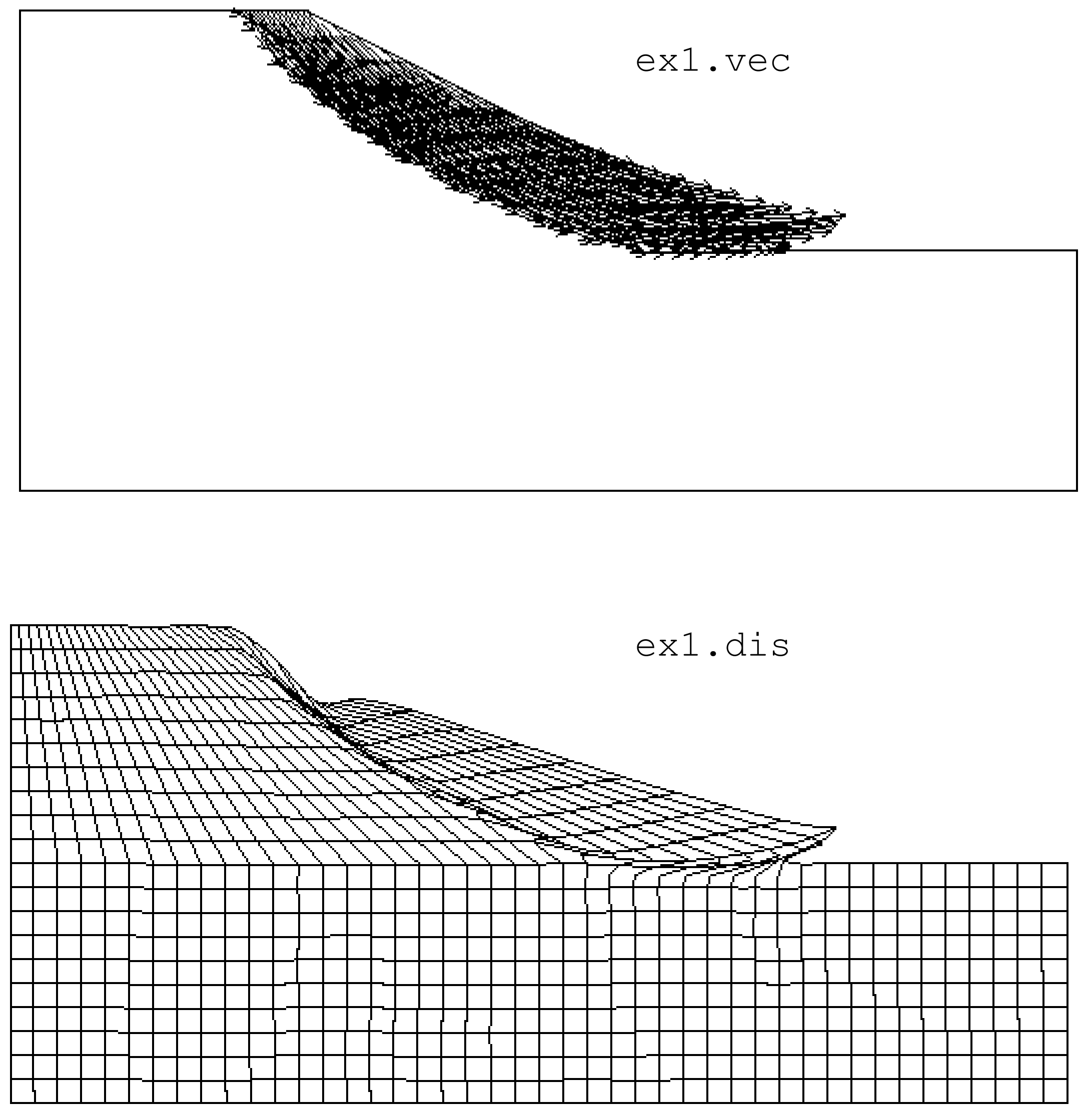


Fig 1.2 Displacement vectors and deformed mesh at failure for Example 1

Example 2: A two-layer slope

The stability analysis is of a two-layer c'-ϕ' slope consisting of a stronger soil in the embankment overlying a weaker soil in the foundation as shown in Figure 2.1.

Data for Example 2 (ex2.dat)

```
"Example 2: A two-layer slope"

"Width of top of embankment (w1)"
1.2

"Width of sloping portion of embankment (s1)"
2.0

"Distance foundation extends to right of embankment toe (w2)"
1.2

"Height of embankment (h1)"
1.0

"Thickness of foundation layer (h2)"
1.0

"Number of x-elements in embankment (nx1)"
5

"Number of x-elements to right of embankment toe (nx2)"
5

"Number of y-elements in embankment (ny1)"
5

"Number of y-elements in foundation (ny2)"
5
```

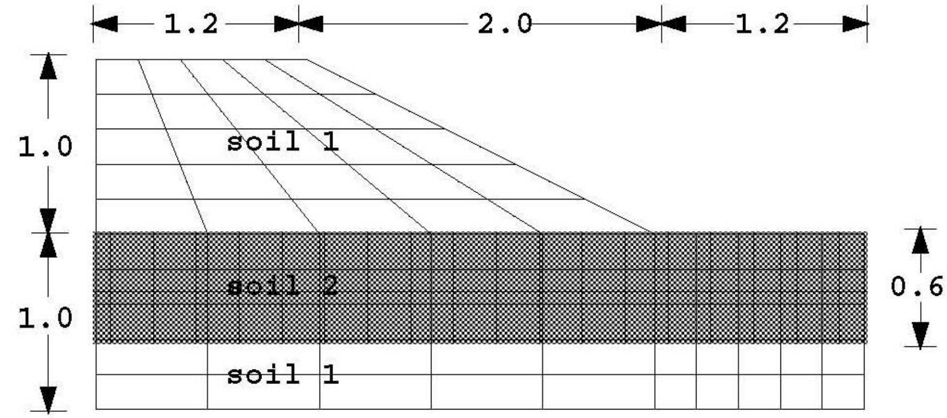


Fig 2.1 Finite element mesh for Example 2

Two-layer

Soil 1

$\phi' = 25^\circ$
$c' = 1.0$
$\gamma = 20.0$

Soil 2

$\phi' = 15^\circ$
$c' = 0.5$
$\gamma = 20.0$

```
"Number of different property groups (np_types)"
2

"Material properties (phi,c,psi,gamma,e,v) for each group"
25.0  1.0  0.0  20.0  1.e5  0.3
15.0  0.5  0.0  20.0  1.e5  0.3

"Property group assigned to each element (etype, data not needed if np_types=1)"
1 1 1 1 1
1 1 1 1 1
1 1 1 1 1
1 1 1 1 1
1 1 1 1 1
2 2 2 2 2 2 2 2 2 2
2 2 2 2 2 2 2 2 2 2
2 2 2 2 2 2 2 2 2 2
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1

"Pseudo-static analysis: Horizontal acceleration factor (k_h)"
0.0

"Number of free surface points and their coordinates (nosurf, surf(2,nosurf))"
0

"Unit weight of water (gam_w)"
9.81

"Iteration ceiling (limit)"
500

"Factor of safety tolerance (fos_tol)"
0.05
```

