DEEP FOUNDATIONS INSTITUTE

S3: Slopes, Slides and Stabilization

Hotel Kabuki | San Francisco & Online

August 3-5, 2021

Software Discussion Introduction:

Moderator: Jeff Segar, PE, SE

Braun Intertec Corp.



BRAUN INTERTEC
The Science You Build On.

2021 S3 Software Problem:

- **Uses the geometry and pile resistance from, "*Case History: Value Engineering of Driven H-Piles for Slope Stability on the Missouri River*"**
  - **By W. Robert Thompson, Jeffrey R. Hill, and J. Erik Loehr**
- **We've modified / changed everything else**
  - **Soil parameters, water level, permeability, etc.**

2021 S3 Software Problem:

- Task is to add another row of railroad tracks between the existing tracks and the river.



2021 S3 Software Problem:

- Original project found failure planes in front of the piles at FS of less than 1.5 and rapid draw down FS of 0.6. Proposed to armor the slope to improve both.



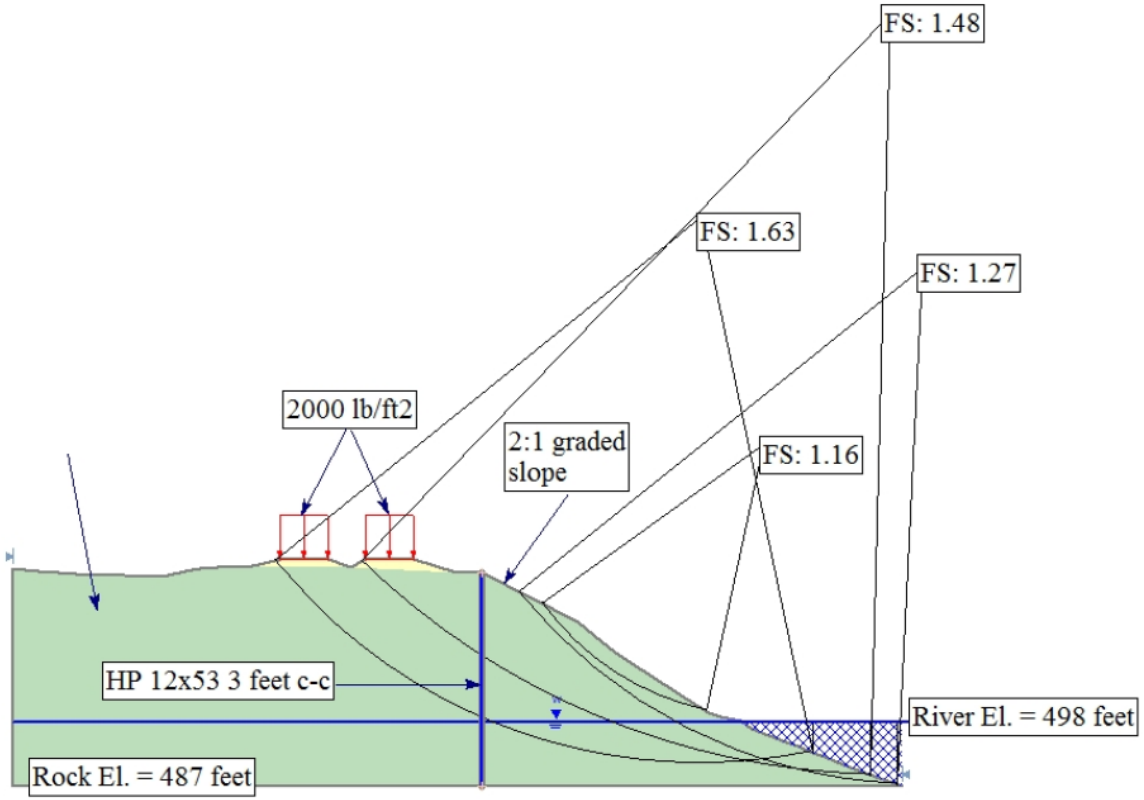


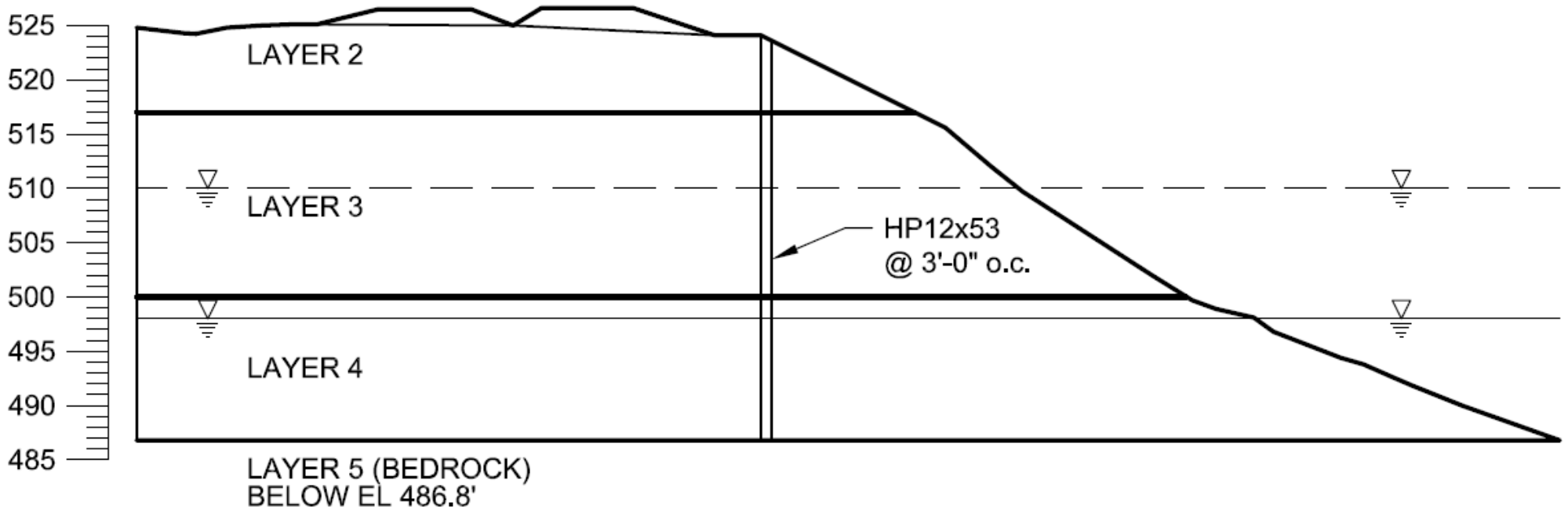
FIG. 4. Typical Result from Analysis of Embankment Stabilized Using H-Piles

2021 S3 Software Problem: Given Instructions to software providers

- Analyze station 4598+00 for:
  - Rapid drawdown from a high water of 510’ to 498’ over a 2 week time frame
  - For simplicity use the HP12x53 @ 3’-0” o.c. from the paper and use the pile resistance from Figure 3. in the paper.
- Identify areas of concern, problems to explore further, but we did not ask the providers to determine alternate solutions.

2021 S3 Software Problem: Given Instructions to software providers

- **Station 4598+00**



Layer	Soil type	Unit Weight (pcf)	Cohesion C' (PSF)	Friction Angle Phi'	Undrained Cohesion Cr (psf)	Undrained Friction Angle Phi(r)	Hydraulic Permeability (cm/sec)
2	Sitly Sand	125	50	30	265	15	1x10-4
3	Sandy Silt	125	50	30	340	15	1x10-4
4	Clay	110	25	32	504	16	1x10-6

2021 S3 Software Problem: Given Instructions to software providers

- For simplicity use the HP12x53 @ 3’-0” o.c. from the paper and use the pile resistance from Figure 3. in the paper.

- Pay attention to the process and the steps

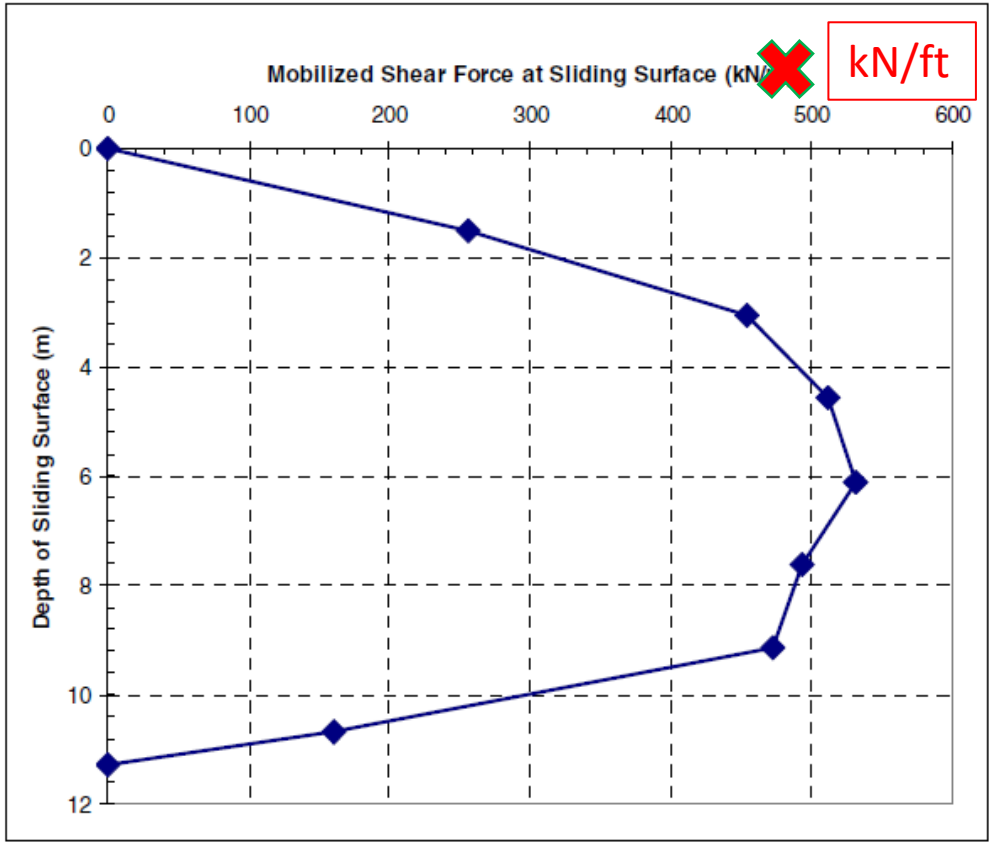


FIG. 3. Predicted Shear Resistance at Sliding Surface for H-Piles subjected to Soil Movement of 127 mm (5 inches)

DEEP FOUNDATIONS INSTITUTE

S3: Slopes, Slides and Stabilization

Hotel Kabuki | San Francisco & Online

August 3-5, 2021

Software Discussion Panelists:

Jeff Lam, M.Eng., P.Eng, Rocscience, Inc.

Sina Javankhoshdel, Ph. D., P.Eng, A.M.ASCE, Rocscience, Inc.

Garry Gregory, Ph.D., P.E., D.GE, Gregory Geotechnical and Oklahoma State University

Murray Fredlund, Ph.D., P.Eng, Bentley

Mohammed Siddiquee, Ph.D., Bentley






The opinions expressed in these presentations and on the following slides are solely those of the presenters and not necessarily those of DFI. DFI does not guarantee the accuracy or reliability of the information or endorse the recommendations offered by the presenters.

DFI S3 Conference Software Discussion

August 5, 2021

Rocscience session presented by:



Sina Javankhoshdel, Ph.D., P.Eng.



Jeff Lam, M.Eng., P.Eng.

rocscience

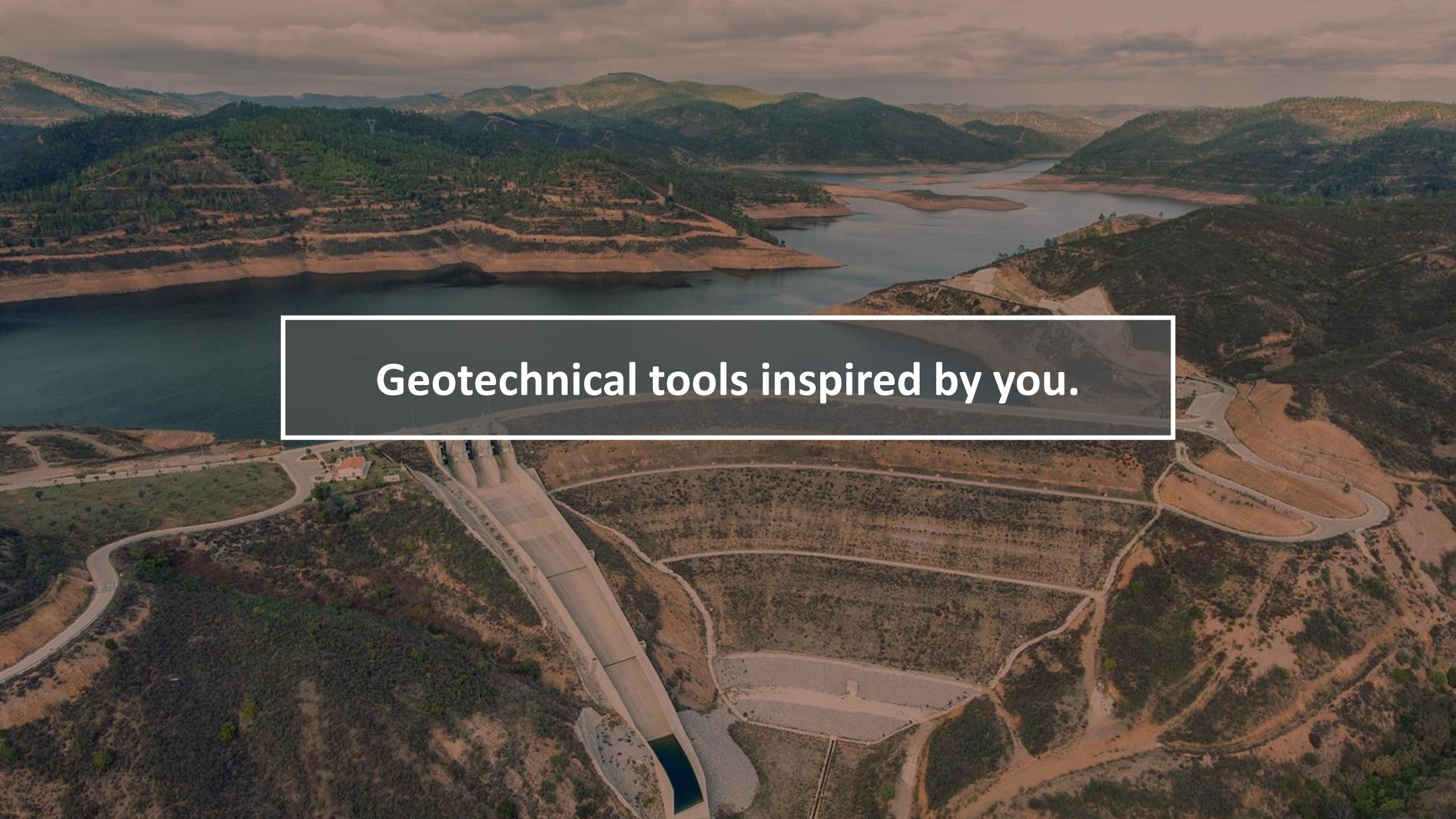


About Rocscience

Rocscience develops 2D & 3D software for civil, mining, and geotechnical engineers. For over 20 years, we've built geotechnical tools used by more than 8,000 users around the world.

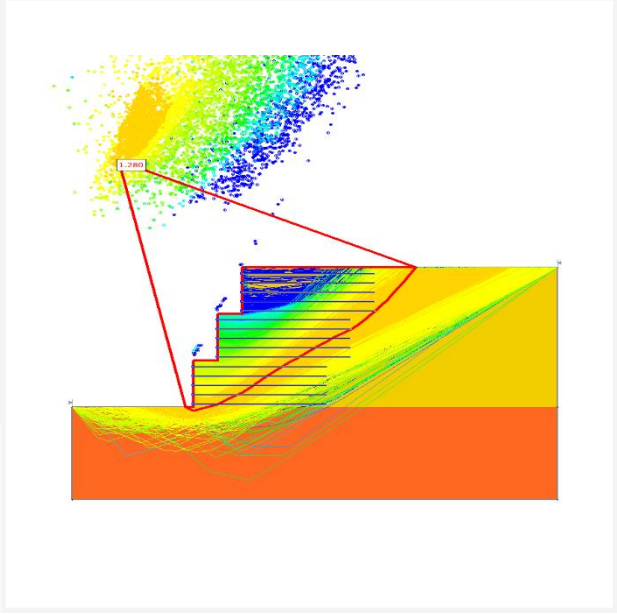
We have over 50 employees at our head office in Toronto, more than half of which hold advanced degrees in engineering.

rocscience

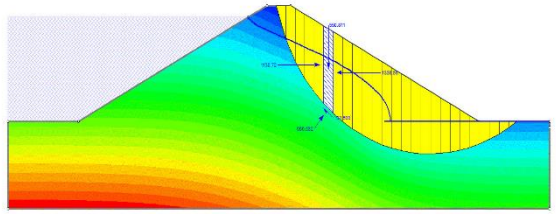

Geotechnical tools inspired by you.

Slide2

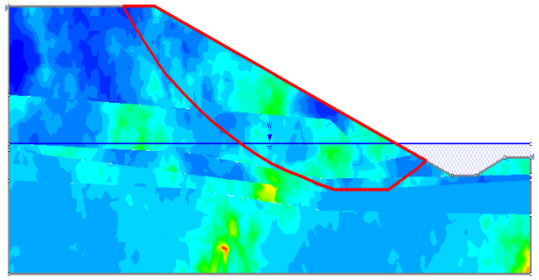
2D Limit Equilibrium Slope Stability Analysis (with FEM seepage)



Support Analysis



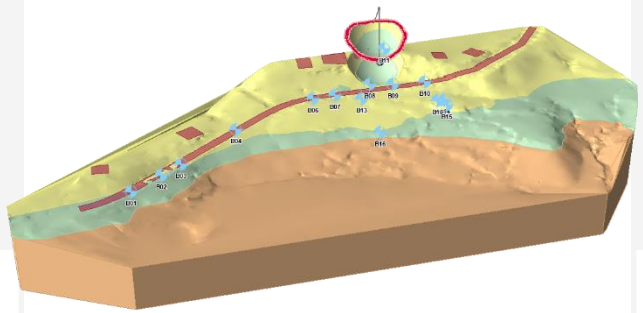
Transient Groundwater Analysis



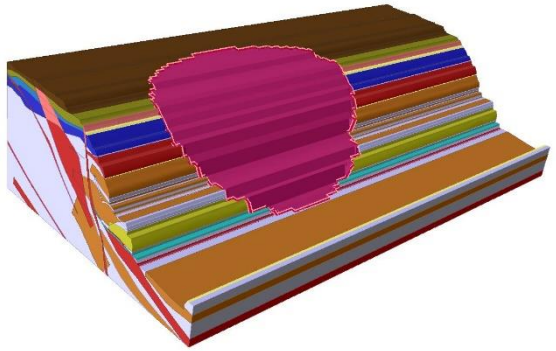
Spatial Variability Analysis

Slide3

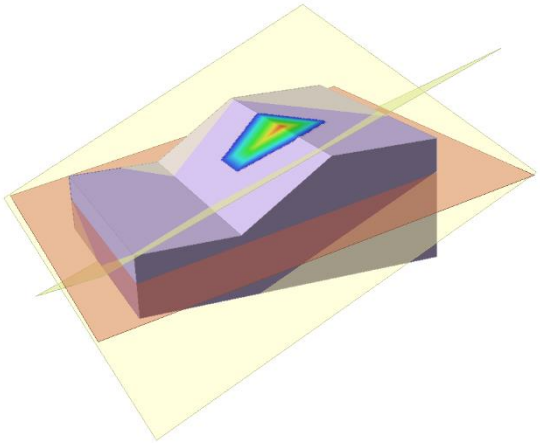
3D Limit Equilibrium Slope Stability Analysis



