Temasdag Jordskjelv

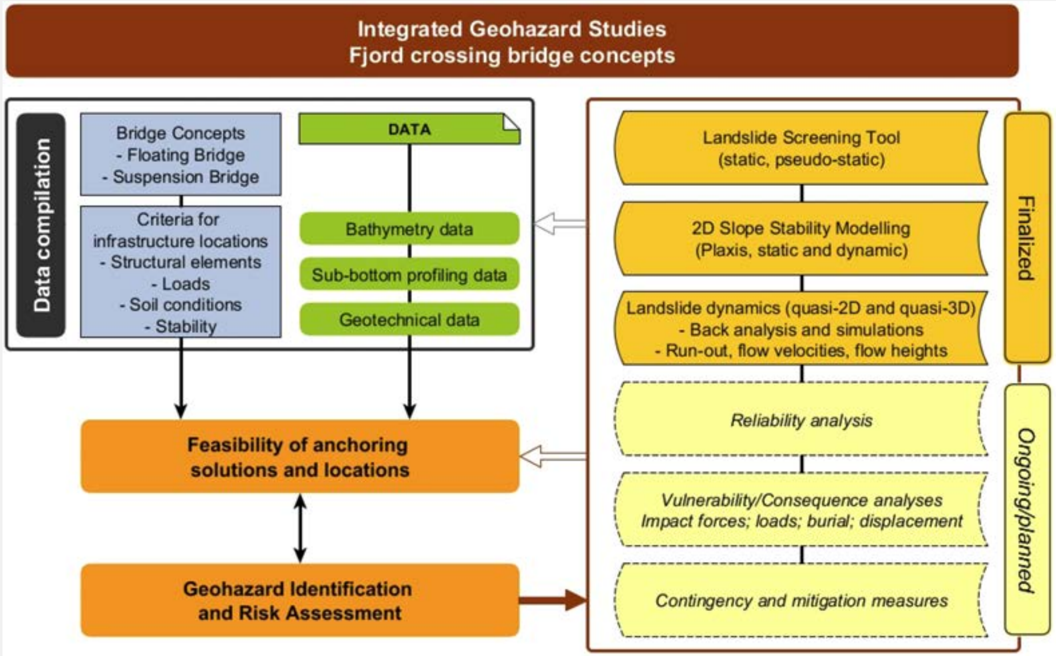
Slope Stability Part 2 – Application

Brian Carlton

1 November 2022

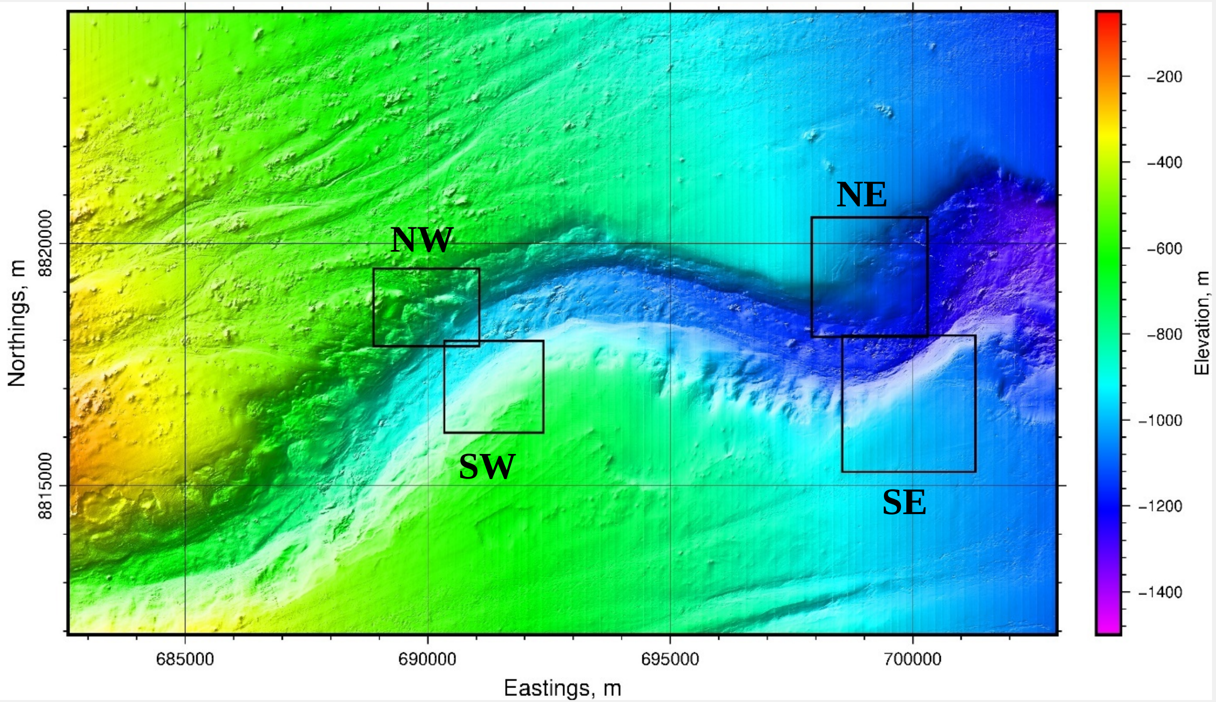
Outline

- 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



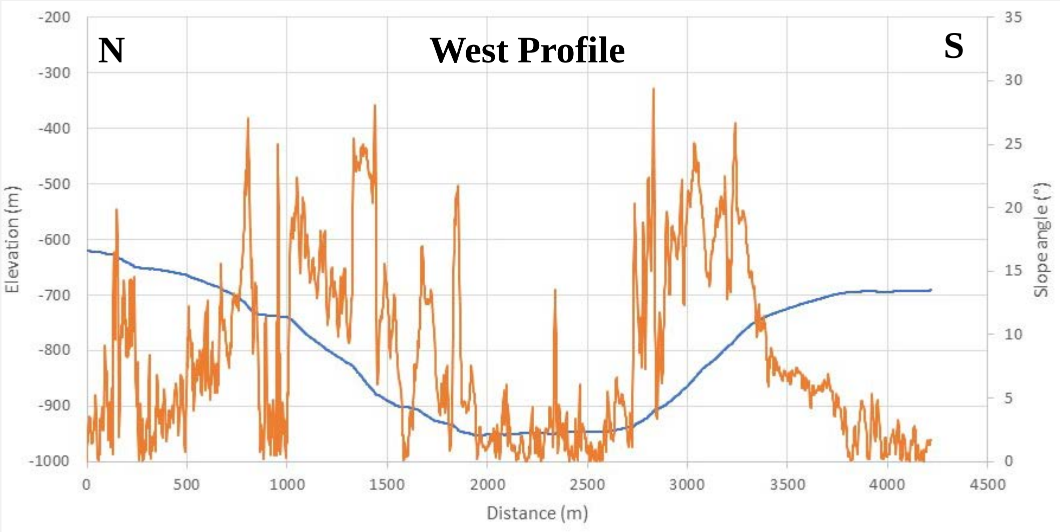
Introduction

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

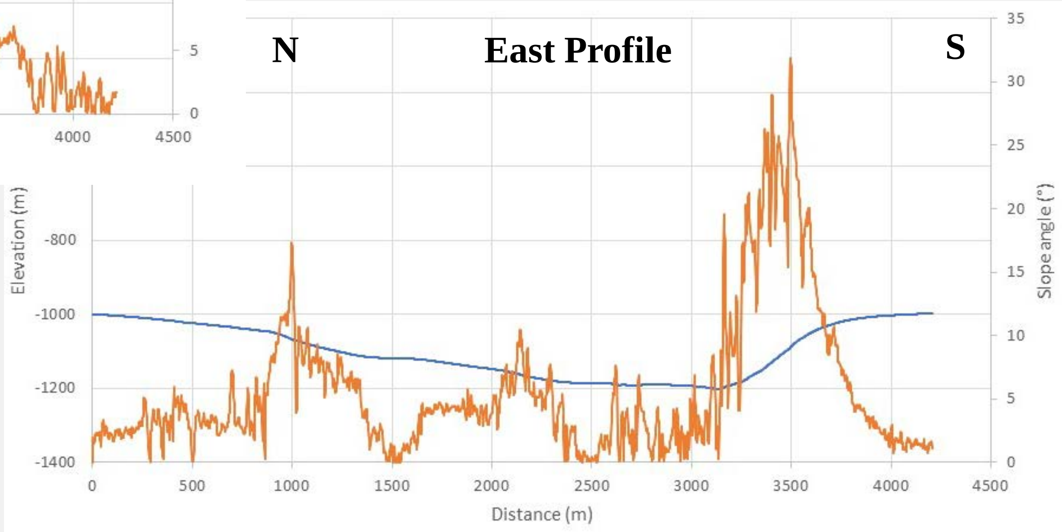


NGI

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



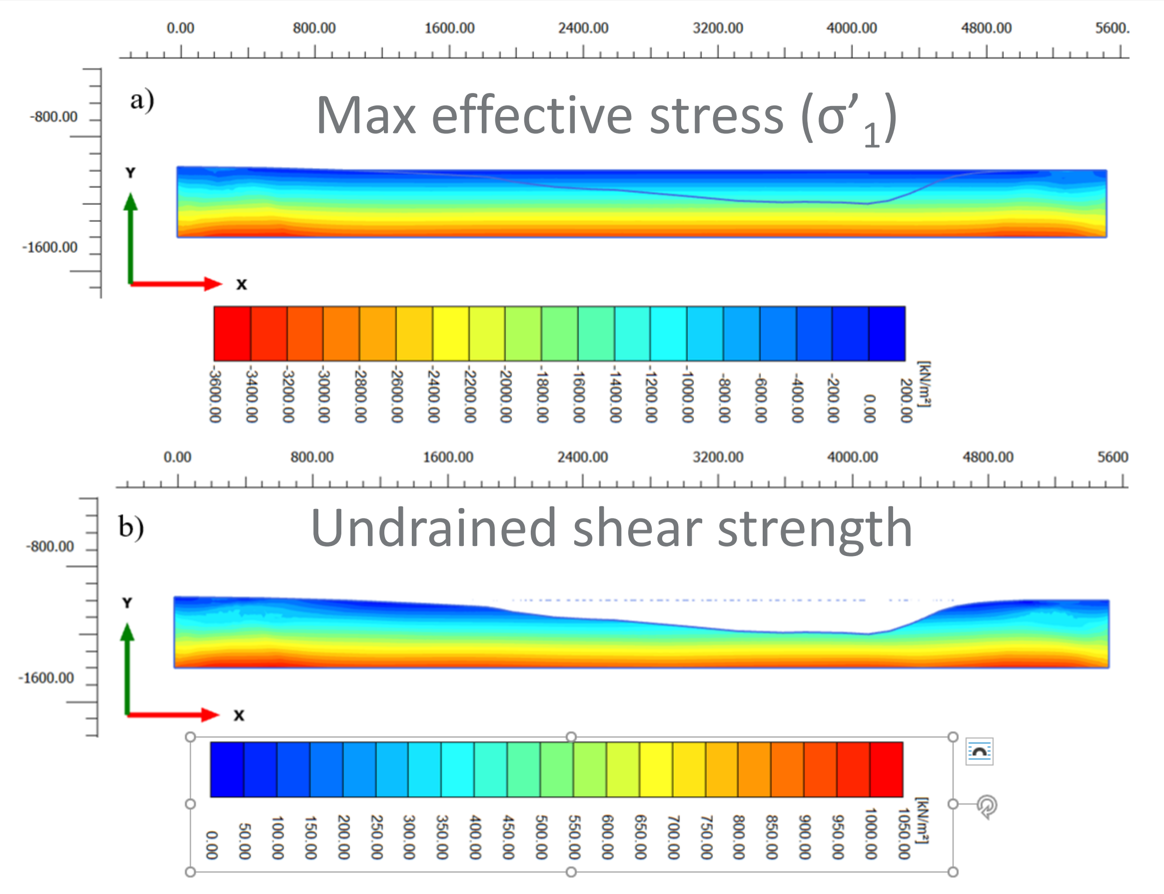
- The Western Crossing has exposed strata on S flank and likely slump-like landslides on the N flank.
- The toes of the slump blocks appear to be buried by canyon floor deposits indicating a very high age

