



Temasdag Jordskjelv

Slope Stability Part 2 – Application

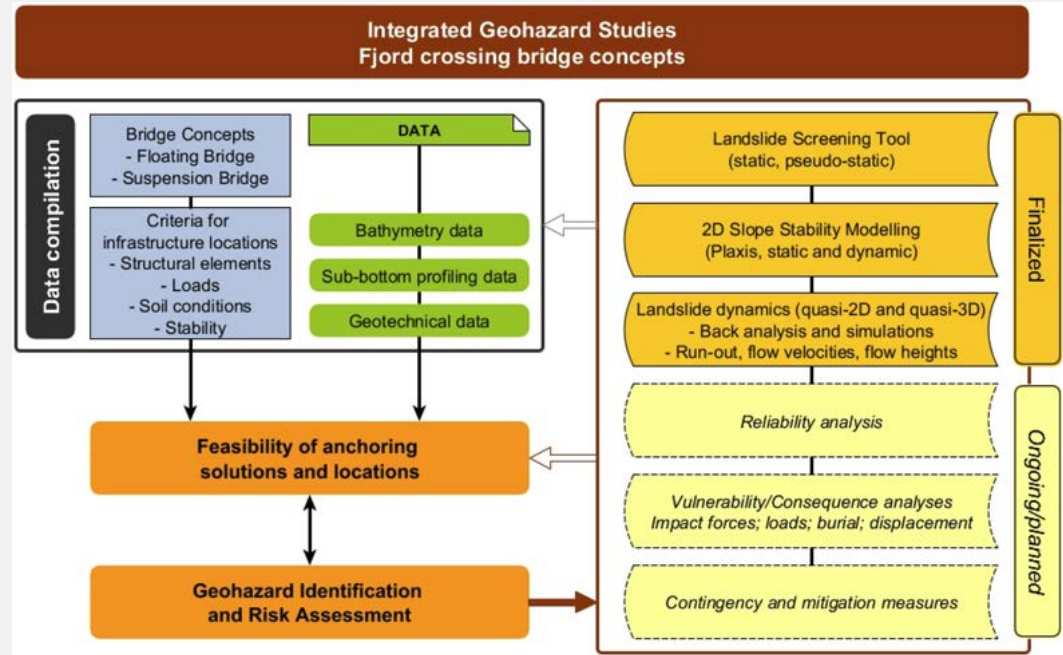
Brian Carlton

1 November 2022



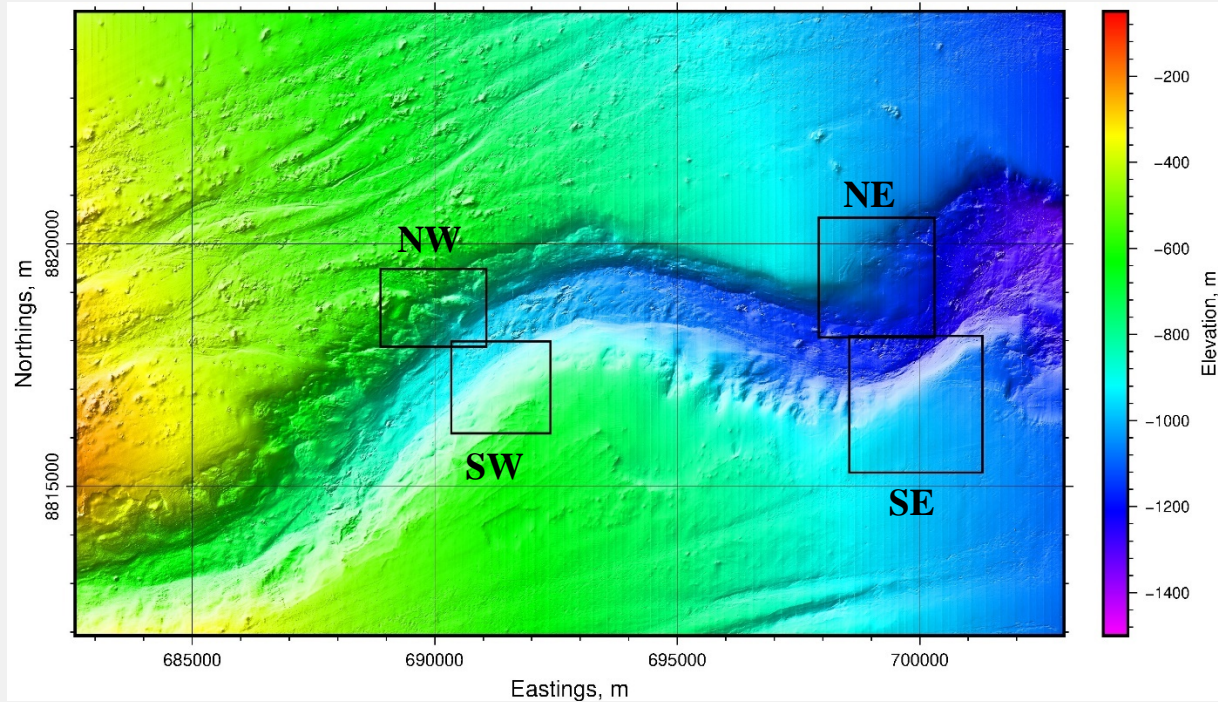
Outline

- Introduction to project
- Input parameters
- Methodology
 - 1D infinite slope
 - 2D deterministic LEM
 - 2D deterministic FEM
 - Probabilistic LEM and FEM
 - 2D dynamic analyses in FEM
- Demonstration
- Conclusions

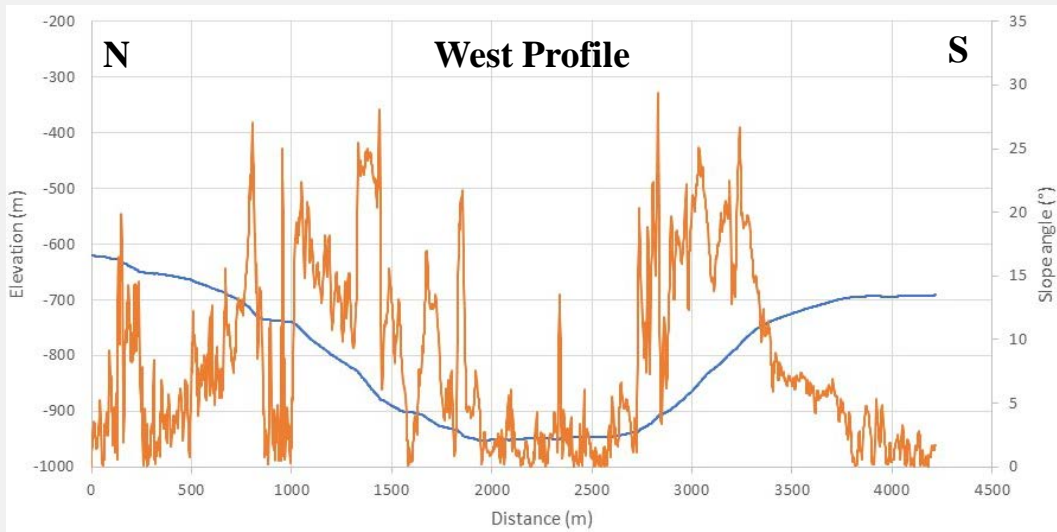


Introduction

- Scope: Slope stability analyses for 4 slopes along a deep-water canyon
- Located in moderately seismic area, dynamic analyses required
- Compare LEM with FEM

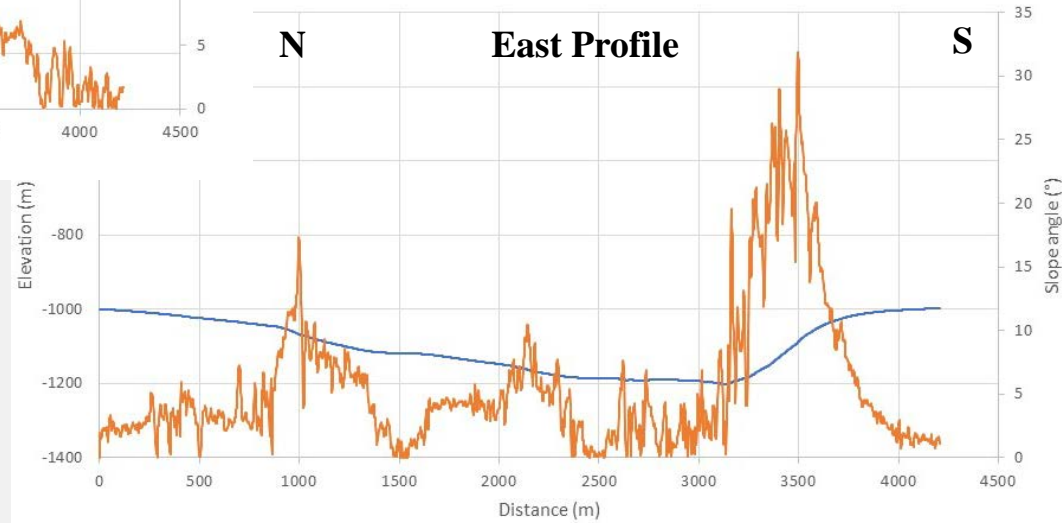


Background



- The Eastern crossing has drift-like sediments on the N flank and exposed deeper strata on S flank.
- Erosion or shallow landslides seen on the drift-like sediments

- The Western Crossing has exposed strata on S flank and likely slump-like landslides on the N flank.
- The toes of the slump blocks appear to be buried by canyon floor deposits indicating a very high age