Output for Example 2 (ex2.res)

trial factor	max displ	iterations
0.5000	0.3050E-03	2
1.0000	0.3507E-03	33
1.1250	0.3731E-03	51
1.1875	0.3954E-03	199
1.2031	0.4150E-03	348
1.2188	0.4573E-03	500

Estimated Factor of Safety = 1.22

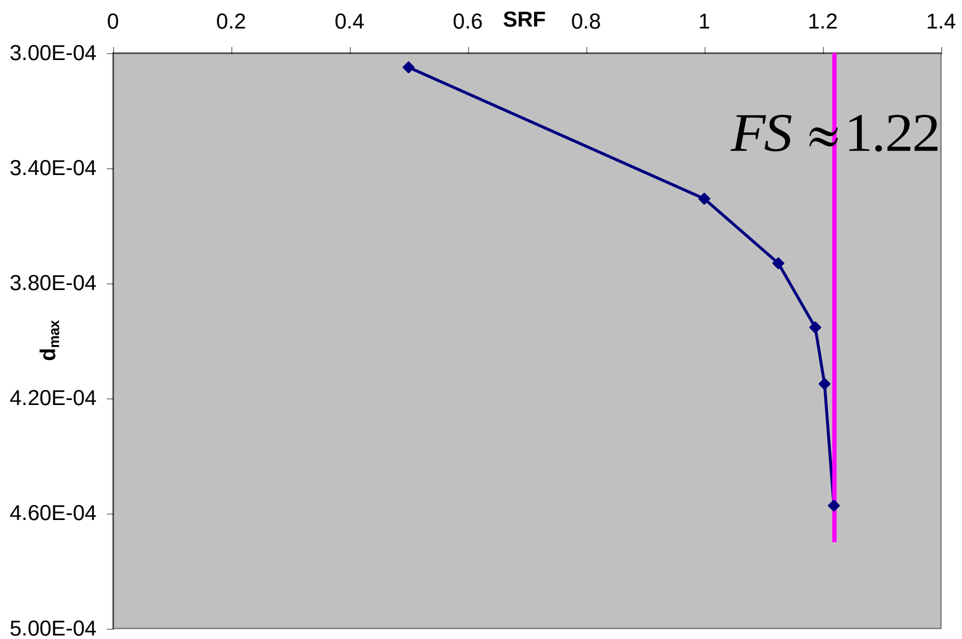
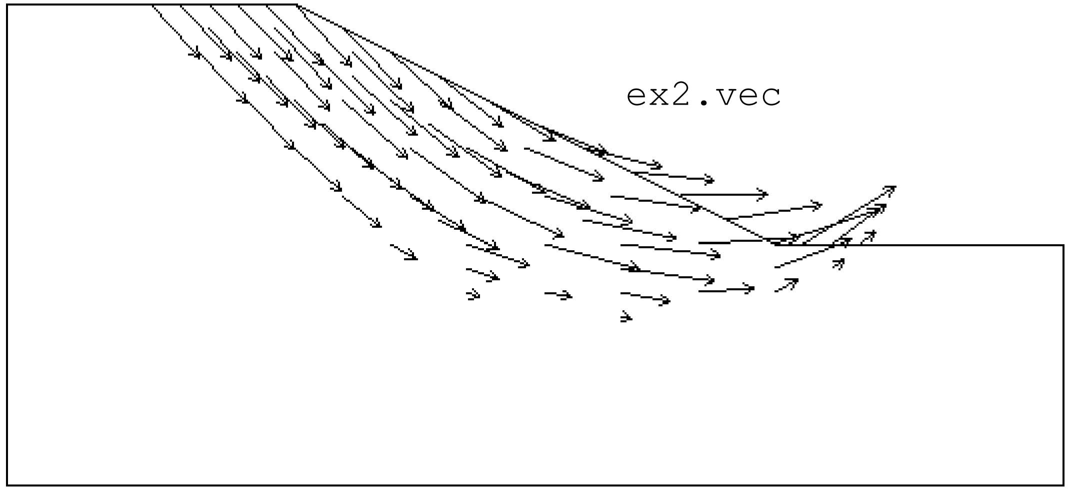


Fig 2.2 SRF vs. d_{max} for Example 2



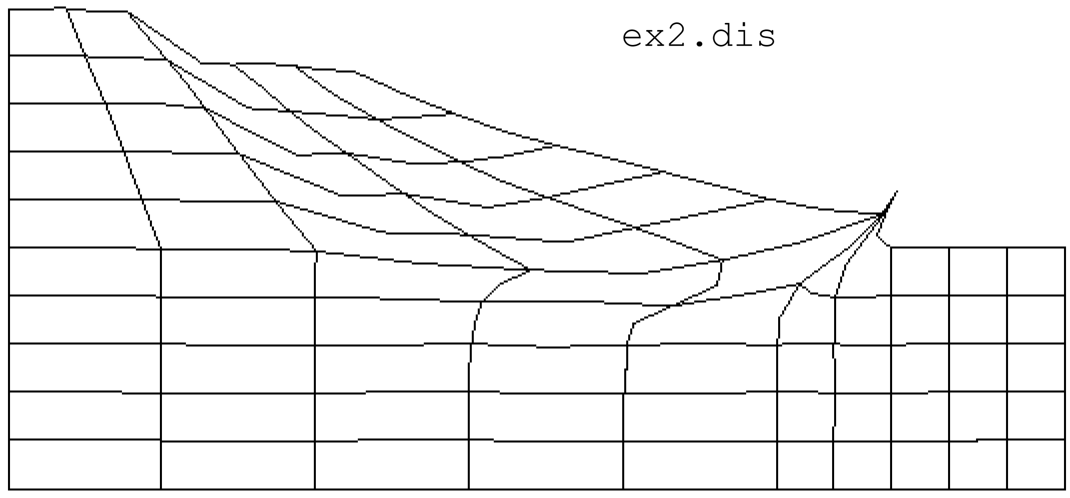


Fig 2.3 Displacement vectors and deformed mesh at failure for Example 2

Example 3: A two-layer undrained clay slope

The stability analysis is of a two-layer undrained clay slope consisting of
embankment overlying a stronger soil in the foundation as shown in Figur