Background

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

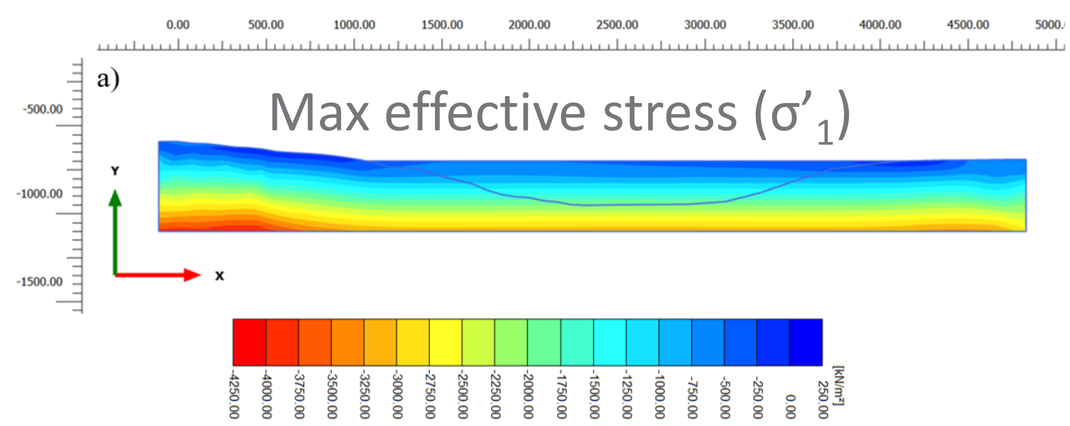
Layers	N-W	S-W	N-E	S-E
SAND	0-4.5 (2) m	-	0-1.9 m	0-1.9 m
Sandy/Clayey SILT Silty/Sandy CLAY	4.5(2) -7.4 m	-	1.9-18 m	1.9-17 m
CLAY	7.4-200 m	0 - 200 m	18-200 m	17-200 m

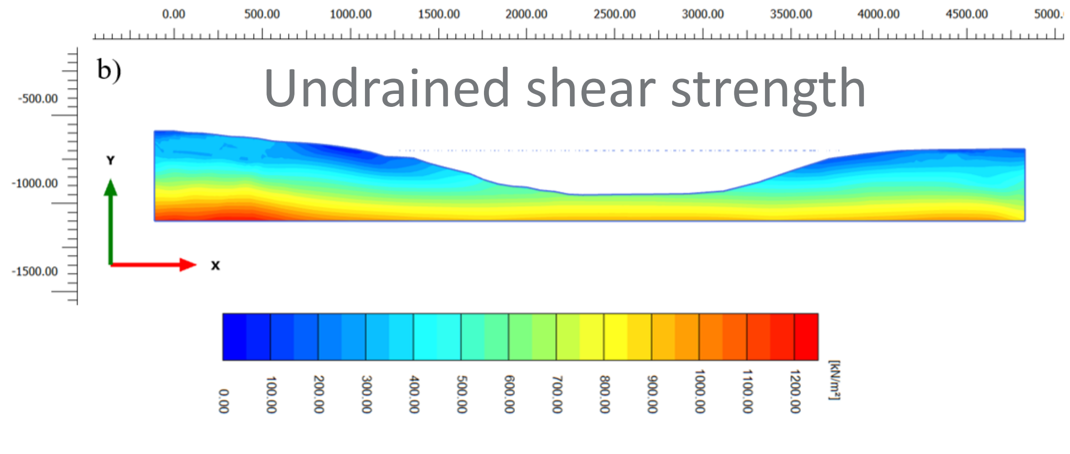
Eastern Crossing Shear Strength: Erosion Model



NGI

Western Crossing Shear Strength: Erosion Model





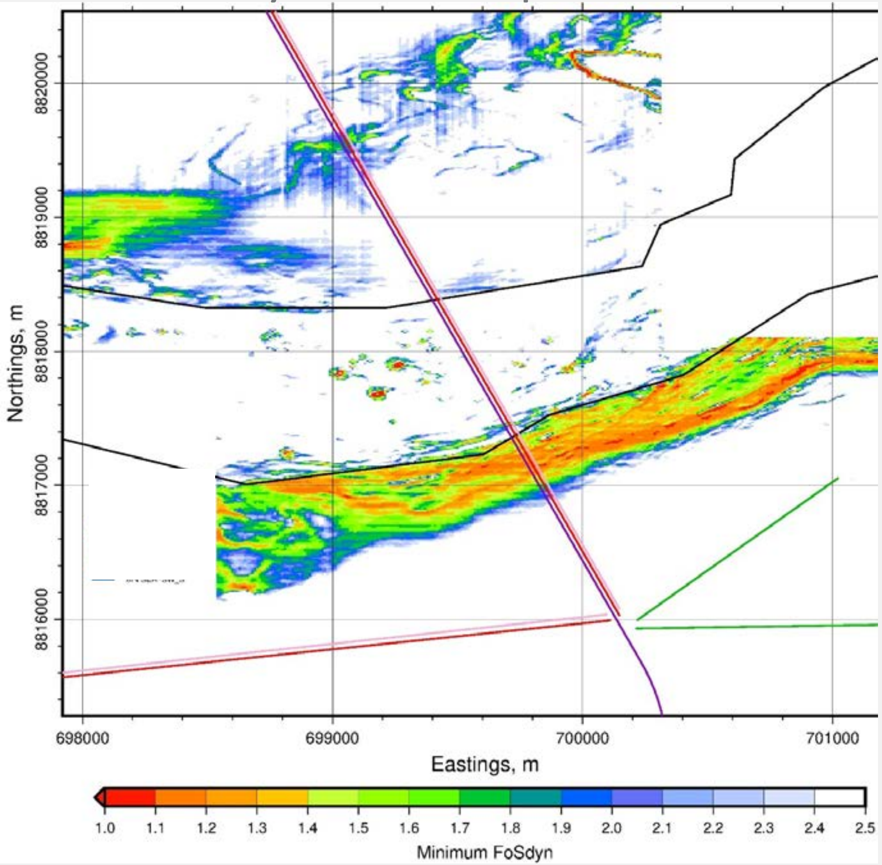
NGI

Methodology

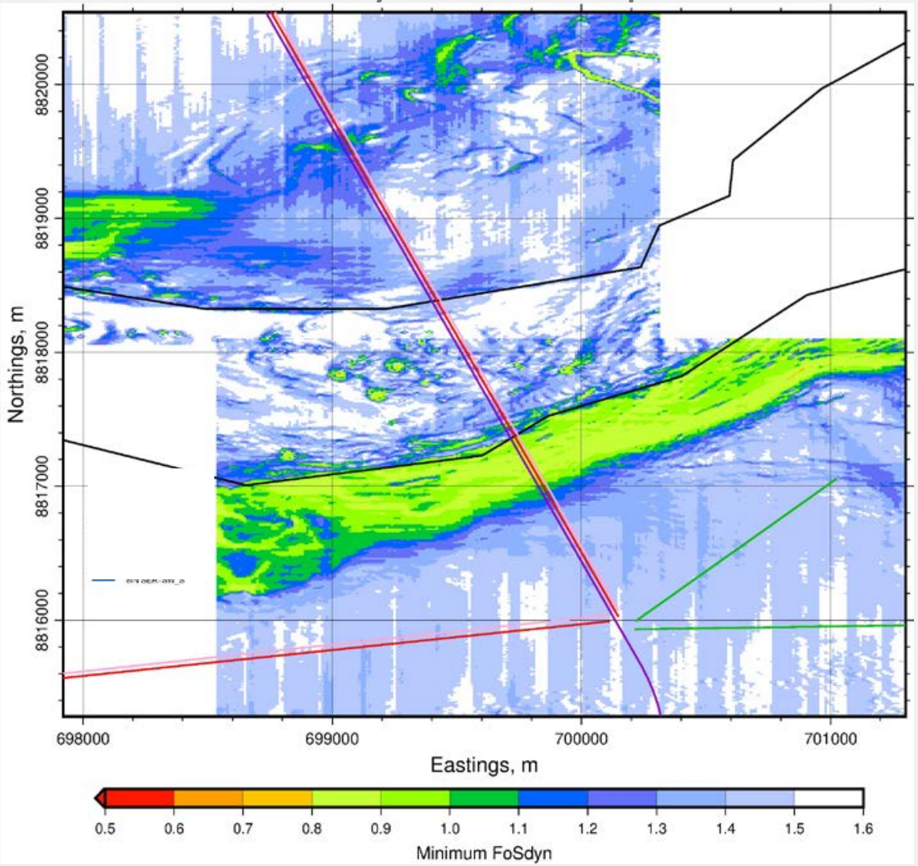
- Compile and interpret all available geological, geophysical, and geotechnical data
- 1D infinite static and pseudo-static slope stability analyses
- 2D static and pseudo-static limit equilibrium (LEM) analyses
- 2D static and pseudo-static finite element analyses (FEM)
- Probabilistic LEM and FEM
-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