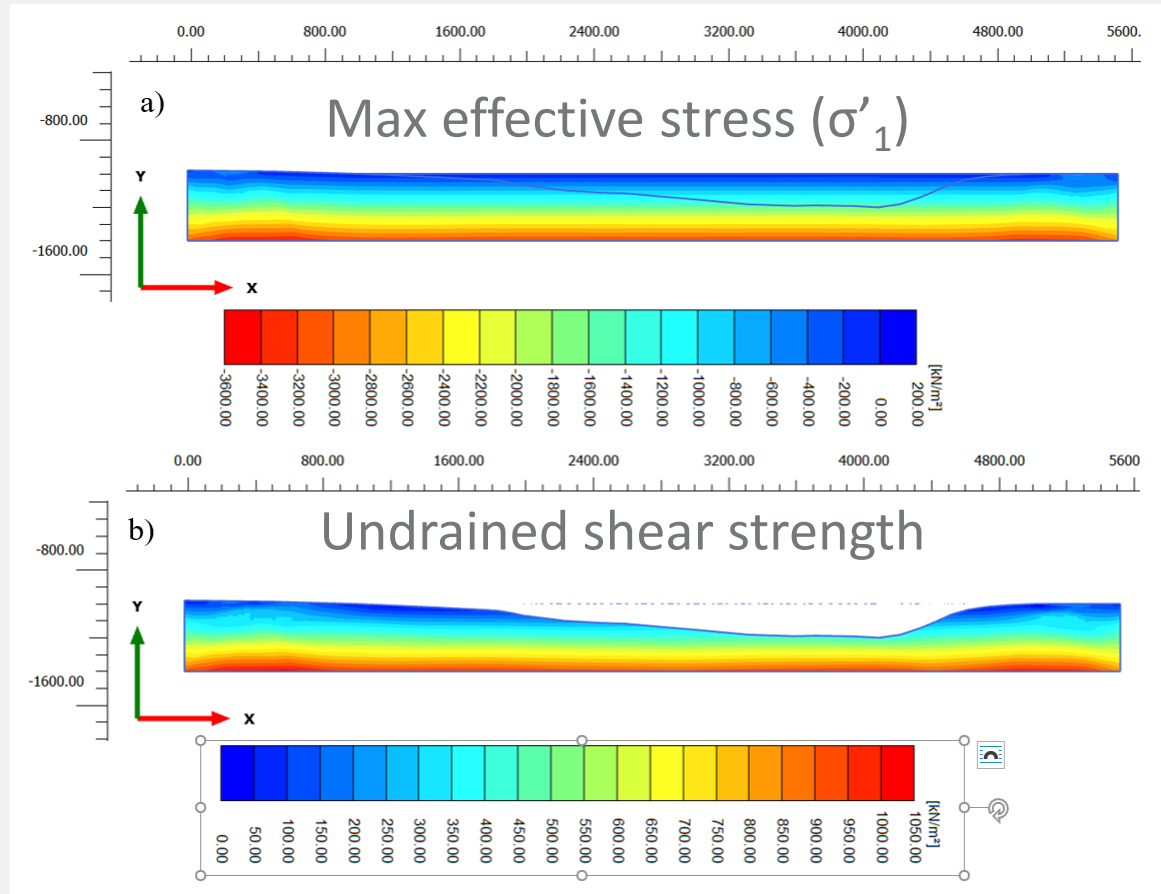


Background

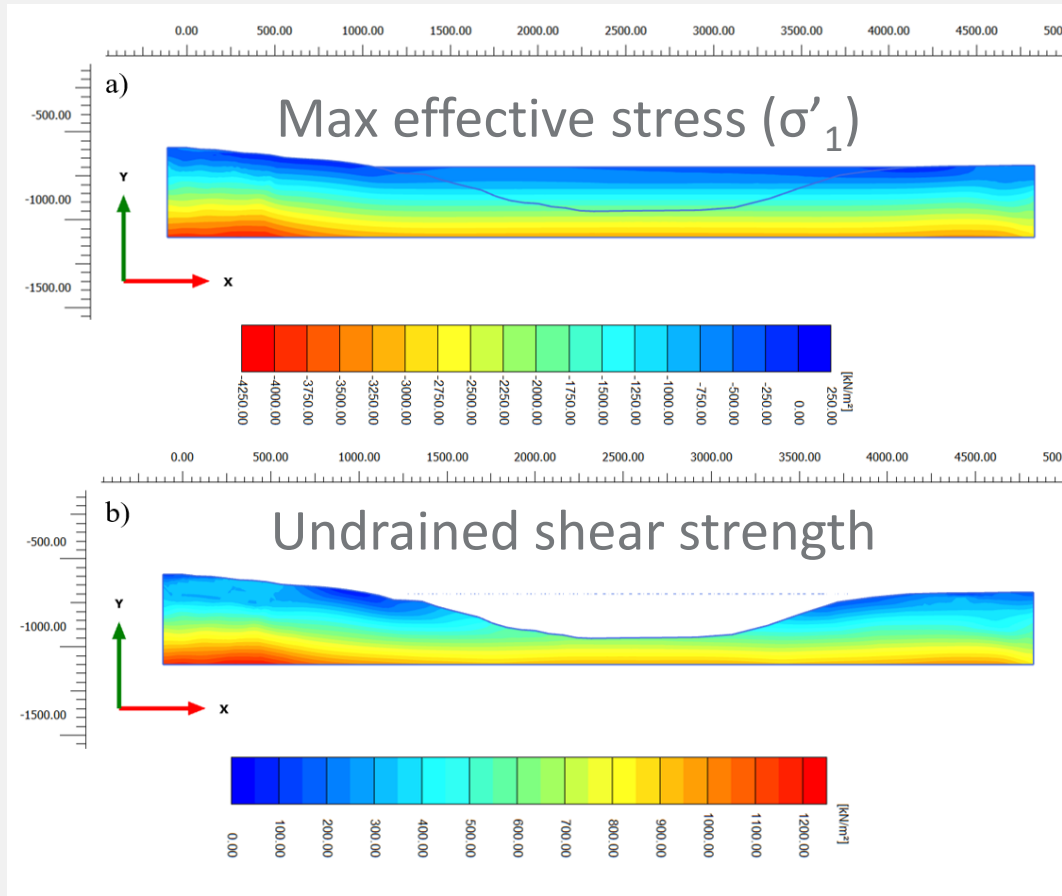
Design Parameters		Return Period (yr)	
		200	2000
Mw		6	6.1
PGA	$V_{s_{30}} = 180 \text{ m/s}$	0.155	0.335
	$V_{s_{30}} = 275 \text{ m/s}$	0.133	0.308
	$V_{s_{30}} = 550 \text{ m/s}$	0.105	0.257
	$V_{s_{30}} = 760 \text{ m/s}$	0.092	0.229
	$V_{s_{30}} = 1100 \text{ m/s}$	0.079	0.197

Layers	N-W	S-W	N-E	S-E
SAND	0-4.5 (2) m	-	0-1.9 m	0-1.9 m
Sandy/Clayey SILT Silty/Sandy CLAY	4.5(2) -7.4 m	-	1.9-18 m	1.9-17 m
CLAY	7.4-200 m	0 - 200 m	18-200 m	17-200 m

Eastern Crossing Shear Strength: Erosion Model

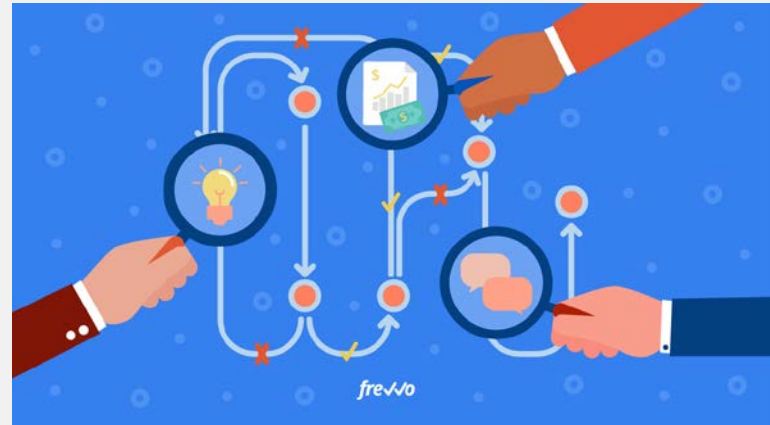


Western Crossing Shear Strength: Erosion Model



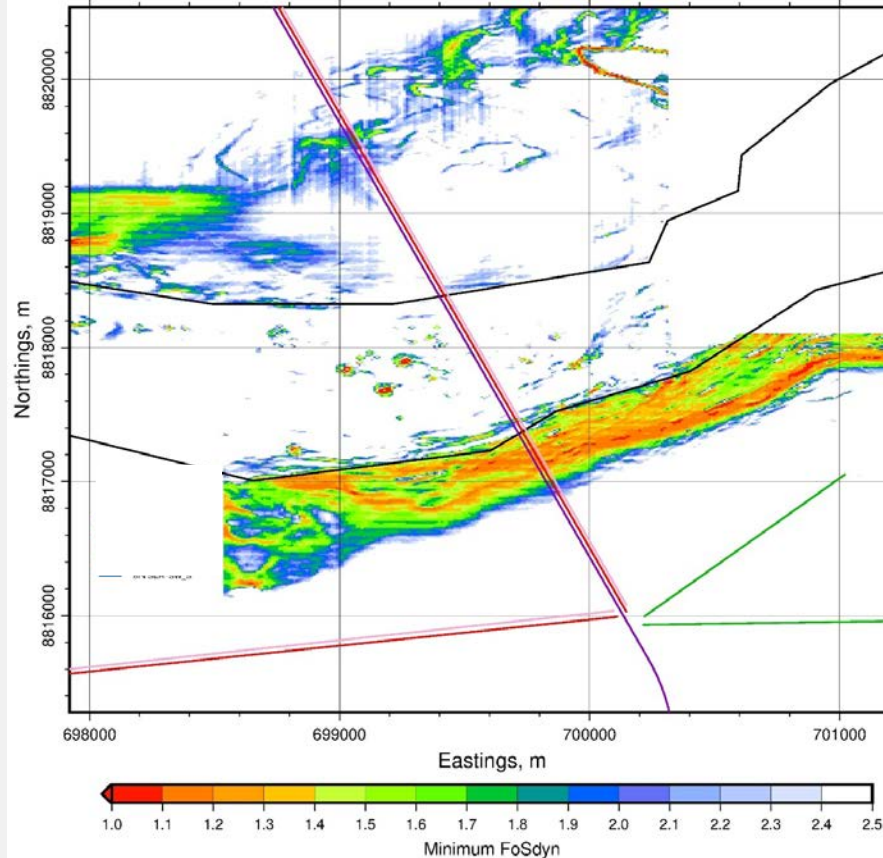
Methodology

- Compile and interpret all available geological, geophysical, and geotechnical data
- 1D infinite static and pseudo-static slope stability analyses
- 2D static and pseudo-static limit equilibrium (LEM) analyses
- 2D static and pseudo-static finite element analyses (FEM)
- Probabilistic LEM and FEM
- 2D dynamic analyses in FEM