Advanced 3D Search



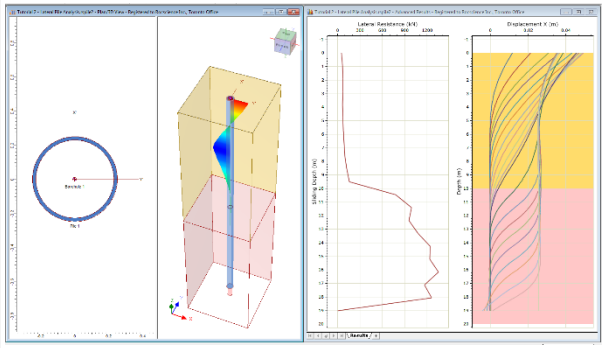
Import from Slide2



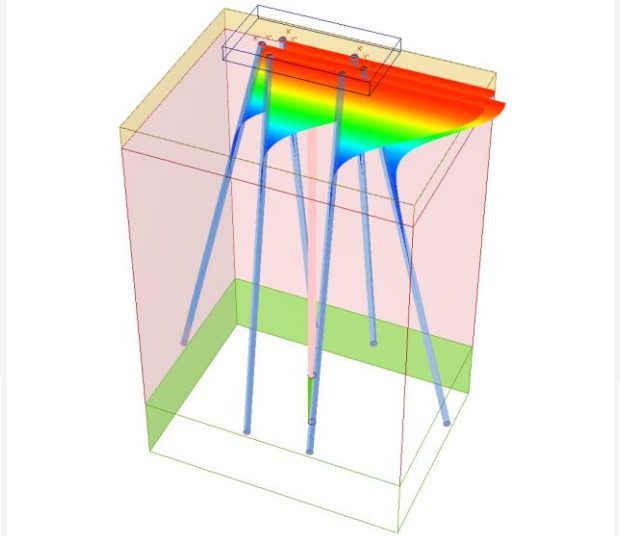
Multiplanar Search

RSPile

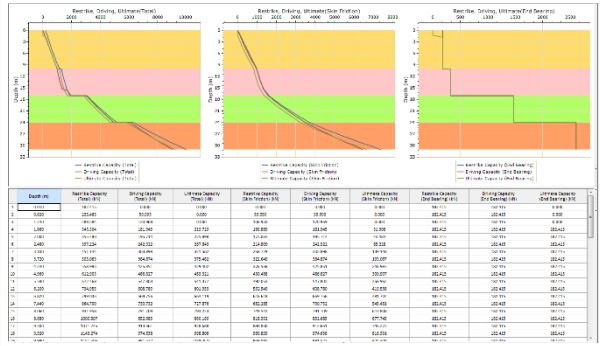
2D&3D Pile Analysis



Axial and Lateral Pile Analysis



Grouped Pile Analysis

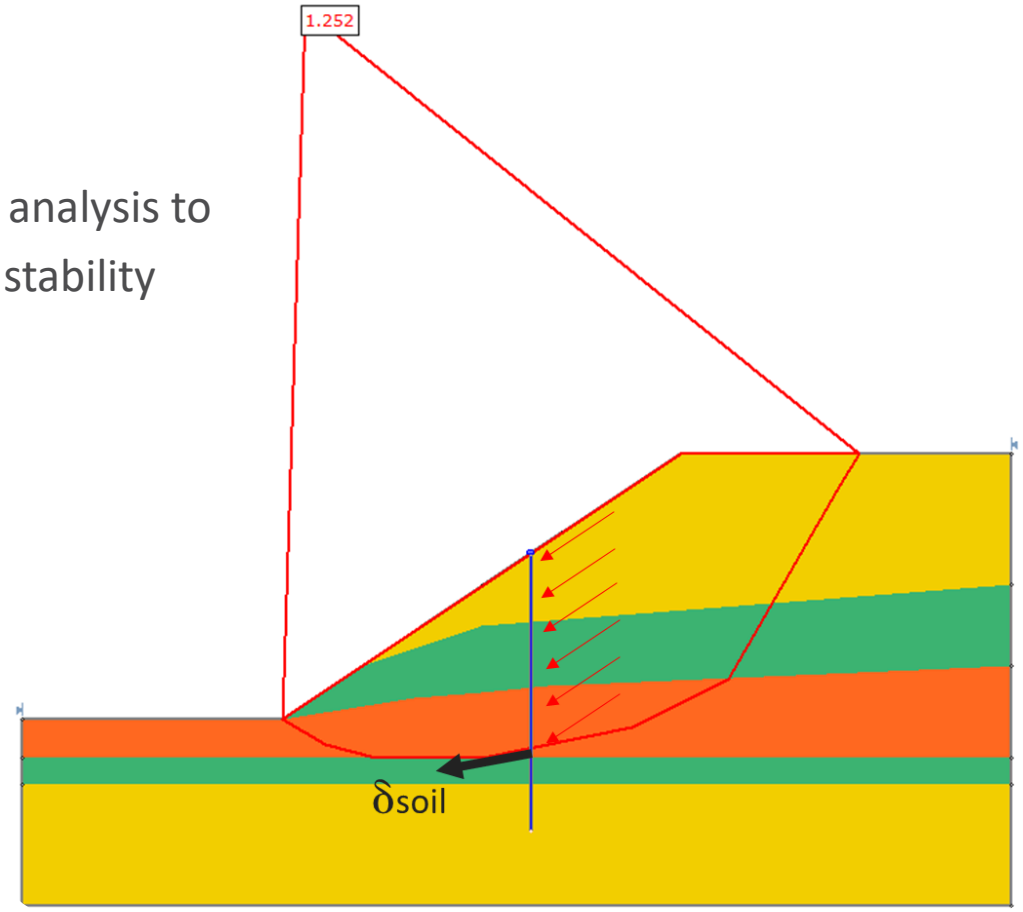


Driven Pile Analysis

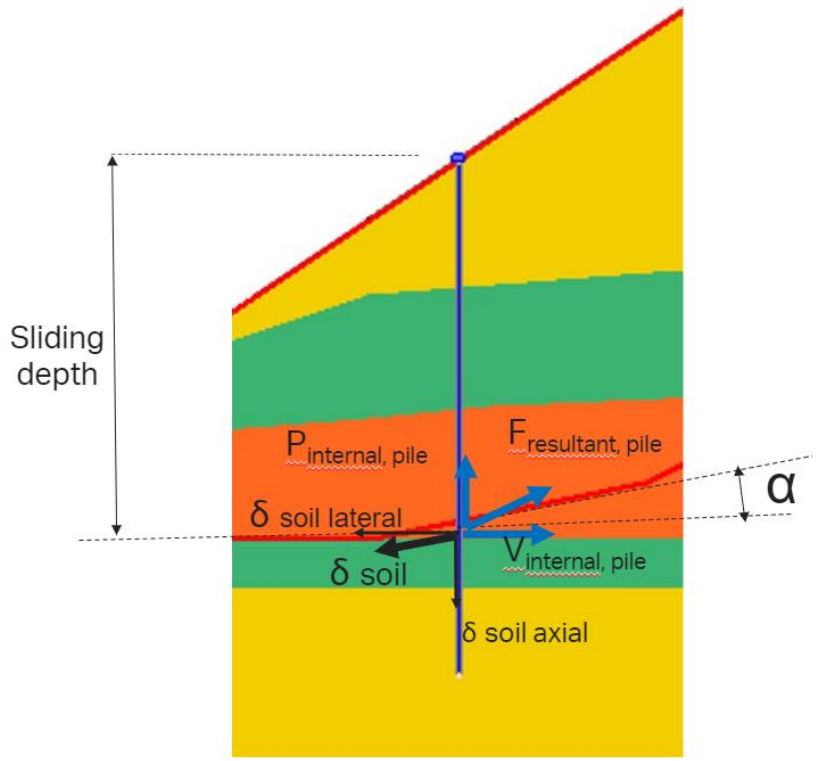
RSPile Integration with Slide2

Concept

Comprehensive pile analysis to enhance your slope stability analysis



Soil Displacement Occurs Due To A Slide Movement – Slide2

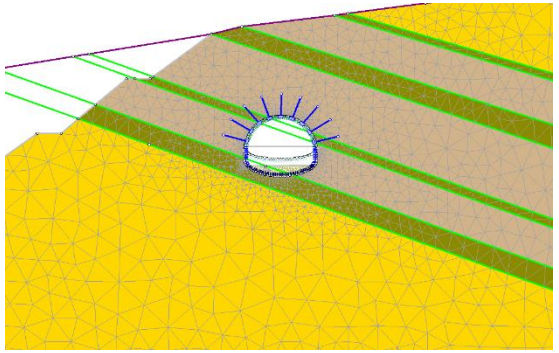


Components Of
Soil Displacement and Resistance

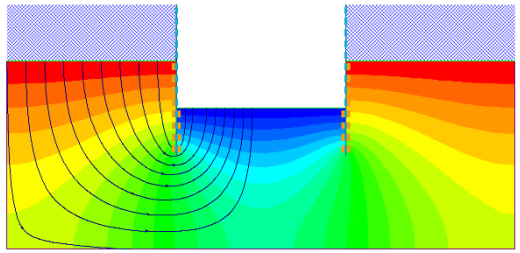
RSPile | rocscience

RS2

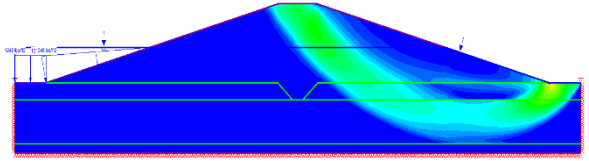
2D Geotechnical Finite Element Analysis



Tunnel Excavation



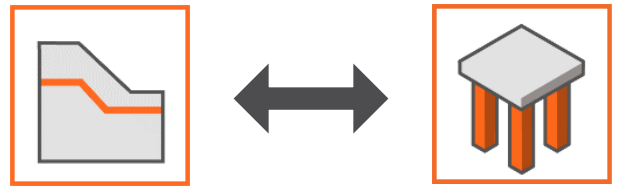
Groundwater Seepage



Shear Strength Reduction

Analysis Workflow

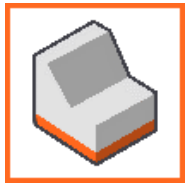
Start with 2D Limit Equilibrium Method (LEM) coupled with Lateral Pile analysis.



Validate results using 2D Finite Element Method (FEM) with Shear Strength Reduction (SSR)

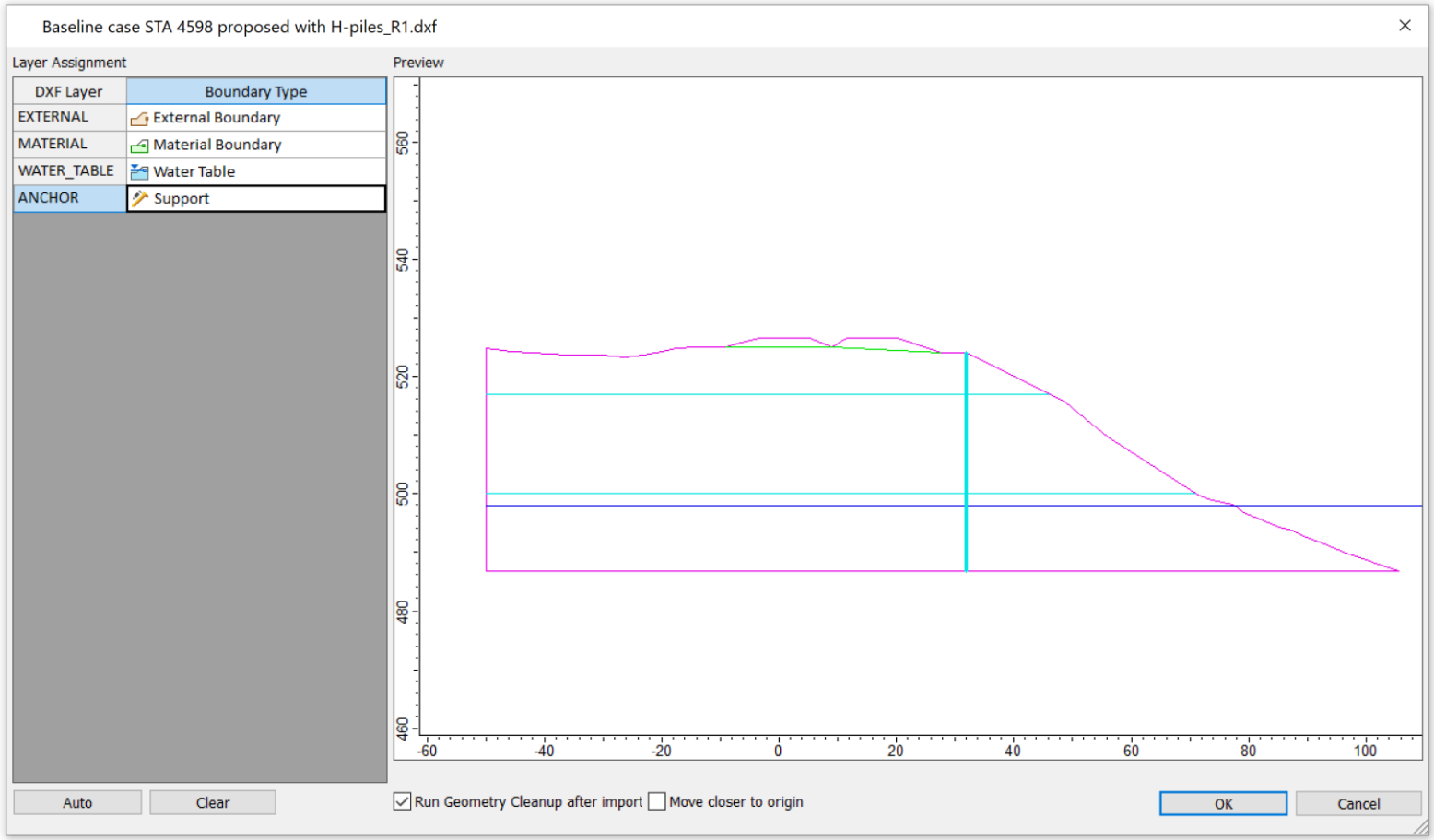


Validate results using 3D Limit Equilibrium Method (LEM)



Model Setup

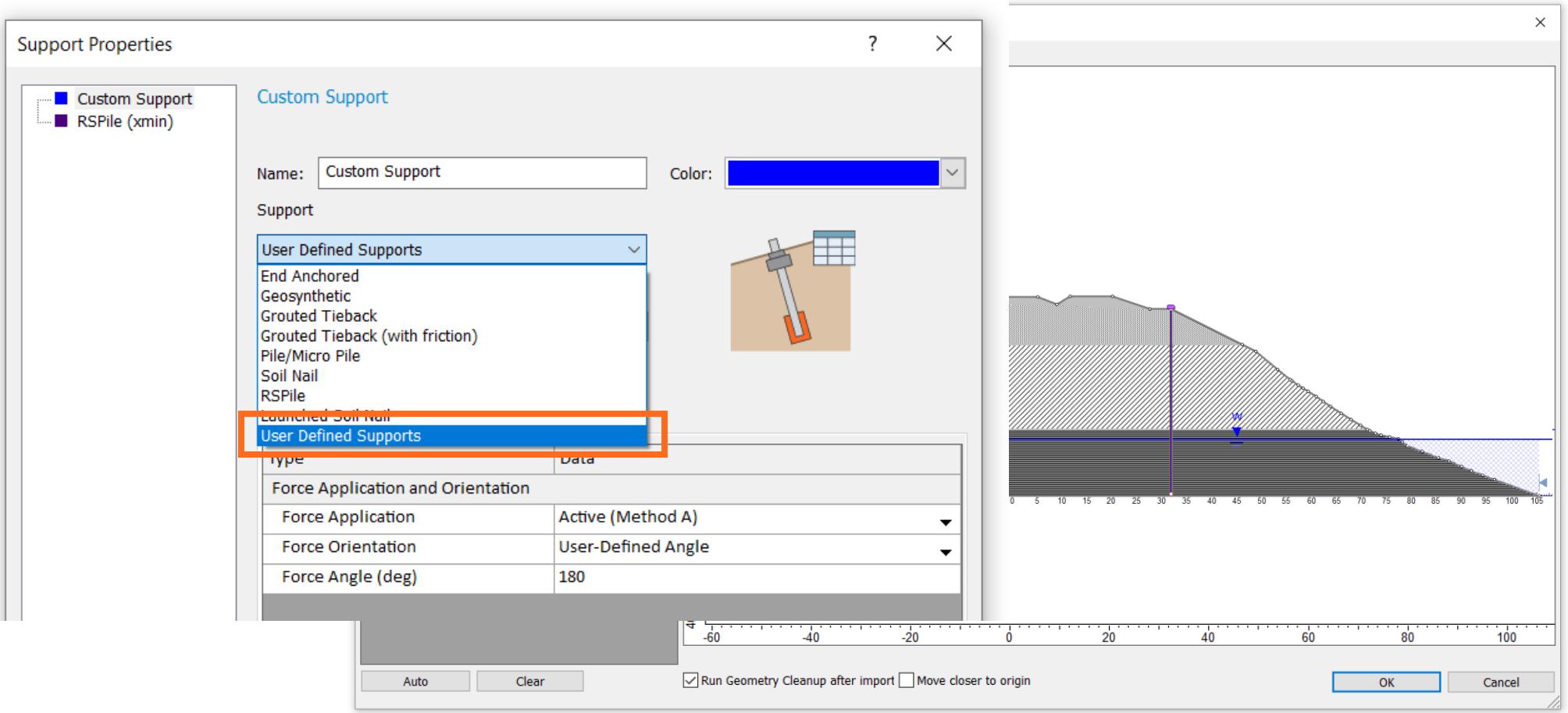
Geometry > Support > Surfaces



Slide2 | rocscience

Model Setup – User Defined Support

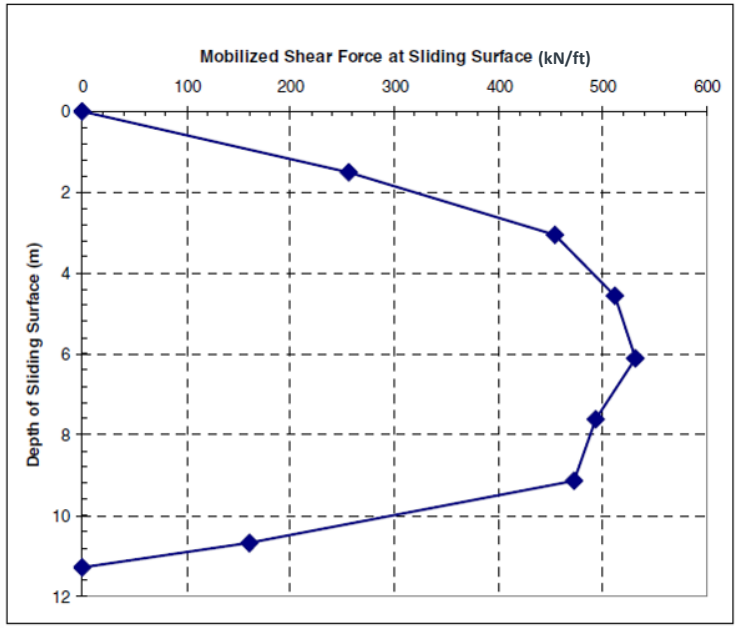
Geometry > Support > Surfaces



Slide2 | rocscience

Model Setup – User Defined Support

Geometry | Support | Surfaces

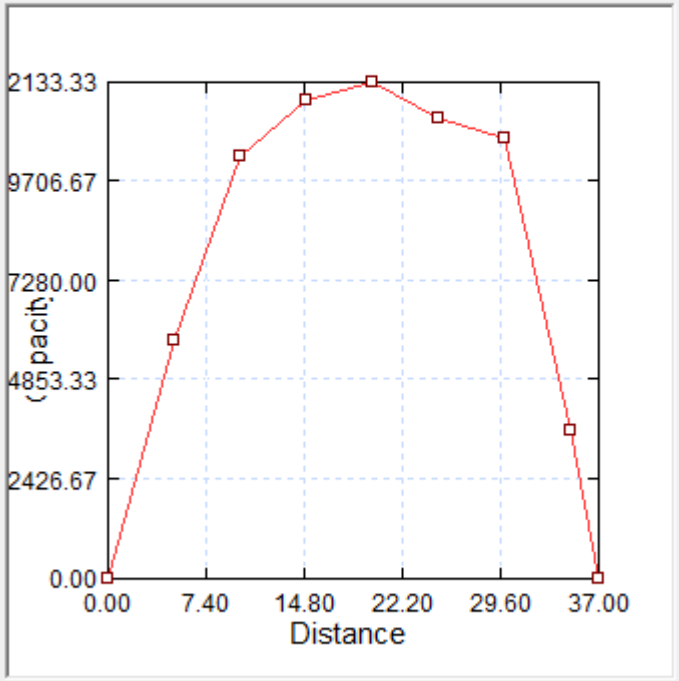


User Defined Support

Name: 750 psf soil

Copy Chart

Point	Distance	Capacity
1	0	0
2	5	5833.3329999999996
3	10	10366.666999999995
4	15	11700
5	20	12133.333000000005
6	25	11266.666999999995
7	30	10800
8	35	3666.6669999999999



Import...

Export...

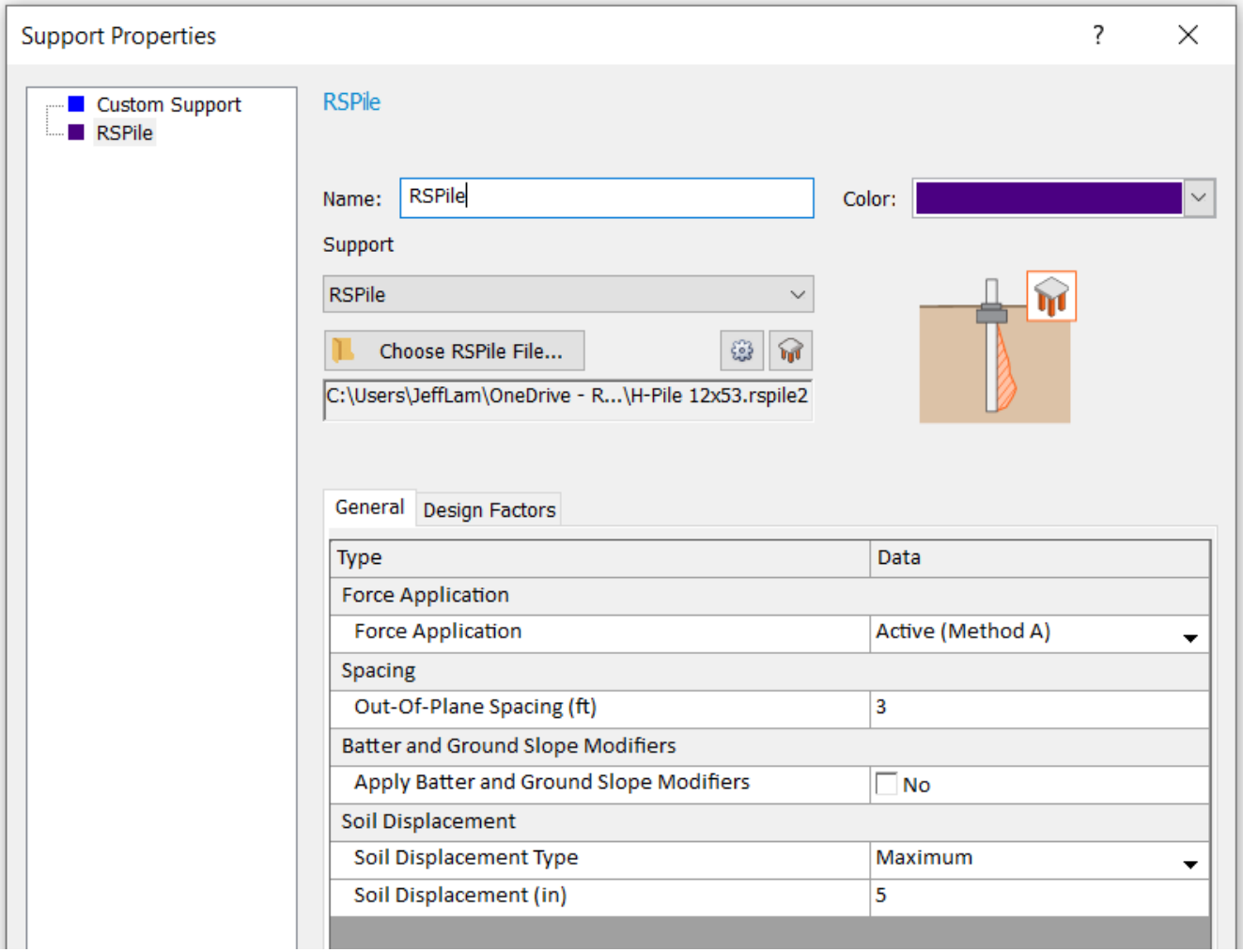
OK

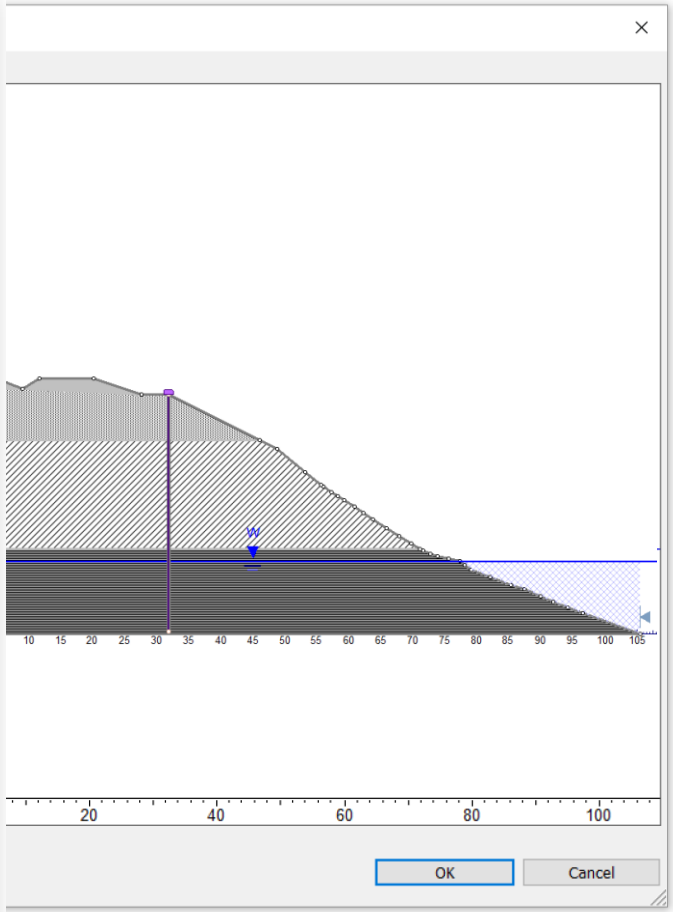
Cancel

Slide2 | rocscience

Model Setup – RSPile Support (coupled)

Geometry > Support > Surfaces





Slide2 | rocscience

Model Setup – RSPile Support (coupled)

Geometry > Support > Surfaces

Support Properties

- Custom Support
- RSPile (xmin)

RSPile (xmin)

Name: RSPile (xmin) Color:

Support

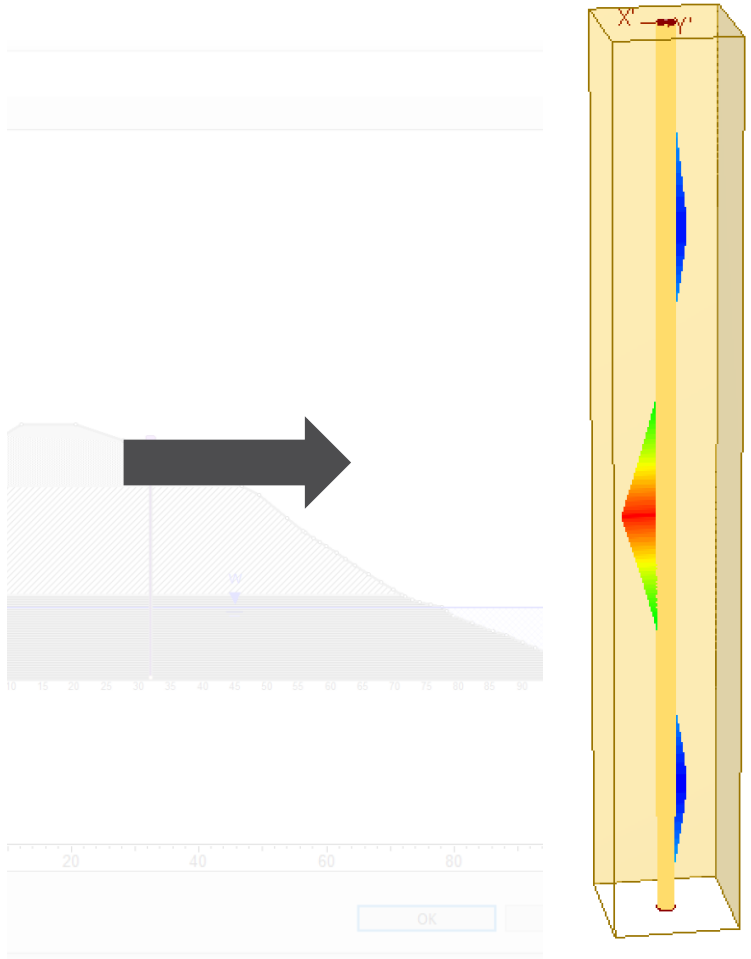
RSPile

Choose RSPile File...