Data for Example 3 (`ex3.dat`)

```
"Example 3: A two-layer undrained clay slope"

"Width of top of embankment (w1)"
20.0

"Width of sloping portion of embankment (s1)"
20.0

"Distance foundation extends to right of embankment toe (w2)"
20.0

"Height of embankment (h1)"
10.0

"Thickness of foundation layer (h2)"
10.0

"Number of x-elements in embankment (nx1)"
20

"Number of x-elements to right of embankment toe (nx2)"
10

"Number of y-elements in embankment (ny1)"
5

"Number of y-elements in foundation (ny2)"
5
```

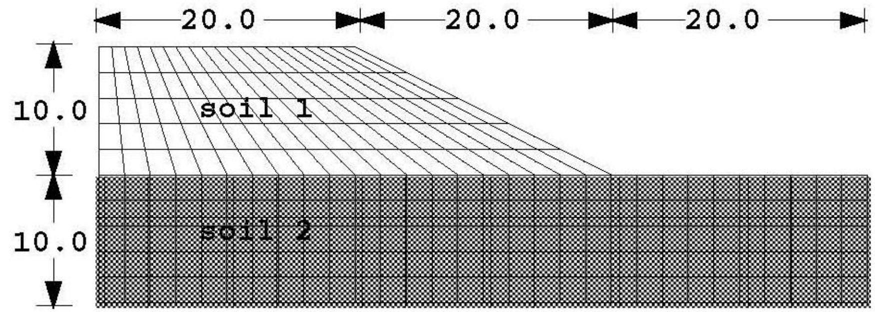


Fig 3.1 Finite element mesh for Example 3

Two-layer Undrained Clay

Soil 1
$\phi_u = 0$
$c_u = 50.0$
$\gamma = 20.0$

Soil 2
$\phi_u = 0$
$c_u = 73.1$
$\gamma = 20.0$

```
"Number of different property groups (np_types)"
2

"Material properties (phi,c,psi,gamma,e,v) for each group"
0.0  50.0   0.0  20.0  1.e5  0.3
0.0  73.1   0.0  20.0  1.e5  0.3

"Property group assigned to each element (etype, data not needed if np_types=1)"
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2

"Pseudo-static analysis: Horizontal acceleration factor (k_h)"
0.0

"Number of free surface points and their coordinates (nosurf, surf(2,nosurf))"
0

"Unit weight of water (gam_w)"
9.81

"Iteration ceiling (limit)"
500

"Factor of safety tolerance (fos_tol)"
0.05
```

Output for Example 3 (ex3.res)

trial factor	max displ	iterations
0.5000	0.3044E-01	2
1.0000	0.3535E-01	6
1.5000	0.4629E-01	35
1.7500	0.5365E-01	67
1.8750	0.5784E-01	82
1.9375	0.6063E-01	107
1.9688	0.6244E-01	143
1.9844	0.6389E-01	195
2.0000	0.7257E-01	500