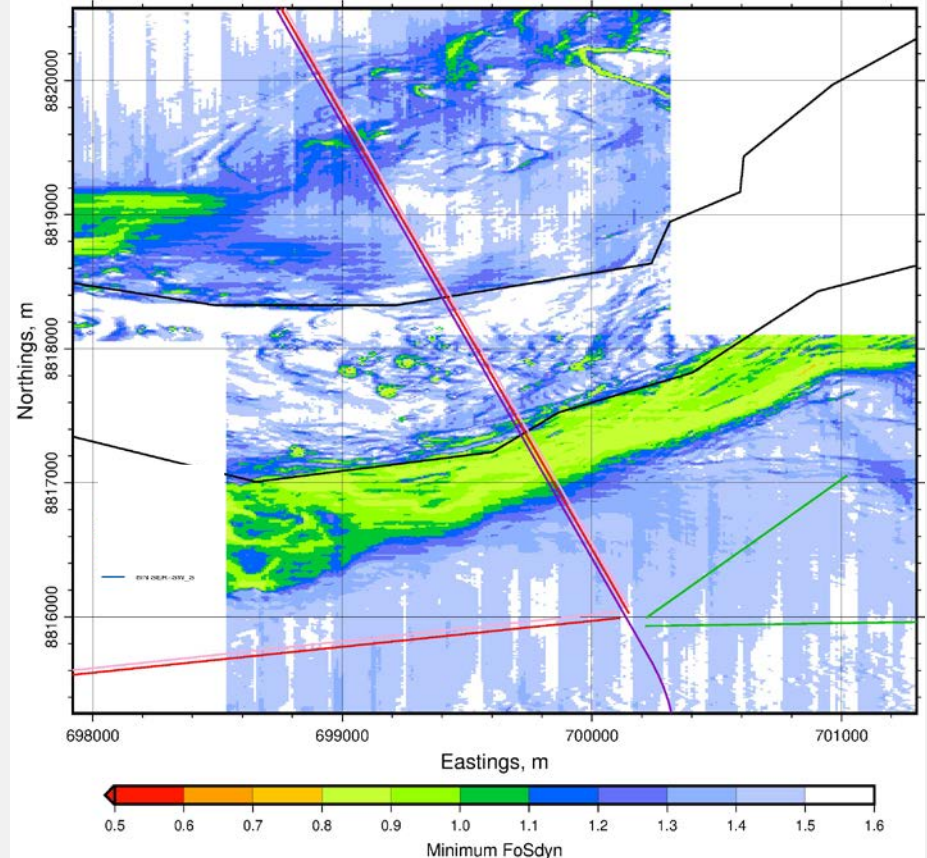


1D Screening: Eastern Crossing FoS

200 year return period

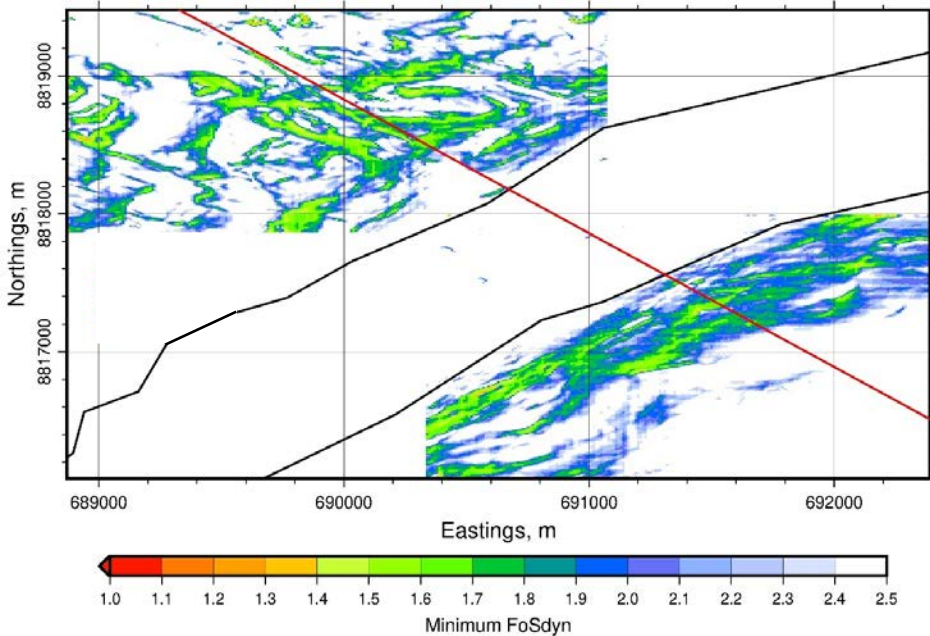


2000 year return period

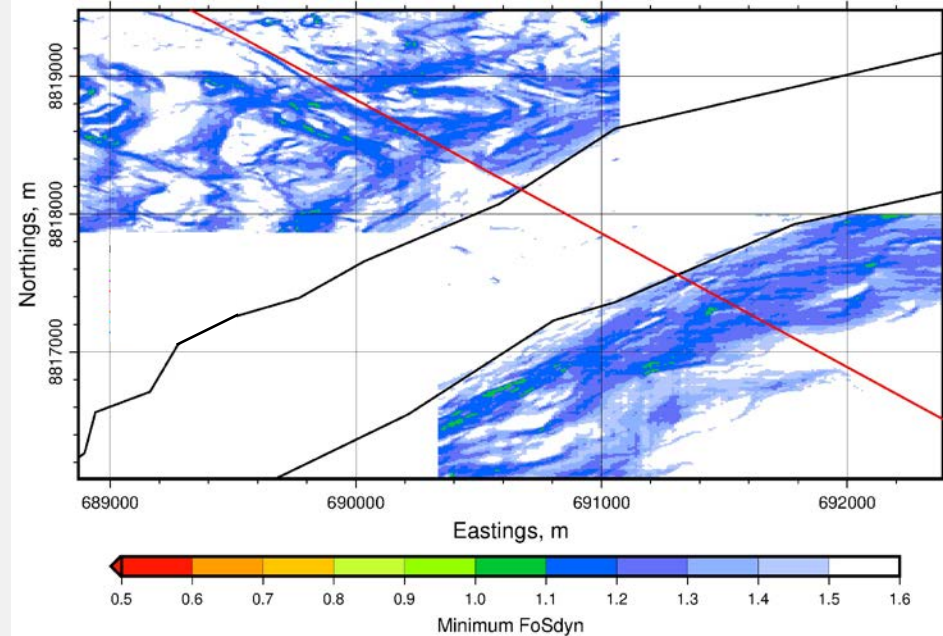


1D Screening: Western Crossing FoS

200 year return period

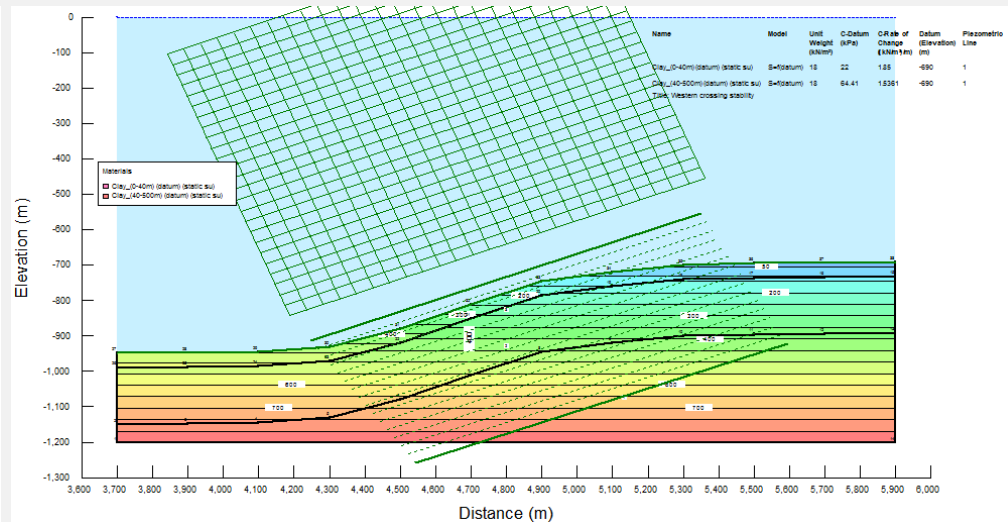
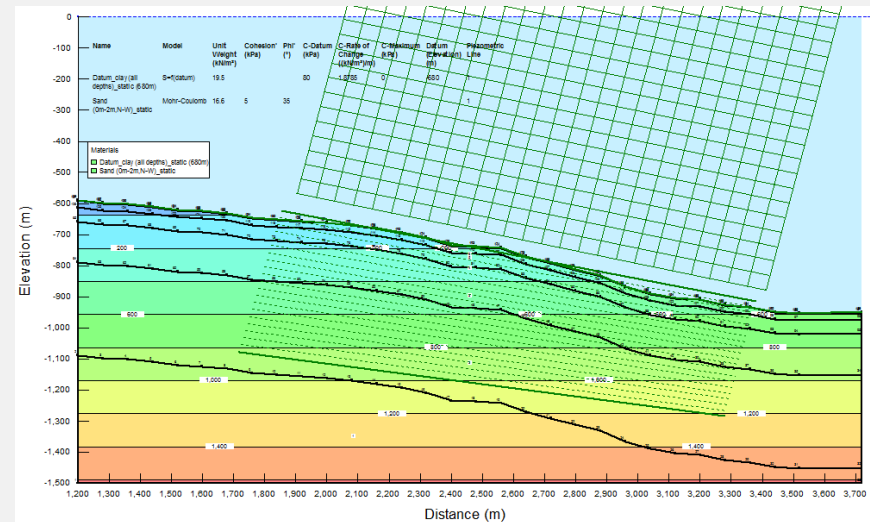