C:\Users\JeffLam\OneDrive - R...\H-Pile 12x53.rspile2

General | Design Factors

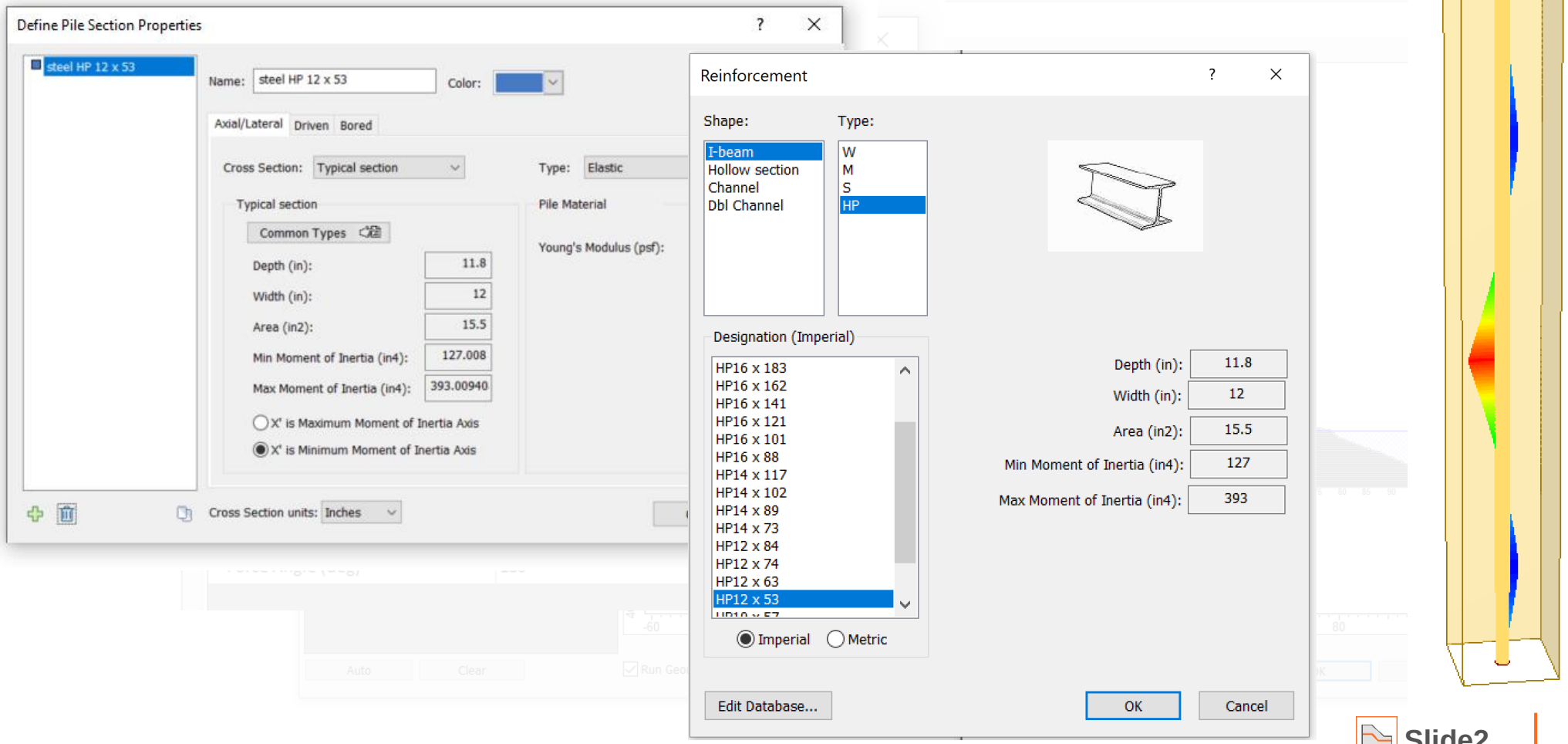
Type	Data
Force Application	
Force Application	Active (Method A)
Spacing	
Out-Of-Plane Spacing (ft)	3
Batter and Ground Slope Modifiers	
Apply Batter and Ground Slope Modifiers	No
Soil Displacement	
Soil Displacement Type	Maximum
Soil Displacement (in)	5



Slide2 | rocscience

Model Setup – RSPile Support (coupled)

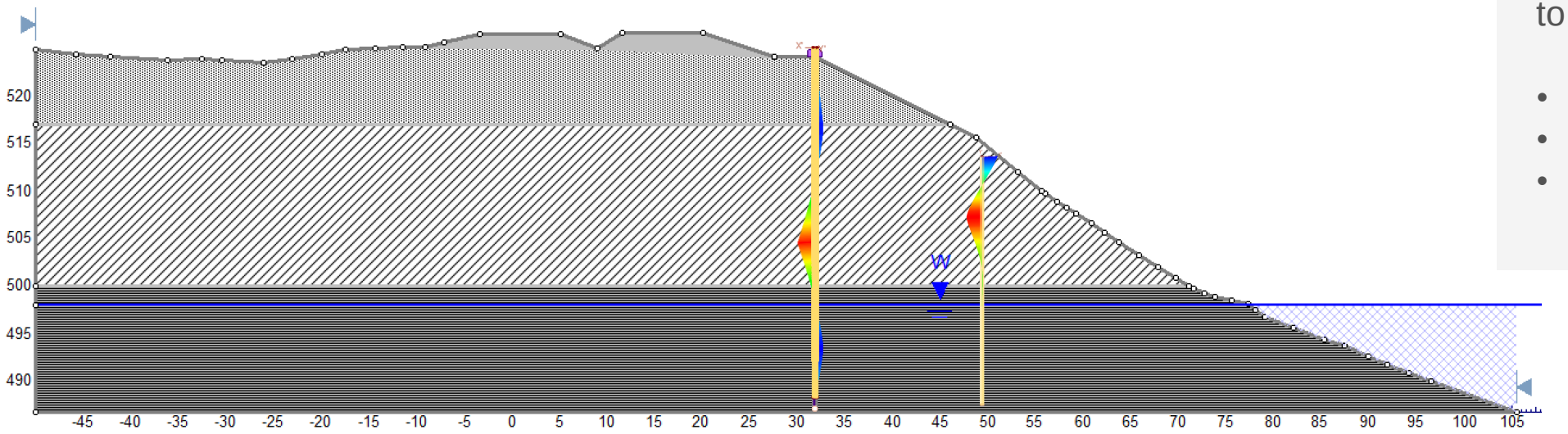
Geometry | Support | Surfaces



Slide2 | rocscience

Model Setup – RSPile Support (coupled)

Geometry > Support > Surfaces



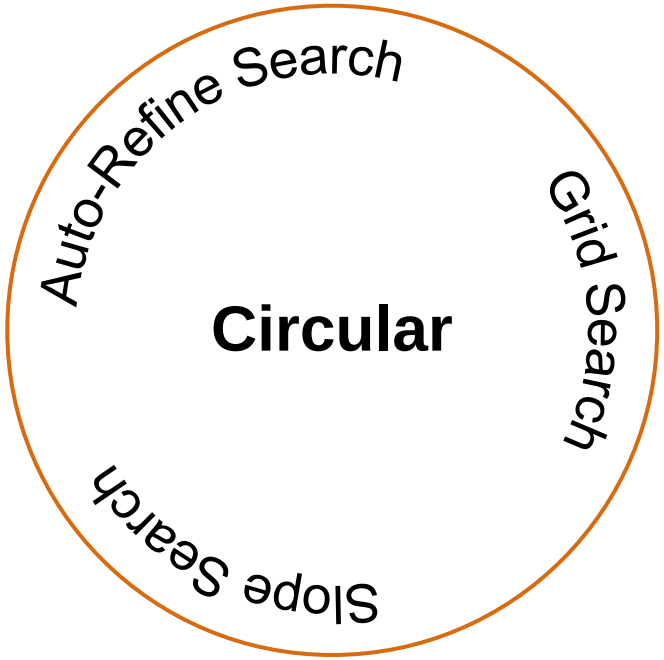
PRO TIP

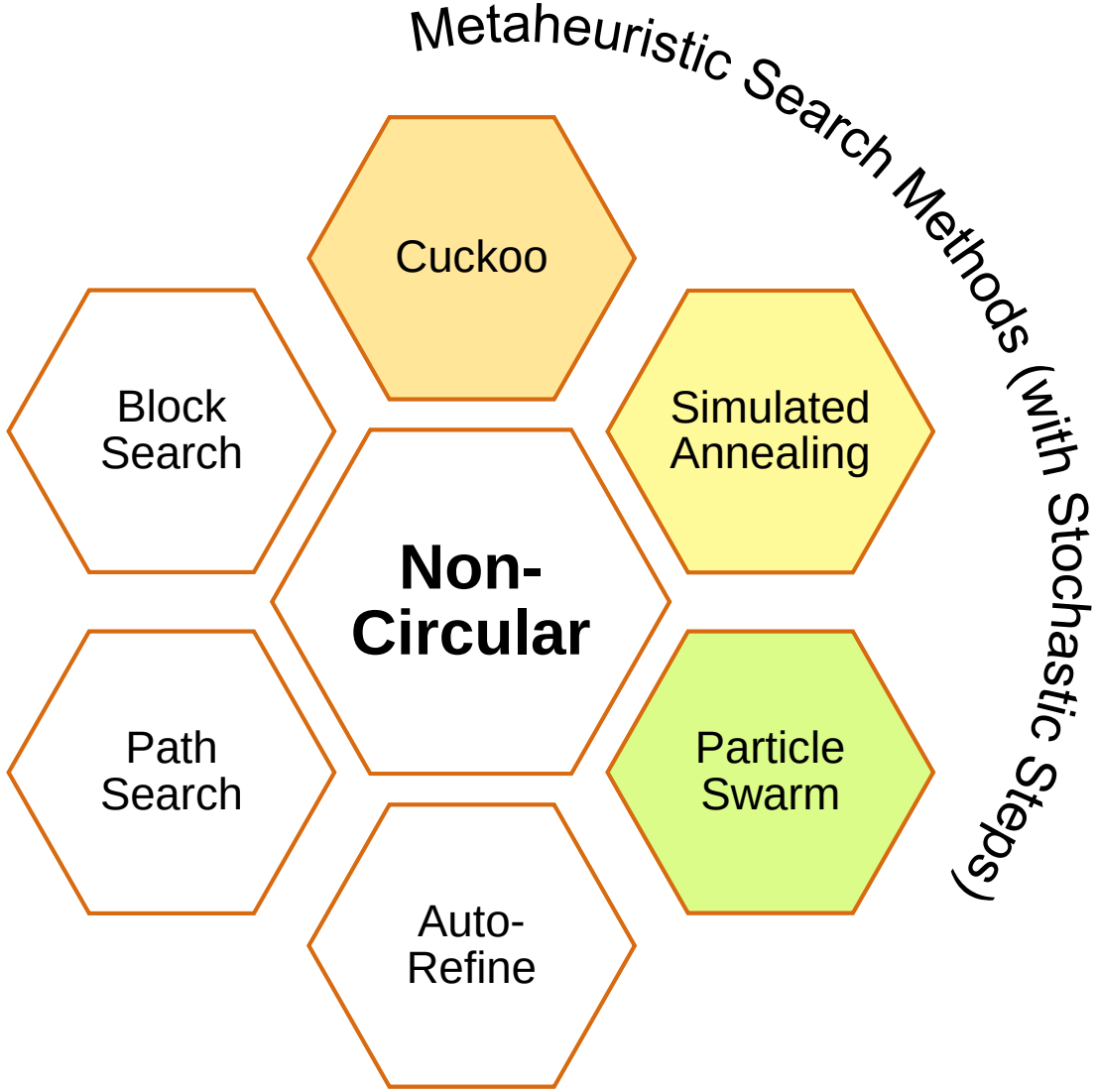
Slide2 and RSPile coupling will automatically recalculate pile resistance envelope to account for:

- Out-of-plane-spacing
- Pile batter angle
- Allowable soil displacement

Model Setup


Geometry
Support
Surfaces

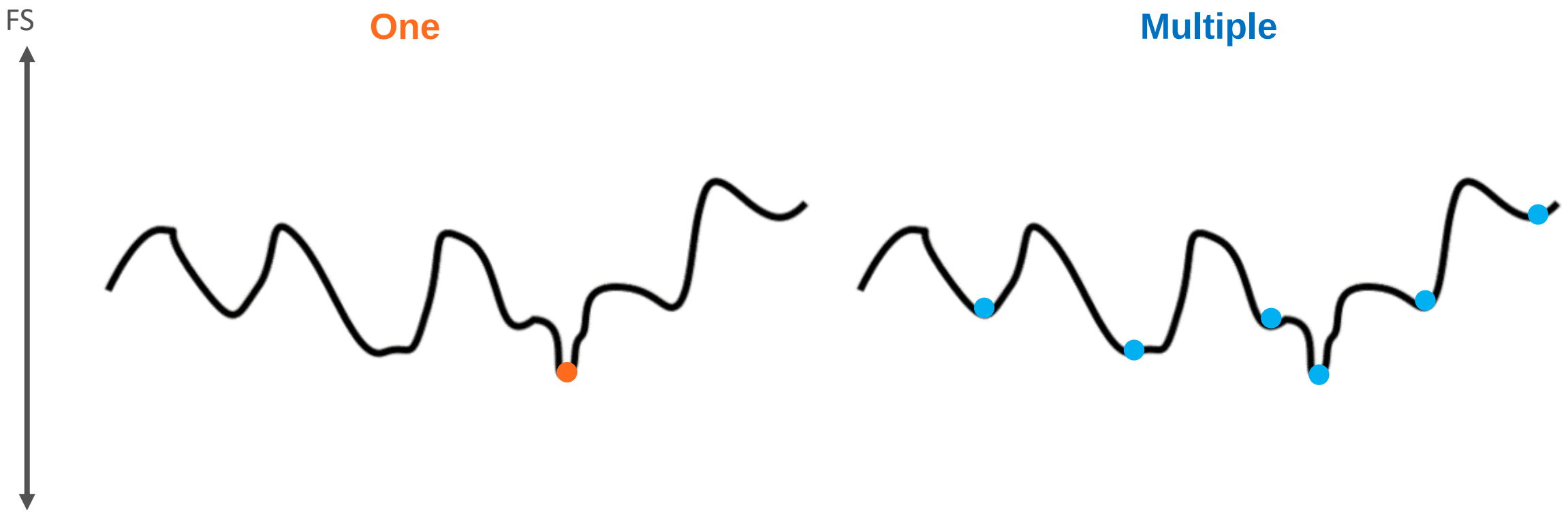

Auto-Refine Search
Grid Search
Slope Search
Circular


Metaheuristic Search Methods (with Stochastic Steps)
Cuckoo
Block Search
Simulated Annealing
Non-Circular
Path Search
Particle Swarm
Auto-Refine

Model Setup

Geometry > Support > Surfaces

One vs Multiple



Model Setup



One vs Multiple behind the scenes

One

1. Each iteration goes towards the global minimum.
2. Global minimum found.
3. Global minimum optimized.
4. Best of optimized and non-optimized global minimum displayed.

Multiple

1. Each iteration goes towards each particle's closest minimum.
2. Three best minima found (separated by at least 10% radius).
3. Three best minima optimized, checked again for 10% filter, and displayed.

Model Setup



Metaheuristic Search Methods



Particle Swarm



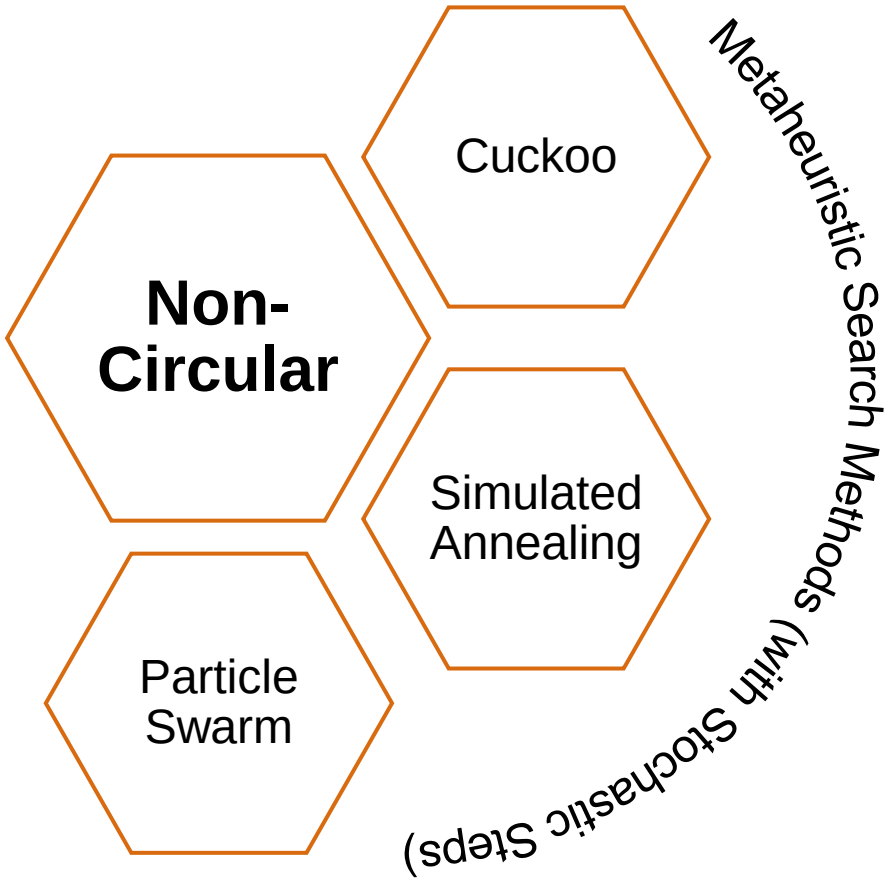
Cuckoo Search

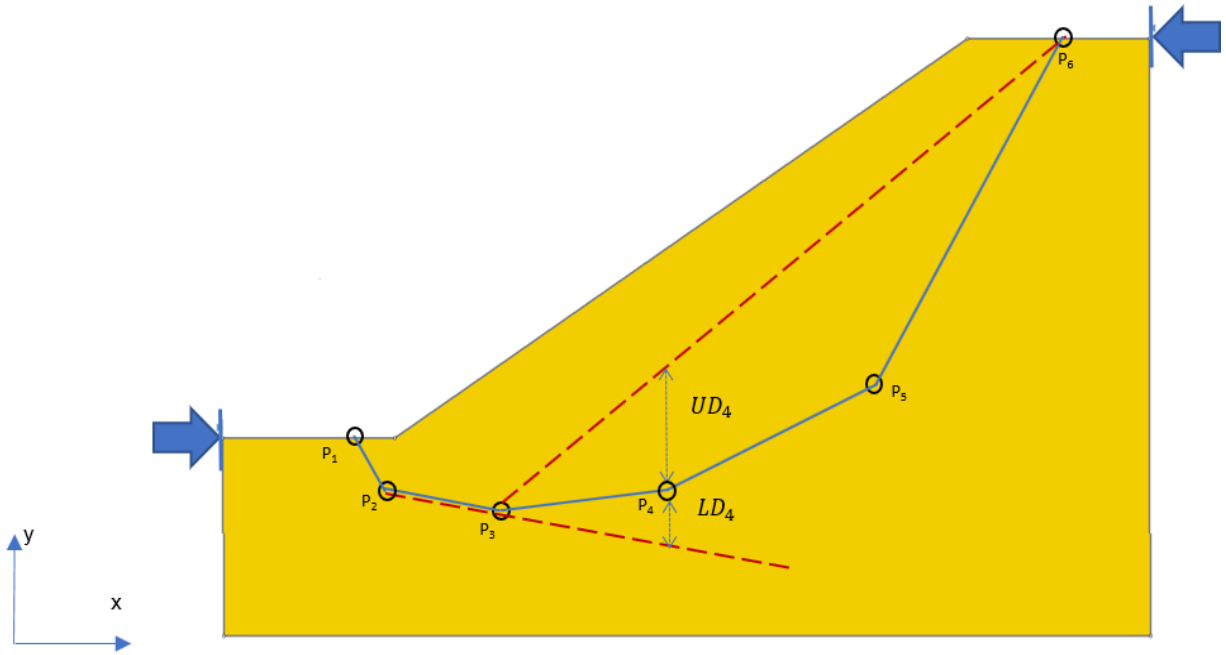


Simulated Annealing

Model Setup

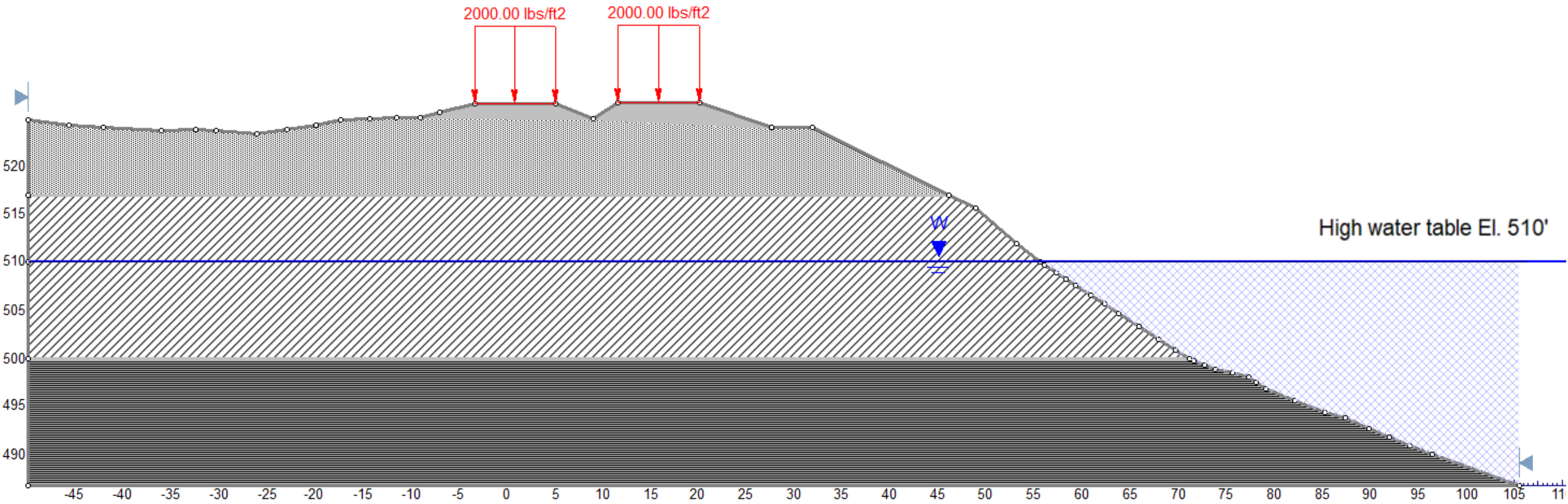






Surface Altering Optimization

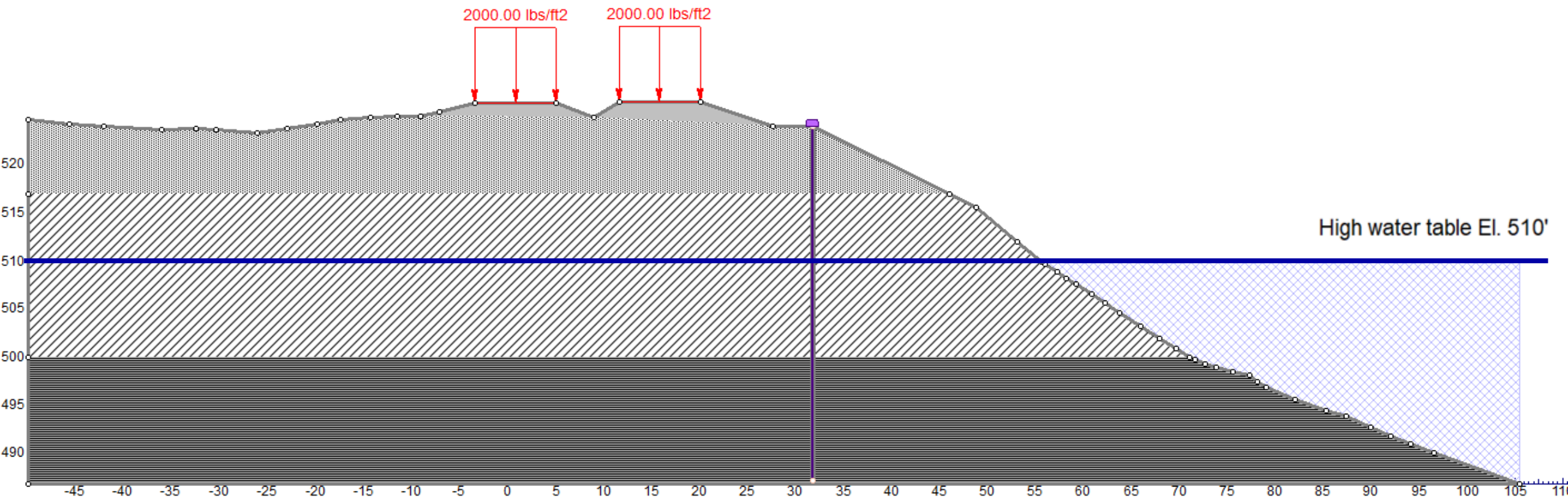
Analysis Approach



High water table steady state | 14-day rapid drawdown | Low water table steady state