Estimated Factor of Safety = 2.00

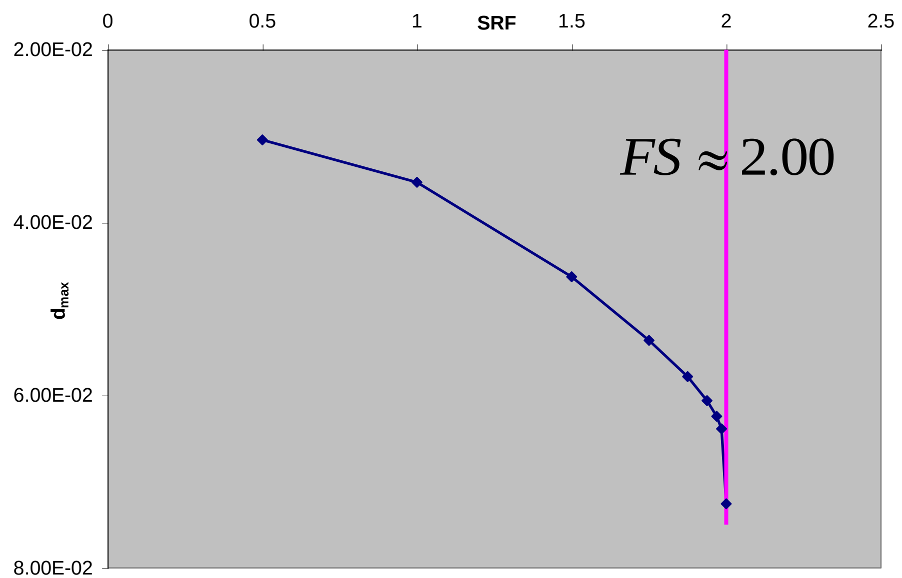


Fig 3.2 SRF vs. d_{max} for Example 3

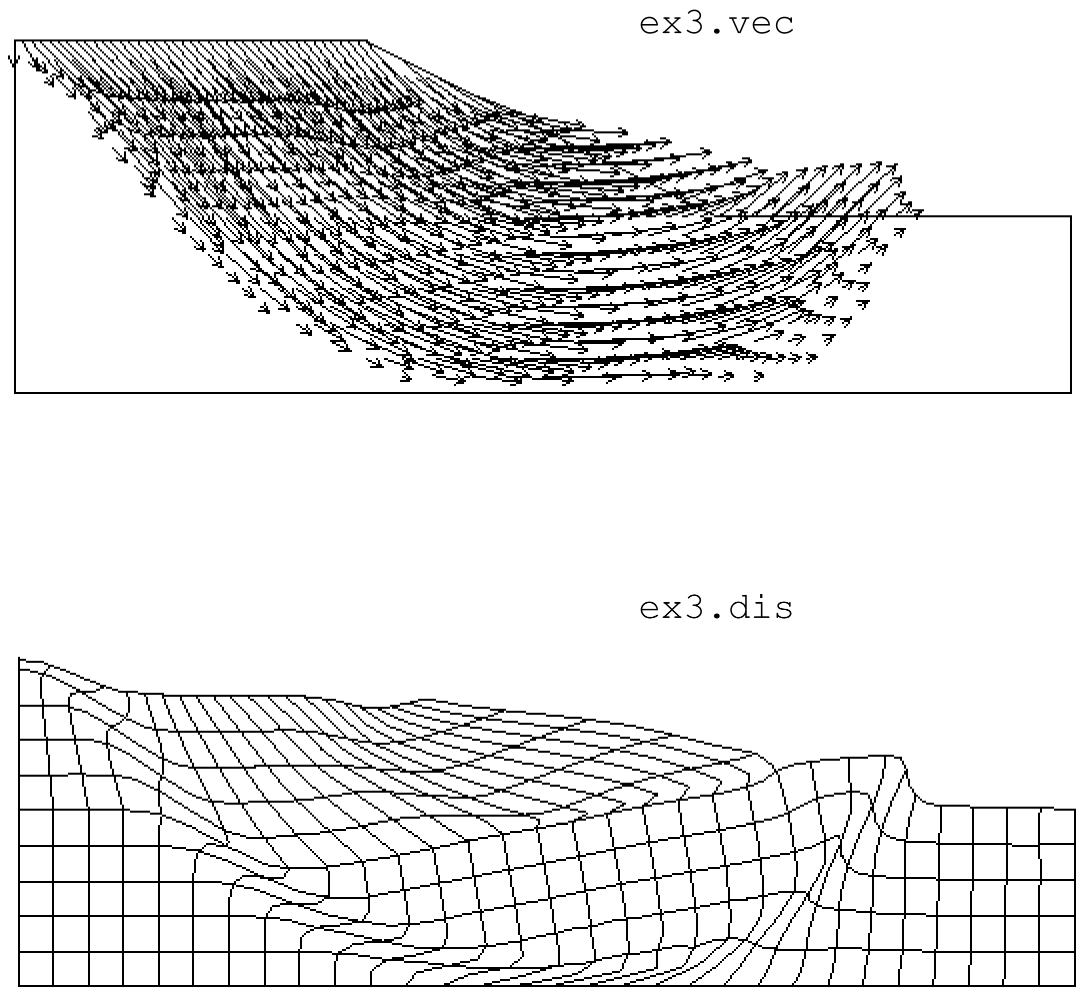


Fig 3.3 Displacement vectors and deformed mesh at failure for Example 3

Example 4: A homogeneous slope including a free-surface

The stability analysis is of the homogeneous c'-ϕ' slope including a free surface as shown in Figure 4.1. It is assumed in this case that the saturated unit weight is applicable both below *and* above the free-surface, so only one property type is needed.

Data for Example 4 (ex4.dat)

```
"Example 4: A homogeneous slope including a
free-surface"

"Width of top of embankment (w1)"
25.0

"Width of sloping portion of embankment (s1)"
17.0

"Distance foundation extends to right of
embankment toe (w2)"
24.0

"Height of embankment (h1)"
10.0

"Thickness of foundation layer (h2)"
10.0

"Number of x-elements in embankment (nx1)"
21

"Number of x-elements to right of embankment
toe (nx2)"
12

"Number of y-elements in embankment (ny1)"
5
```

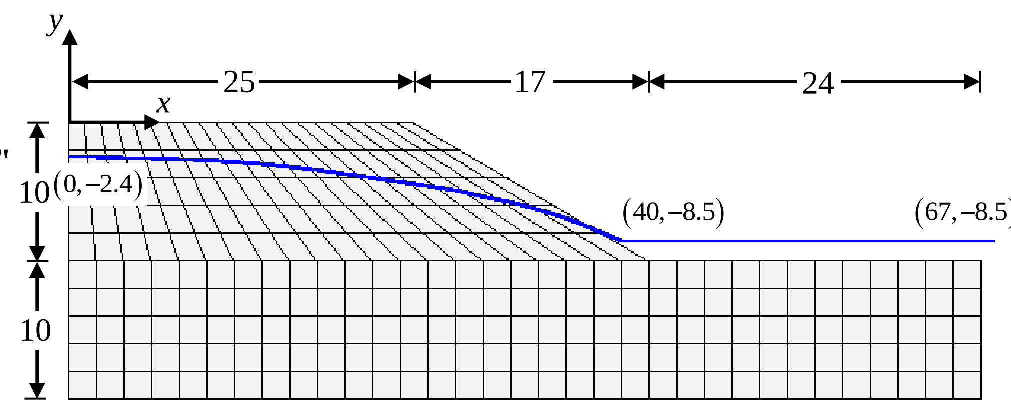


Fig 4.1 Finite element mesh for Example 4

<u>Homogeneous with free surface</u>

$\phi' = 5°$
$c' = 200$
$\gamma = 120$

```
"Number of y-elements in foundation (ny2)"
5

"Number of different property groups (np_types)"
1

"Material properties (phi,c,psi,gamma,e,v) for each group"
5.0   200.0  0.0  120.0  1.e5  0.3

"Property group assigned to each element (etype, data not needed if np_types=1)"

"Pseudo-static analysis: Horizontal acceleration factor (k_h)"
0.0

"Number of free surface points and their coordinates (nosurf, surf(2,nosurf))"
22
 0.0  -2.40   2.0  -2.45   4.0  -2.50   6.0  -2.55   8.0  -2.60
10.0  -2.67  12.0  -2.80  14.0  -2.95  16.0  -3.15  18.0  -3.40
20.0  -3.65  22.0  -3.95  24.0  -4.25  26.0  -4.55  28.0  -4.85
30.0  -5.30  32.0  -5.70  34.0  -6.25  36.0  -6.85  38.0  -7.65
40.0  -8.50  67.0  -8.50

"Unit weight of water (gam_w)"
62.4

"Iteration ceiling (limit)"
1000

"Factor of Safety accuracy tolerance (fos_tol)"
0.05
```

Output for Example 4 (`ex4.res`)

```
   0.5000       0.1950E+00               5
   1.0000       0.2803E+00              33
   1.2500       0.3630E+00             184
   1.2656       0.4893E+00            1000

Estimated Factor of Safety =      1.27
```