2000 year return period

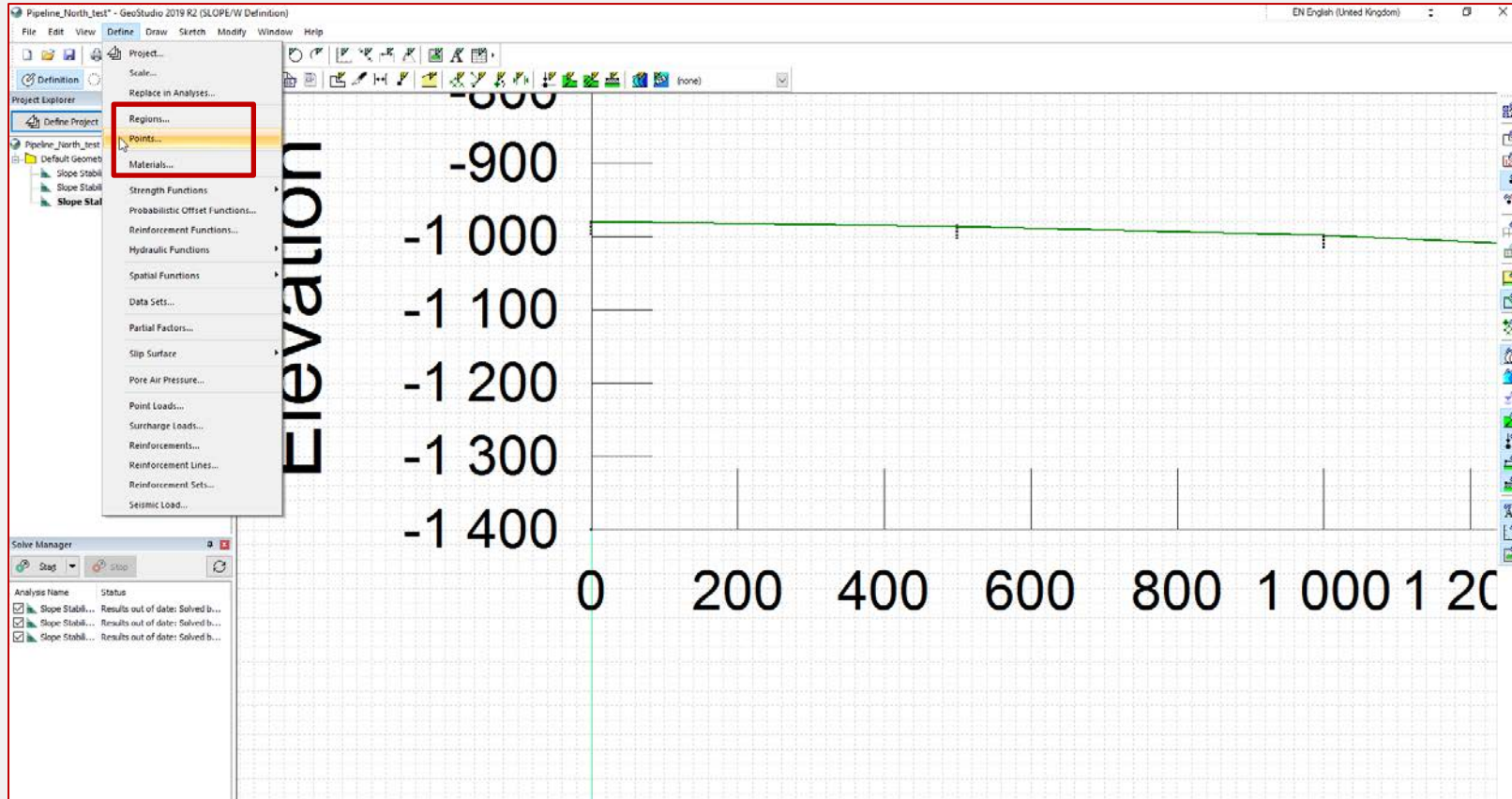


Limit Equilibrium Method: SLOPE/W

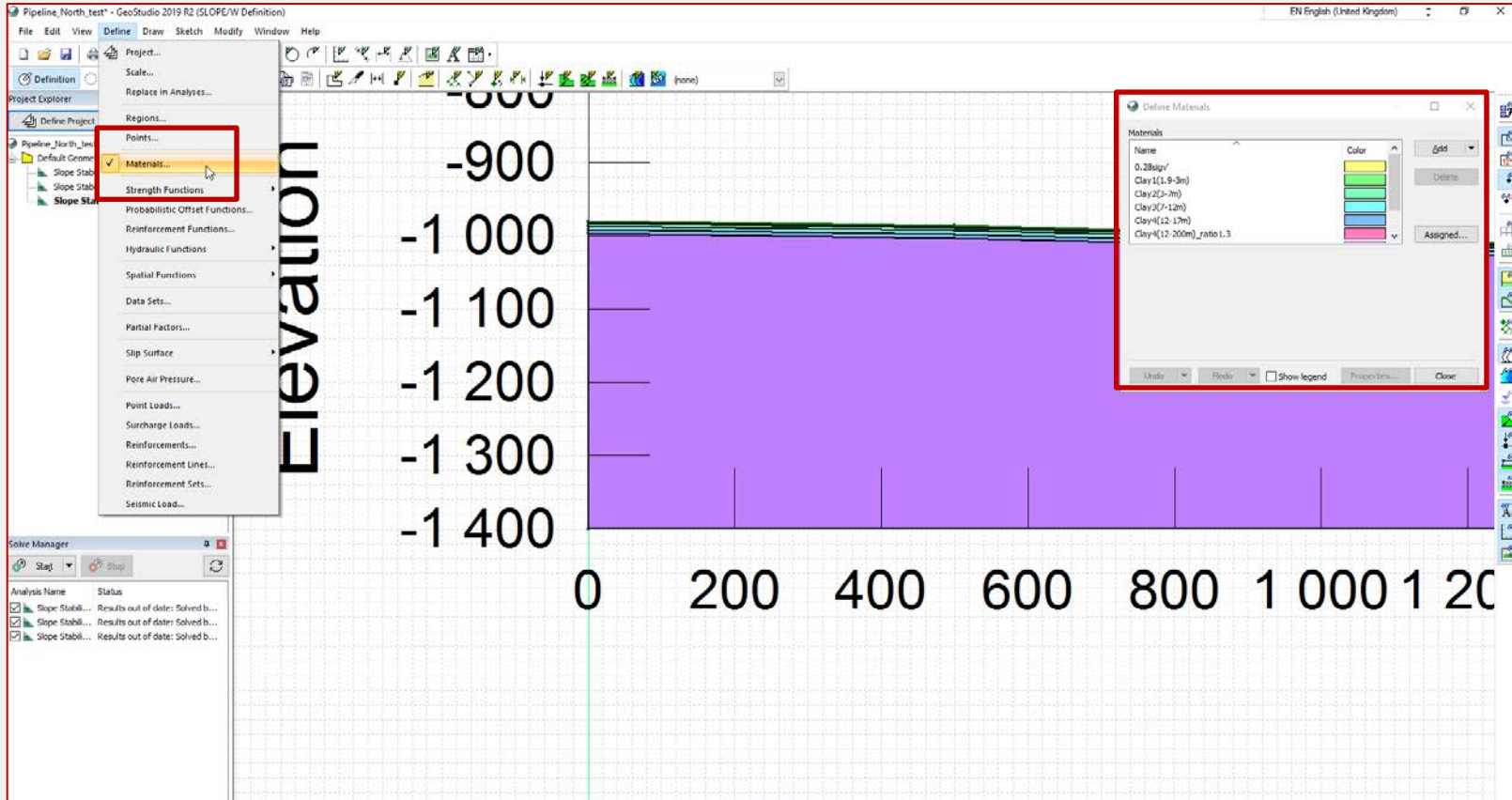
- Morgenstern-Price method
- Grid of slip surface centers with predefined slip radii
- Optimization technique used to allow non-circular slip surfaces
- Strength defined by elevation



Input parameter/ define point, region



Input parameter/ material properties




Input parameter/ material properties

Define Materials

Materials

- 0.28sigv'
- Clay1(1.9-3m)
- Clay2(3-7m)
- Clay3(7-12m)
- Clay4(12-17m)
- Clay4(12-200m)_ratio1.3
- Clay5(17-200m)
- New Material
- Sand_phi32.5

Name: Clay2(3-7m) Color:  Set...