1D Screening: Eastern Crossing FoS

200 year return period

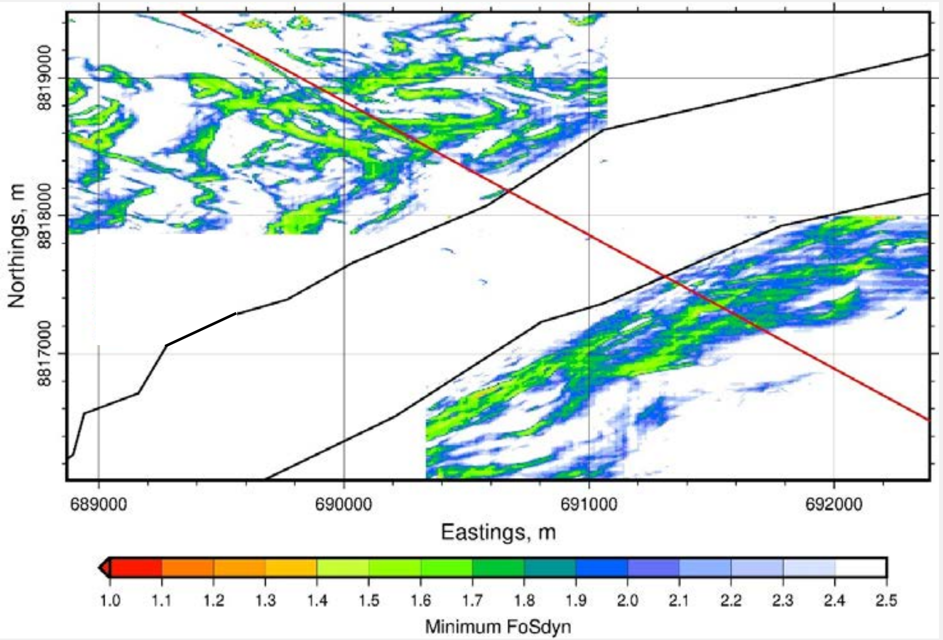


2000 year return period

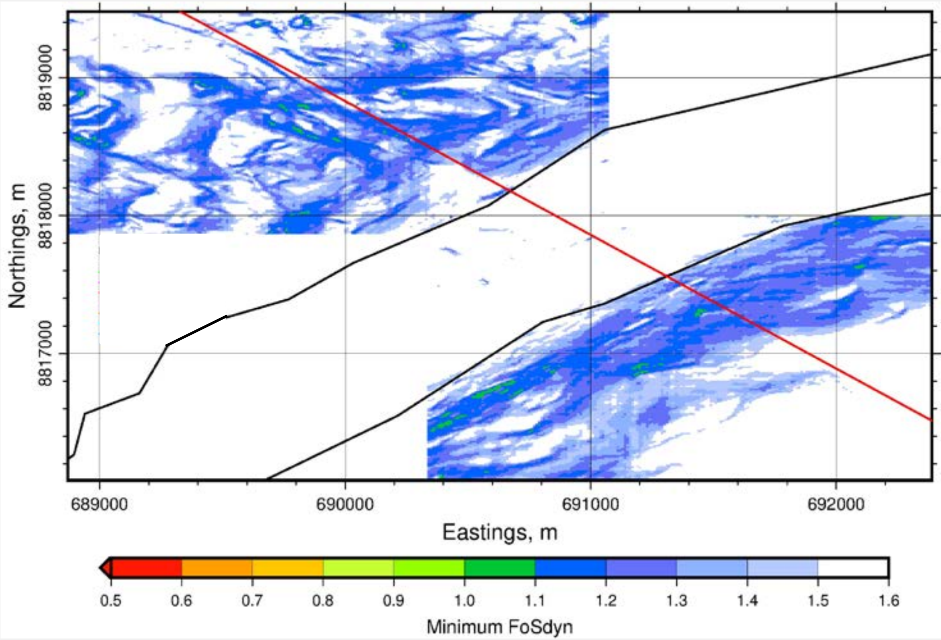


1D Screening: Western Crossing FoS

200 year return period



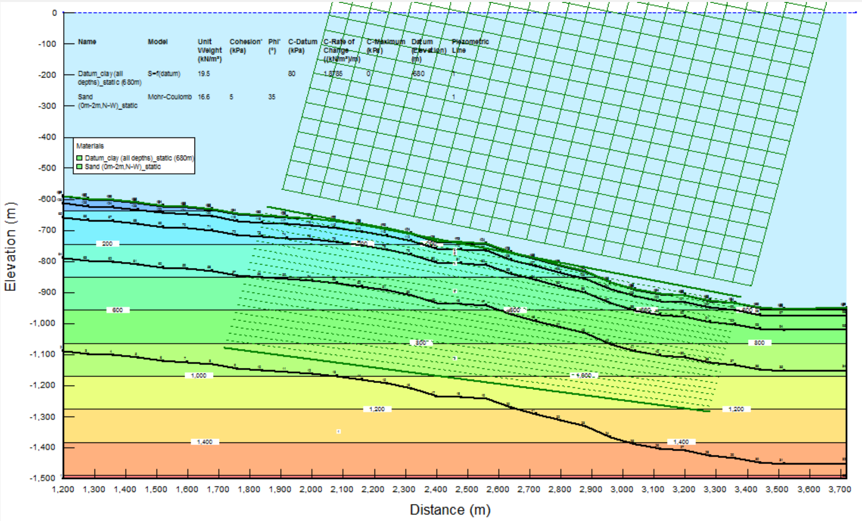
2000 year return period

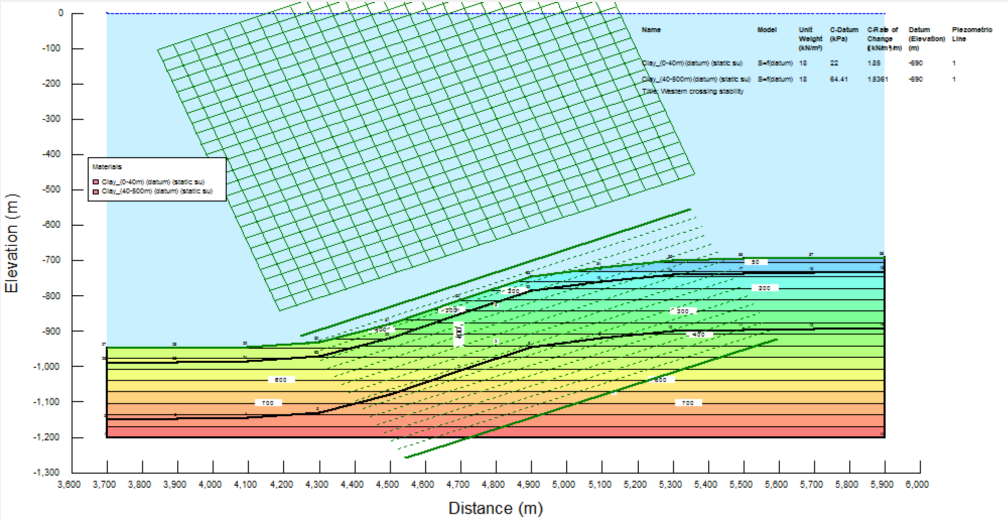


NGI

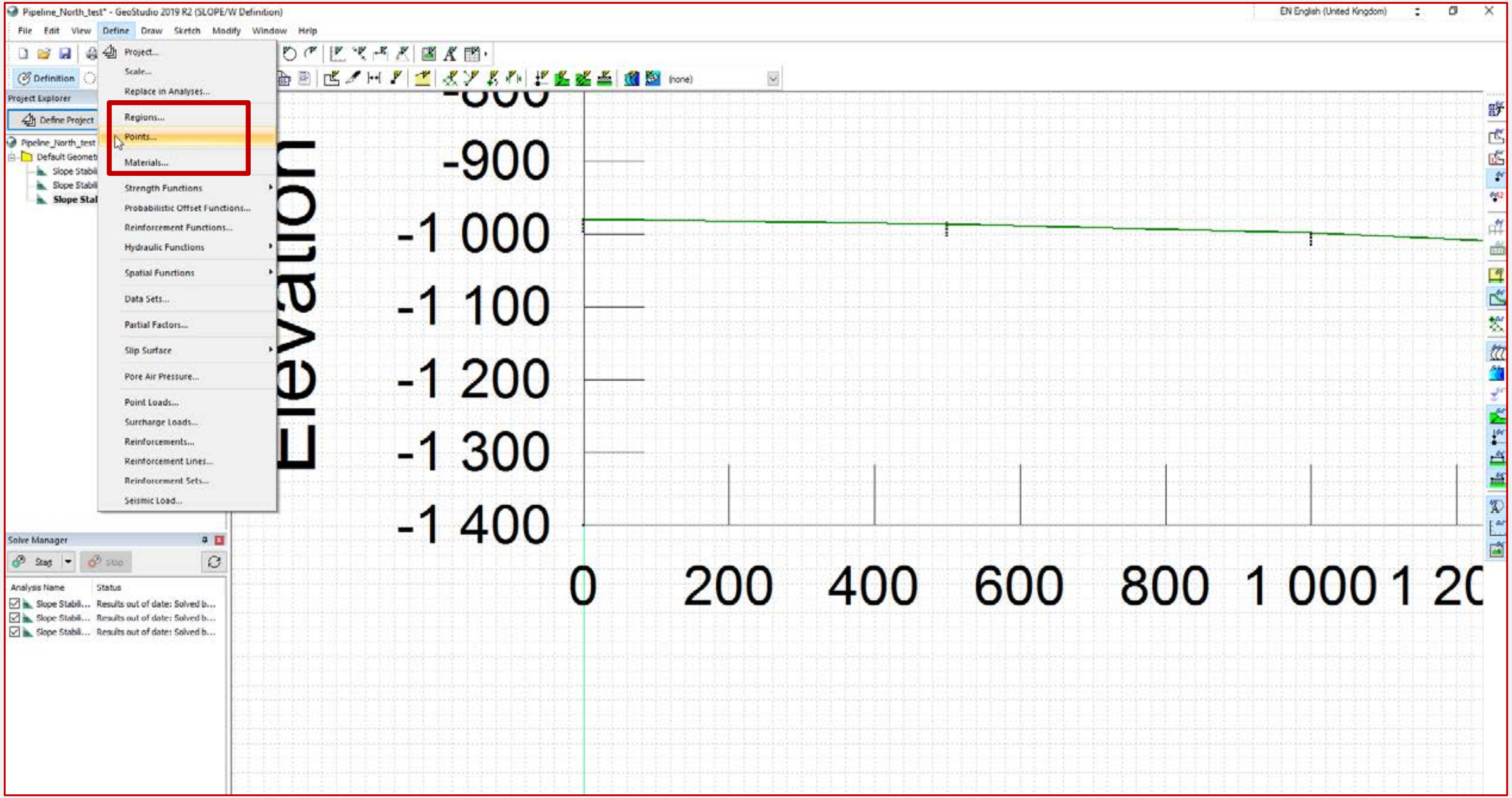
Limit Equilibrium Method: SLOPE/W

- 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



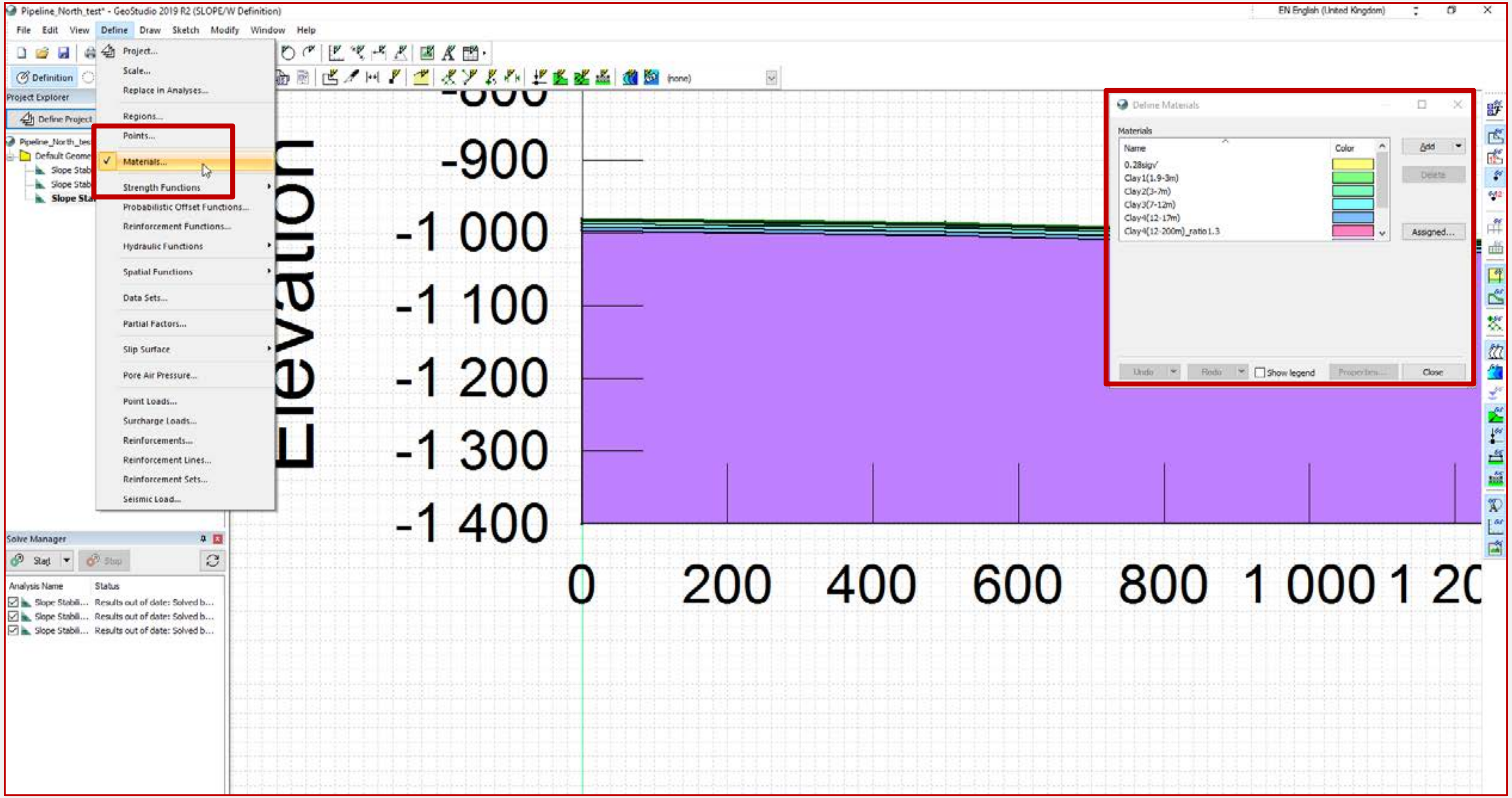


Input parameter/ define point, region

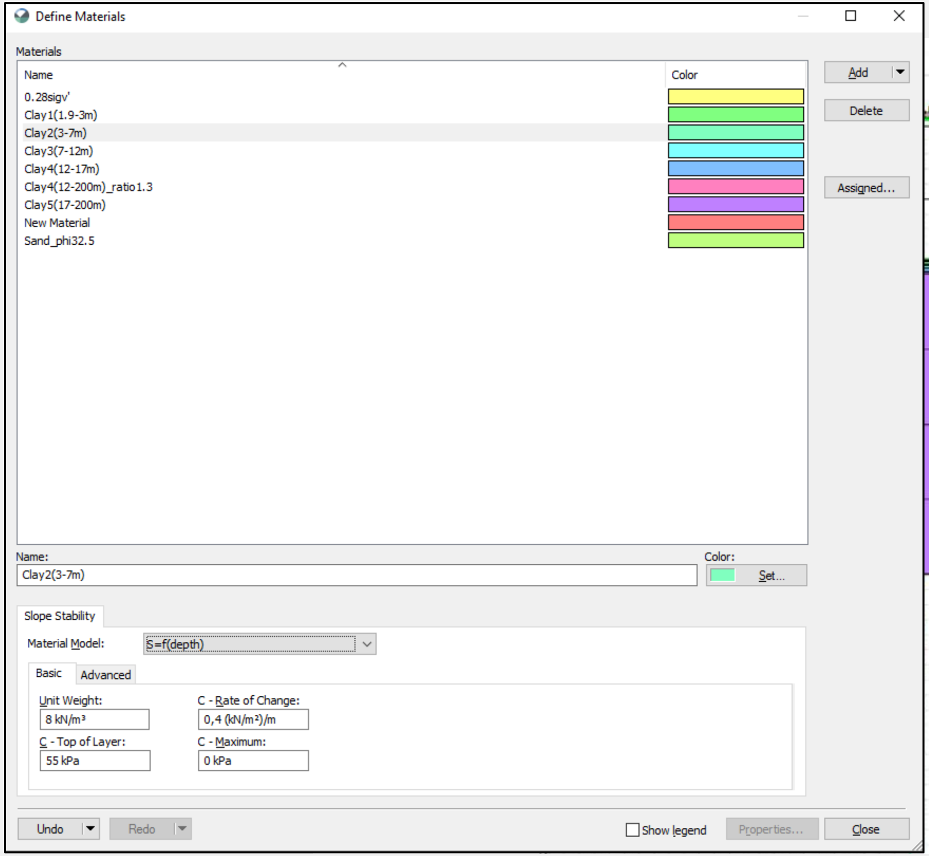