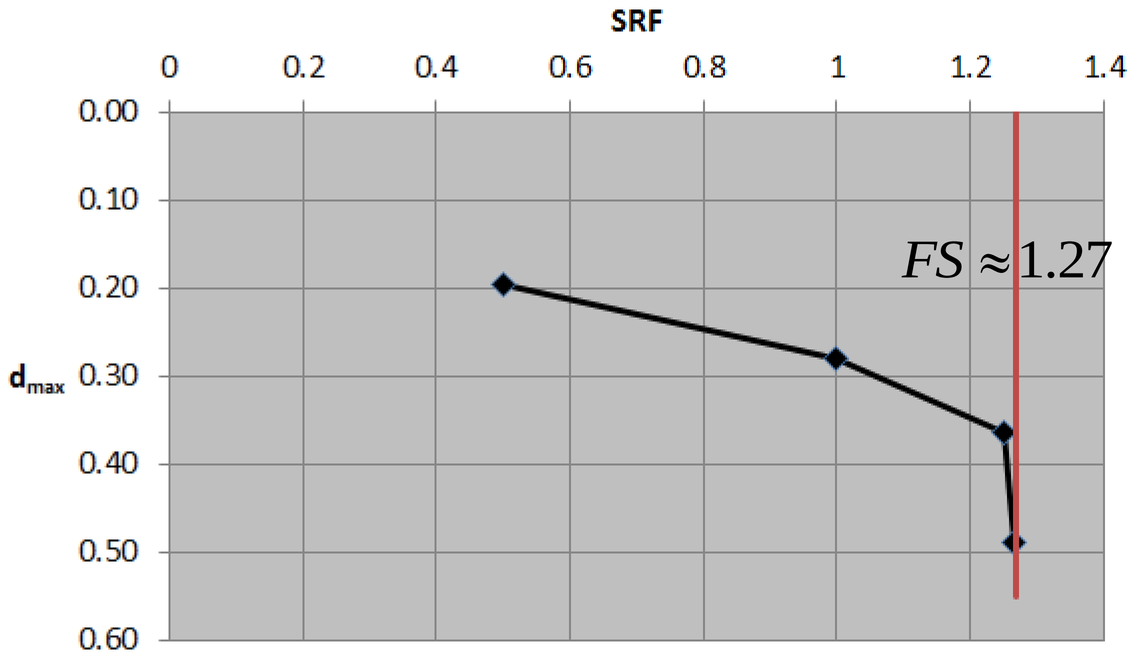
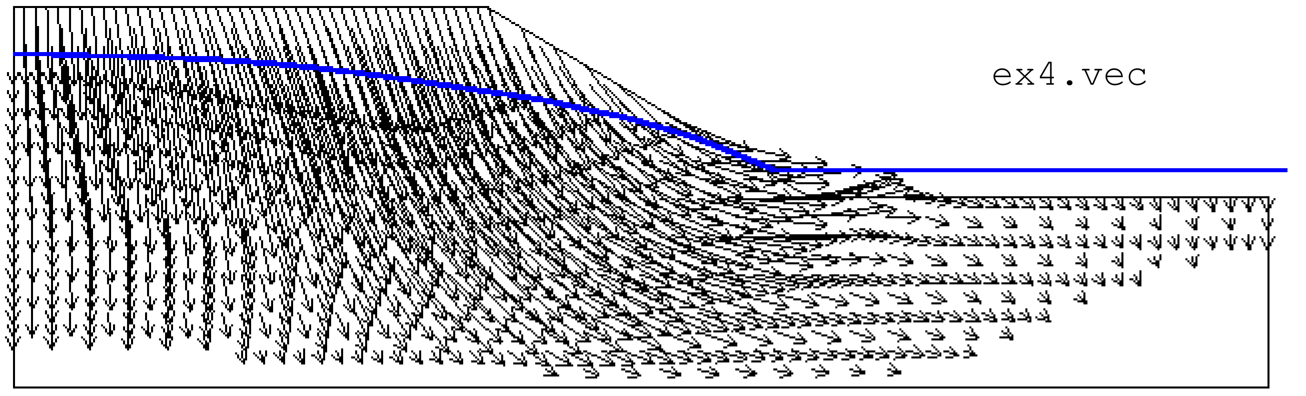


Fig 4.2 SRF vs. d_{max} for Example 4



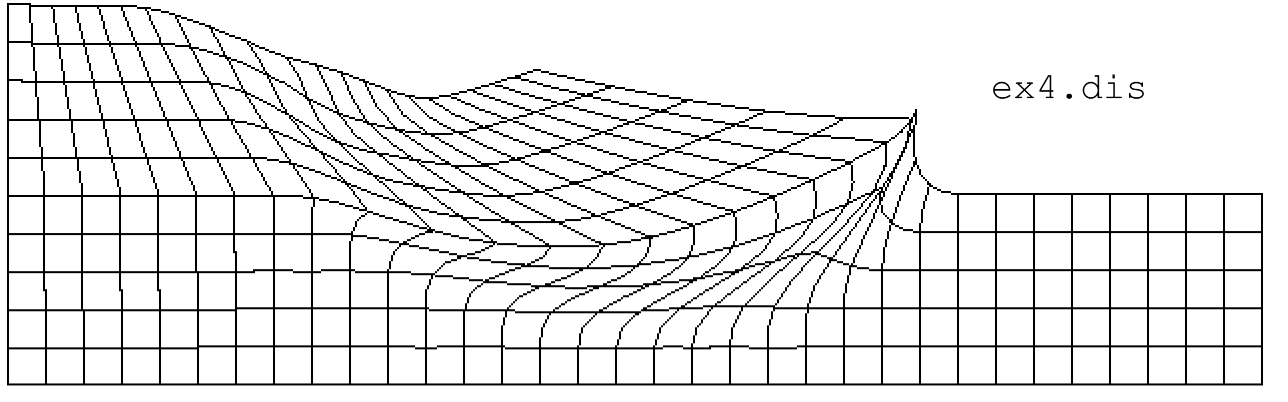


Fig 4.3 Displacement vectors and deformed mesh at failure for Example 4

Example 5: A completely submerged homogeneous slope

The stability analysis is of a homogeneous c'-ϕ' slope completely submerged beneath 2m of water as shown in Figure 5.1.

Data for Example 5 (ex5.dat)

```
"Example 5: A completely submerged homogeneous slope"

"Width of top of embankment (w1)"
30.0

"Width of sloping portion of embankment (s1)"
20.0

"Distance foundation extends to right of embankment toe (w2)"
0.0

"Height of embankment (h1)"
10.0

"Thickness of foundation layer (h2)"
0.0

"Number of x-elements in embankment (nx1)"
20

"Number of x-elements to right of embankment toe (nx2)"
0

"Number of y-elements in embankment (ny1)"
10

"Number of y-elements in foundation (ny2)"
0
```

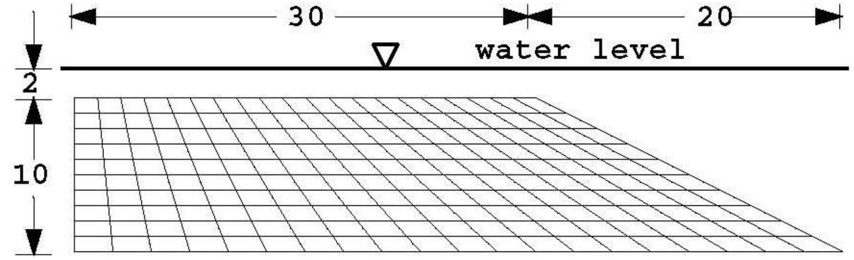


Fig 5.1 Finite element mesh for Example 5

Fully submerged and homogeneous

$\phi' = 20^{\circ}$
$c' = 10$
$\gamma = 20$

```
"Number of different property groups (np_types)"
1

"Material properties (phi,c,psi,gamma,e,v) for each group"
20.0   10.0  0.0  20.0  1.e5  0.3

"Property group assigned to each element (etype, data not needed if np_types=1)"

"Pseudo-static analysis: Horizontal acceleration factor (k_h)"
0.0

"Number of free surface points and their coordinates (nosurf, surf(2,nosurf))"
2
 0.0  2.0
50.0  2.0

"Unit weight of water (gam_w)"
9.81

"Iteration ceiling (limit)"
500

"Factor of safety tolerance (fos_tol)"
0.05
```