Slide2 | rocscience

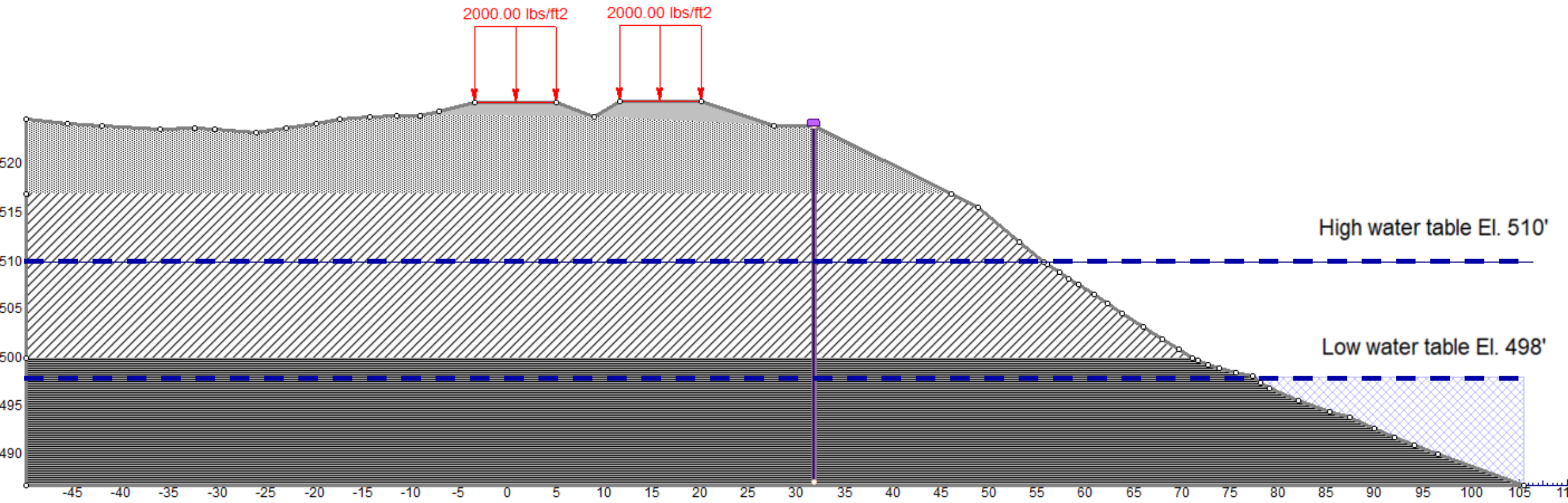
Analysis Approach



High water table steady state | 14-day rapid drawdown | Low water table steady state

Slide2 | rocscience

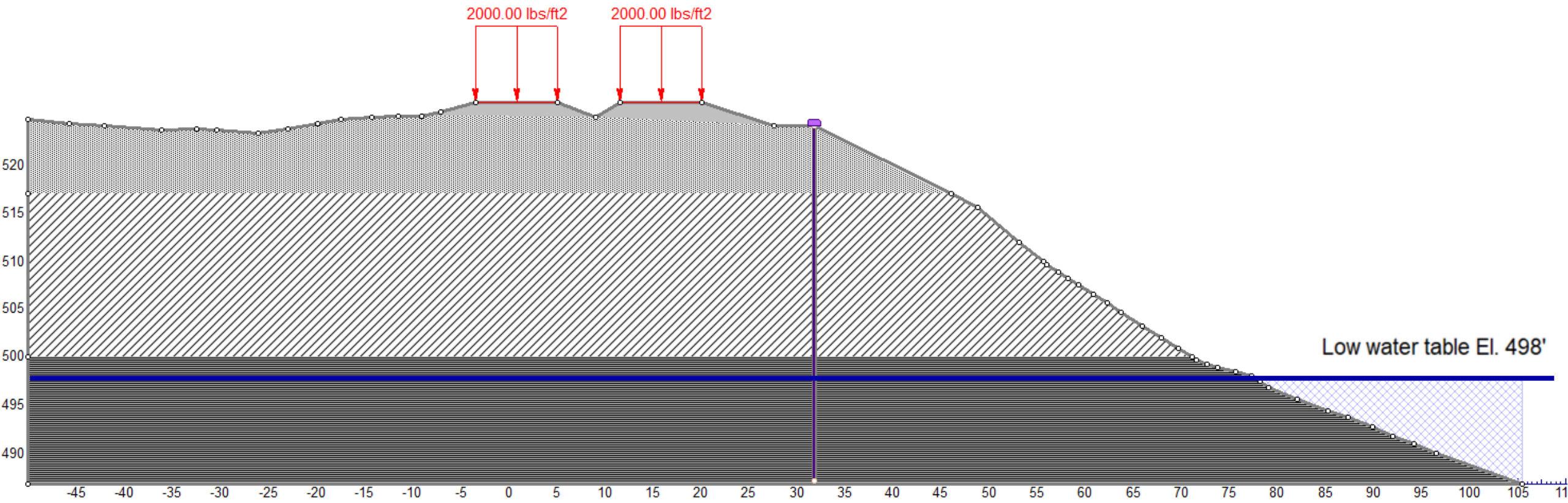
Analysis Approach



High water table steady state | 14-day rapid drawdown | Low water table steady state

Slide2 | rocscience

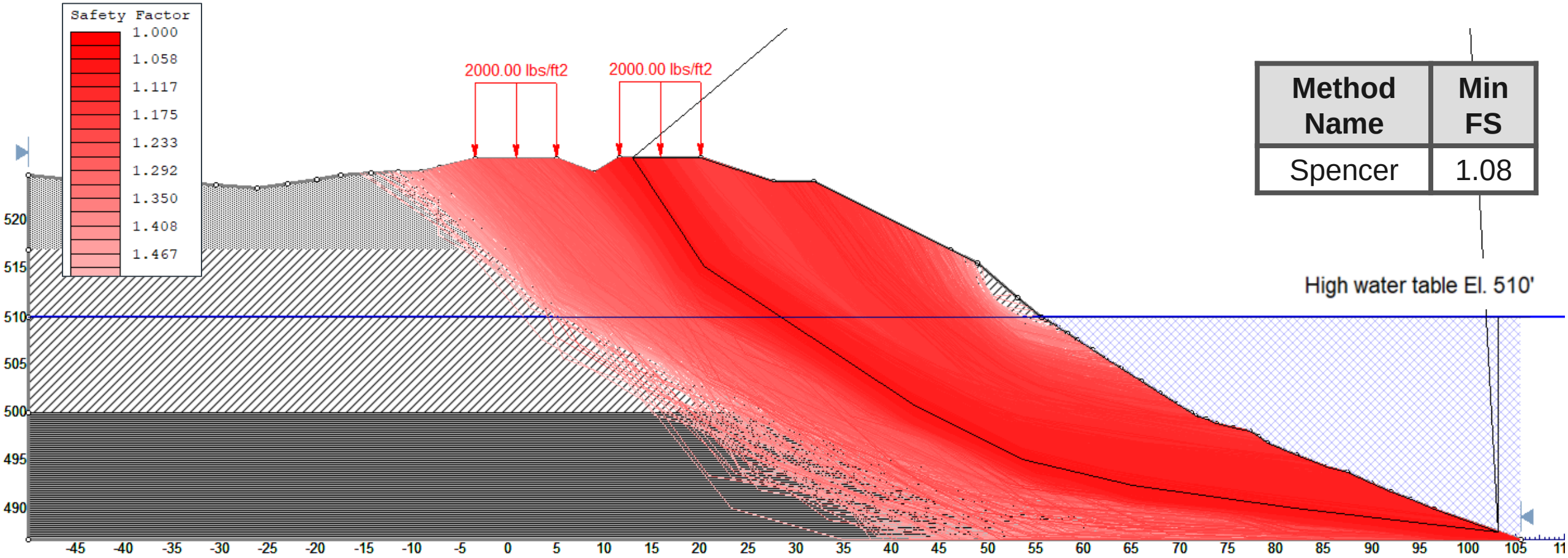
Analysis Approach



High water table steady state | 14-day rapid drawdown | Low water table steady state

Slide2 | rocscience

2D LEM Results - No Support

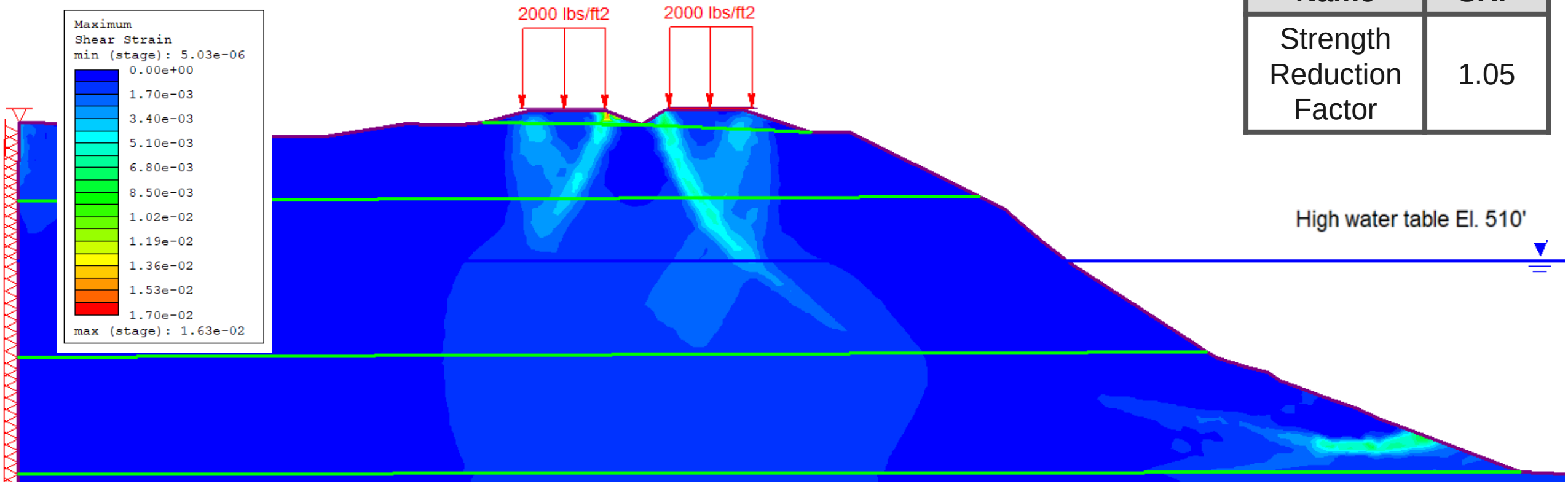


Method Name	Min FS
Spencer	1.08

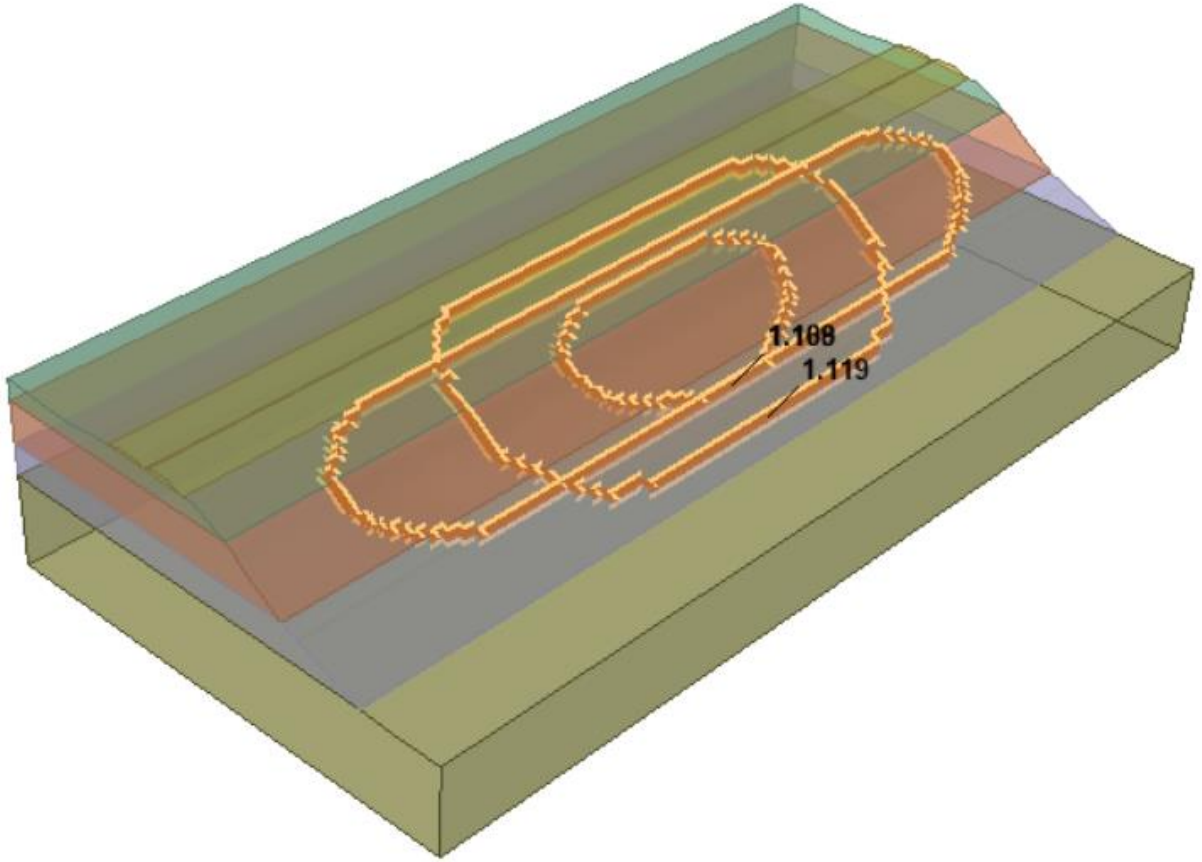
24,050 Slip surfaces analyzed, FoS<1.5 highlighted in red

FEM Results - No Support

Method Name	Critical SRF
Strength Reduction Factor	1.05

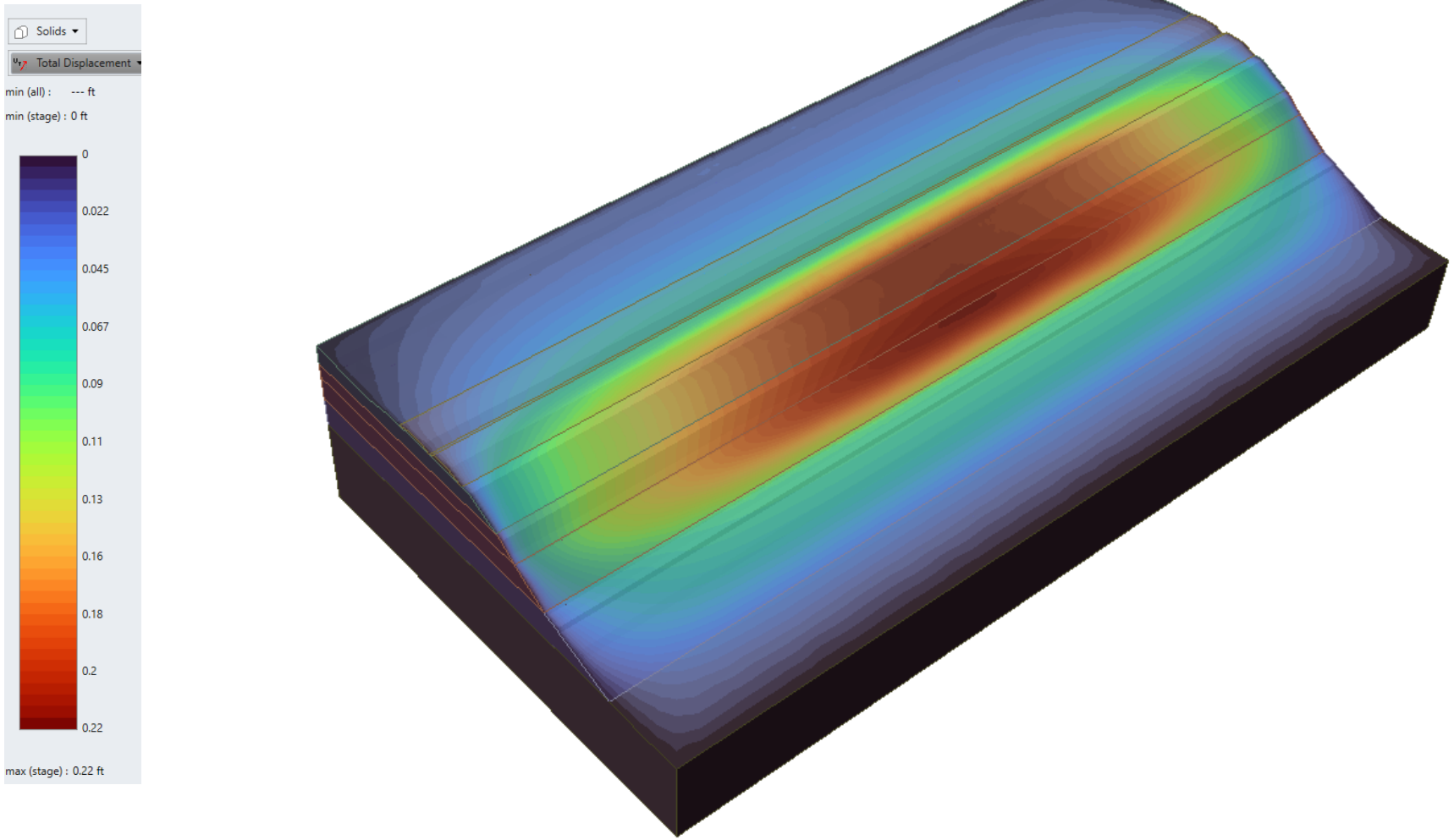


3D LEM Results - No Support



Surface	FS
Spencer Altered Min 1	1.109
Spencer Altered Min 2	1.119
Spencer Altered Min 3	1.168

3D FEM Validation - No Support



Method Name	Critical SRF
Strength Reduction Factor	1.13

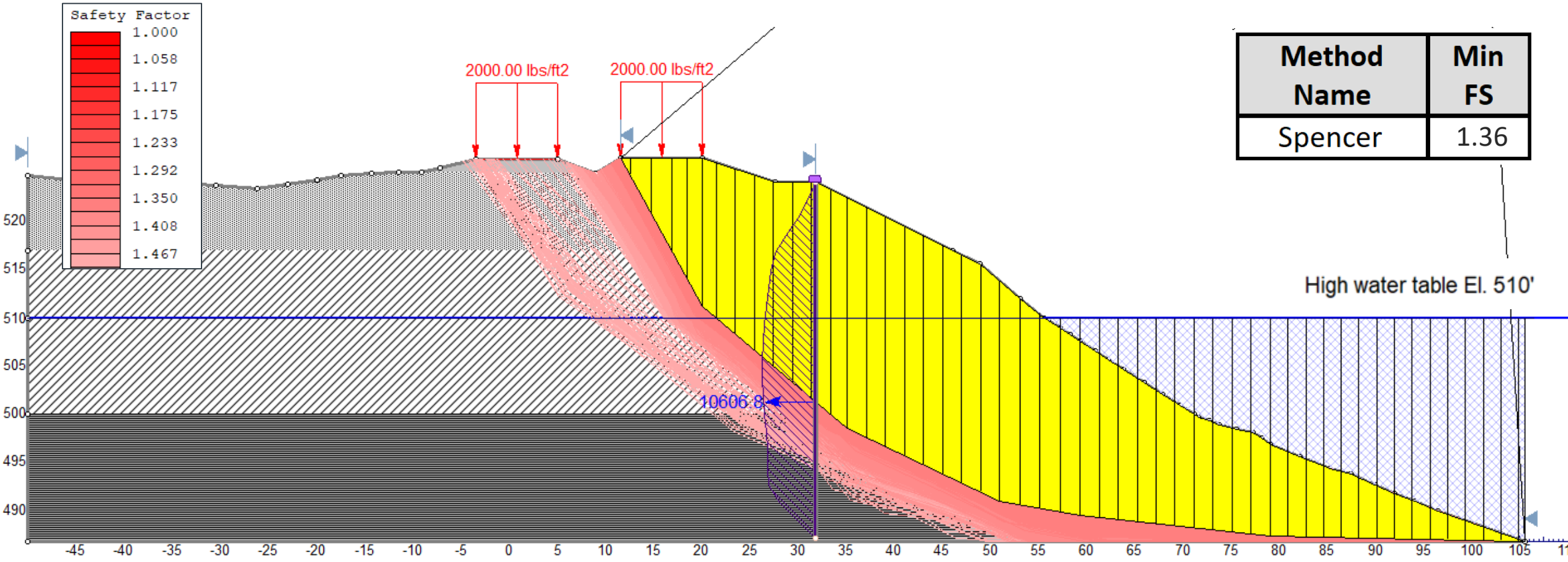
High water table steady state | 14-day rapid drawdown | Low water table steady state

FoS Summary- No Support

Scenario	Slide2	RS2	Slide3	Target FoS
Drained (High water table)	1.08	1.05	1.11	1.5

rocscience

2D LEM Results

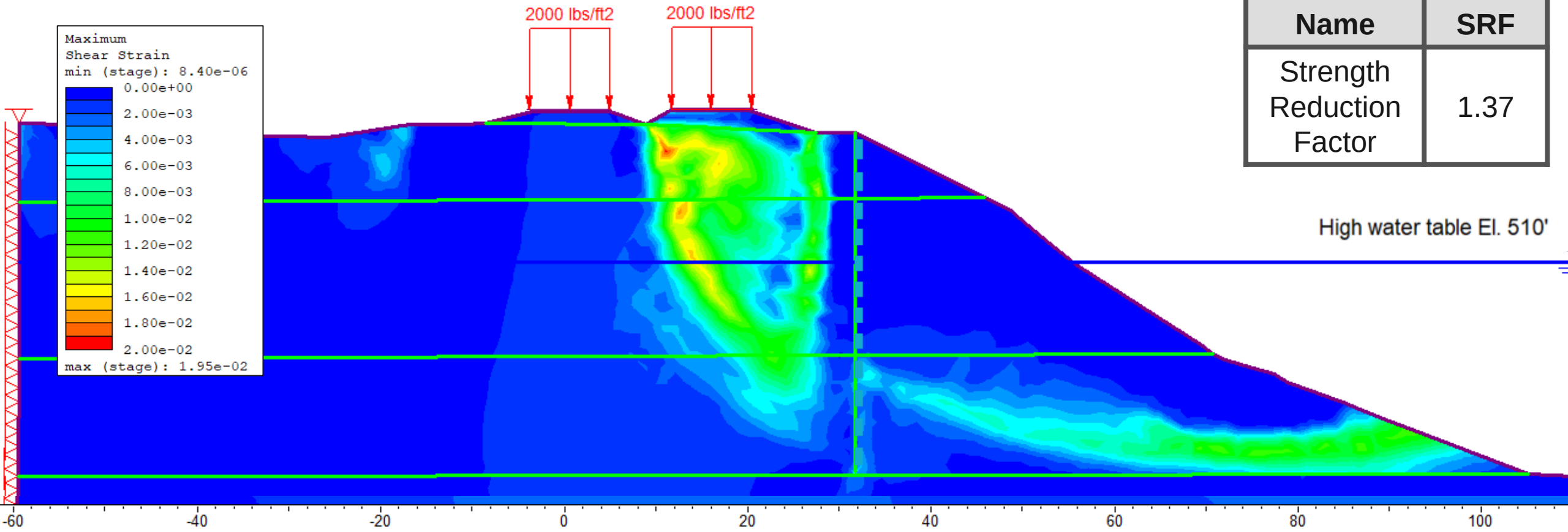


Method Name	Min FS
Spencer	1.36

22,972 Slip surfaces analyzed, FoS<1.5 highlighted in red

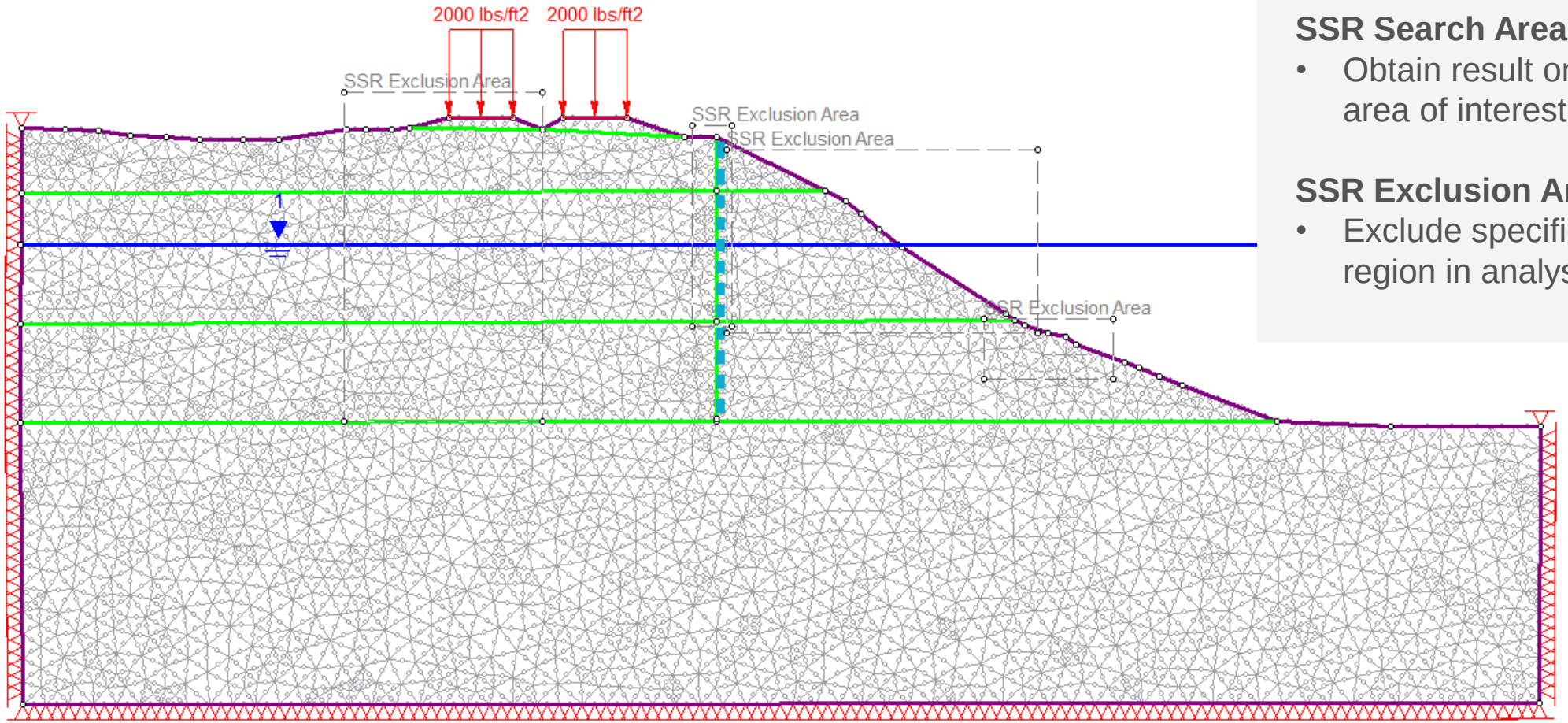
FEM Results

Method Name	Critical SRF
Strength Reduction Factor	1.37



High water table steady state | 14-day rapid drawdown | Low water table steady state