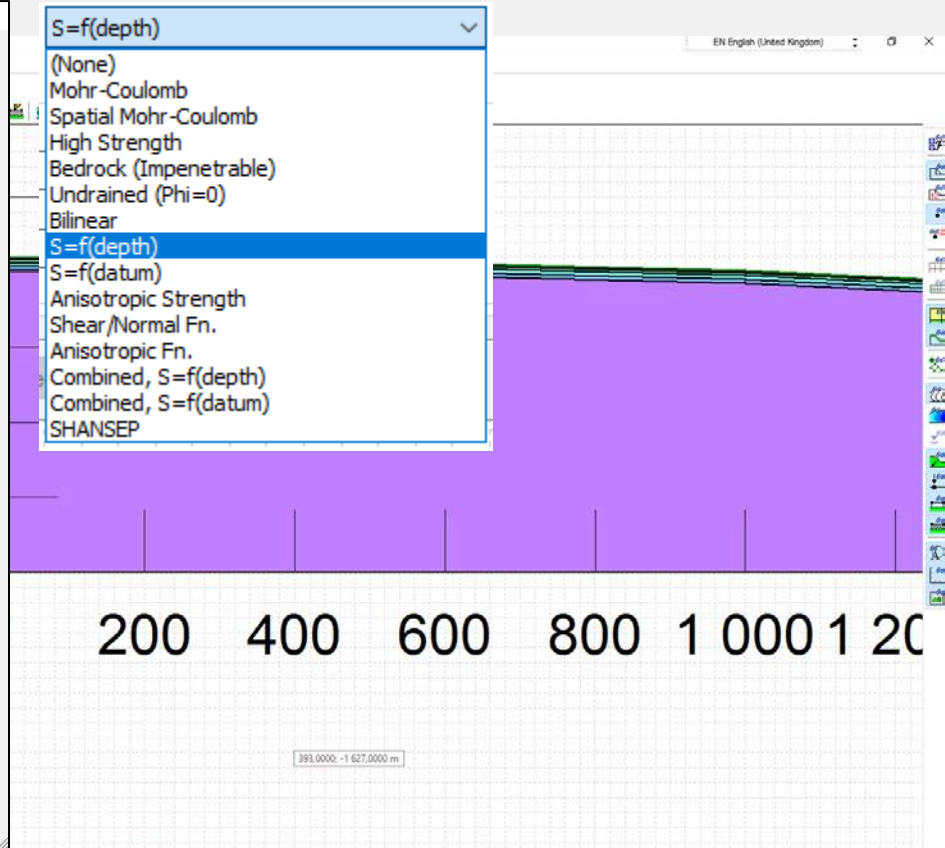
Slope Stability

Material Model: $S=f(\text{depth})$

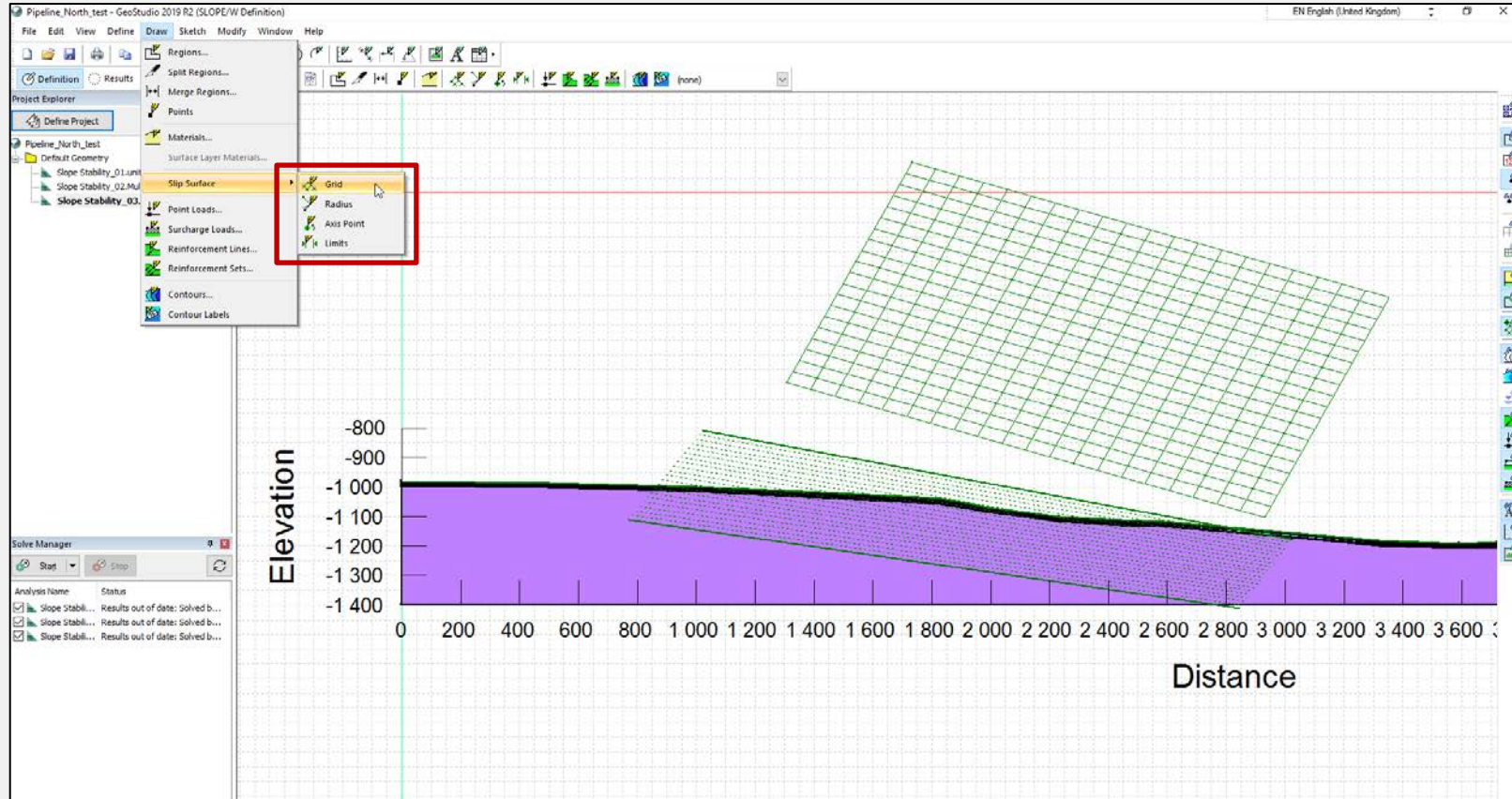
Basic Advanced

Unit Weight:	C - Rate of Change:
8 kN/m ³	0,4 (kN/m ²)/m
C - Top of Layer:	C - Maximum:
55 kPa	0 kPa

Undo Redo Show legend Properties... Close



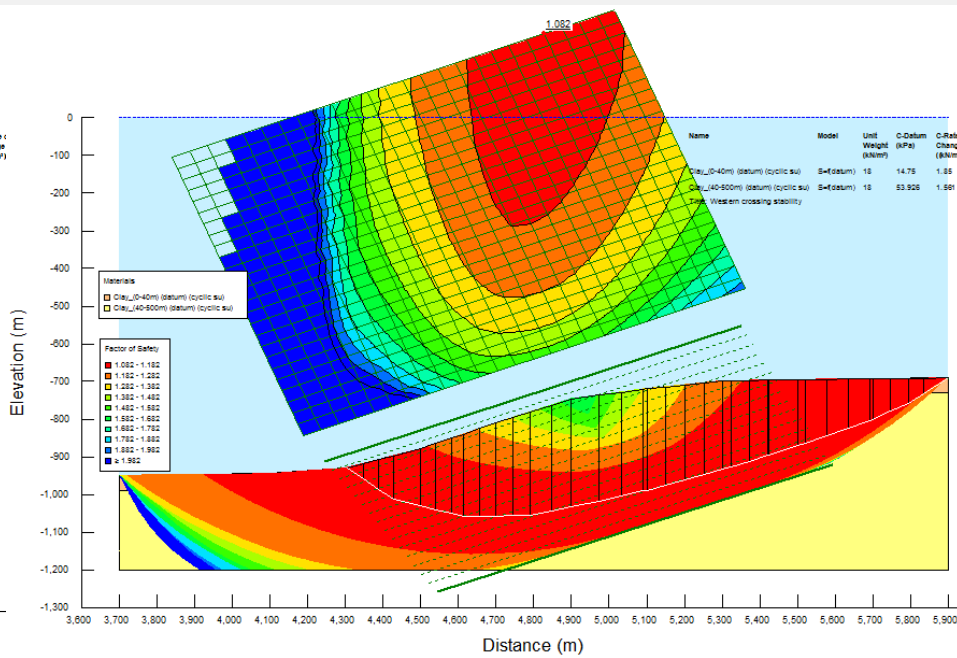
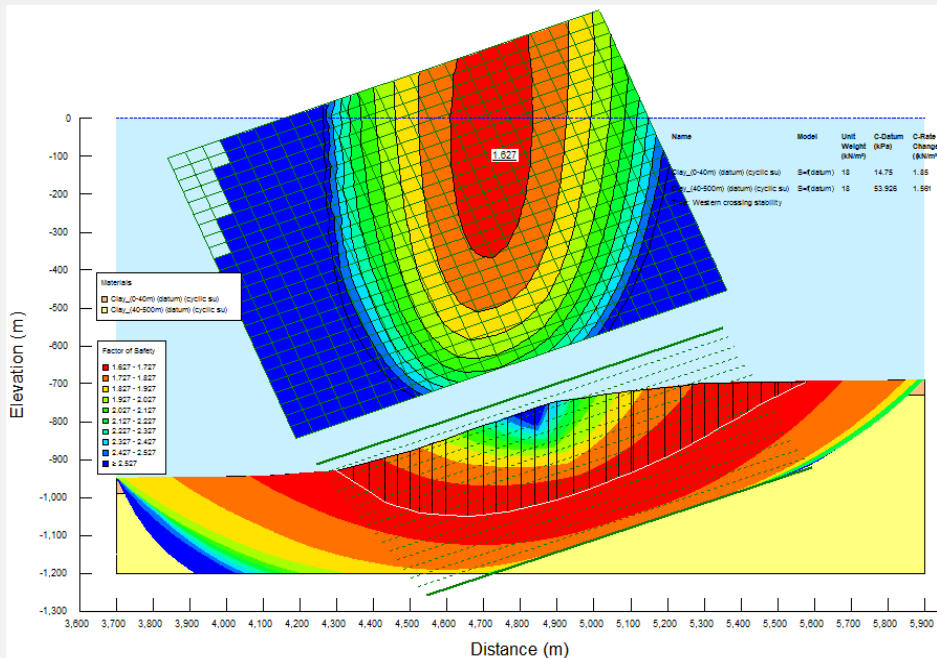
Input parameter/ set failure radius and grid points