Output for Example 5 (ex5.res)

0.5000	0.9791E-02	9
1.0000	0.1162E-01	10
1.5000	0.1285E-01	20
1.7500	0.1344E-01	36
1.8125	0.1380E-01	94
1.8281	0.1496E-01	500

```
Estimated Factor of Safety =       1.83
```

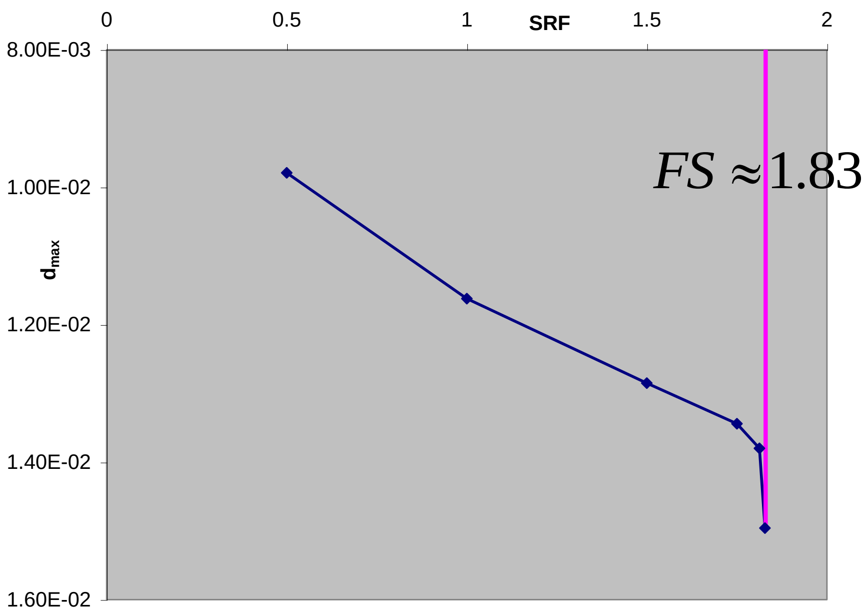


Fig 5.2 SRF vs. d_{max} for Example 5

Example 6: Rapid drawdown of a homogeneous slope from full submergence

The stability analysis is of a homogeneous c'-ϕ' slope (same slope as in Example 5) following 5m of rapid drawdown from full submergence as shown in Figure 6.1.

Data for Example 6 (ex6.dat)

```
"Example 6: Rapid drawdown of a homogeneous slope from full submergence"

"Width of top of embankment (w1)"
30.0

"Width of sloping portion of embankment (s1)"
20.0

"Distance foundation extends to right of embankment toe (w2)"
0.0

"Height of embankment (h1)"
10.0

"Thickness of foundation layer (h2)"
0.0

"Number of x-elements in embankment (nx1)"
20

"Number of x-elements to right of embankment toe (nx2)"
0

"Number of y-elements in embankment (ny1)"
10

"Number of y-elements in foundation (ny2)"
0
```

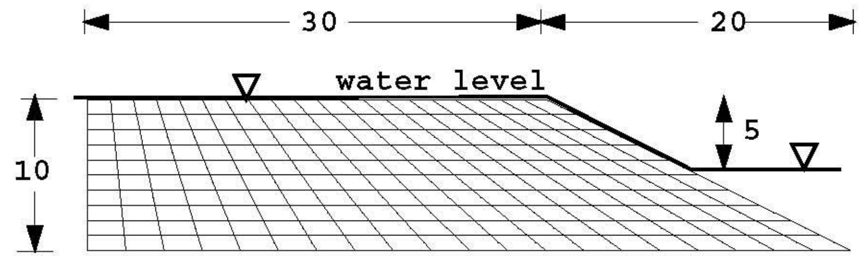


Fig 6.1 Finite element mesh for Example 6

Rapid drawdown from full submergence, homogeneous

$\phi' = 20^\circ$
$c' = 10$
$\gamma = 20$

```
"Number of different property groups (np_types)"
1

"Material properties (phi,c,psi,gamma,e,v) for each group"
20.0   10.0  0.0  20.0  1.e5  0.3

"Property group assigned to each element (etype, data not needed if np_types=1)"

"Pseudo-static analysis: Horizontal acceleration factor (k_h)"
0.0

"Number of free surface points and their coordinates (nosurf, surf(2,nosurf))"
4
  0.0    0.0
 30.0    0.0
 40.0   -5.0
 50.0   -5.0

"Unit weight of water (gam_w)"
9.81

"Iteration ceiling (limit)"
500

"Factor of safety tolerance (fos_tol)"
0.05
```

Output for Example 6 (`ex6.res`)

0.5000	0.8548E-02	24
1.0000	0.1272E-01	111
1.0156	0.1327E-01	179
1.0312	0.1607E-01	500

```
Estimated Factor of Safety =      1.03
```