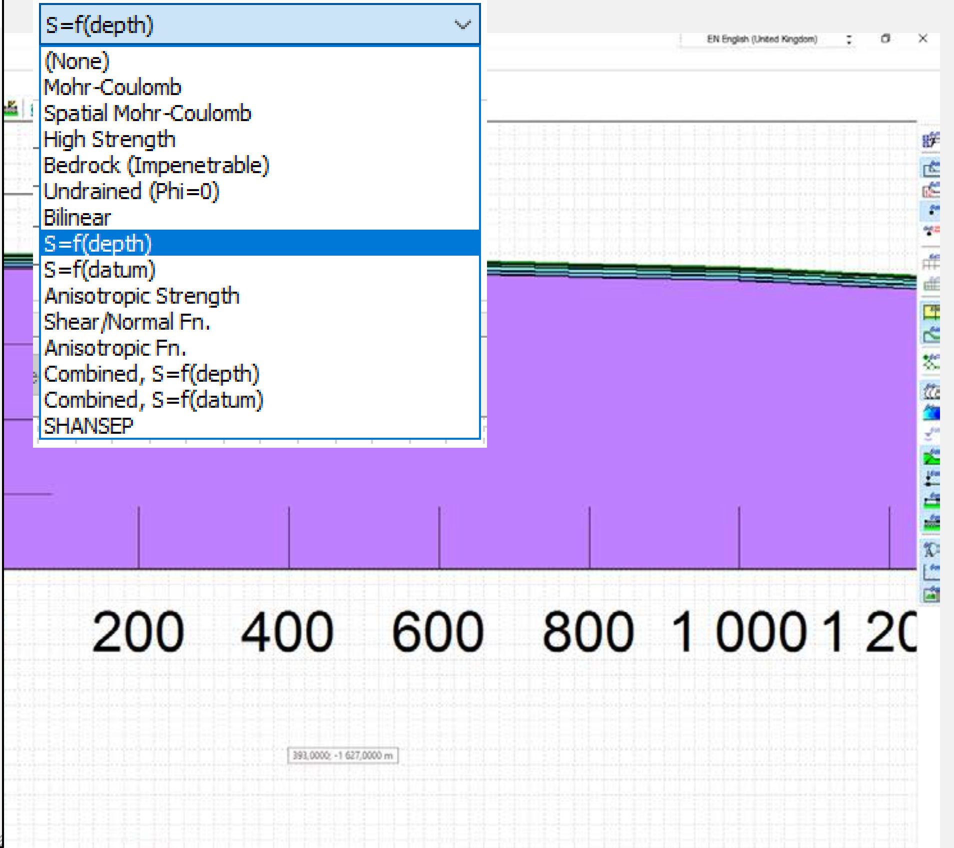
NGI

Input parameter/ material properties

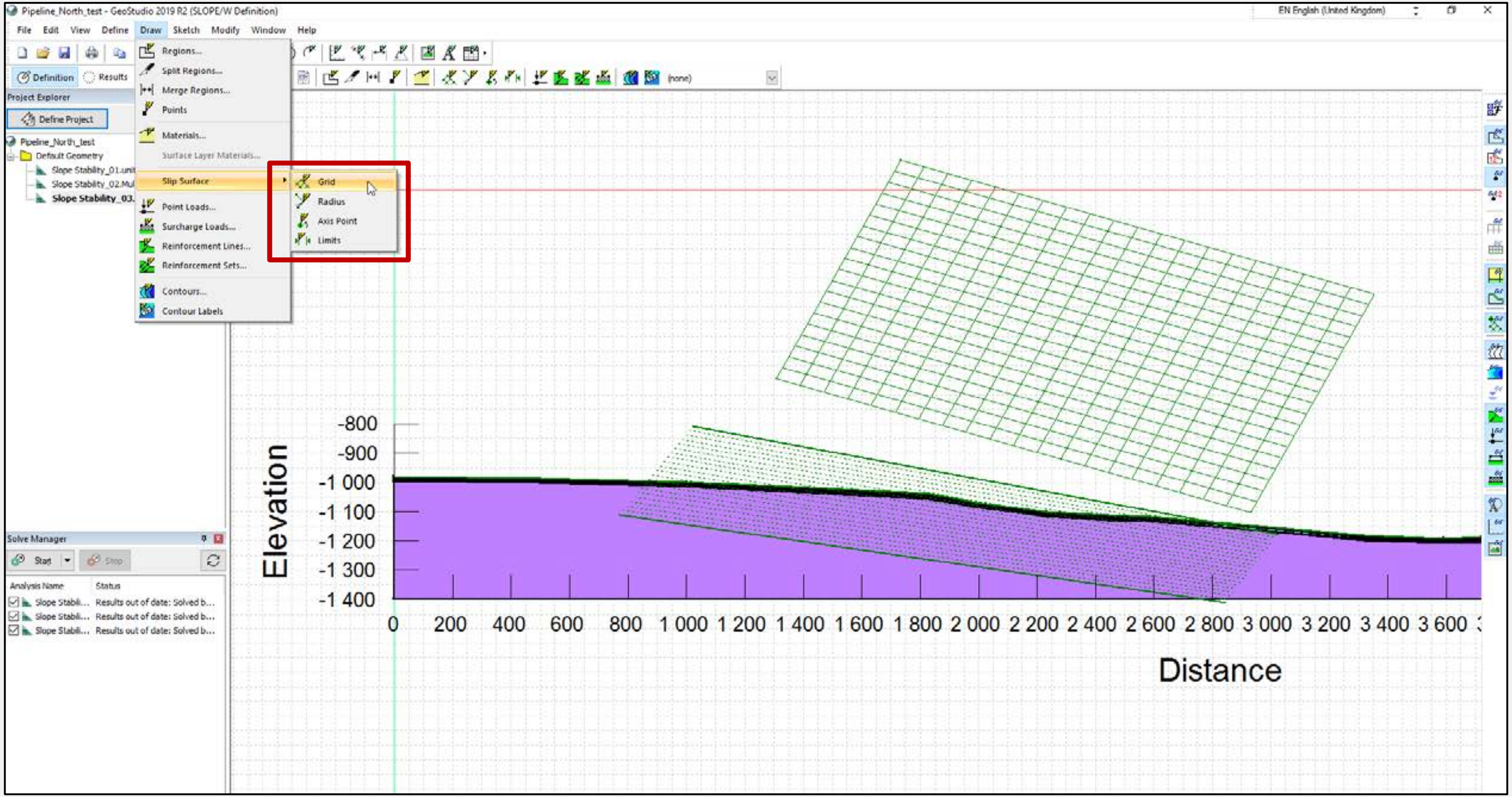


Input parameter/ material properties

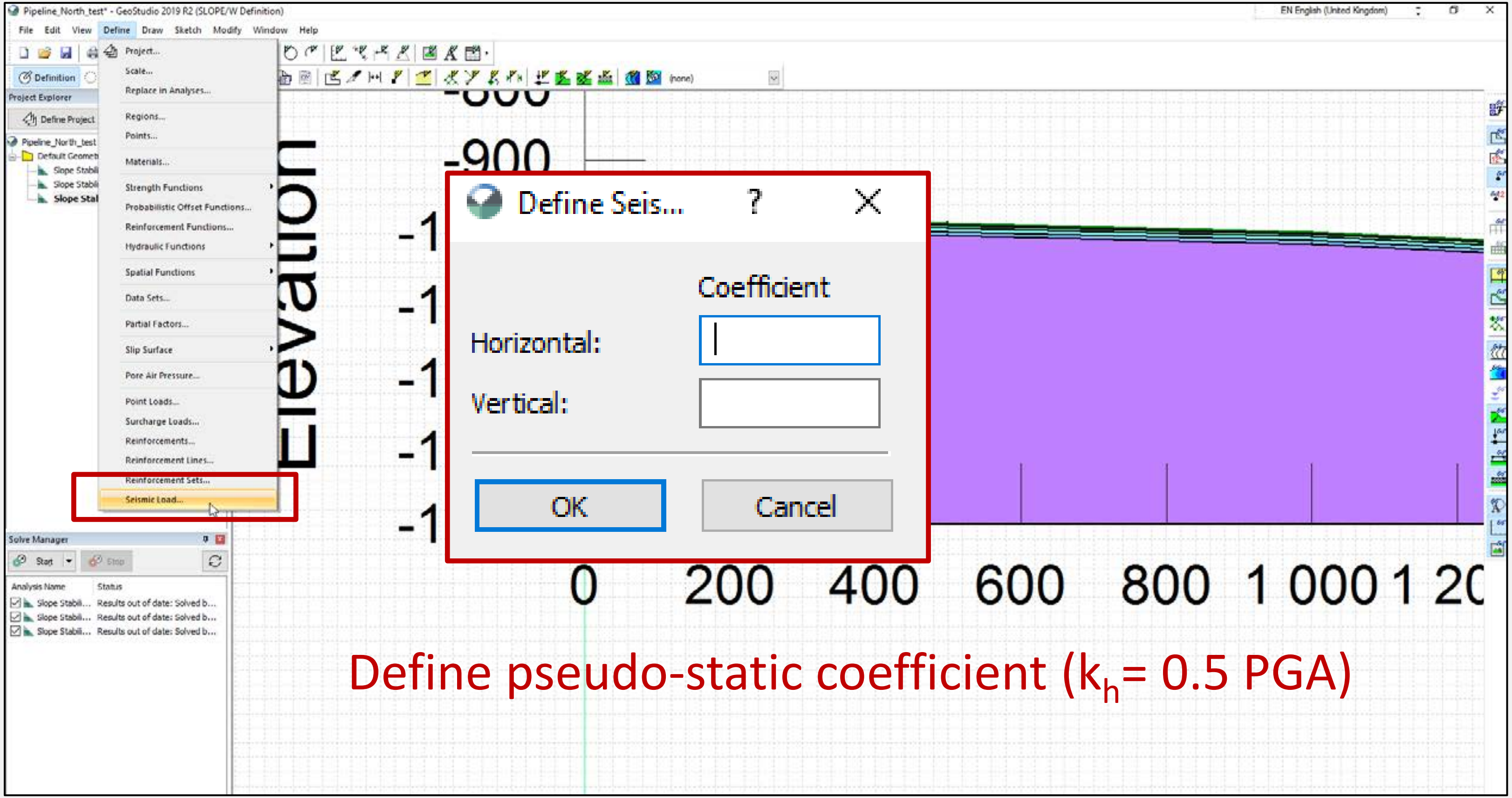




Input parameter/ set failure radius and grid points



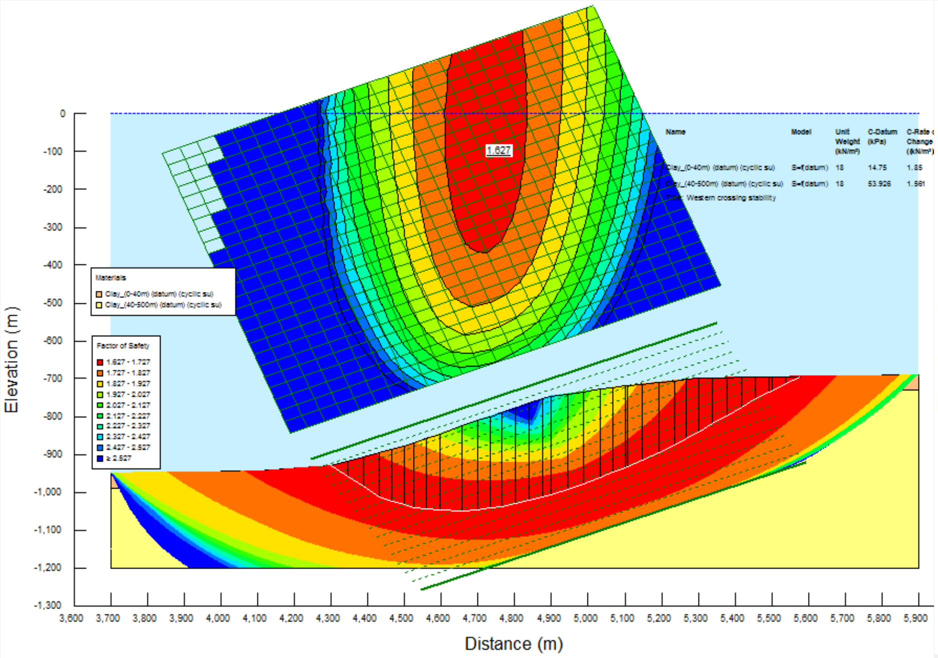
Input parameter/ EQ pseudo-static



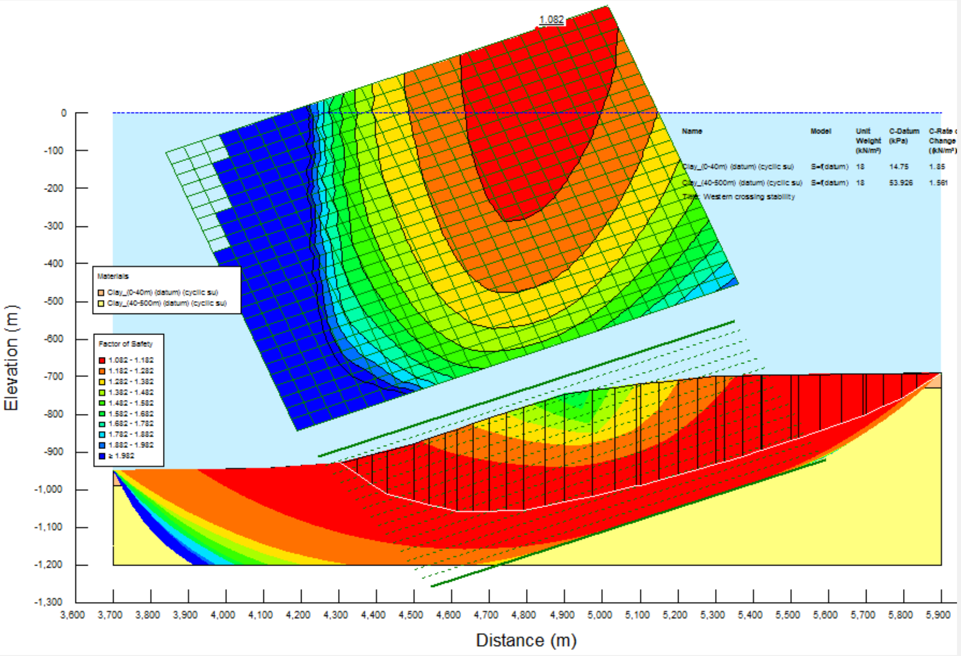
Define pseudo-static coefficient (k_h= 0.5 PGA)

Results: Southwest Slope

200 year return period



2000 year return period

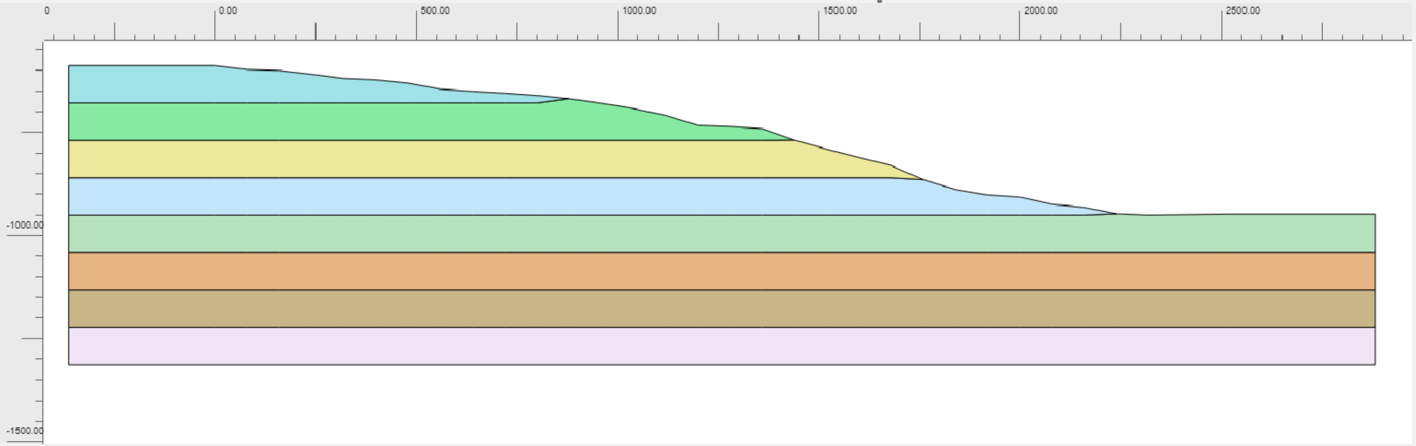


NGI

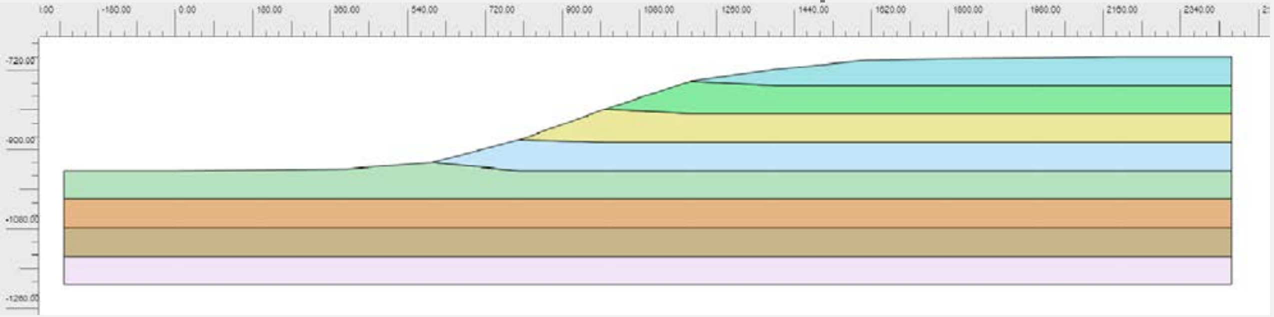