Results: Southwest Slope

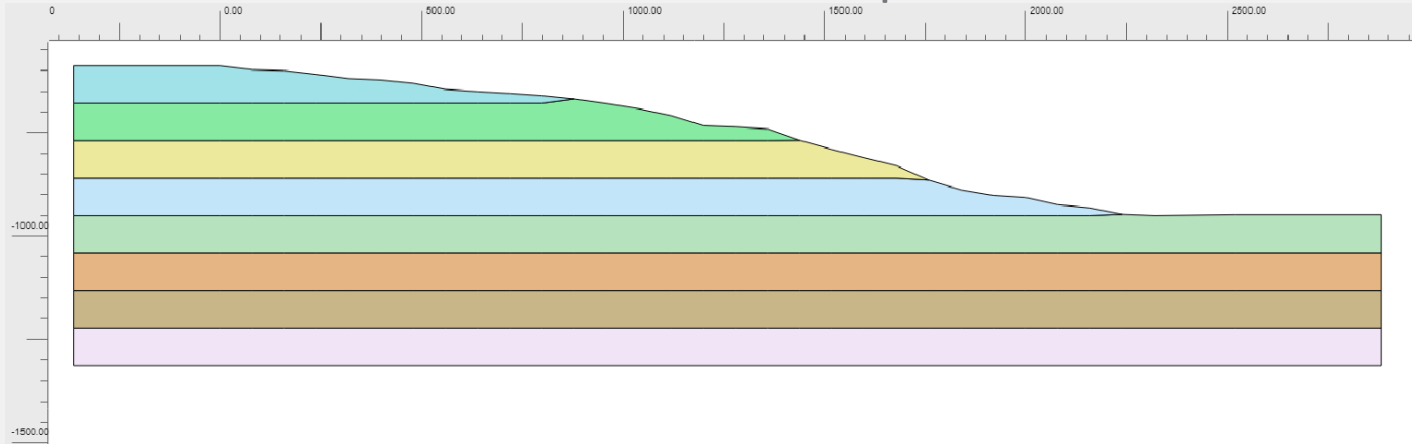
200 year return period

2000 year return period



Finite Element Method: PLAXIS

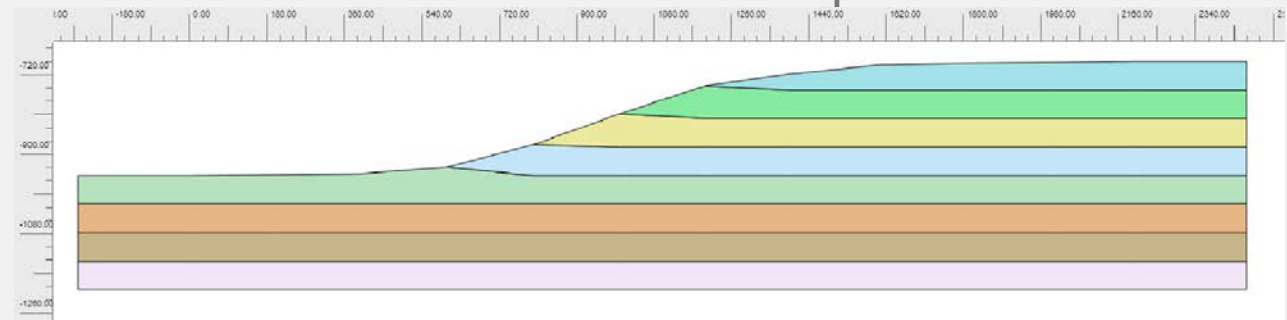
North West Slope



➤ Used the same profiles, k_H , and soil unit weights and strengths as LEM

➤ Mohr-Coulomb constitutive model

South West Slope



Comparison of Results

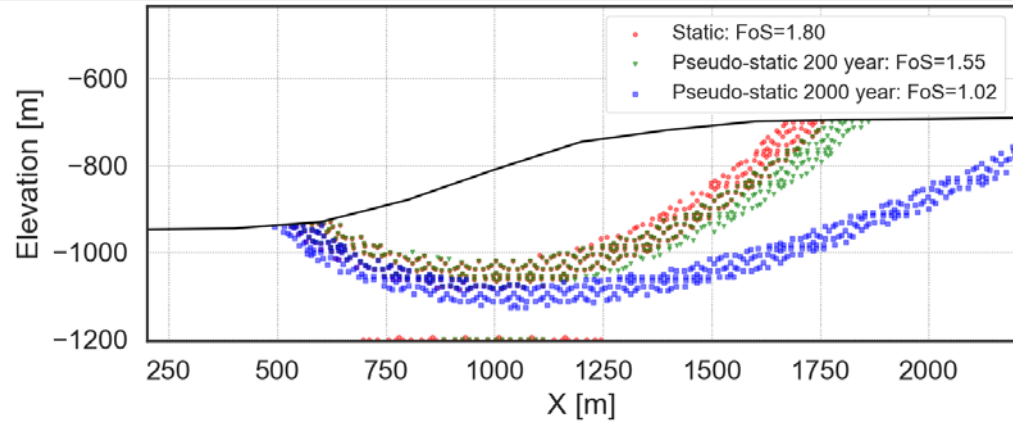
FEM Results

Profile	Static	Pseudo-static FoS	
	FoS	200-yr RP	2000-yr RP
NE	3.82	3.49	2.00
SE	1.84	1.62	1.16
NW	1.71	1.69	1.37
SW	1.80	1.55	1.02

LEM Results

Profile	Static	Pseudo-static FoS	
	FoS	200-yr RP	2000-yr RP
NE	4.16	3.27	1.92
SE	1.93	1.67	1.22
NW	1.90	1.76	1.48
SW	1.93	1.63	1.08

South West Slope

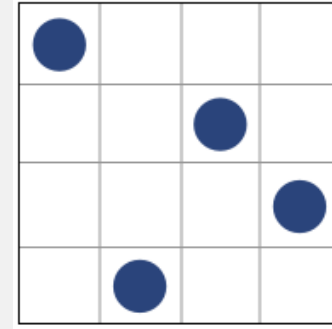


➤ LEM and FEM predict similar FoS and most likely failure planes for static and pseudo-static analyses

Probabilistic Analyses

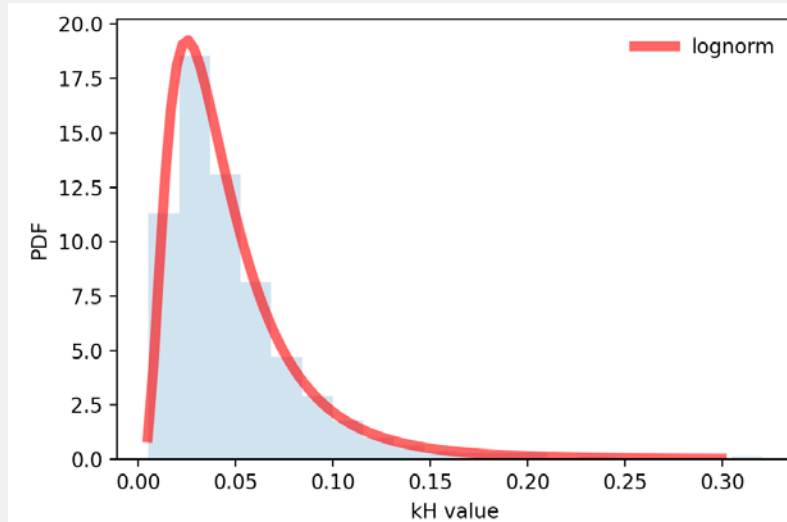
LEM

- Monte Carlo simulation with 20,000 realizations
- Varied k_H and cyclic strength
- Normal distributions



FEM with python scripting

- Monte Carlo with Latin Hypercube sampling, 500 realizations
- Varied k_H and cyclic strength
- Lognormal and Beta distributions



Probabilistic Analyses: Results

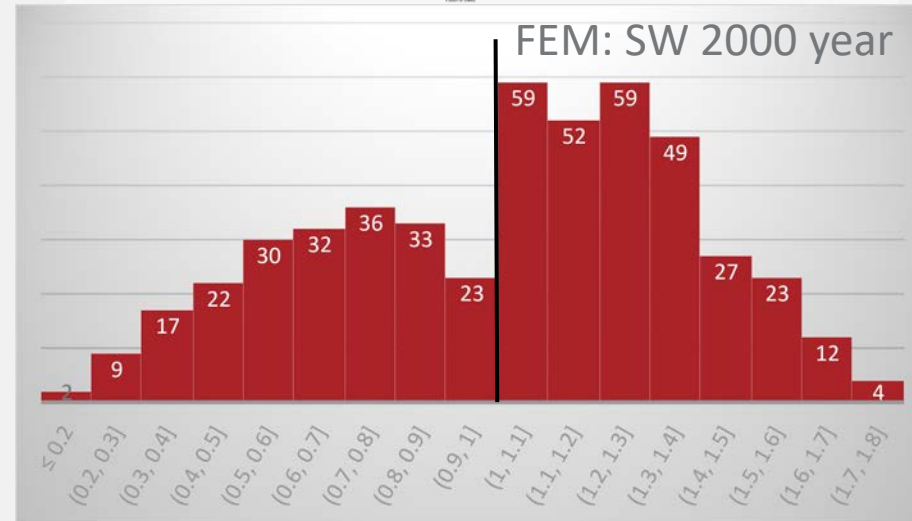
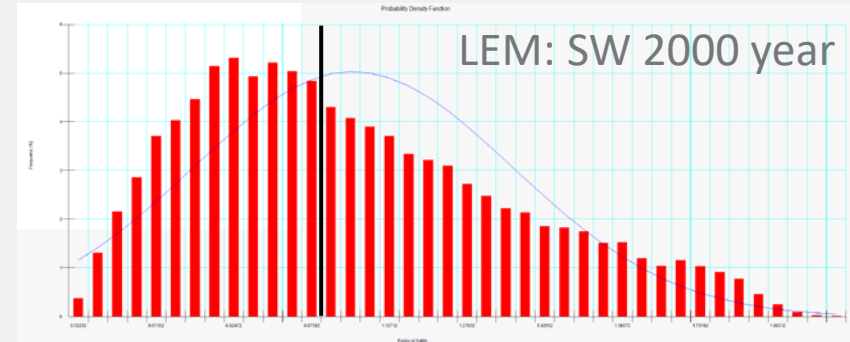
- Probability of FoS < 1 low for 200 yr, high for 2000 yr
- Similar values for FEM and LEM

FEM 200 year

Profile	Mean	Std. dev.	Median	$P_f = P[\text{FoS} < 1]$ (%)
NE	3.01	0.51	3.09	~0.06
NW	1.87	0.12	1.89	~ $6.0 \cdot 10^{-3}$
SE	1.54	0.15	1.56	0.6
SW	1.58	0.19	1.62	1.2

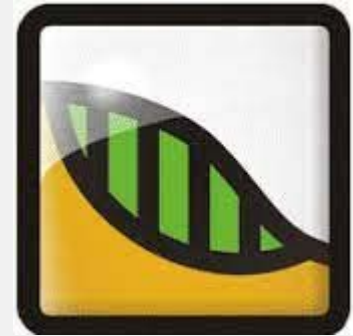
FEM: 2000 year

Profile	Mean	Std. dev.	Median	$P_f = P[\text{FoS} < 1]$ (%)
NE	1.95	0.67	1.93	8.0
NW	1.49	0.28	1.52	6.0
SE	1.06	0.33	1.13	36 41
SW	1.02	0.36	1.08	45 54



Dynamic FEM in PLAXIS

- Static and pseudo-static deterministic and probabilistic analyses with LEM and FEM give similar results
- When to use FEM?
 - More advanced constitutive models
 - Complicated geometry requiring 3D analyses
 - More flexibility
 - Dynamic analyses