RS2 | rocscience



PRO TIP

SSR Search Area

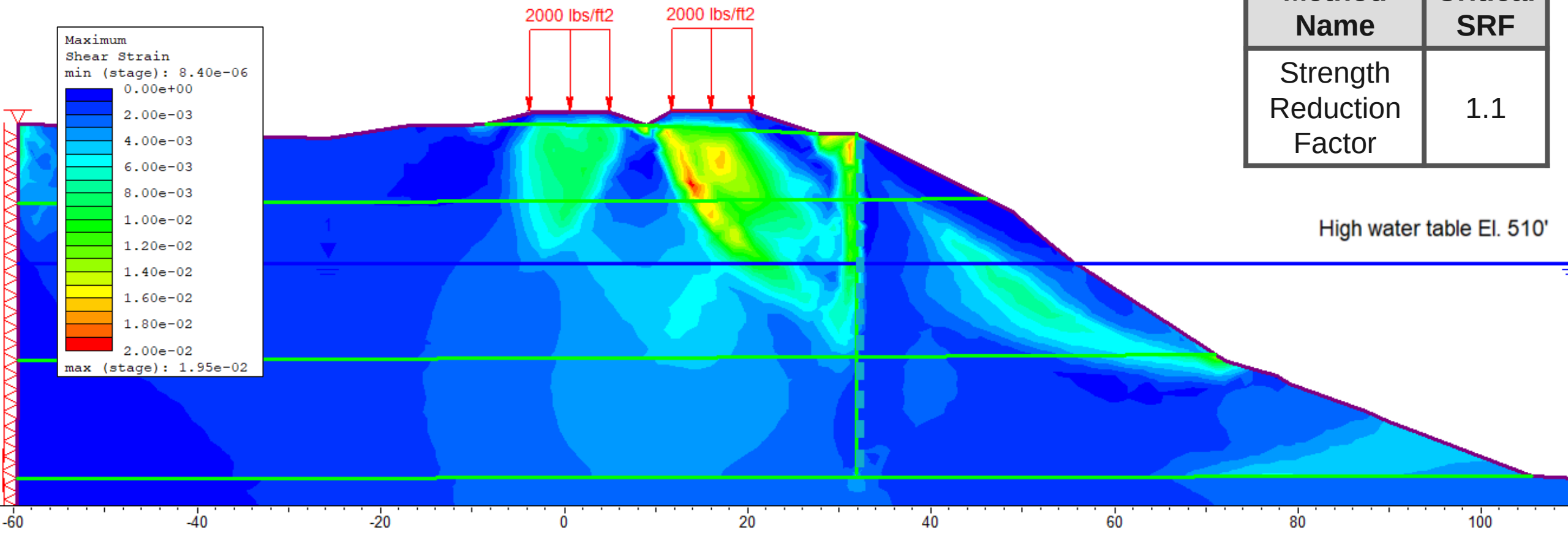
- Obtain result only in area of interest.

SSR Exclusion Area

- Exclude specified region in analysis.

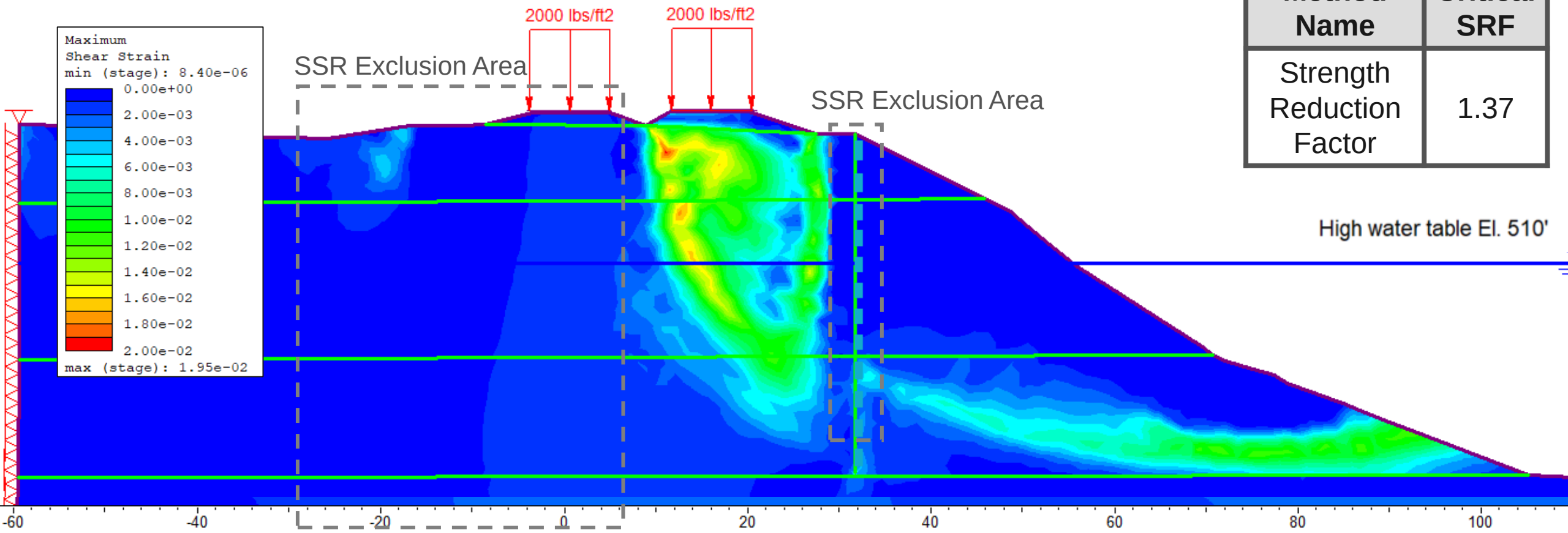
FEM Results – without exclusion area

Method Name	Critical SRF
Strength Reduction Factor	1.1



FEM Results – with exclusion area

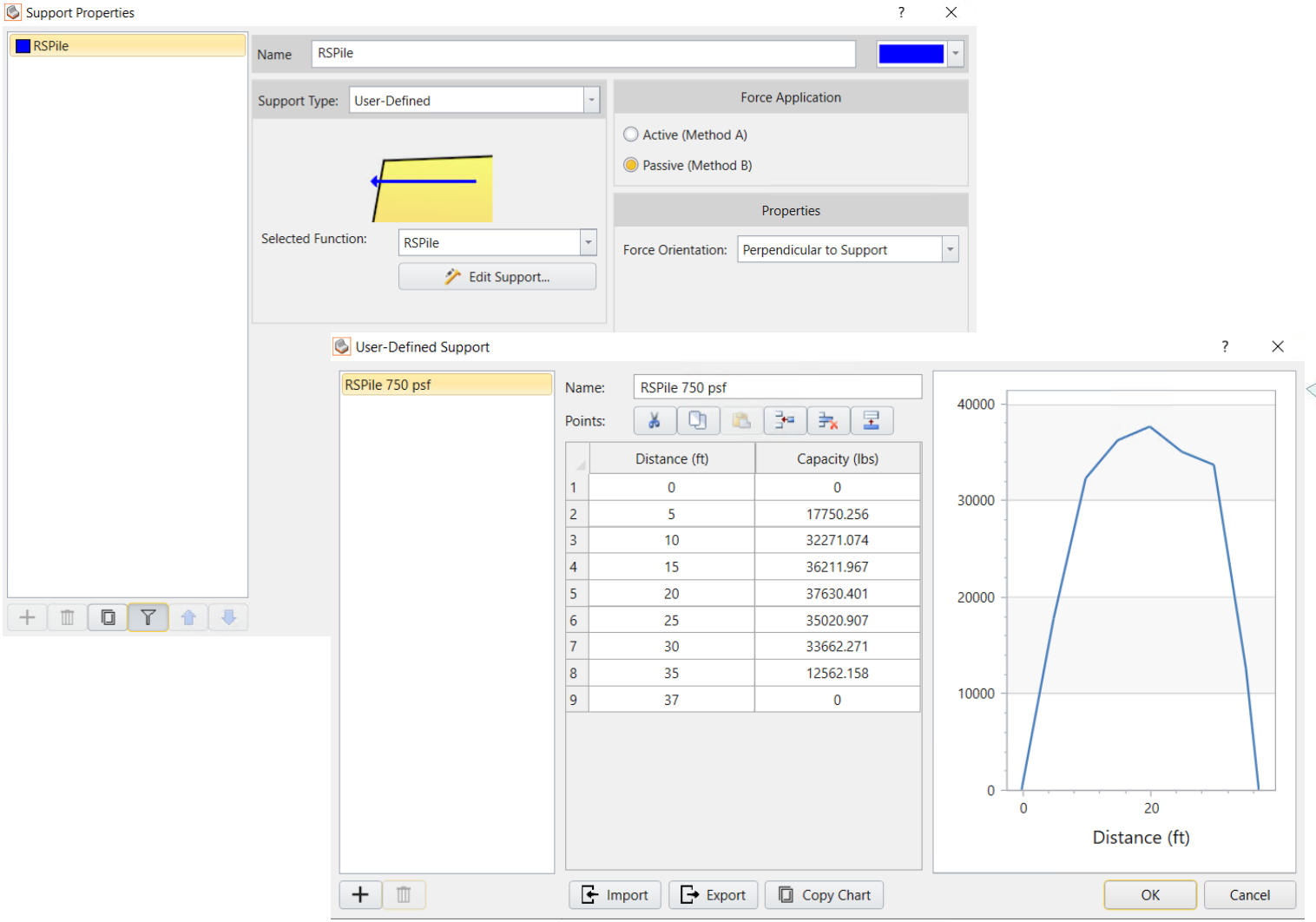
Method Name	Critical SRF
Strength Reduction Factor	1.37

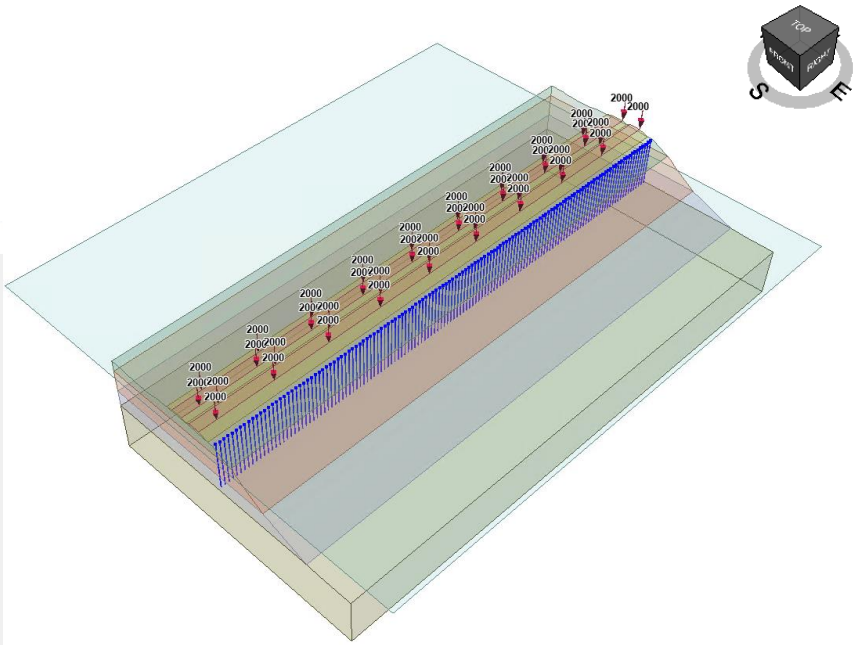


High water table steady state | 14-day rapid drawdown | Low water table steady state

RS2 | rocscience

3D LEM Results – Importing Pile Resistance

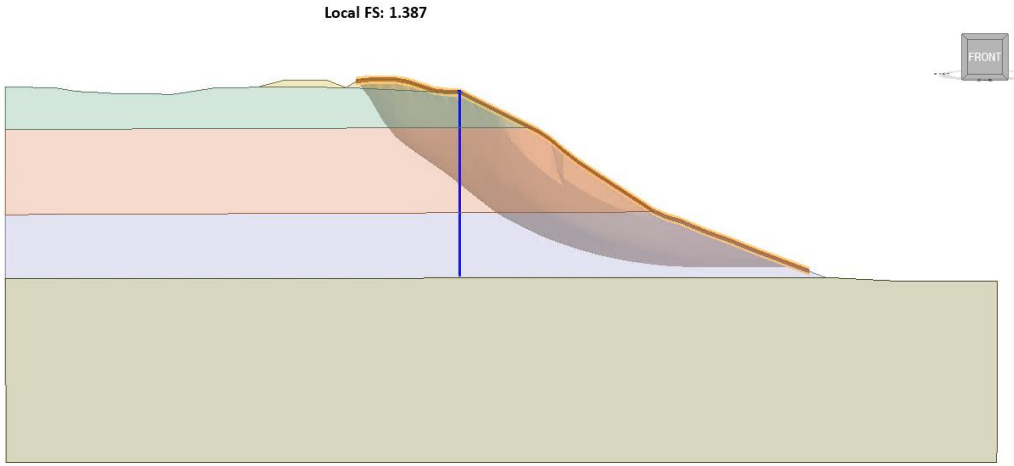


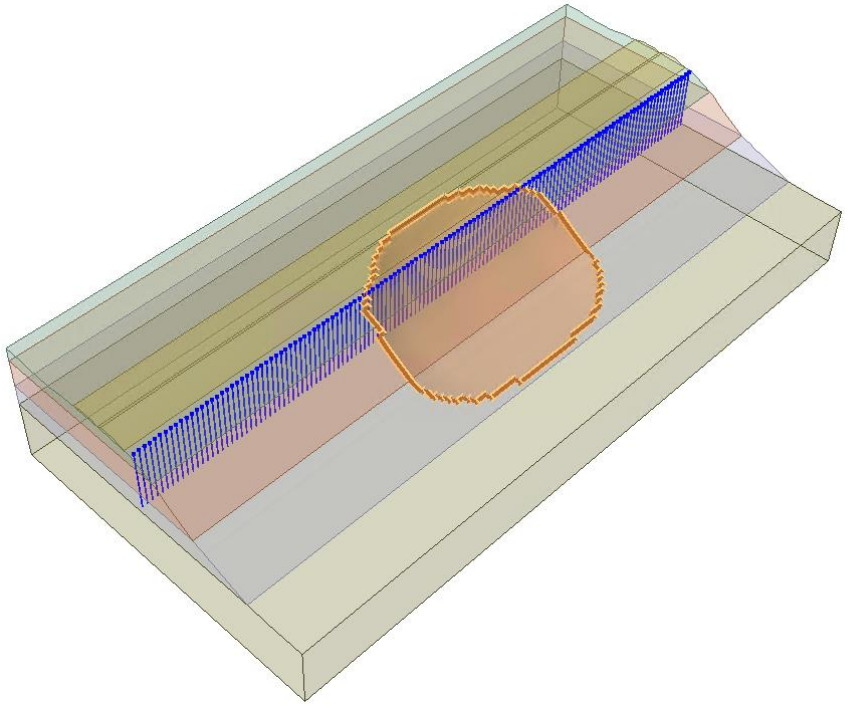


High water table steady state | **14-day rapid drawdown** | **Low water table steady state**

Slide3 | rocscience

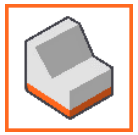
3D LEM Results



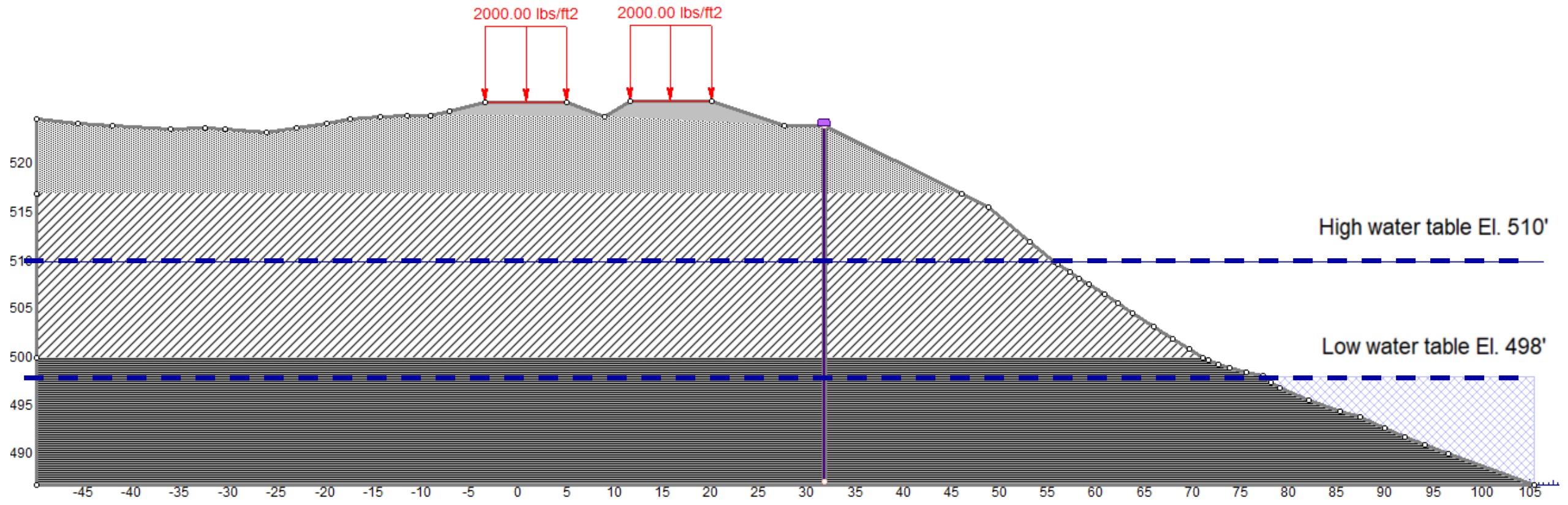


Method Name	Min FS
Spencer	1.39

FoS Summary

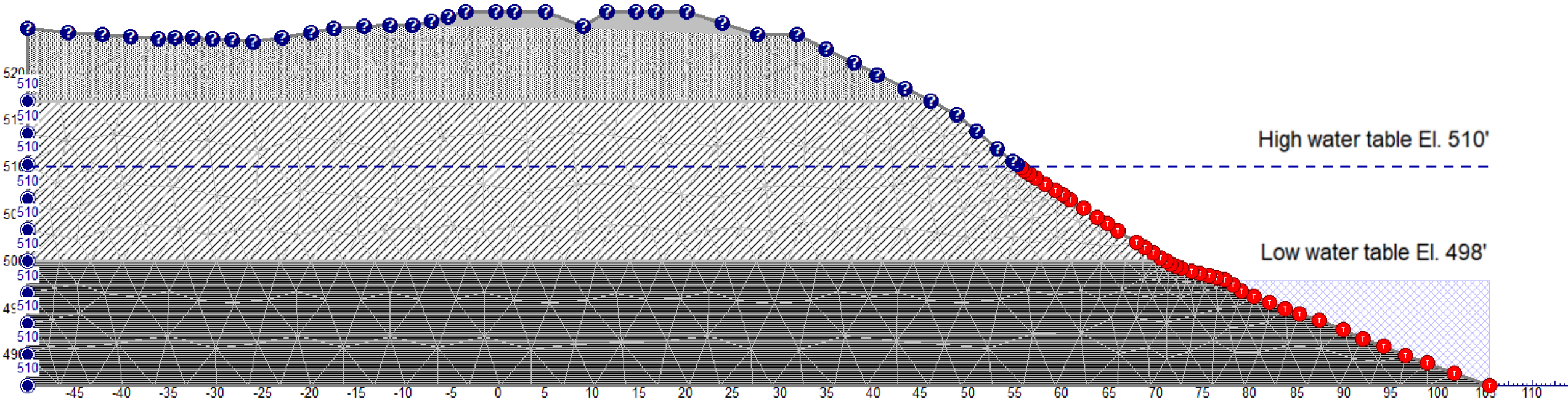
Scenario	 Slide2	 RS2	 Slide3	Target FoS
Drained (High water table)	1.36	1.37	1.39	1.5