Finite Element Method: PLAXIS

- Used the same profiles, k_H, and soil unit weights and strengths as LEM
- Mohr-Coulomb constitutive model

North West Slope



South West Slope



Comparison of Results

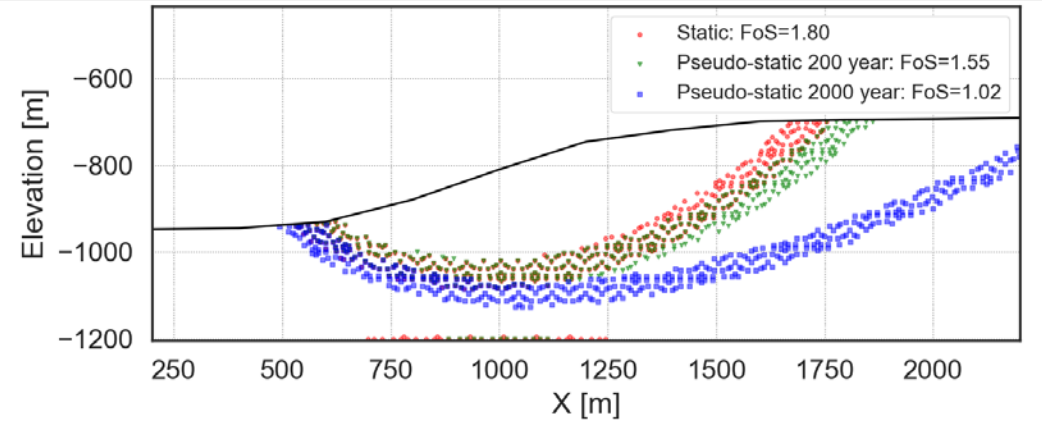
FEM Results

Profile	Static FoS	Pseudo-static 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 FoS	Pseudo-static 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

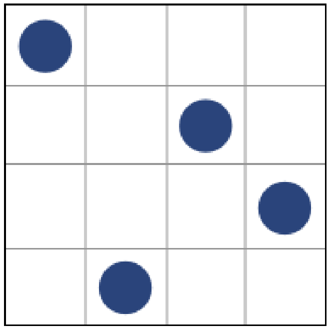
South West Slope

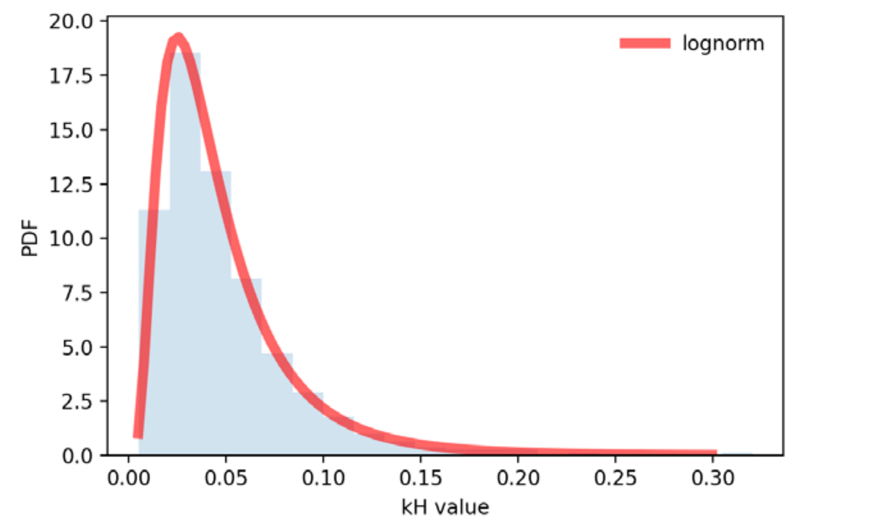


- LEM and FEM predict similar FoS and most likely failure planes for static and pseudo-static analyses