Dynamic FEM in PLAXIS

Main differences with static analyses:

- Specification of acceleration time series
- Soil damping
- Need more advanced constitutive models
- Numerical considerations
 - Mesh size
 - Boundary conditions
 - Calculation type

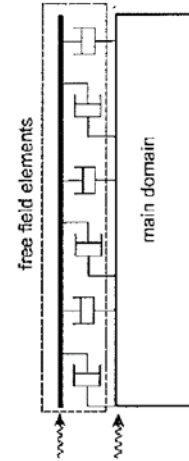
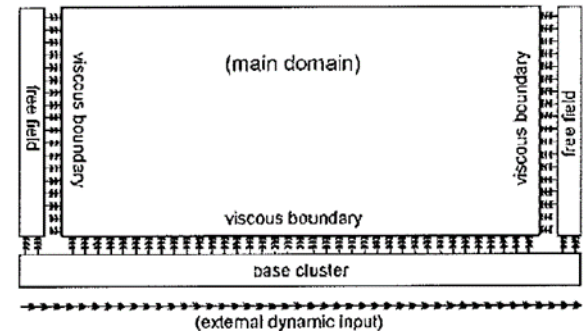
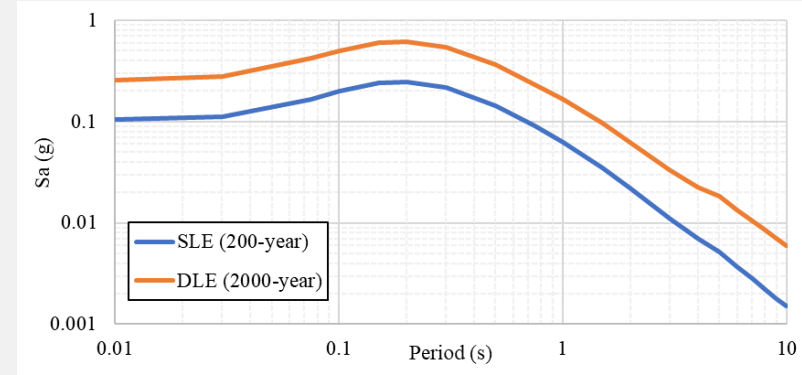


Figure 1 Free field elements



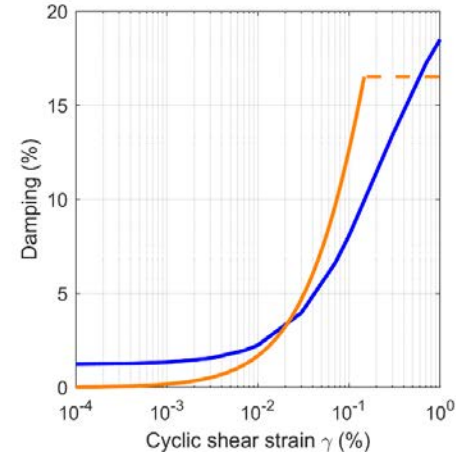
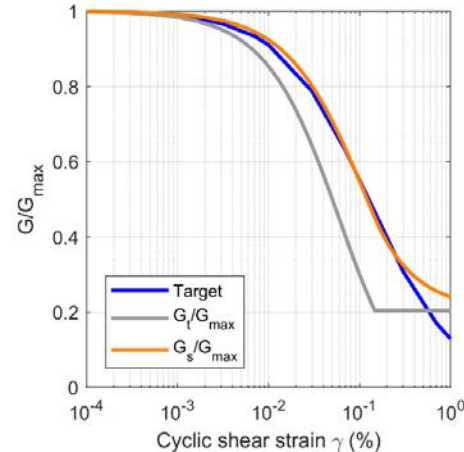
Dynamic FEM in PLAXIS

- 3 acceleration time series scaled to UHS for 200 and 2000 year return periods
- Free field lateral boundaries and a compliant boundary at the base
- HSsmall constitutive model



$$\frac{G_s}{G_{max}} = \frac{1}{1 + 0.385 \times \left(\frac{\gamma}{\gamma_{0.7}}\right)}$$

$$G_0 = G_0^{ref} \left(\frac{c \cos\phi + \sigma'_3 \sin\phi}{c \cos\phi + p^{ref} \sin\phi} \right)^m$$

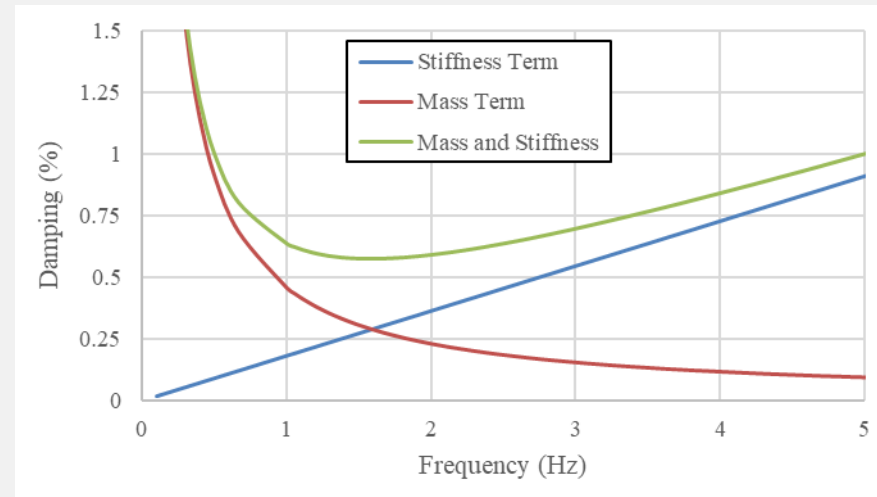


Rayleigh Damping

$$C = \alpha[M] + \beta[K]$$

$$\begin{bmatrix} \zeta_i \\ \zeta_j \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \frac{1}{2\pi f_i} & 2\pi f_i \\ \frac{1}{2\pi f_j} & 2\pi f_j \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

- HSsmall constitutive model accounts for damping at larger strains, but need Rayleigh damping for small strains and other models
- Rayleigh damping is viscous damping that is proportional to a linear combination of mass and stiffness
- ζ_i and ζ_j are the target damping ratios and f_i and f_j are target frequencies



PLAXIS Demonstration

Boundary interfaces

The screenshot displays the PLAXIS software interface. The main window shows a 2D cross-section of a soil structure with various layers and boundary conditions. The x-axis ranges from -500.00 to 3000.00, and the y-axis ranges from -1500.00 to 500.00. The structure consists of several layers: a top layer (blue), a middle layer (green), a bottom layer (yellow), and a base layer (orange). The structure is supported by a foundation (brown) and a pile (black). The interface includes a menu bar (File, Edit, Structures, Options, Expert, Help), a toolbar, a Selection explorer, a Model explorer, and a Command line.

The Model explorer on the left shows the following structure:

- Attributes library
- Stratigraphy
- Geometry
- Groups
- Interfaces
- Line displacements
- Soils

The Command line shows the following text:

```
Session | Model history
commands can be called as follows:
  command [target] [param1 [param2 [...]]]
for example:
  point 1 2
  info point_1
Use the "info" command to access information about an object
Use the "commands" command to view the command parameters expected by the commands of the target object
0273> #~ running PLaxis2DKInput.exe 22.1.0.452
OK
#174v_entruststructures
Command
```

PLAXIS Demonstration

Set line displacement on bottom of model

The screenshot shows the PLAXIS software interface. The main window displays a cross-section of a soil model with a horizontal line at the bottom boundary. The 'Model explorer' on the left shows a tree view with 'LineDisplacement_1' selected, indicating a 'Prescribed' displacement of 4.905 m. The 'Command line' at the bottom shows the following text:

```
Session Model history
Commands can be called as follows:
command [target] [param1 [param2 [...]]]
for example:
point 1 2
info point_1
Use the "info" command to access information about an object
Use the "commands" command to view the command parameters expected by the commands of the target object
0273> run -r PLAXIS2D\input.exe 22.1.0.452
OK
a174> _entstructures
```

PLAXIS Demonstration

Define earthquake loading

The screenshot shows the PLAXIS software interface with the 'Multipliers' dialog box open. The dialog box is divided into several sections:

- Displacement multipliers:** A list of multipliers, with 'EQSTP183' selected.
- Name:** EQSTP183
- Signal:** Table
- Data type:** Accelerations
- Drift correction:**
- Table:** A table with columns: Time [s], Multiplier, and Transformed multiplier.
- Scaling type:** Scaling factor, Value: 1.000
- Signal:** Fourier spectra, Response spectra, Arias intensity
- Graph:** Dynamic multiplier (acceleration) vs Time [s]. The graph shows a blue line representing the transformed multiplier and a black line representing the multiplier.
- Buttons:** OK, Cancel, Load multipliers (highlighted with a red box), Add, Remove, Refresh.

The 'Model explorer (Phase_2)' on the left shows the 'DynLineDisplacement_1_1' multiplier selected, with a red box around it.

The 'EQSTP183.txt - Notepad' window on the right displays the following data:

```
EQSTP183.txt - Notepad
File Edit Format View Help
1700 0.02
0.0200 +3.476543E-06
0.0400 +4.244405E-06
0.0600 +4.204279E-06
0.0800 +5.589457E-06
0.1000 +6.362596E-06
0.1200 +8.279303E-06
0.1400 +9.723131E-06
0.1600 +1.202133E-05
0.1800 +1.391183E-05
0.2000 +1.628749E-05
0.2200 +1.799801E-05
0.2400 +1.894083E-05
0.2600 +1.637795E-05
0.2800 +6.328784E-06
0.3000 -1.697989E-05
0.3200 -5.406675E-05
0.3400 -9.512915E-05
0.3600 -1.292355E-04
0.3800 -1.631444E-04
```

PLAXIS Demonstration

Boundary Conditions

The screenshot displays the PLAXIS software interface for a 2D cross-section of a soil slope. The main window shows a cross-section with a horizontal axis from -500.00 to 3000.00 and a vertical axis from -1500.00 to -500.00. The slope is composed of several layers of soil, each represented by a different color. The layers from top to bottom are: light blue, green, yellow, light blue, green, orange, brown, and purple. The bottom boundary is a horizontal line at approximately -1500.00. The left boundary is a vertical line at -500.00. The right boundary is a vertical line at 3000.00. The top boundary is a curved line representing the ground surface. The interface includes a menu bar (File, Edit, Phases, Options, Expert, Help) and several toolbars. The Phases explorer panel on the left shows three phases: Initial phase [InitialPhase], Initialization [Phase_1], and EQ Load [Phase_2]. The Selection explorer panel shows a selection of objects. The Model explorer panel shows a list of model conditions, with the Dynamics section expanded and highlighted in red. The Command line panel at the bottom shows the following commands:

```
Session Model history
OK
#278> _displMultiplier
Added DisplacementMultiplier_1
#279> _set DynLineDisplacement_1.1.MultiplierX Phase_2 DisplacementMultiplier_1
OK
#280> _delete DisplacementMultiplier_1
Deleted DisplacementMultiplier_1
#281> _set DynLineDisplacement_1.1.MultiplierX Phase_2 EQSTP183
OK
```

PLAXIS Demonstration

Phase parameters

The image shows the PLAXIS software interface with the 'Phases' dialog box open. The 'EQ Load [Phase_2]' phase is selected. The 'Calculation type' is set to 'Dynamic', and the 'Dynamic time interval' is 34.00 s. The 'Numerical control parameters' section shows 'Max steps' set to 1700 and 'Time step determination' set to 'Semi-automatic'. A Notepad window titled 'EQSTP183.txt - Notepad' displays the output data, which is a table of values for various parameters over time.