Assess Drainage



Assess Drainage

Transient Analysis

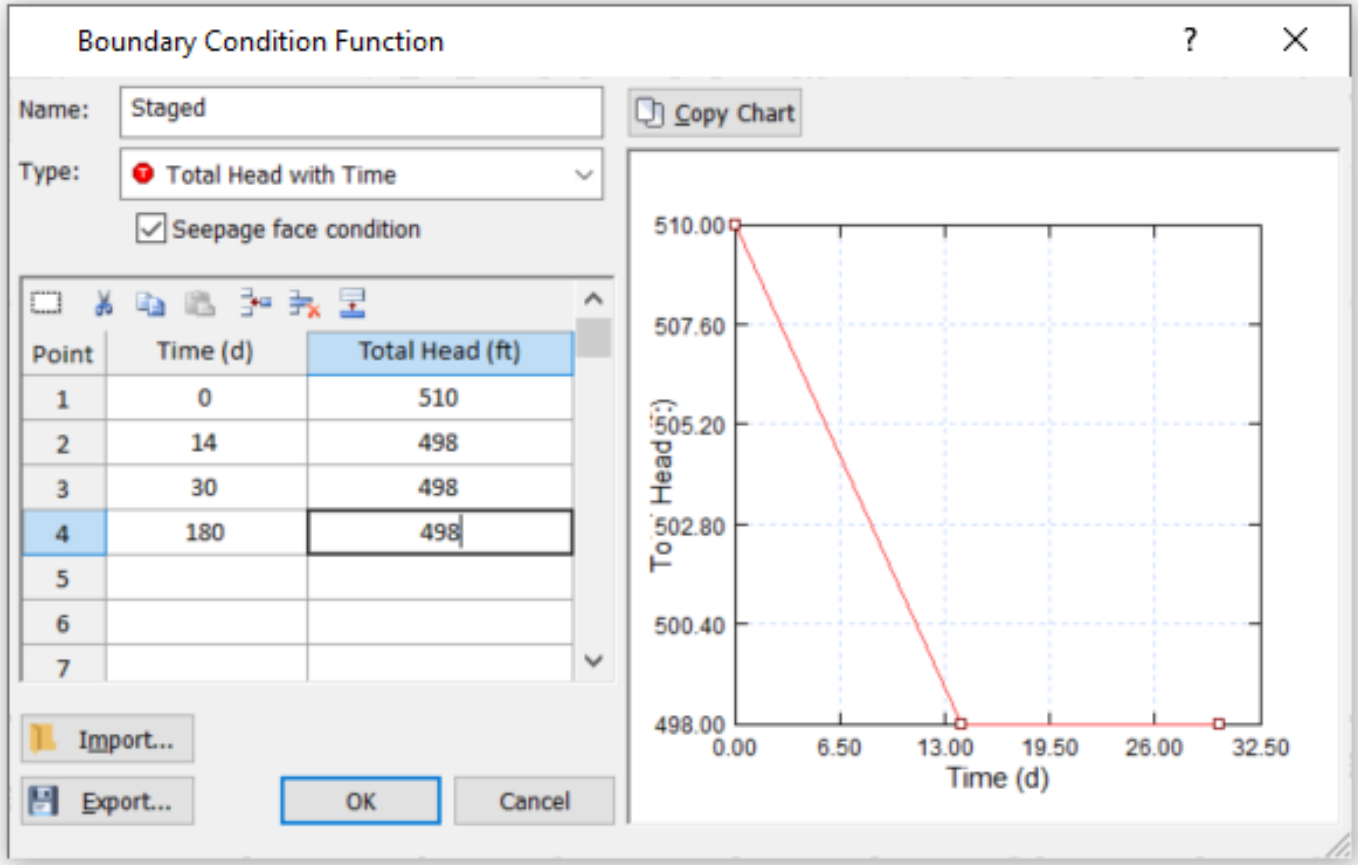


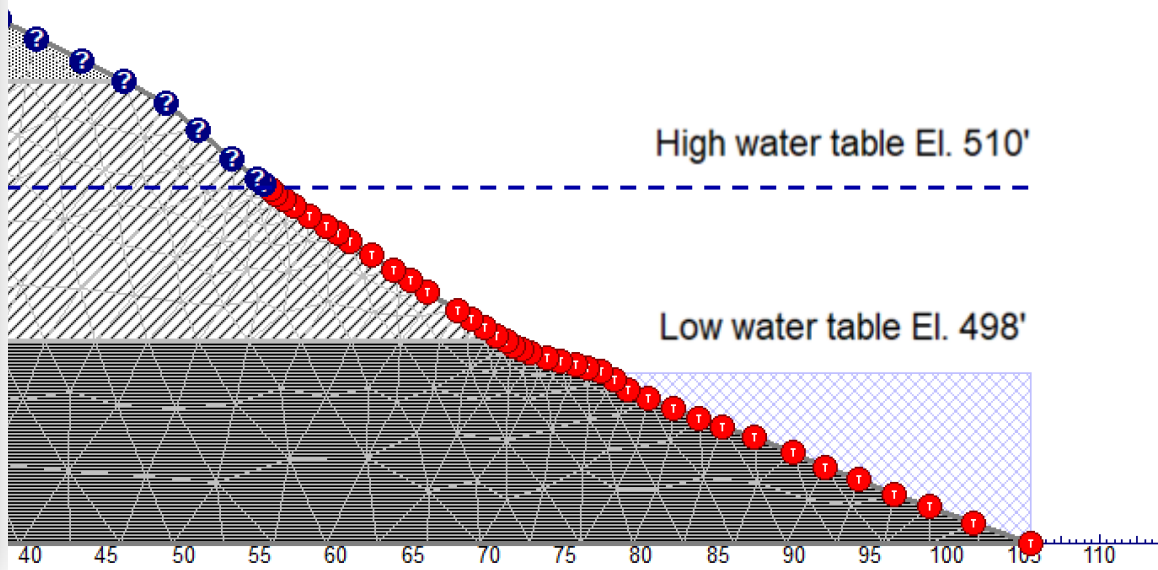
High water table steady state | 14-day rapid drawdown | Low water table steady state

Slide2 | rocscience

Assess Drainage

Transient Analysis



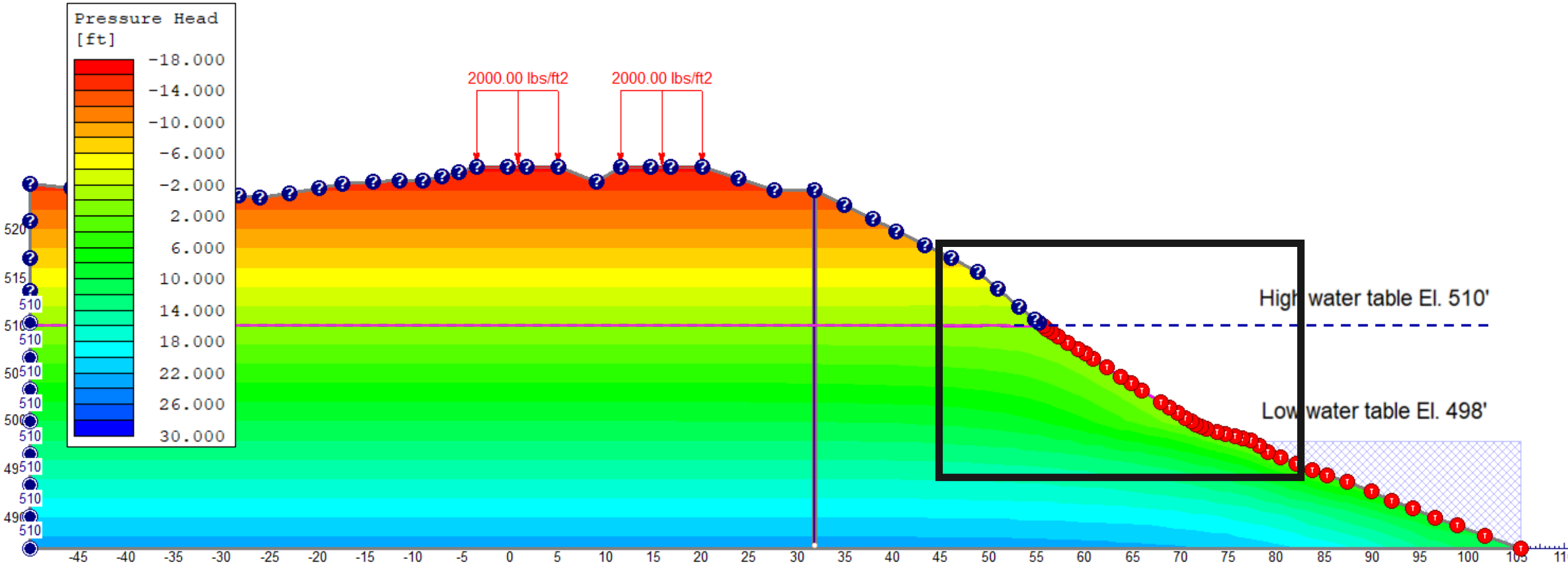


High water table steady state | 14-day rapid drawdown | Low water table steady state

Slide2 | rocscience

Assess Drainage – No drainage!

Transient Analysis

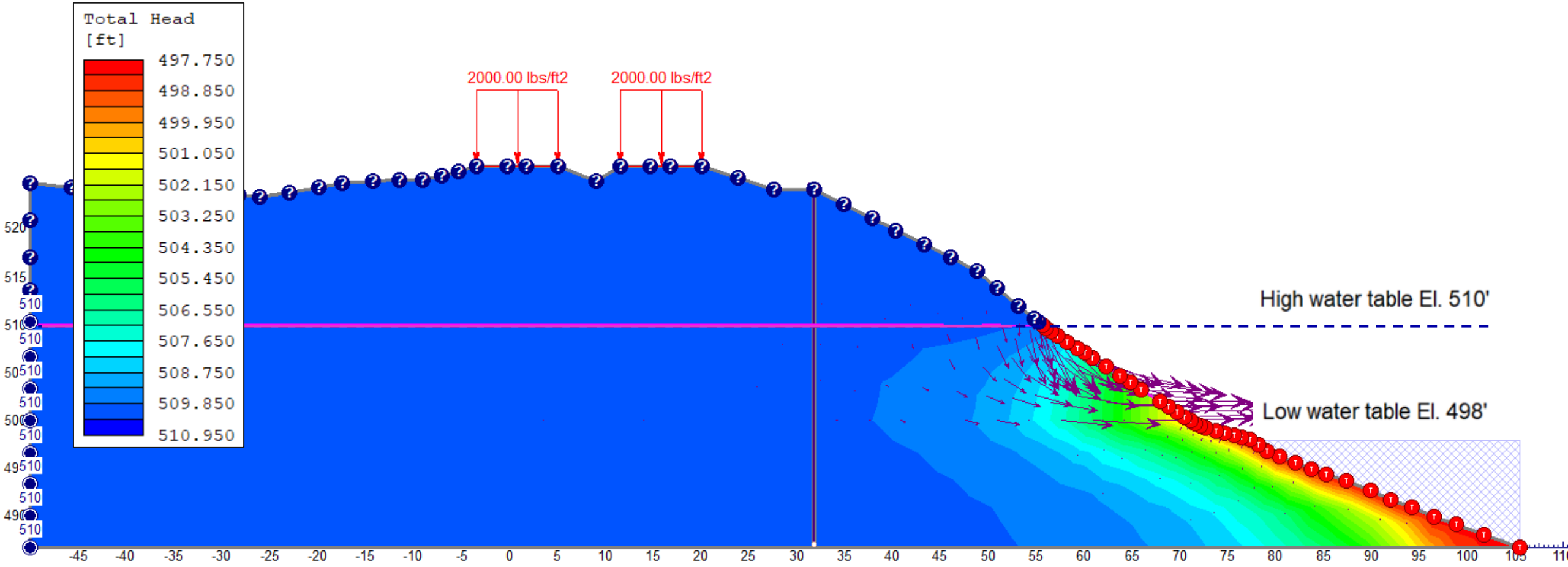


High water table steady state | 14-day rapid drawdown | Low water table steady state

Slide2 | rocscience

Assess Drainage

Transient Analysis

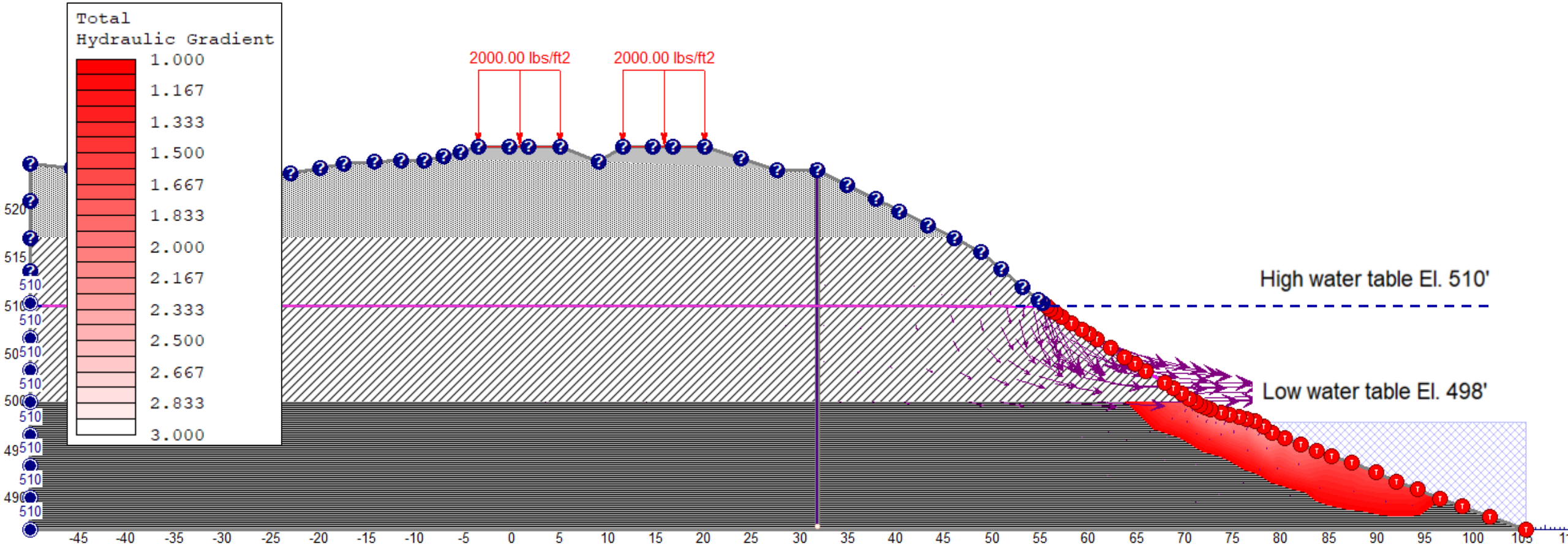


High water table steady state | **14-day rapid drawdown** | Low water table steady state

Slide2 | rocscience

Assess Drainage

Transient Analysis

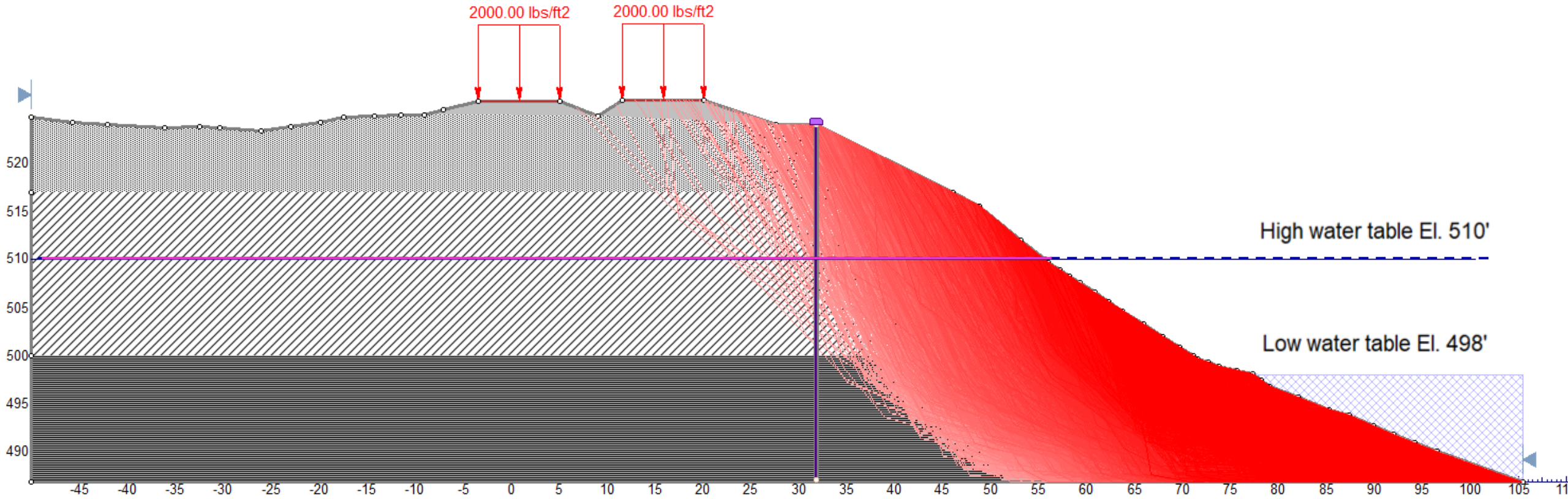


High water table steady state | 14-day rapid drawdown | Low water table steady state

Slide2 | rocscience

Assess Drainage

Transient Analysis



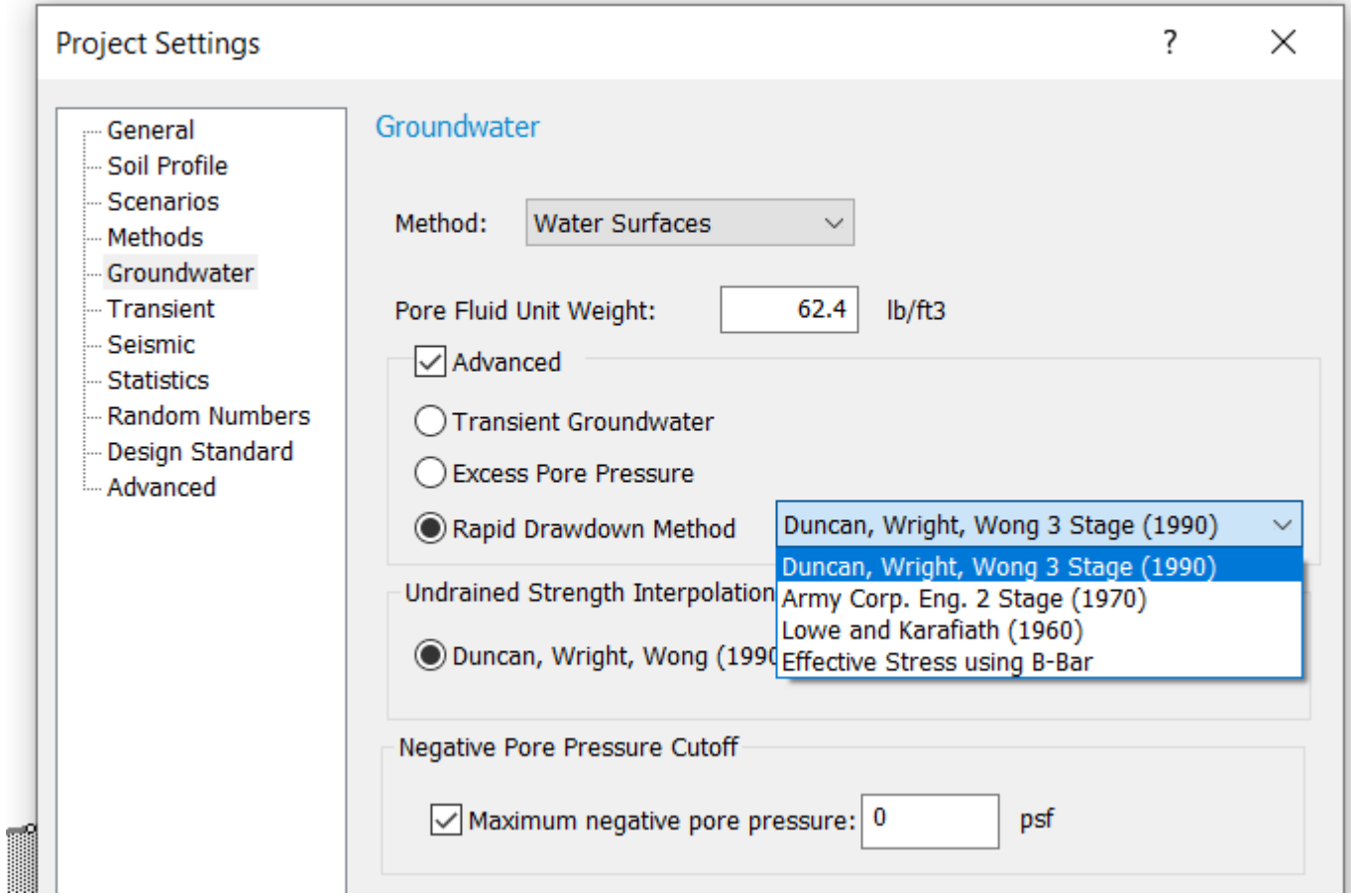
21,114 Slip surfaces analyzed, FoS<1 highlighted

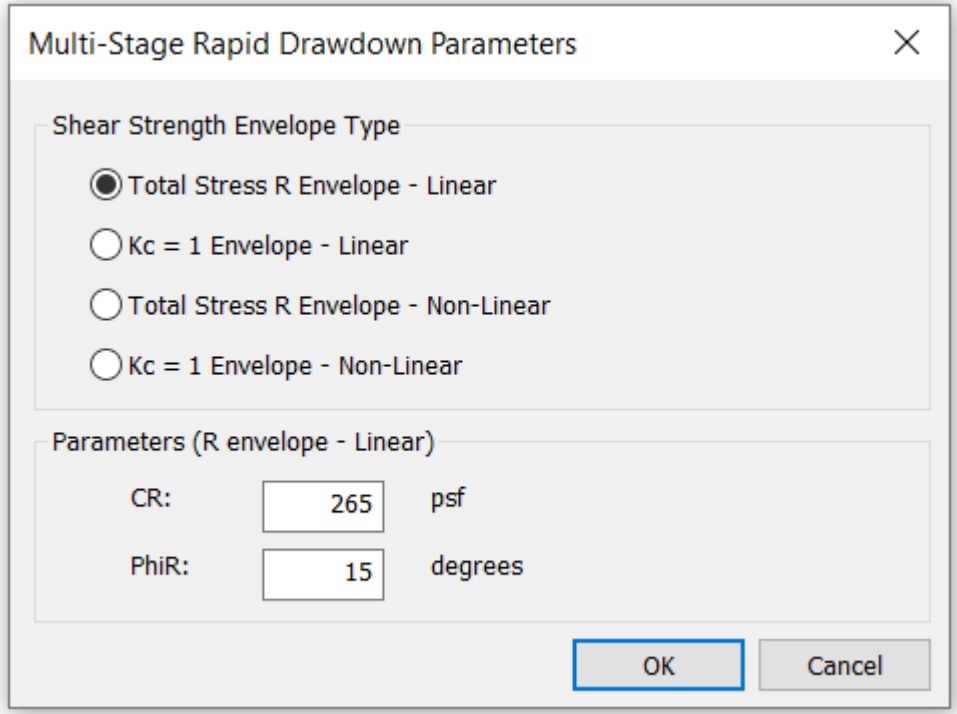
High water table steady state | 14-day rapid drawdown | Low water table steady state

Slide2 | rocscience

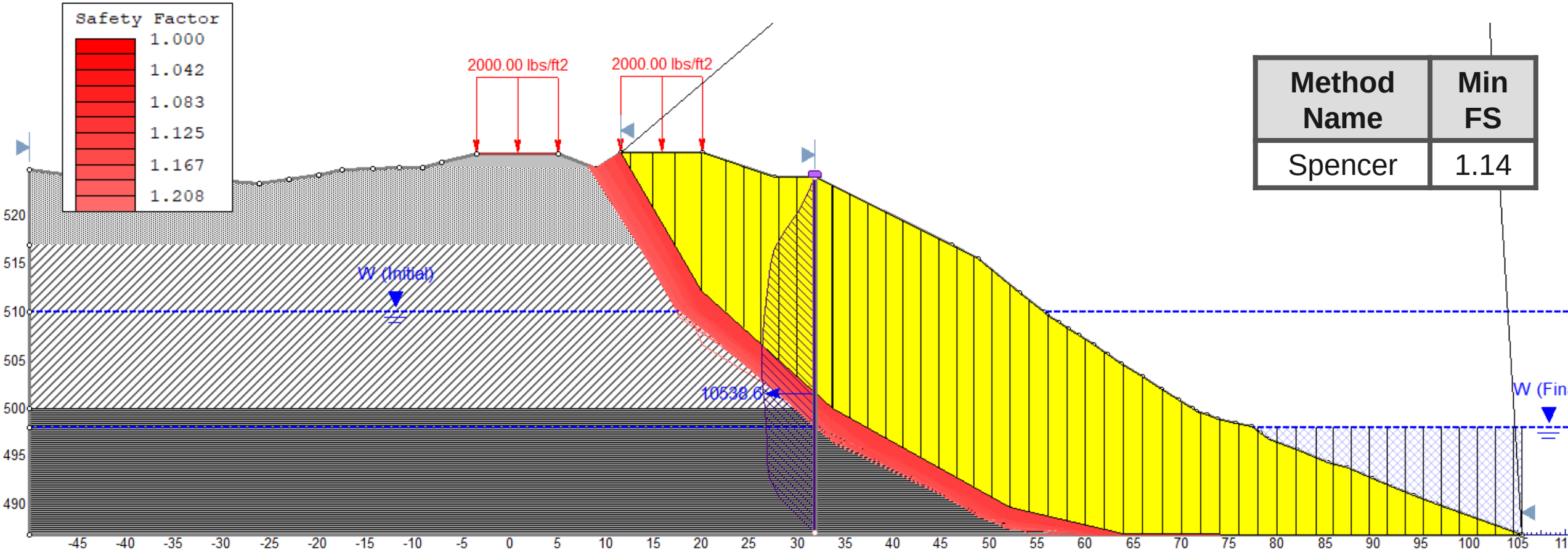
Rapid drawdown analysis method

Use Duncan, Wright, Wong 3-Stage Rapid Drawdown Analysis (1990)