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

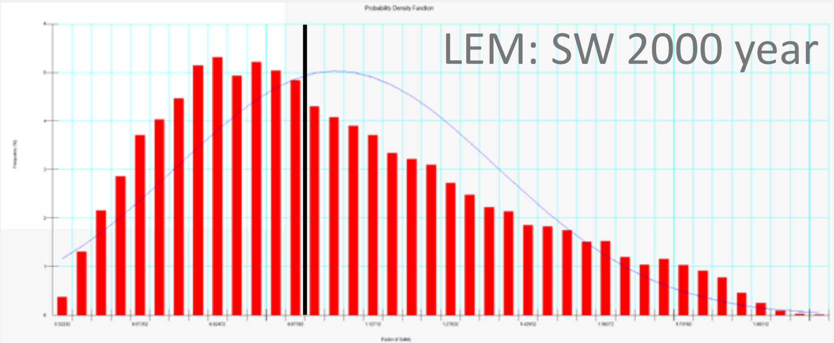
- Probability of FoS < 1 low for 200 yr, high for 2000 yr
- Similar values for FEM and LEM

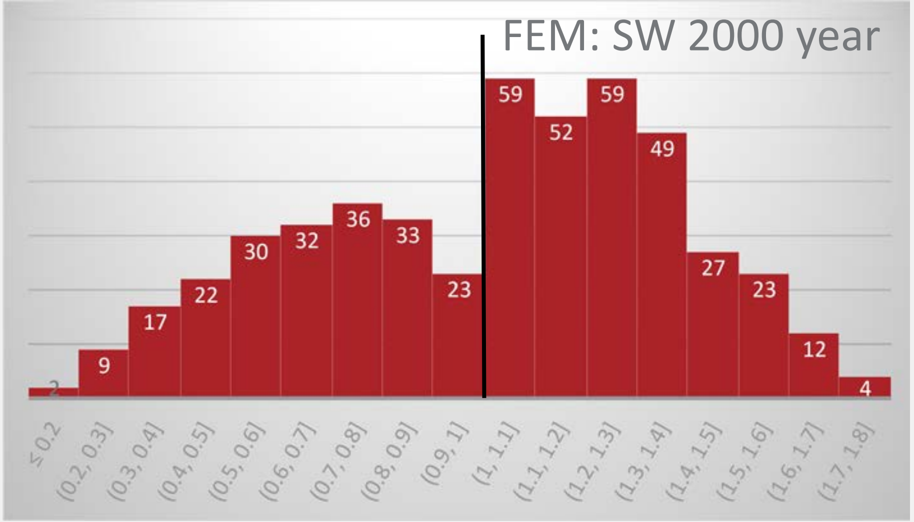
FEM 200 year

Profile	Mean	Std. dev.	Median	P_f = P[FoS < 1] (%)
NE	3.01	0.51	3.09	~0.06
NW	1.87	0.12	1.89	$\sim 6.0 \cdot 10^{-3}$
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[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

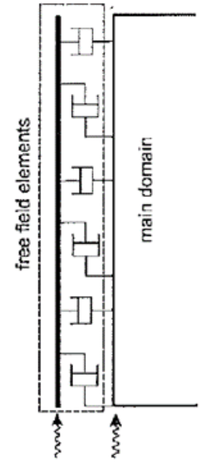
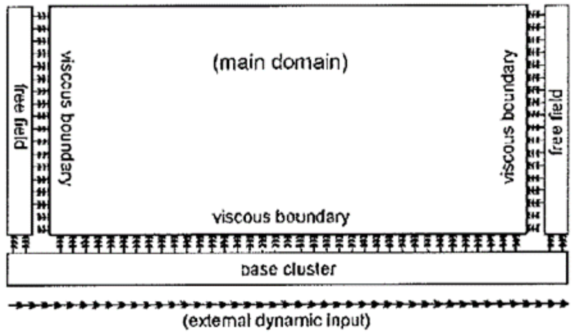


Figure 1 Free field elements

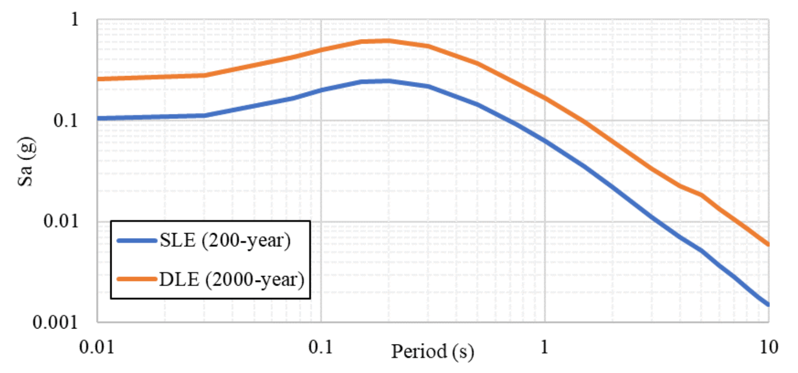


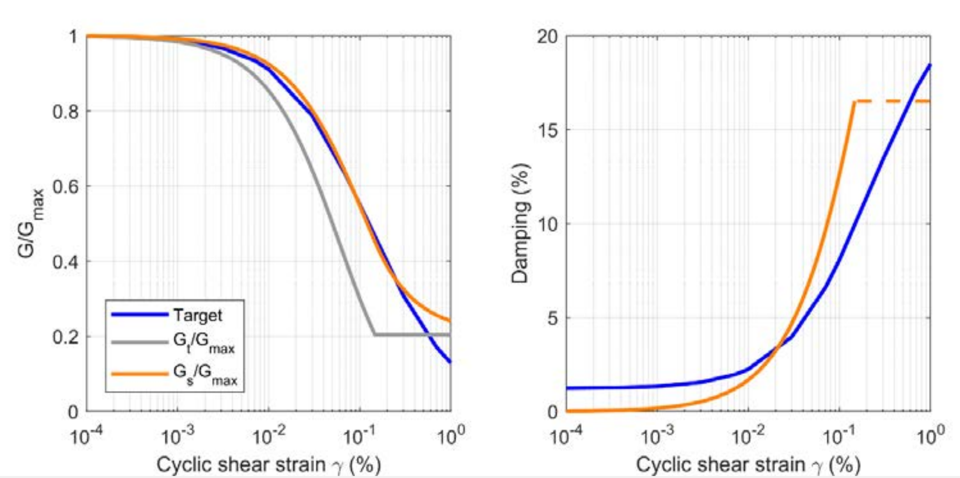
Dynamic FEM in PLAXIS

- 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

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

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





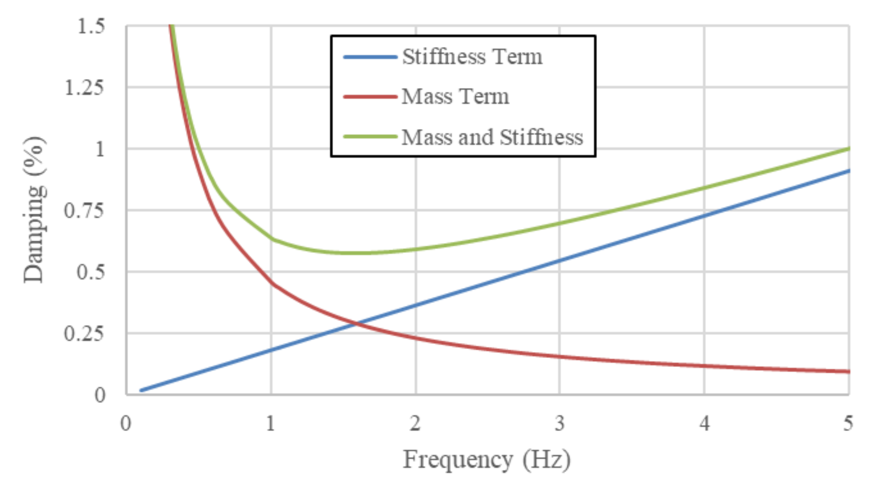
NGI

Rayleigh Damping

- 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

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

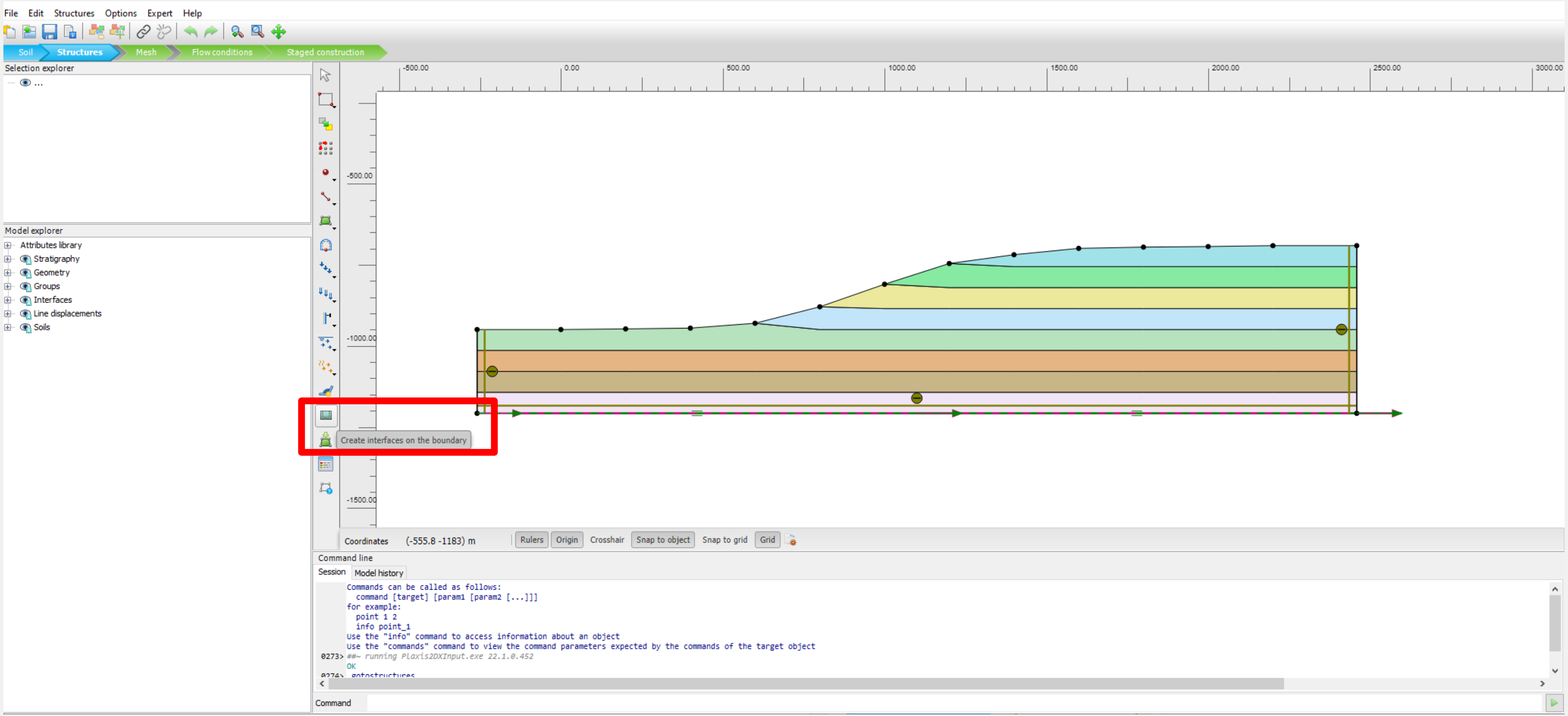
$$\begin{bmatrix} \zeta_i \\ \zeta_j \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \frac{1}{2\pi f_i} & 2\pi f_i \\ \frac{1}{2\pi f_j} & 2\pi f_j \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$