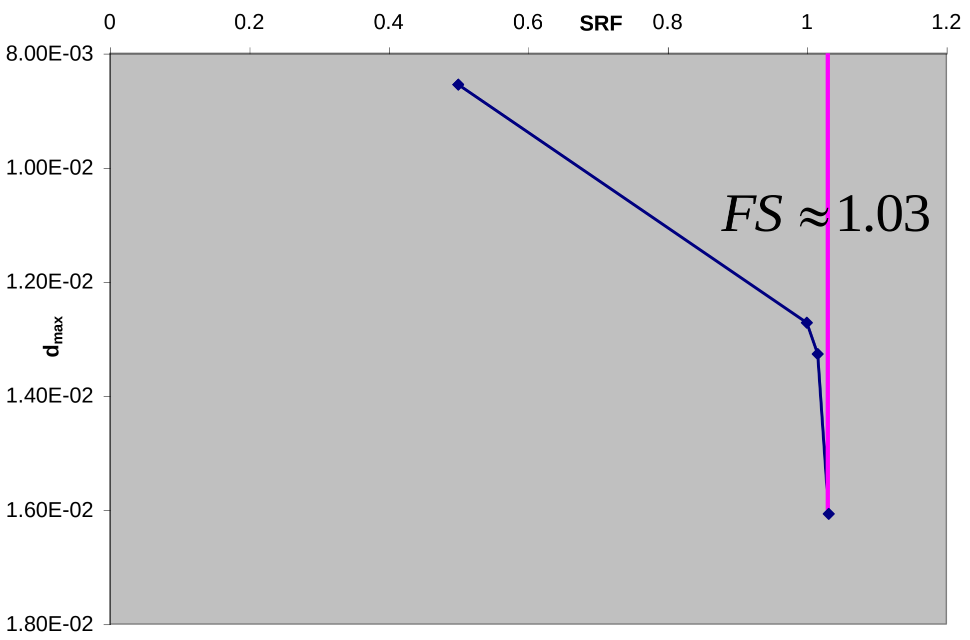


Fig 6.2 SRF vs. d_{max} for Example 6

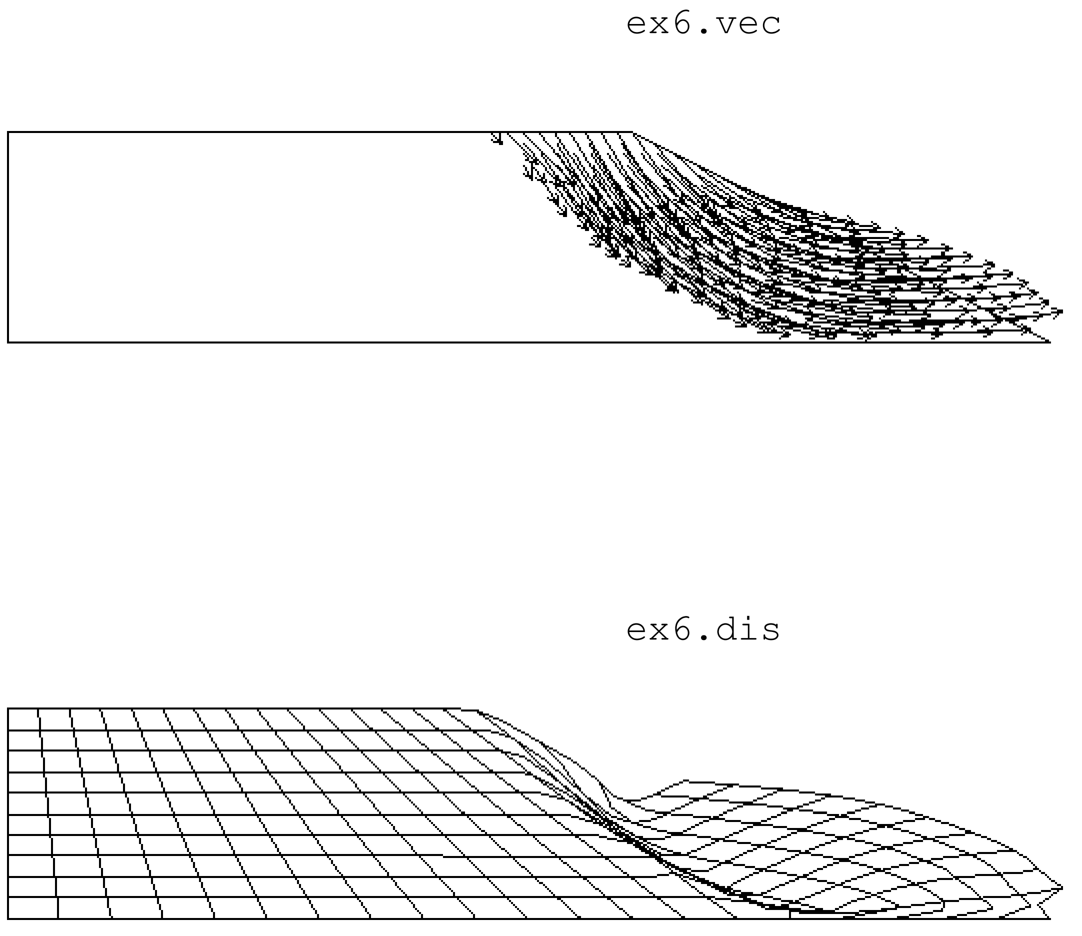


Fig 6.3 Displacement vectors and deformed mesh at failure for Example 6

Example 7: A homogeneous slope subjected to a horizontal pseudo-acceleration

The stability analysis is of a homogeneous slope subjected to a horizontal acceleration factor of $0.25g$ as shown in Figure 7.1

Data for Example 7 (`ex7.dat`)

```
'Example 7: A homogeneous slope subjected to a horizontal pseudo-acceleration'

"Width of top of embankment (w1)"
30.0

"Width of sloping portion of embankment (s1)"
20.0

"Distance foundation extends to right of embankment toe (w2)"
30.0

"Height of embankment (h1)"
10.0

"Thickness of foundation layer (h2)"
10.0

"Number of x-elements in embankment (nx1)"
50

"Number of x-elements to right of embankment toe (nx2)"
30

"Number of y-elements in embankment (ny1)"
10

"Number of y-elements in foundation (ny2)"
10
```

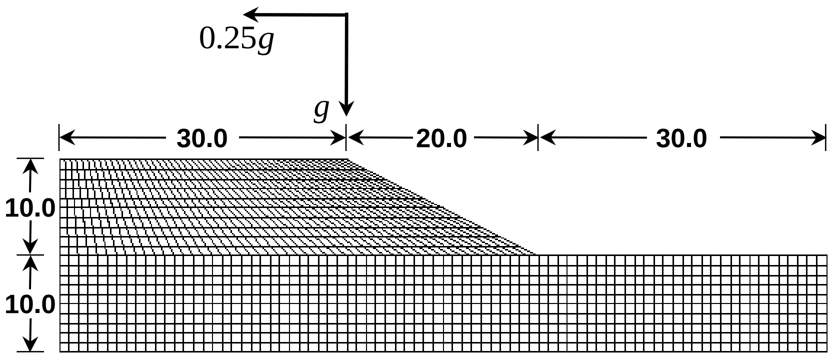


Fig 7.1 Finite element mesh for Example 7

Homogeneous slope with a horizontal acceleration of 0.25*g*

$$\phi' = 30°$$

$$c' = 20.0$$

$$\gamma = 20.0$$

```
"Number of different property groups (np_types)"
1

"Material properties (phi,c,psi,gamma,e,v) for each group"
30.0  20.0  0.0  20.0  1.e5  0.3

"Property group assigned to each element (etype, data not needed if np_types=1)"

"Pseudo-static analysis: Horizontal acceleration factor (k_h)"
0.25

"Number of free surface points and their coordinates (nosurf, surf(2,nosurf))"
0

"Unit weight of water (gam_w)"
9.81

"Iteration ceiling (limit)"
2000

"Factor of Safety accuracy tolerance (fos_tol)"
0.05
```