2D LEM Results

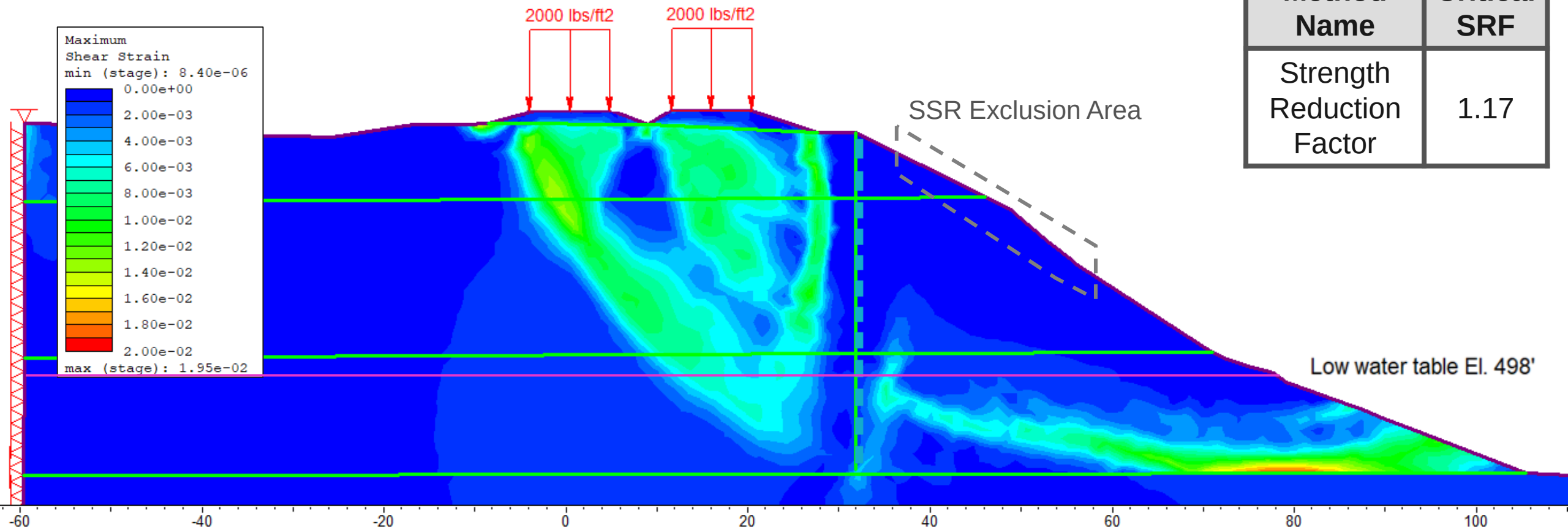


Method Name	Min FS
Spencer	1.14

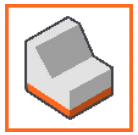
23,230 Slip surfaces analyzed, FoS<1.2 highlighted in red

FEM Results - coupled

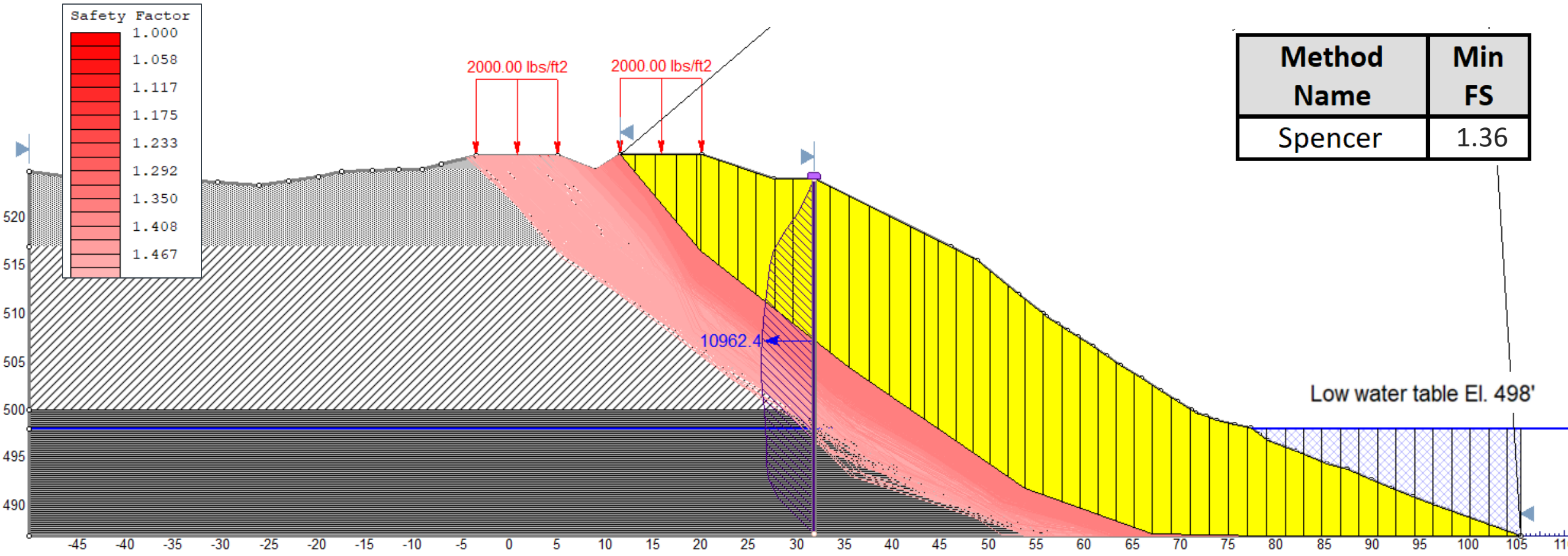
Method Name	Critical SRF
Strength Reduction Factor	1.17



FoS Summary

Scenario	 Slide2	 RS2	 Slide3	Target FoS
High water table	1.36	1.37	1.39	1.5
Rapid drawdown	1.14	1.17	-	1.2

2D LEM Results

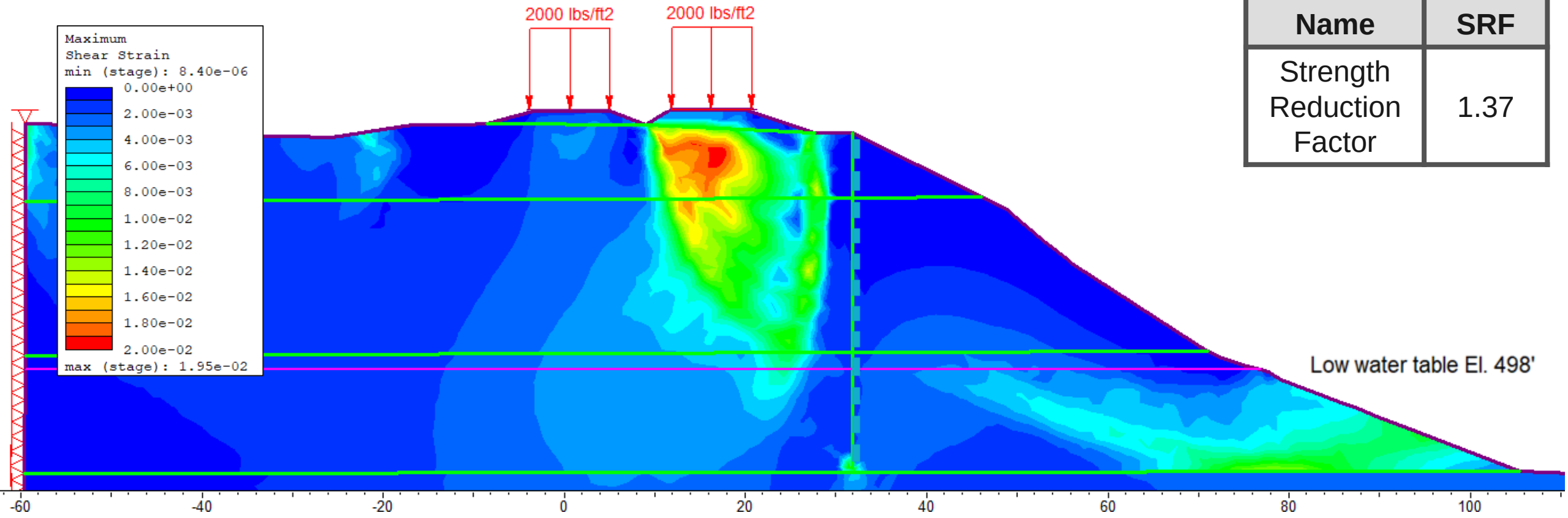


Method Name	Min FS
Spencer	1.36

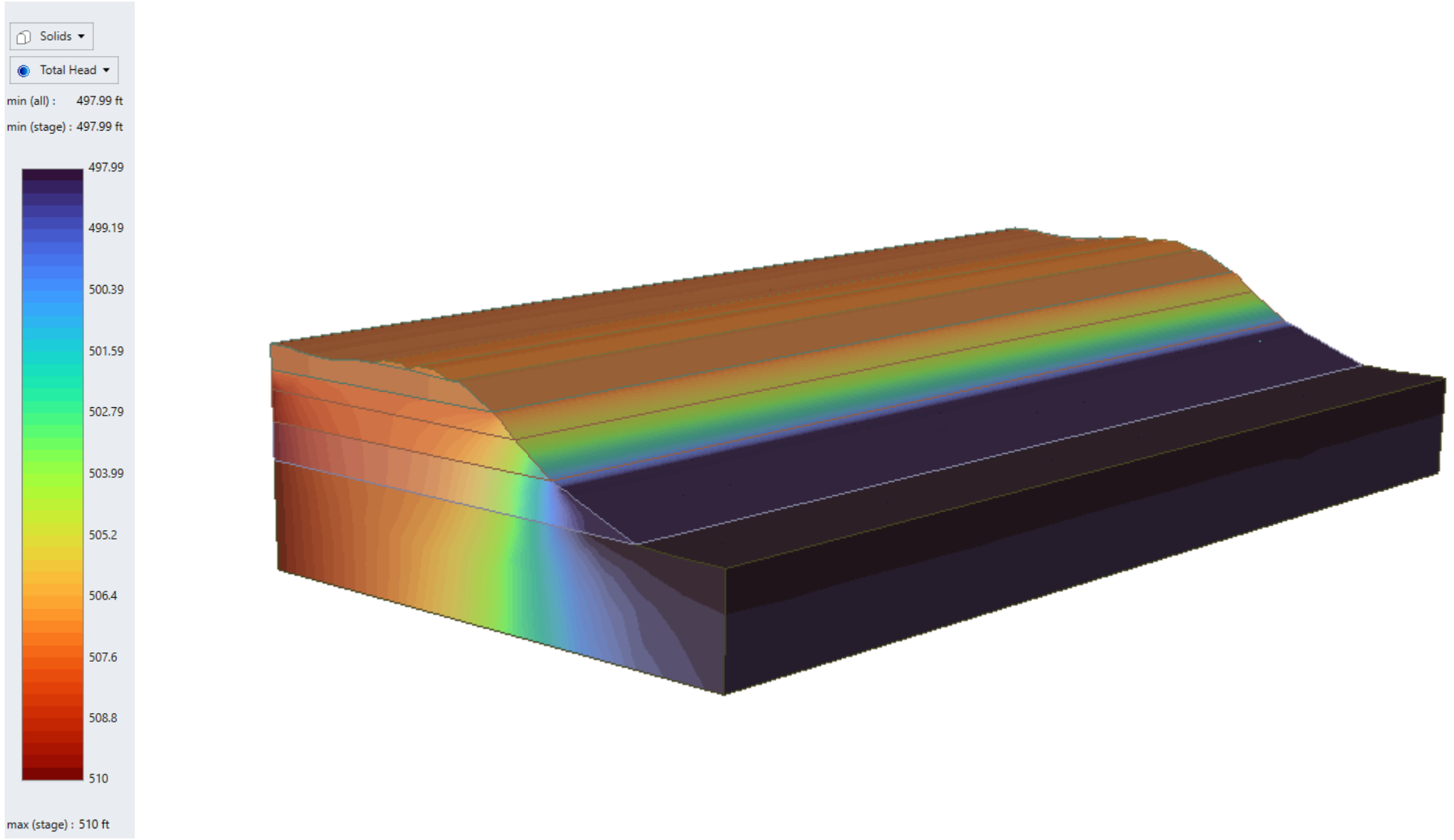
22,972 Slip surfaces analyzed, FoS<1.5 highlighted in red

2D FEM Results

Method Name	Critical SRF
Strength Reduction Factor	1.37



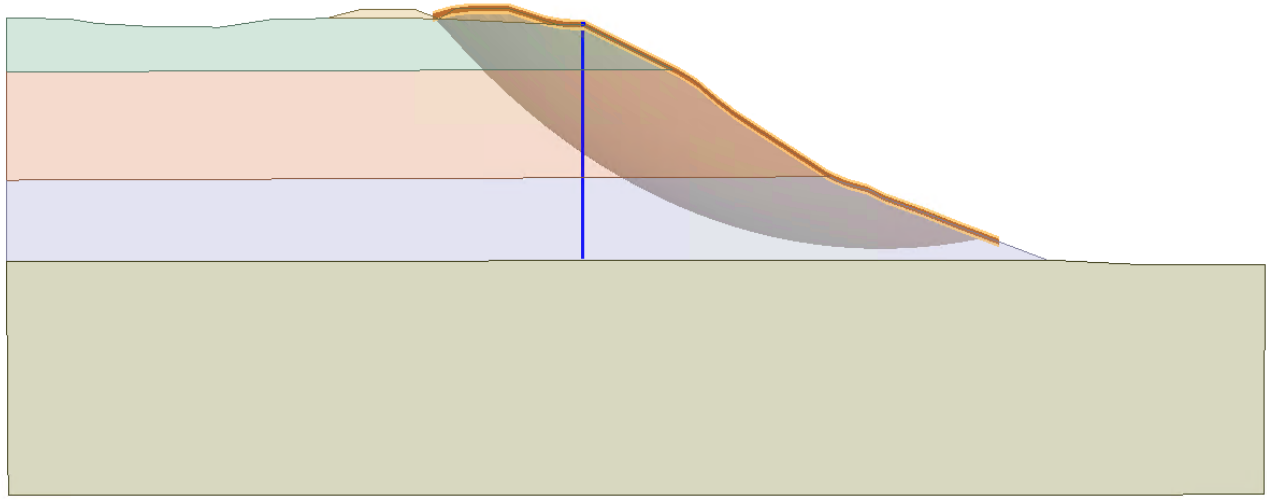
RS3 Seepage Analysis

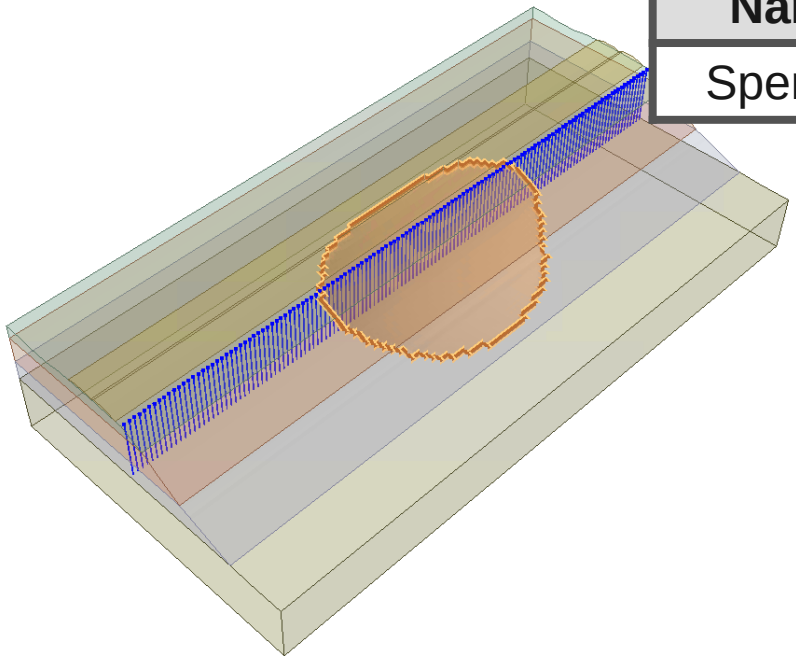


High water table steady state | 14-day rapid drawdown | Low water table steady state

rocscience

3D LEM Results





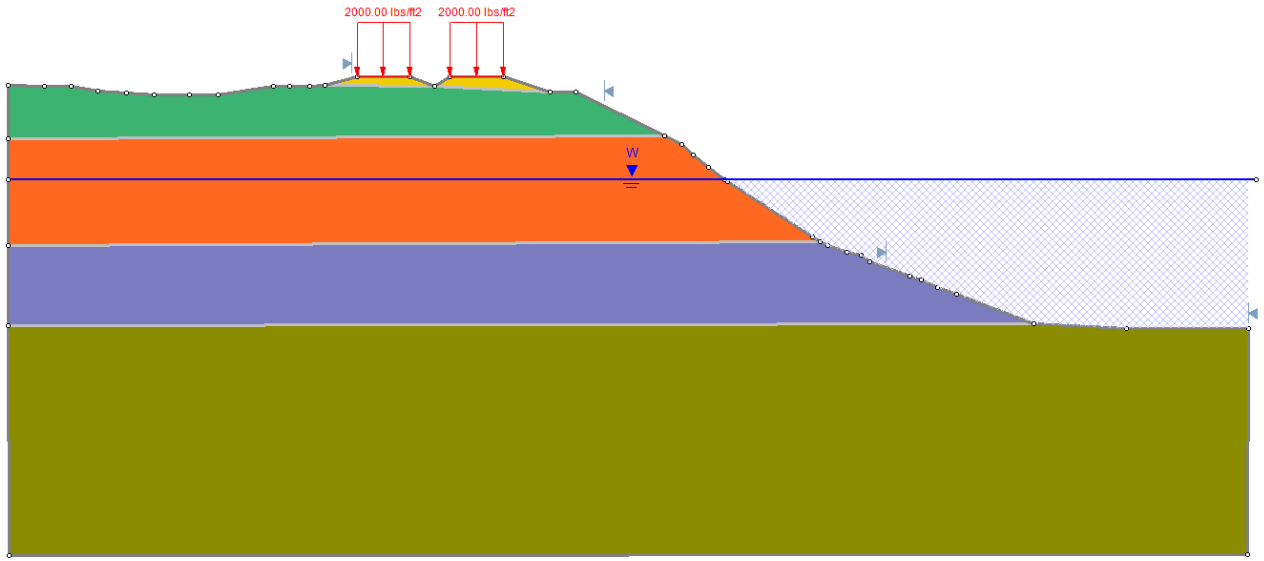
Method Name	Min FS
Spencer	1.37

3D LEM Results

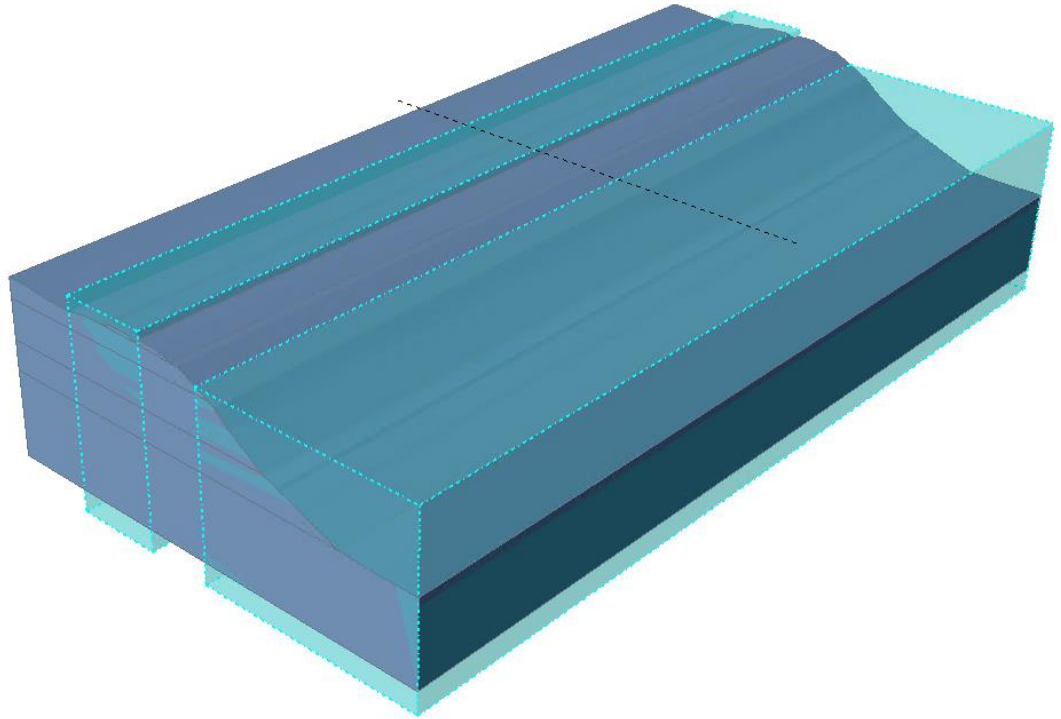
PRO TIP

Use 3D search limits to computer FoS in area of interest.

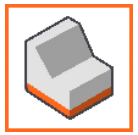
Slope limits in 2D



Search Limits in 3D



FoS Summary

Scenario	 Slide2	 RS2	 Slide3	Target FoS
High water table	1.36	1.37	1.39	1.5
Rapid drawdown	1.14	1.17	-	1.2
Low water table	1.36	1.38	1.37	1.5



Geotechnical tools inspired by you.

jeff.lam@rocscience.com



STATION 4598 - SLOPE STABILIZATION FOR TRACK EXPANSION

Stabilization with H Piles

Limit Equilibrium: 3-Stage Rapid Drawdown

Finite Element Method: Steady State Seepage Analyses

Software: GEOSTASE & PLAXIS

Dr. Garry H. Gregory, PhD, PE, SE, D.GE

GREGORY GEOTECHNICAL

LIMIT EQUILIBRIUM ANALYSES

1. Circular search with steady-state conditions for verification.
2. 3-Stage Rapid Drawdown - Circular search with horizontal water surfaces.
3. 3-Stage Rapid Drawdown - Circular search with water surfaces from FEM analyses.
4. 3-Stage Rapid Drawdown – Non-Circular ZRSAUTO search.
5. 3-Stage Rapid Drawdown – Non-Circular ZRSAUTO search with curved strength envelope for C_R and ϕ_R.
6. 3-Stage Rapid Drawdown – Non-Circular ZRSAUTO search with curved strength envelope for C_R and ϕ_R – Simplified 3D.