NGI

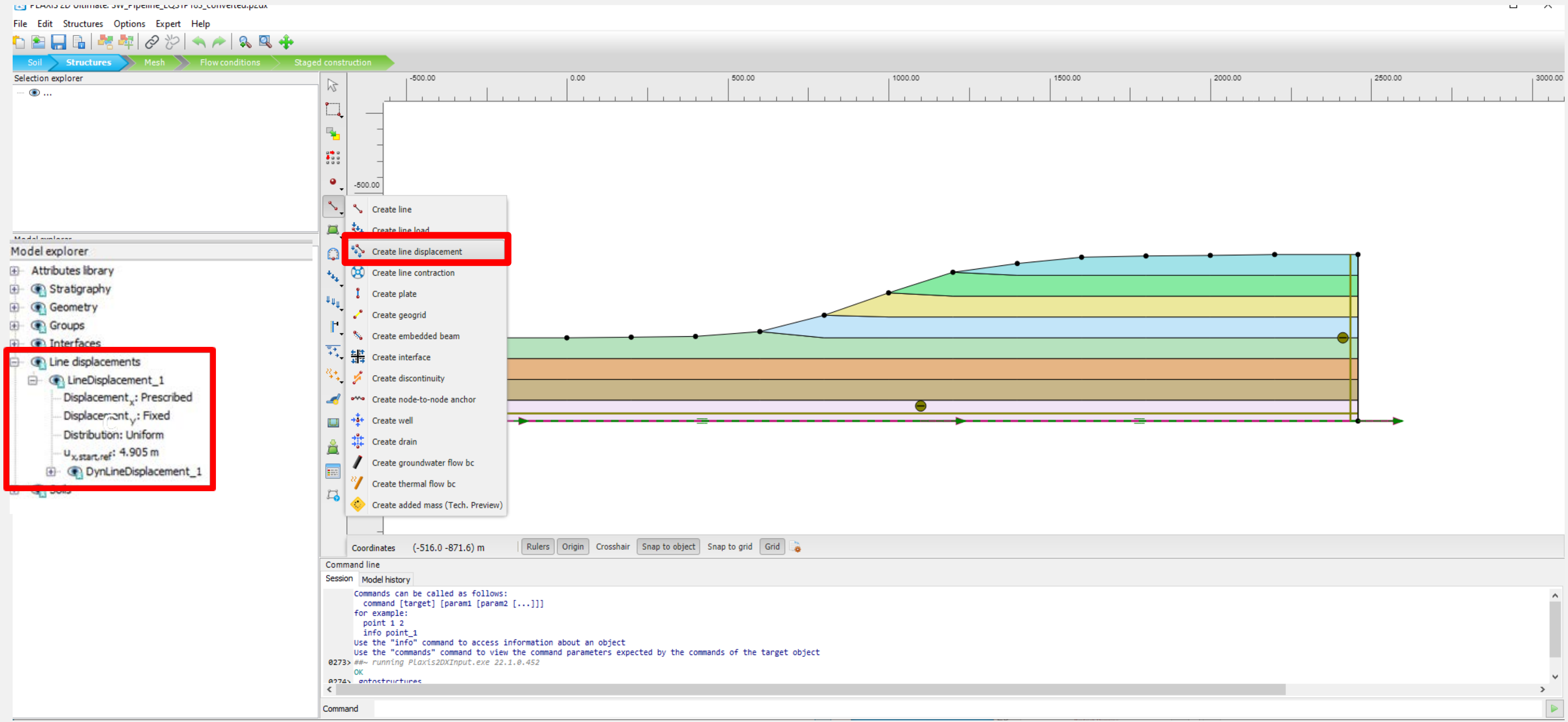
PLAXIS Demonstration

Boundary interfaces



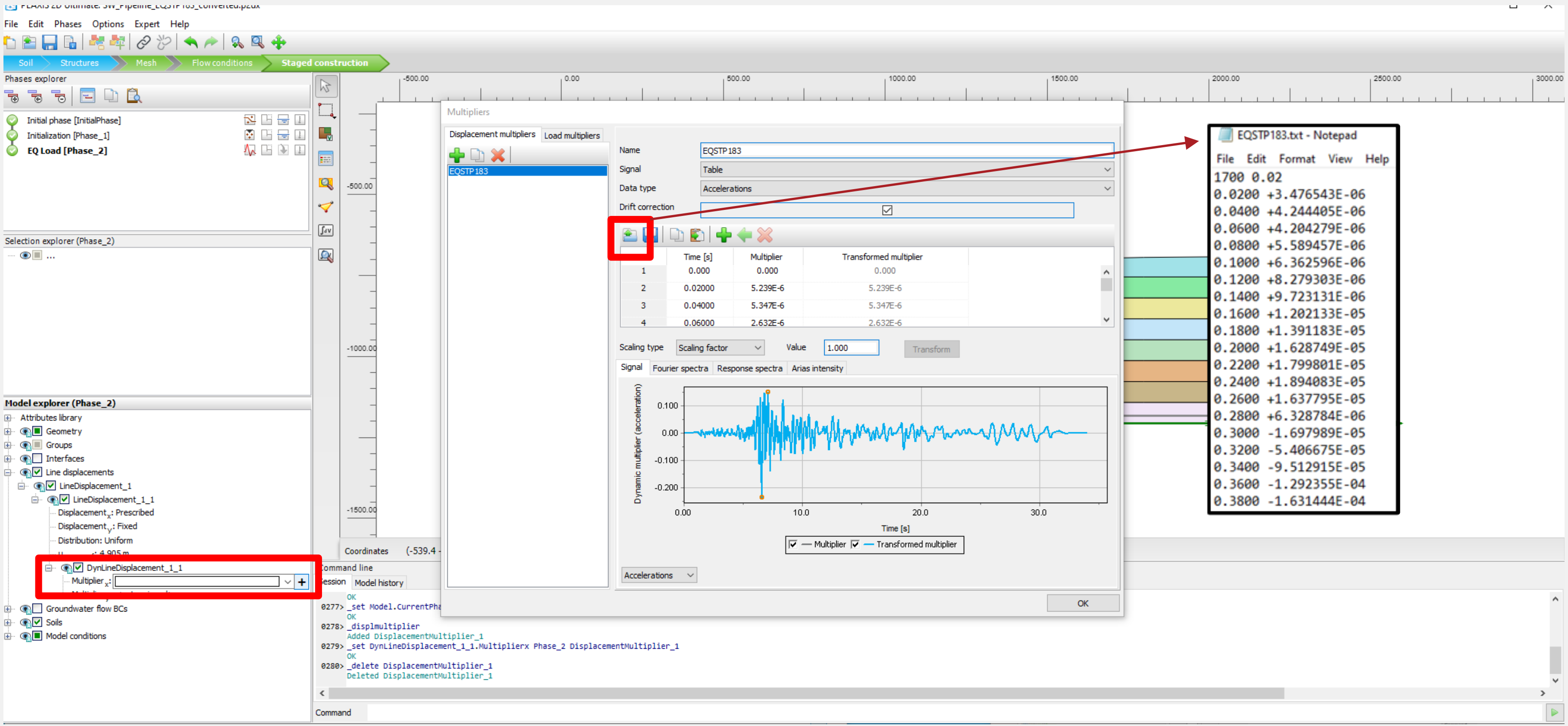
PLAXIS Demonstration

Set line displacement on bottom of model



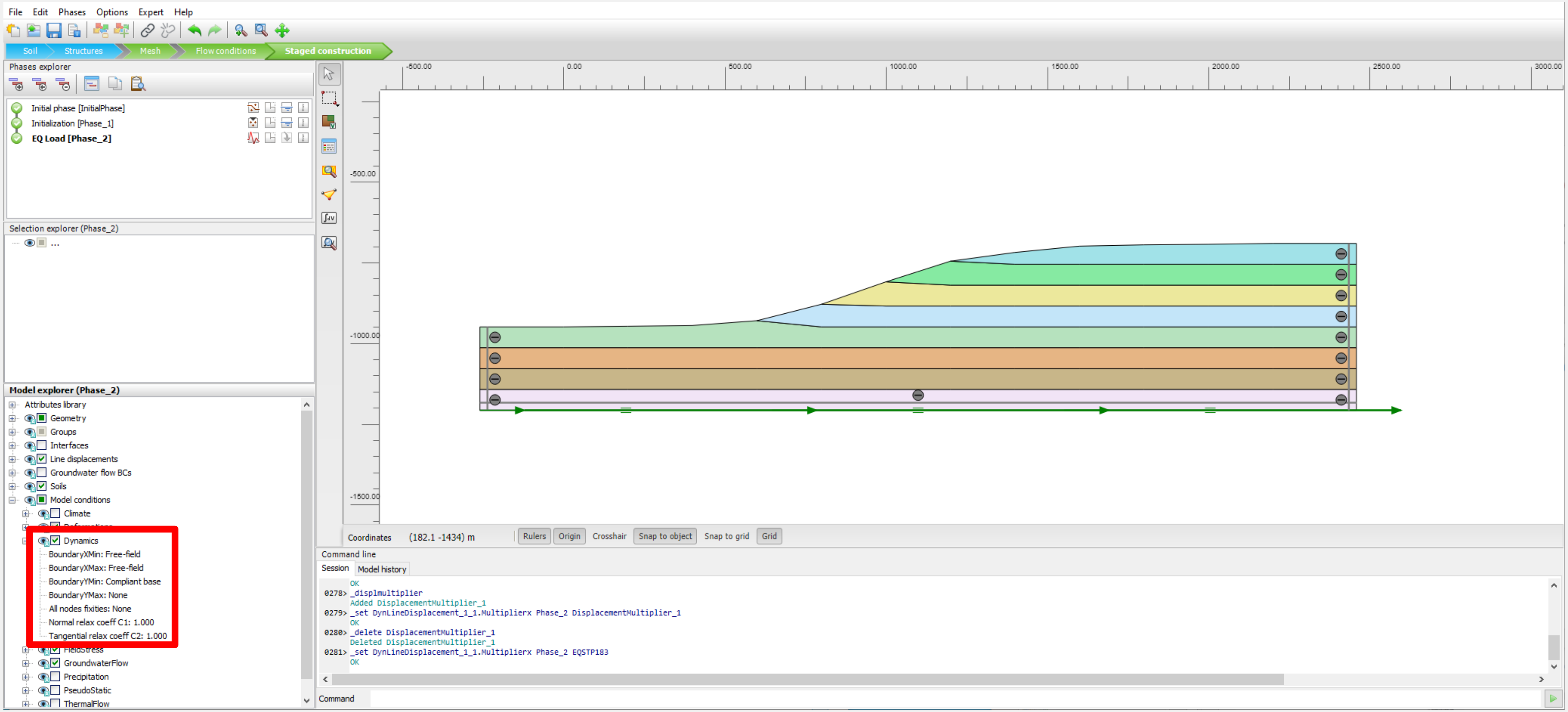
PLAXIS Demonstration

Define earthquake loading



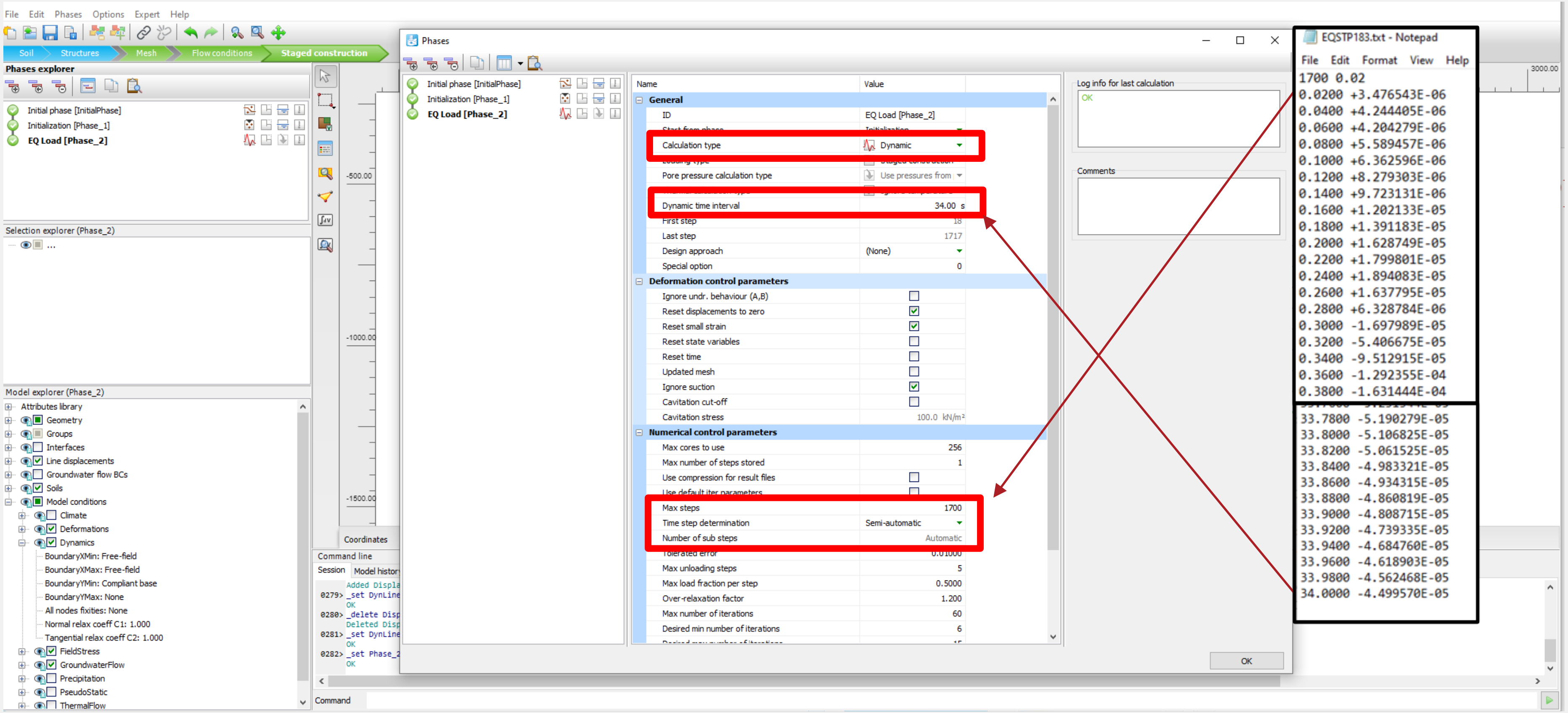
PLAXIS Demonstration

Boundary Conditions



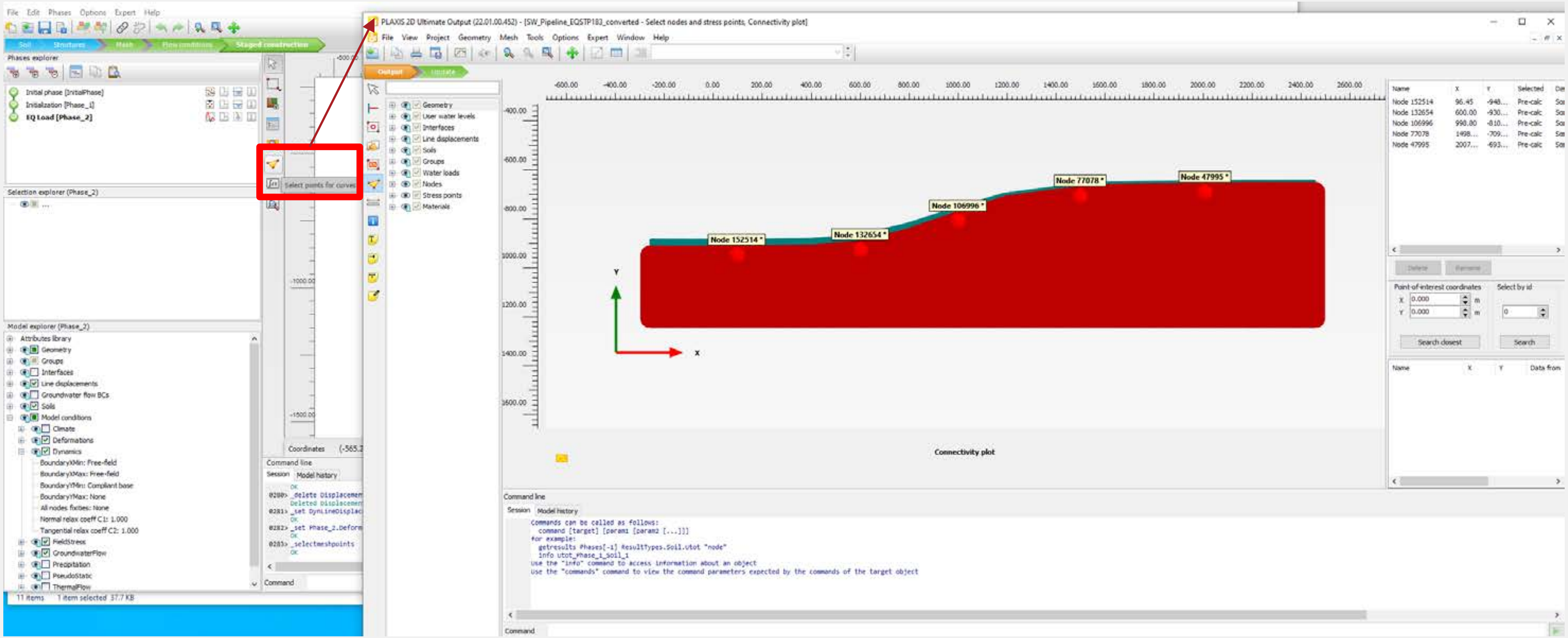