Output for Example 7 (ex7.res)

0.5000	0.4984E-01	227
1.0000	0.5313E-01	31
1.2500	0.6154E-01	79
1.3750	0.6896E-01	350
1.3906	0.6978E-01	599
1.4062	0.8632E-01	2000

```
Estimated Factor of Safety =       1.41
```

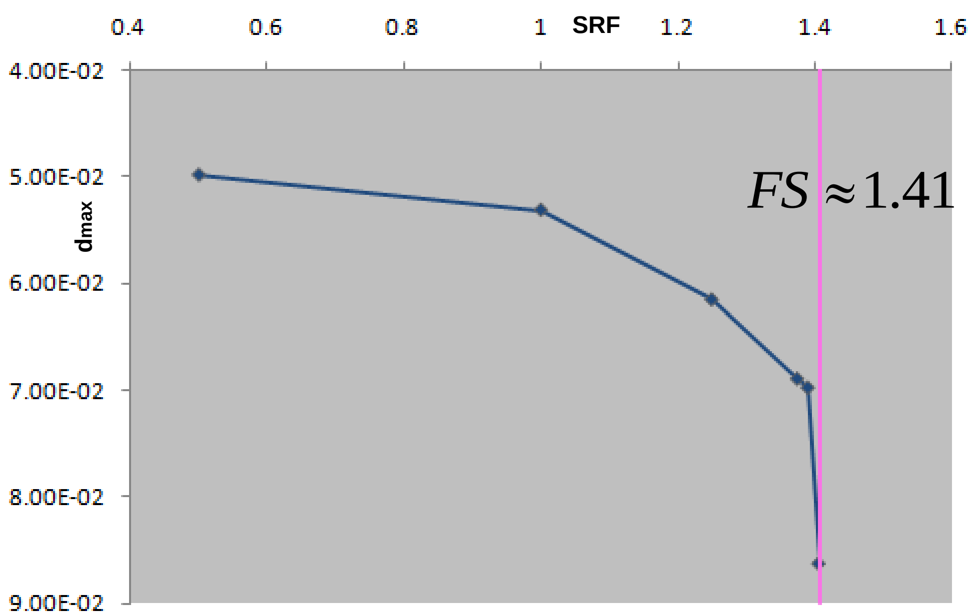


Fig 7.2 SRF vs. d_{max} for Example 7

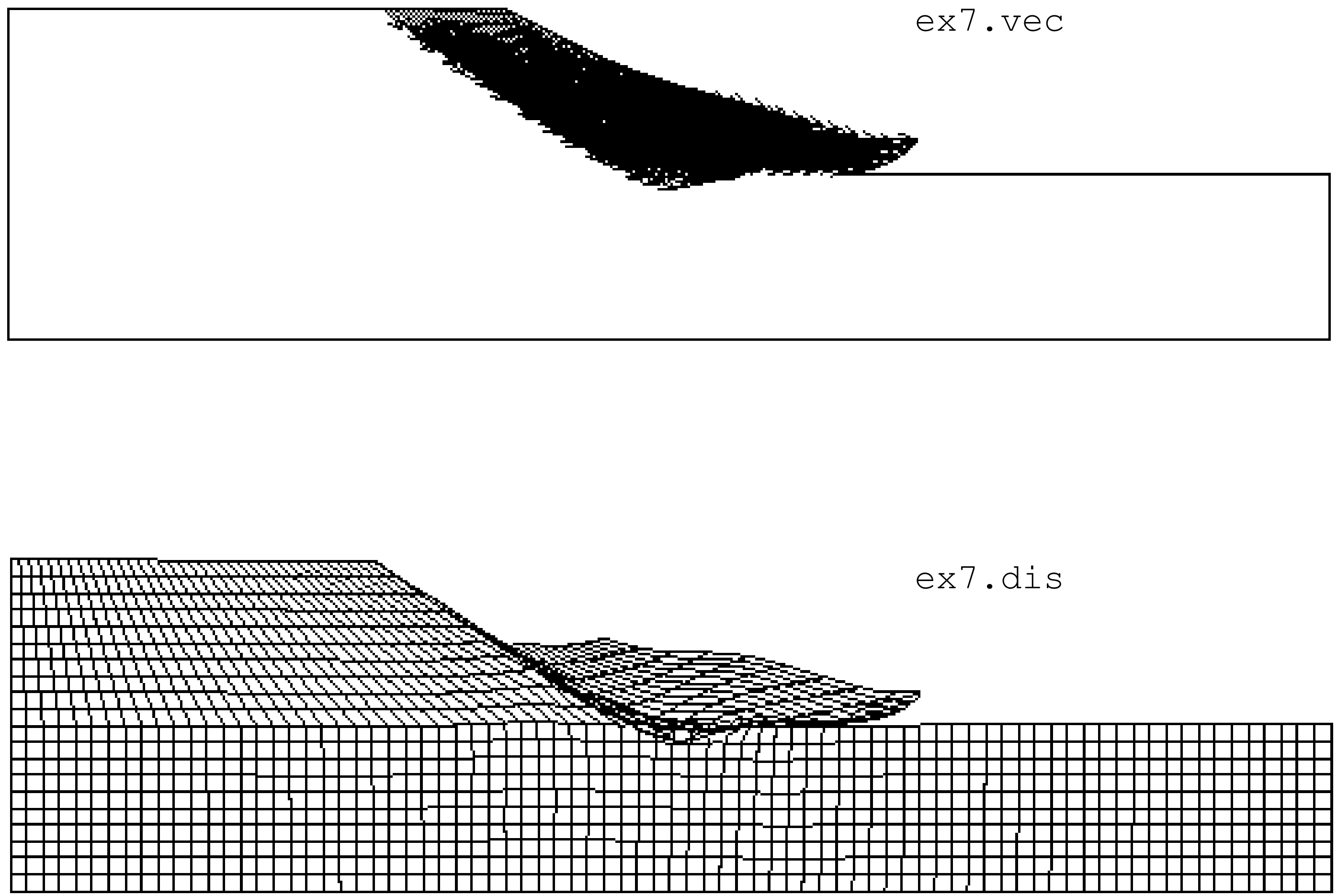


Fig 7.3 Displacement vectors and deformed mesh at failure for Example 7