Phases explorer

- Initial phase [InitialPhase]
- Initialization [Phase_1]
- EQ Load [Phase_2]

Selection explorer (Phase_2)

- ...

Model explorer (Phase_2)

- Attributes library
- Geometry
- Groups
- Interfaces
- Line displacements
- Groundwater flow BCs
- Sols
- Model conditions
 - Climate
 - Deformations
 - Dynamics
- Boundary/Min: Free-field
- Boundary/Max: Free-field
- Boundary/Min: Compliant base
- Boundary/Max: None
- All nodes fixities: None
- Normal relax coeff C1: 1.000
- Tangential relax coeff C2: 1.000
- FieldStress
- GroundwaterFlow
- Precipitation
- PseudoStatic
- ThermalFlow

Phases

Name	Value
General	
ID	EQ Load [Phase_2]
Calculation type	Dynamic
Dynamic time interval	34.00 s
First step	18
Last step	1717
Design approach	(None)
Special option	0
Deformation control parameters	
Ignore undr. behaviour (A,B)	<input type="checkbox"/>
Reset displacements to zero	<input checked="" type="checkbox"/>
Reset small strain	<input checked="" type="checkbox"/>
Reset state variables	<input checked="" type="checkbox"/>
Reset time	<input type="checkbox"/>
Updated mesh	<input type="checkbox"/>
Ignore suction	<input checked="" type="checkbox"/>
Cavitation cut-off	<input type="checkbox"/>
Cavitation stress	100.0 kN/m ²
Numerical control parameters	
Max cores to use	256
Max number of steps stored	1
Use compression for result files	<input type="checkbox"/>
Use default iter. parameters	<input type="checkbox"/>
Max steps	1700
Time step determination	Semi-automatic
Number of sub steps	Automatic
Tolerated error	0.01000
Max unloading steps	5
Max load fraction per step	0.5000
Over-relaxation factor	1.200
Max number of iterations	60
Desired min number of iterations	6

EQSTP183.txt - Notepad

```
File Edit Format View Help
1700 0.02
0.0200 +3.476543E-06
0.0400 +4.244405E-06
0.0600 +4.204279E-06
0.0800 +5.589457E-06
0.1000 +6.362596E-06
0.1200 +8.279303E-06
0.1400 +9.723131E-06
0.1600 +1.202133E-05
0.1800 +1.391183E-05
0.2000 +1.628749E-05
0.2200 +1.799801E-05
0.2400 +1.894083E-05
0.2600 +1.637795E-05
0.2800 +6.328784E-06
0.3000 -1.697989E-05
0.3200 -5.406675E-05
0.3400 -9.512915E-05
0.3600 -1.292355E-04
0.3800 -1.631444E-04
33.7800 -5.190279E-05
33.8000 -5.106825E-05
33.8200 -5.061525E-05
33.8400 -4.983321E-05
33.8600 -4.934315E-05
33.8800 -4.860819E-05
33.9000 -4.808715E-05
33.9200 -4.739335E-05
33.9400 -4.684760E-05
33.9600 -4.618903E-05
33.9800 -4.562468E-05
34.0000 -4.499570E-05
```

PLAXIS Demonstration

Select curve points to save data

The screenshot displays the PLAXIS 2D software interface. The main window shows a connectivity plot of a dam cross-section. The plot is a red-filled area with a black outline, representing the dam's geometry. Several nodes are highlighted with red dots and labeled with their IDs: Node 152514, Node 132654, Node 106996, Node 77078, and Node 47995. A red box highlights the 'Select points for curves' button in the left-hand toolbar. A red arrow points from this button to the selected nodes in the plot. The interface includes a menu bar at the top, a toolbar with various icons, and several panels on the left: 'Phases explorer', 'Selection explorer (Phase_2)', and 'Model explorer (Phase_2)'. The 'Model explorer' panel shows a tree view of the model's components, including geometry, groups, interfaces, line displacements, groundwater flow BCs, soils, model conditions, climate, deformations, and dynamics. The 'Command line' at the bottom shows a list of commands and their parameters, such as 'delete displacement' and 'set dyn.linexplac'. The right-hand side of the interface features a 'Data from' table and a 'Search' button.

Name	X	Y	Selected	De
Node 152514	96.45	-948...	Pre-calc	50a
Node 132654	600.00	-930...	Pre-calc	50a
Node 106996	990.80	-810...	Pre-calc	50a
Node 77078	1498...	-709...	Pre-calc	50a
Node 47995	2007...	-693...	Pre-calc	50a

```
Command line
Session Model history
or
@200> delete displacement
@281> set dyn.linexplac
or
@282> set phase_2.deform
or
@283> selectstresspoints
or
Command
```

PLAXIS Demonstration

Define Rayleigh damping for each soil material

The screenshot displays the PLAXIS software interface during the definition of Rayleigh damping for a soil material. The main window shows a 3D model of a soil structure with a coordinate system ranging from -500.00 to 3000.00. The 'Soil - HS small - Soil_mat_1' dialog box is open, showing the 'Rayleigh damping' section highlighted in red. The dialog box contains the following data:

Property	Unit	Value
Material set		
Identification		Soil_mat_1
Soil model		HS small
Drainage type		Undrained B
Colour		RGB 161, 226, 232
Comments		
Unit weights		
γ_{unsat}	kN/m ³	18.00
γ_{sat}	kN/m ³	18.00
Void ratio		
e_{init}		0.5000
n_{init}		0.3333
Rayleigh damping		
Input method		SDOF equivalent
Rayleigh α		0.02417
Rayleigh β		0.6121E-3
ϵ_1	%	1.000
ϵ_2	%	1.000
f_1	Hz	0.2000
f_2	Hz	5.000

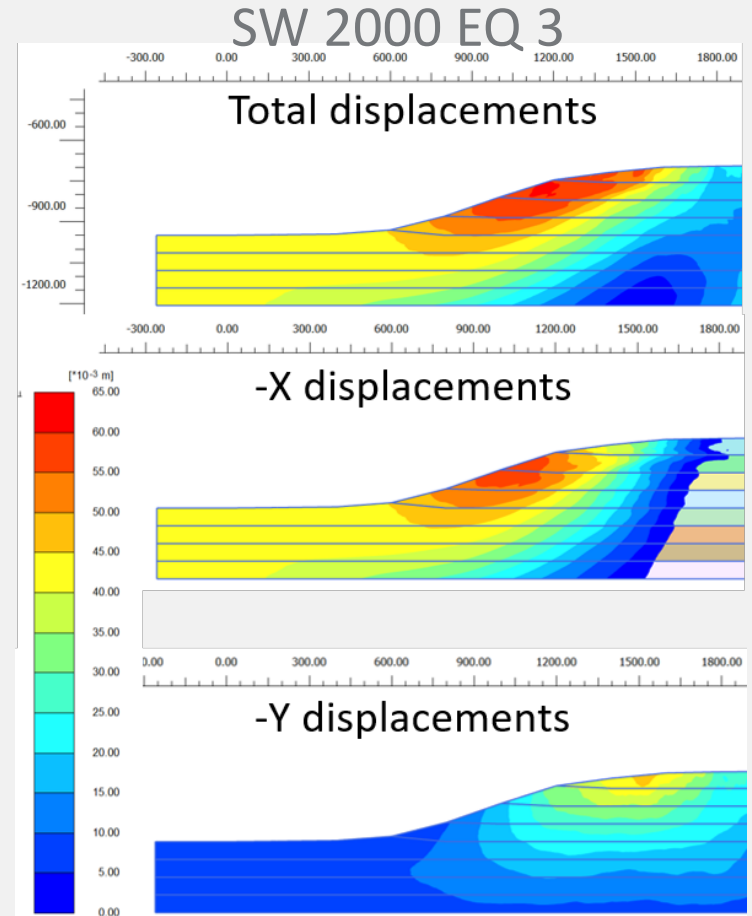
The graph on the right shows the damping ratio ϵ (%) versus frequency f [Hz] on a log scale. The curve is U-shaped, with a minimum damping ratio of approximately 0.5% at a frequency of 1 Hz. The damping ratio increases to 20% at frequencies of 0.01 Hz and 10 Hz. The graph includes a 'Log scale' checkbox and 'Next', 'OK', and 'Cancel' buttons.

Dynamic FEM in PLAXIS: Results

Max permanent displacement (cm)

EQ	200 year RP			
	NE	NW	SE	SW
1	1.22	1.71	4.19	1.89
2	0.96	2.00	5.04	2.52
3	1.14	1.86	4.19	2.53

EQ	2000 year RP			
	NE	NW	SE	SW
1	3.79	6.25	6.07	5.72
2	4.00	7.32	7.73	7.51
3	3.96	6.72	4.64	6.97



Conclusions

- Static and pseudo-static deterministic and probabilistic analyses with LEM and FEM give similar results
- Probabilistic analyses show low probability of failure for 200 year, but high probability for 2000 year return period
- Dynamic analyses predict only minor displacements for 2000 year return period