PLAXIS Demonstration

Phase parameters



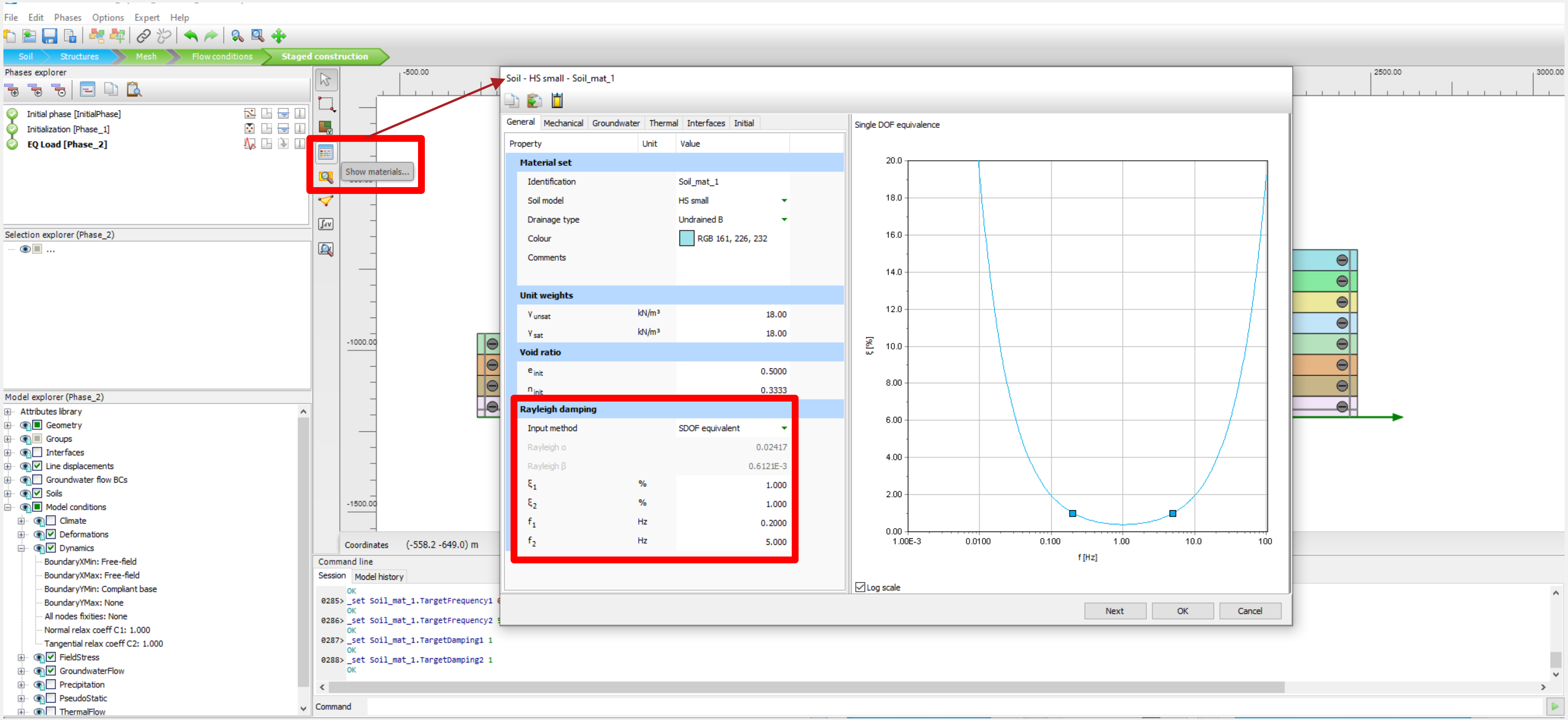
PLAXIS Demonstration

Select curve points to save data



PLAXIS Demonstration

Define Rayleigh damping for each soil material



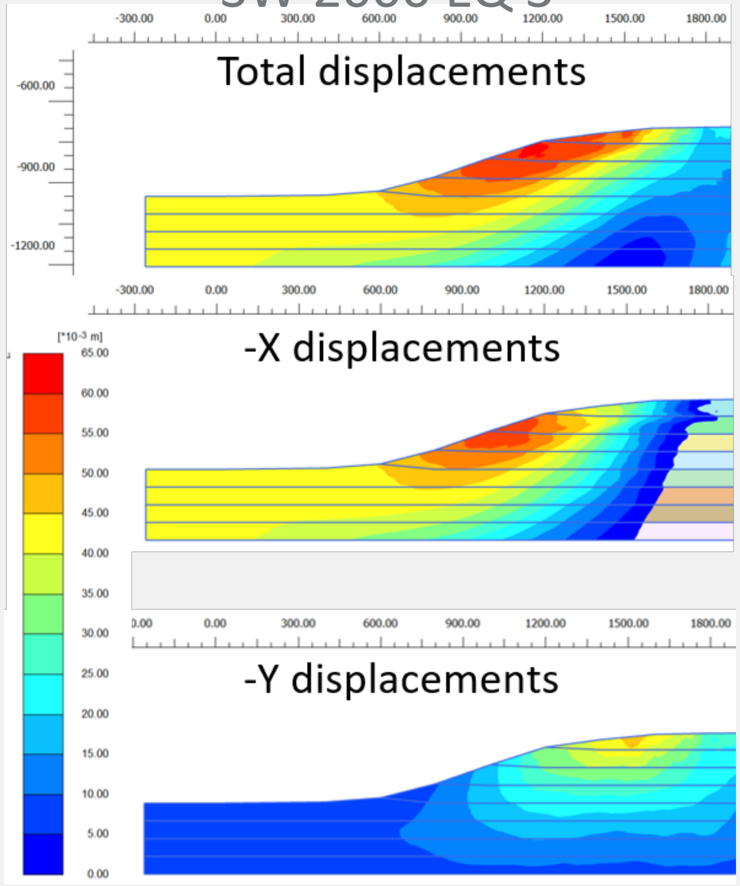
Dynamic FEM in PLAXIS: Results

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

SW 2000 EQ 3



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