STATION 4598 - SLOPE STABILIZATION FOR TRACK EXPANSION

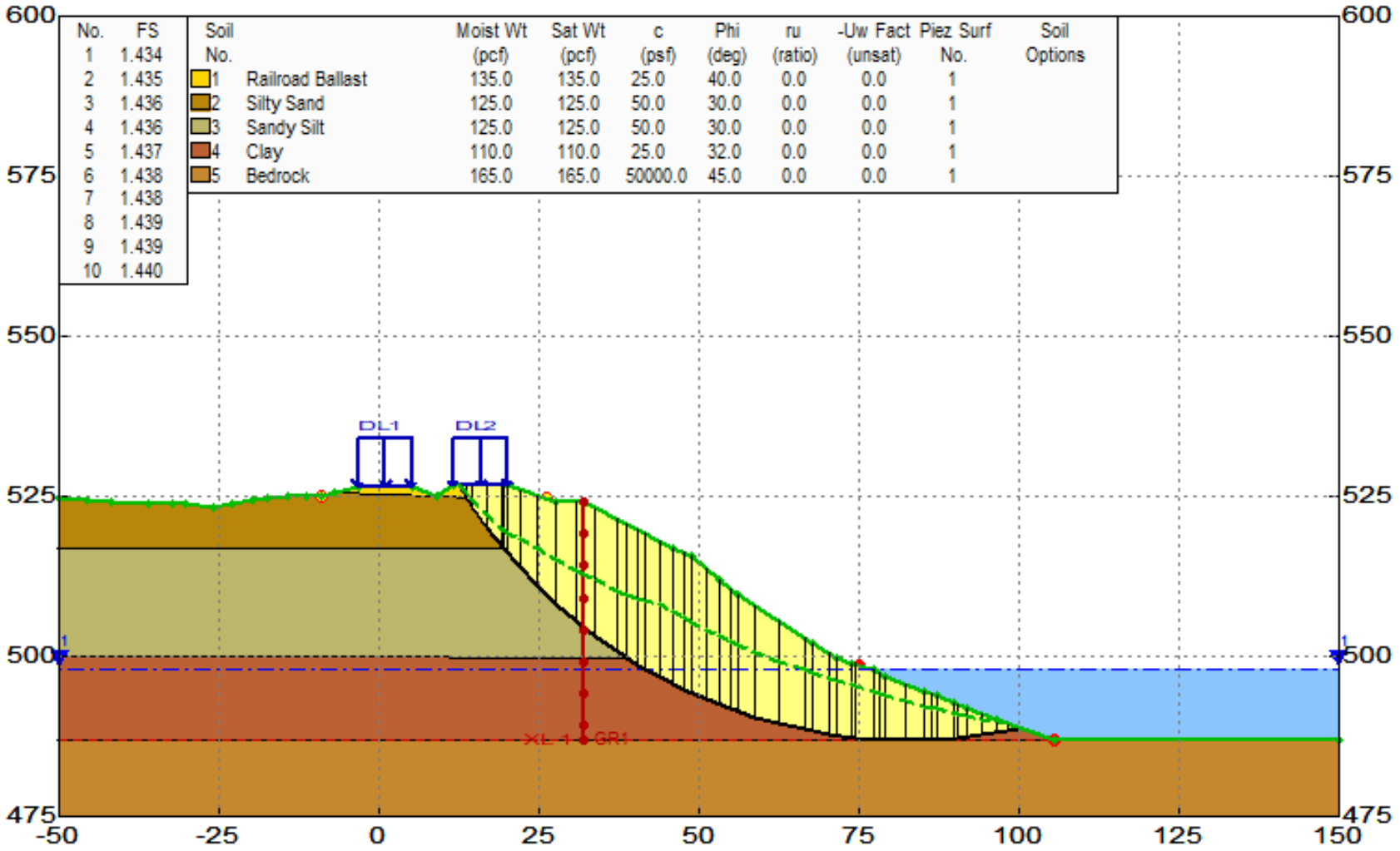
Long-Term Steady State with Piles - Circular Search for Verification

GREGORY GEOTECHNICAL - GHG

\S3-2021-Initial-Deep.gsd

No.	FS
1	1.434
2	1.435
3	1.436
4	1.436
5	1.437
6	1.438
7	1.438
8	1.439
9	1.439
10	1.440

Soil No.		Moist Wt (pcf)	Sat Wt (pcf)	c (psf)	Phi (deg)	ru (ratio)	-Uw Fact (unsat)	Piez Surf No.	Soil Options
1	Railroad Ballast	135.0	135.0	25.0	40.0	0.0	0.0	1	
2	Silty Sand	125.0	125.0	50.0	30.0	0.0	0.0	1	
3	Sandy Silt	125.0	125.0	50.0	30.0	0.0	0.0	1	
4	Clay	110.0	110.0	25.0	32.0	0.0	0.0	1	
5	Bedrock	165.0	165.0	50000.0	45.0	0.0	0.0	1	



GEOSTASE FS = 1.434

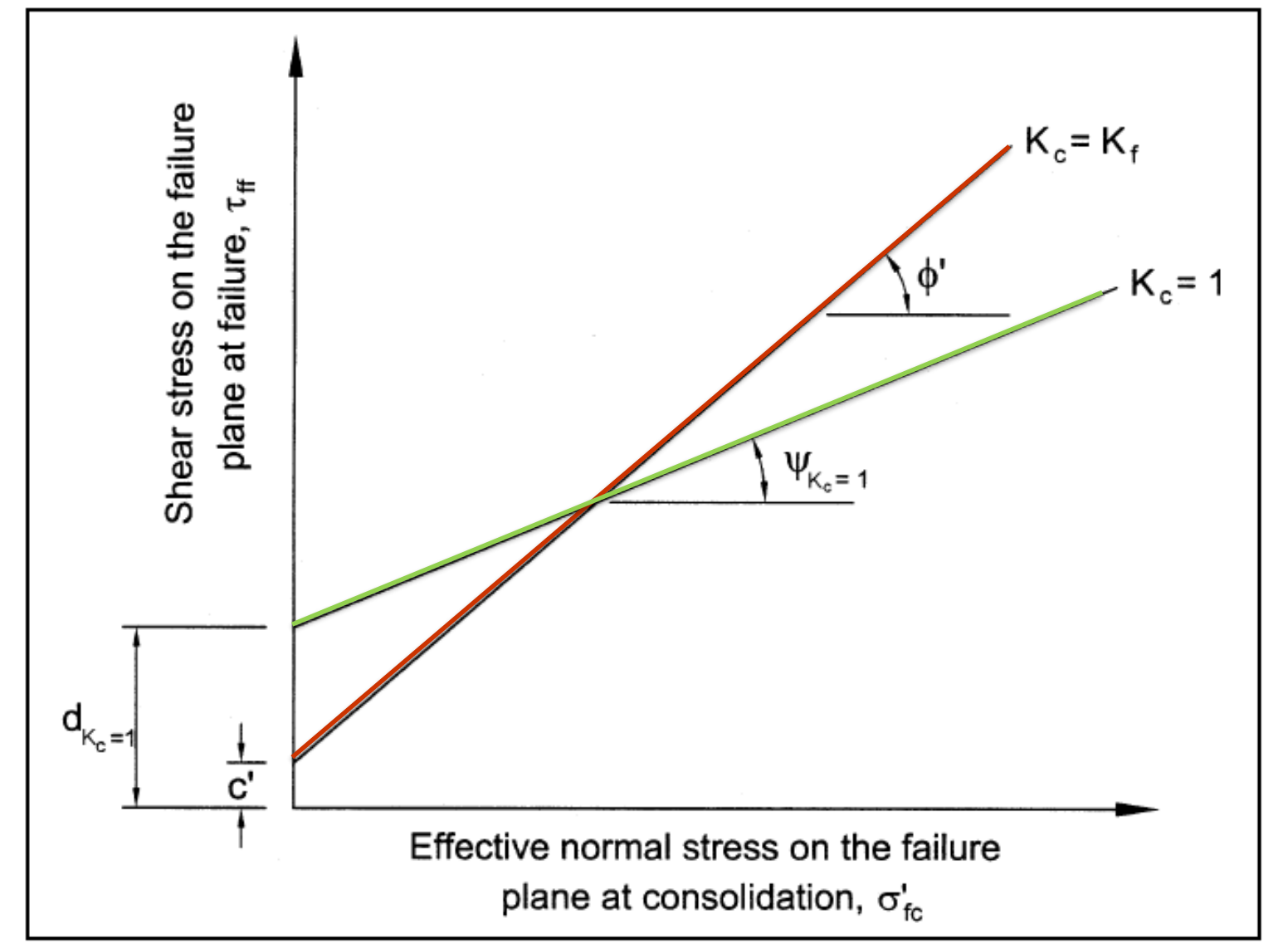
Spencer Method

GEOSTASE
Slope Stability Analysis

GREGORY GEOTECHNICAL

3-Stage Rapid Drawdown – Duncan, Wright and Wong (1990)

(After USACE EM 1110-2-1902, 2003)



STATION 4598 - SLOPE STABILIZATION FOR TRACK EXPANSION

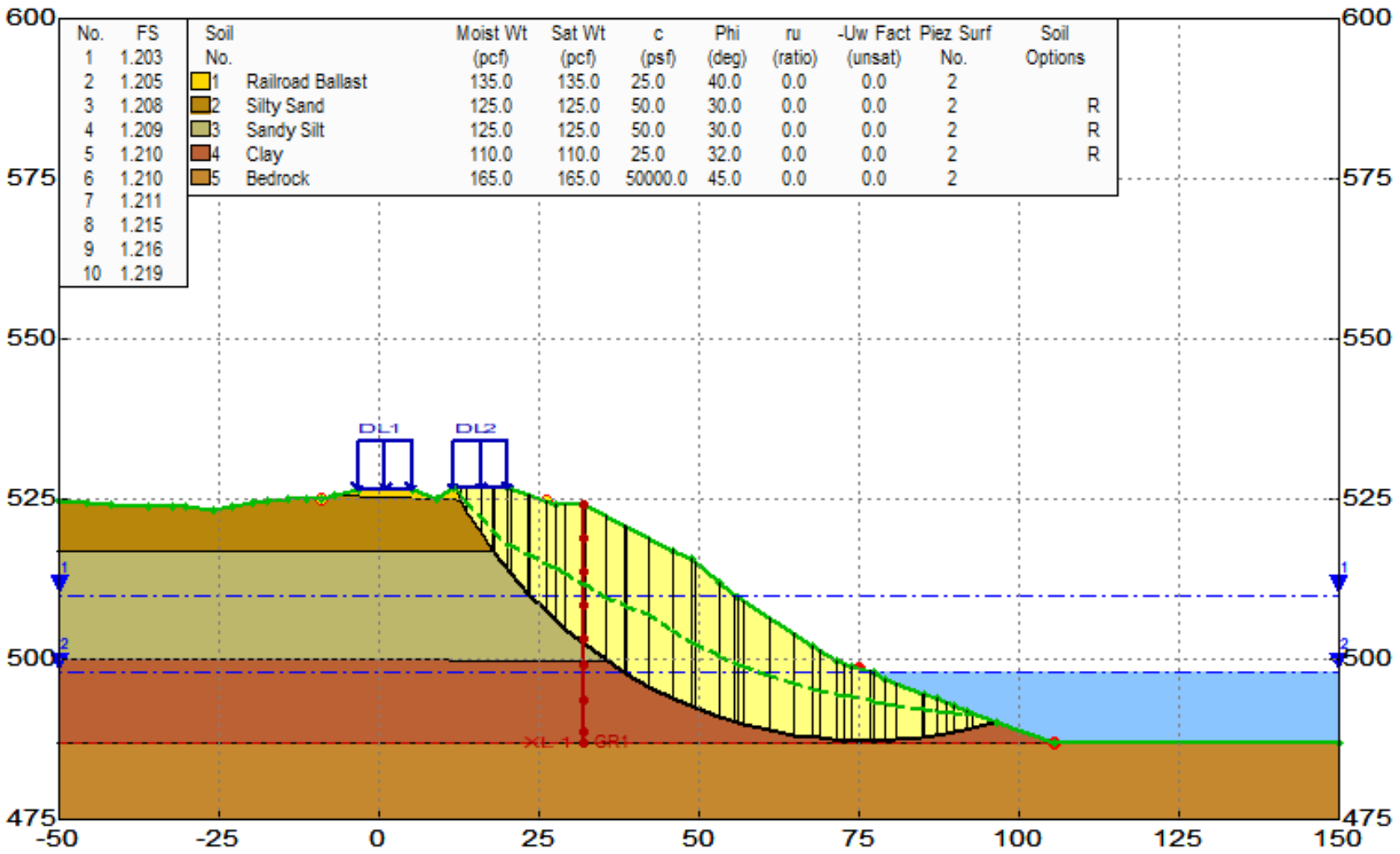
3-Stage Rapid Drawdown - Horizontal Water Surfaces - Circular Search

GREGORY GEOTECHNICAL - GHG

\S3-2021-Initial-Deep-RD-A.gsd

No.	FS
1	1.203
2	1.205
3	1.208
4	1.209
5	1.210
6	1.210
7	1.211
8	1.215
9	1.216
10	1.219

Soil No.		Moist Wt (pcf)	Sat Wt (pcf)	c (psf)	Phi (deg)	ru (ratio)	-Uw Fact (unsat)	Piez Surf No.	Soil Options
1	Railroad Ballast	135.0	135.0	25.0	40.0	0.0	0.0	2	
2	Silty Sand	125.0	125.0	50.0	30.0	0.0	0.0	2	R
3	Sandy Silt	125.0	125.0	50.0	30.0	0.0	0.0	2	R
4	Clay	110.0	110.0	25.0	32.0	0.0	0.0	2	R
5	Bedrock	165.0	165.0	50000.0	45.0	0.0	0.0	2	



GEOSTASE FS = 1.203

Spencer Method

GEOSTASE
Slope Stability Analysis

GREGORY GEOTECHNICAL

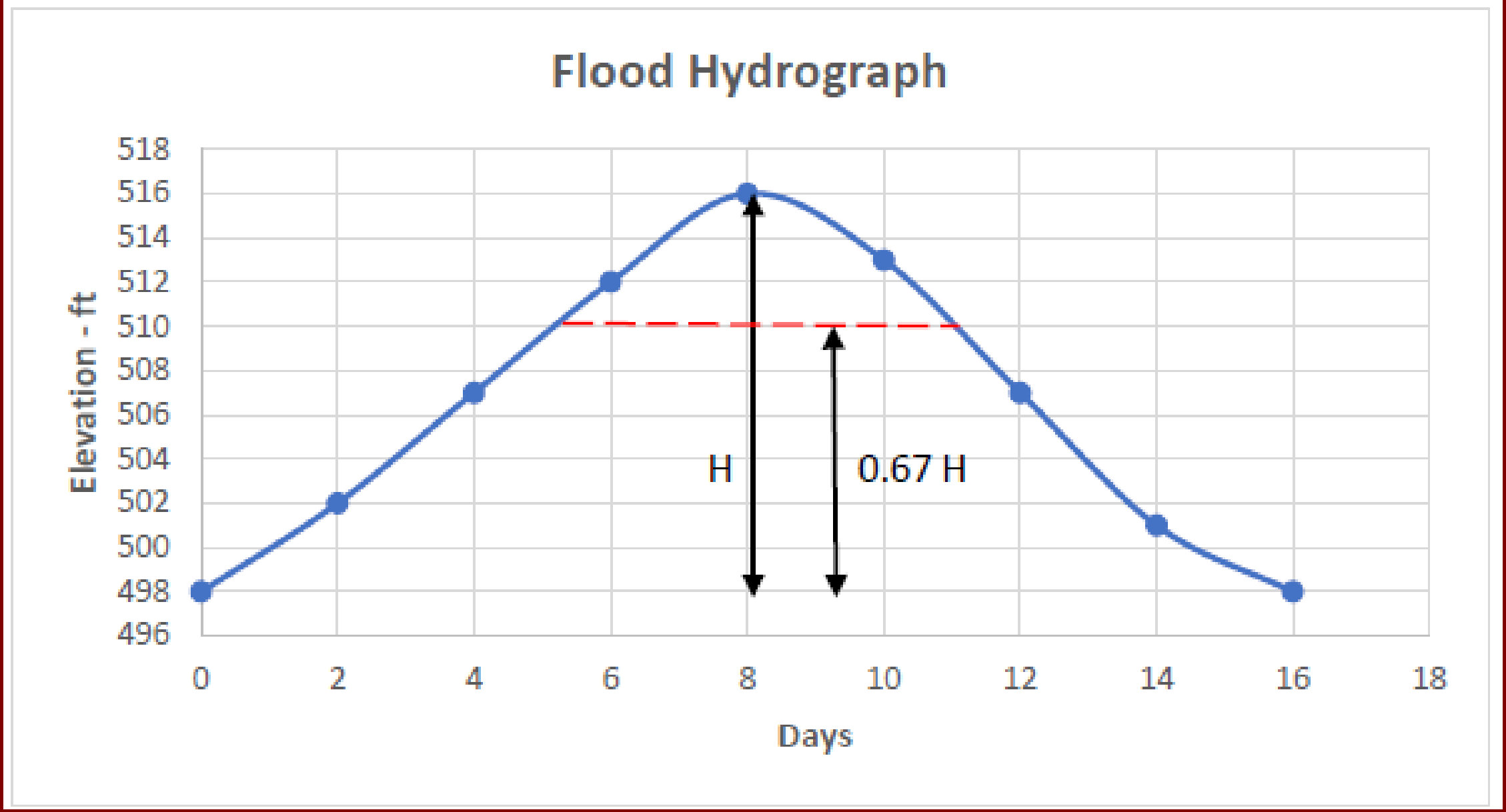
GEOSTASE® by GREGORY GEOTECHNICAL SOFTWARE

PLATE S3-RD.2A

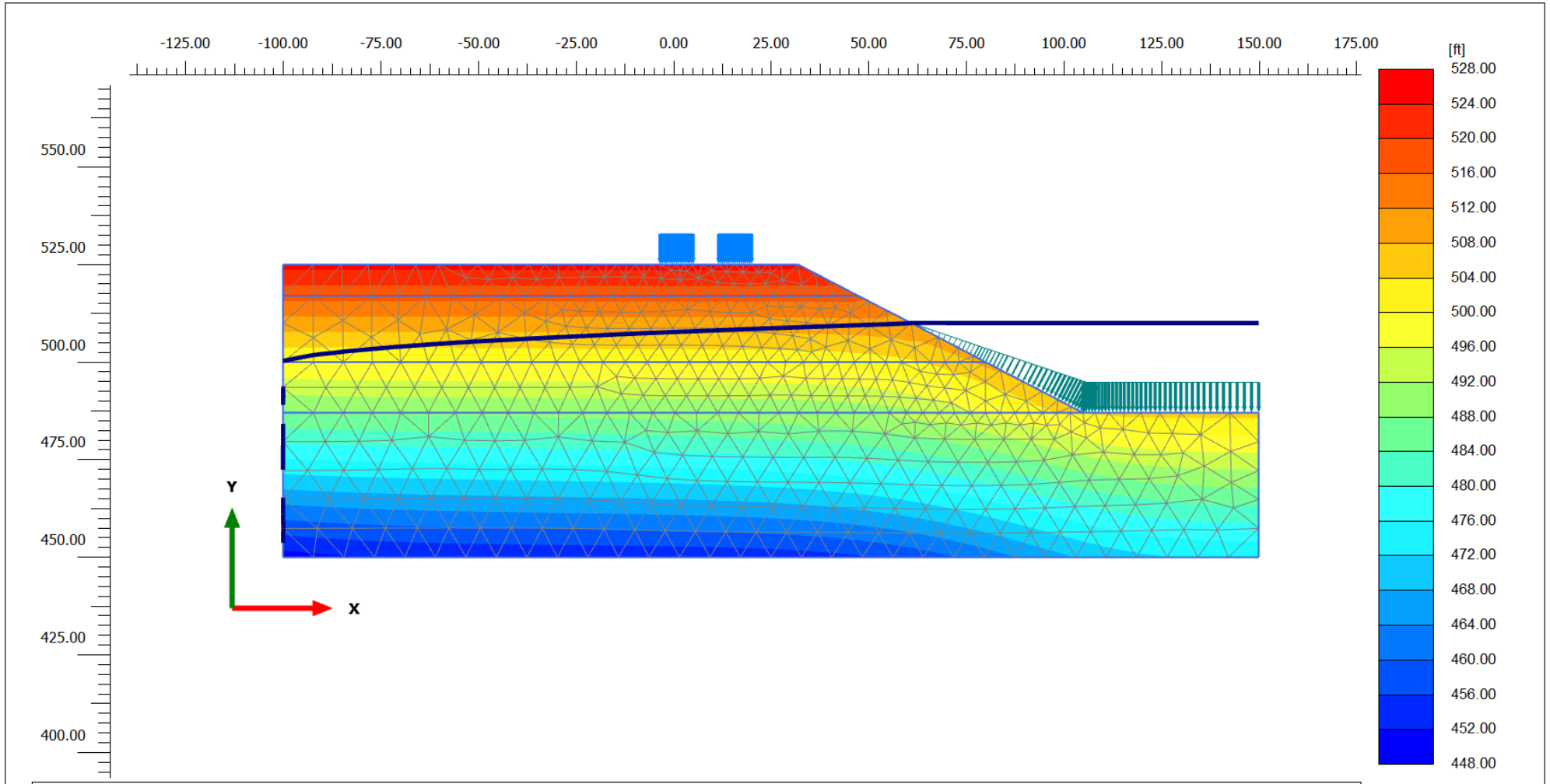
Truncated Hydrograph Method for Determining the “Steady-State” High Water Level for Intermittently Hydraulically Loaded Slopes

- The “steady-state” water levels for the water surfaces before drawdown and after drawdown are required for the 3-stage rapid drawdown analysis (Duncan et al., 1990). The before drawdown high water surface at the face of the slope is relatively easy to determine for dams and impoundments (normal pool level, etc.), but is more difficult to estimate for intermittent water surfaces on riverbanks and levees.
- The “Truncated Hydrograph Method” developed by the Author is useful in estimating the “steady-state” high water level on the face of the slope.
- The data from the Truncated Hydrograph Method can then be used in seepage analyses to determine the shape and elevations of the phreatic surface within the slope.

TRUNCATED HYDROGRAPH METHOD (Example Only)



Output Version 2019.0.0.0



Groundwater head (scaled up 0.0200 times)

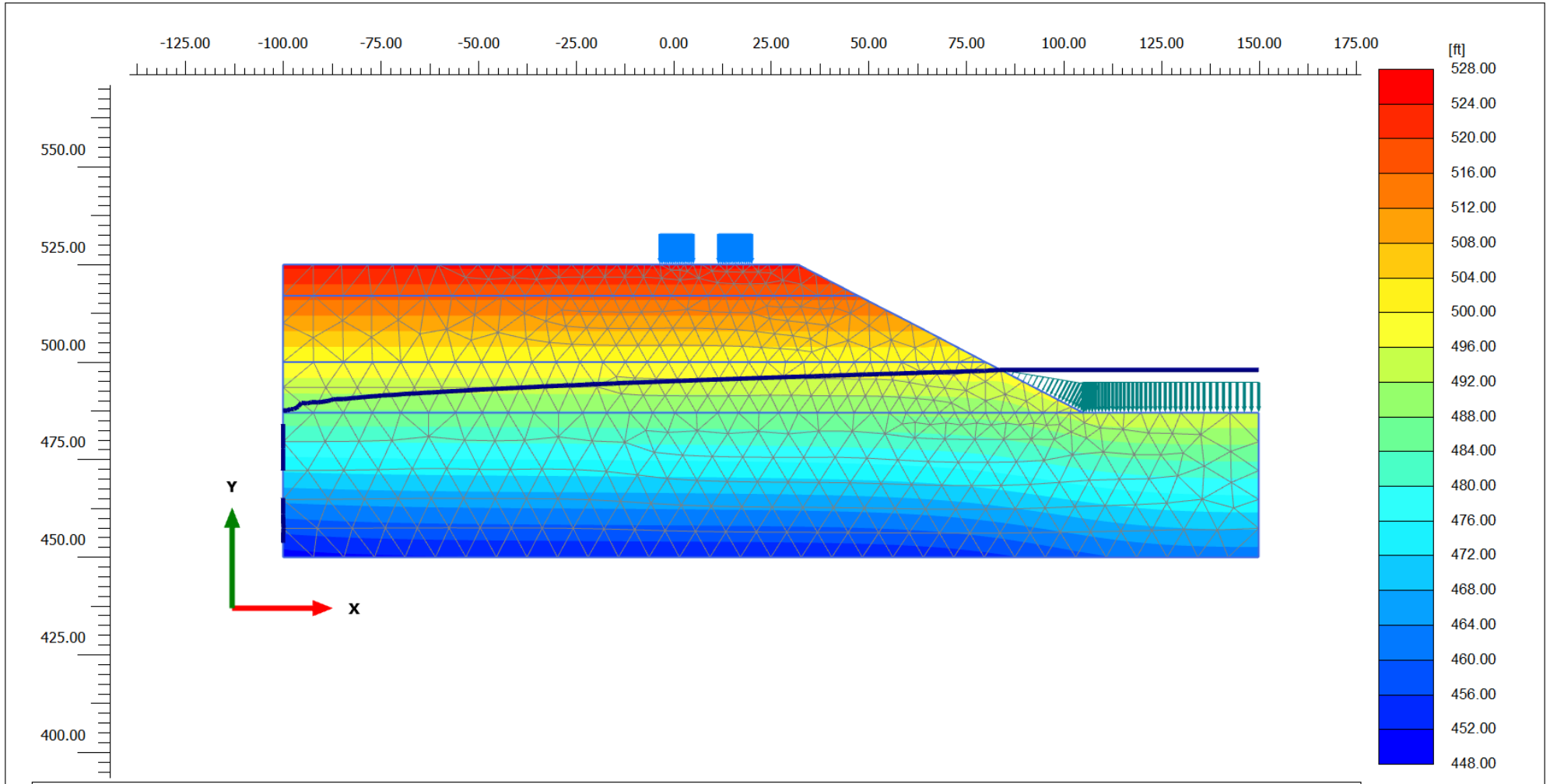
Maximum value = 525.5 ft (Element 75 at Node 1300)

Minimum value = 450.2 ft (Element 549 at Node 563)

PLAXIS

Project description		Date
STA 4598 SLOPE STABILIZATION FOR TRACK EXPANSION		7/27/2021
Project filename	*Step*	*User name*
STA 4598 SLOPE STABILI ...	11	Gregory Geotechnical

Output Version 2019.0.0.0



Groundwater head (scaled up 0.0200 times)

Maximum value = 525.4 ft (Element 81 at Node 1586)

Minimum value = 450.0 ft (Element 549 at Node 563)

PLAXIS

Project description		Date
STA 4598 SLOPE STABILIZATION FOR TRACK EXPANSION		7/27/2021
Project filename	*Step*	*User name*
STA 4598 SLOPE STABILI ...	14	Gregory Geotechnical

STATION 4598 - SLOPE STABILIZATION FOR TRACK EXPANSION

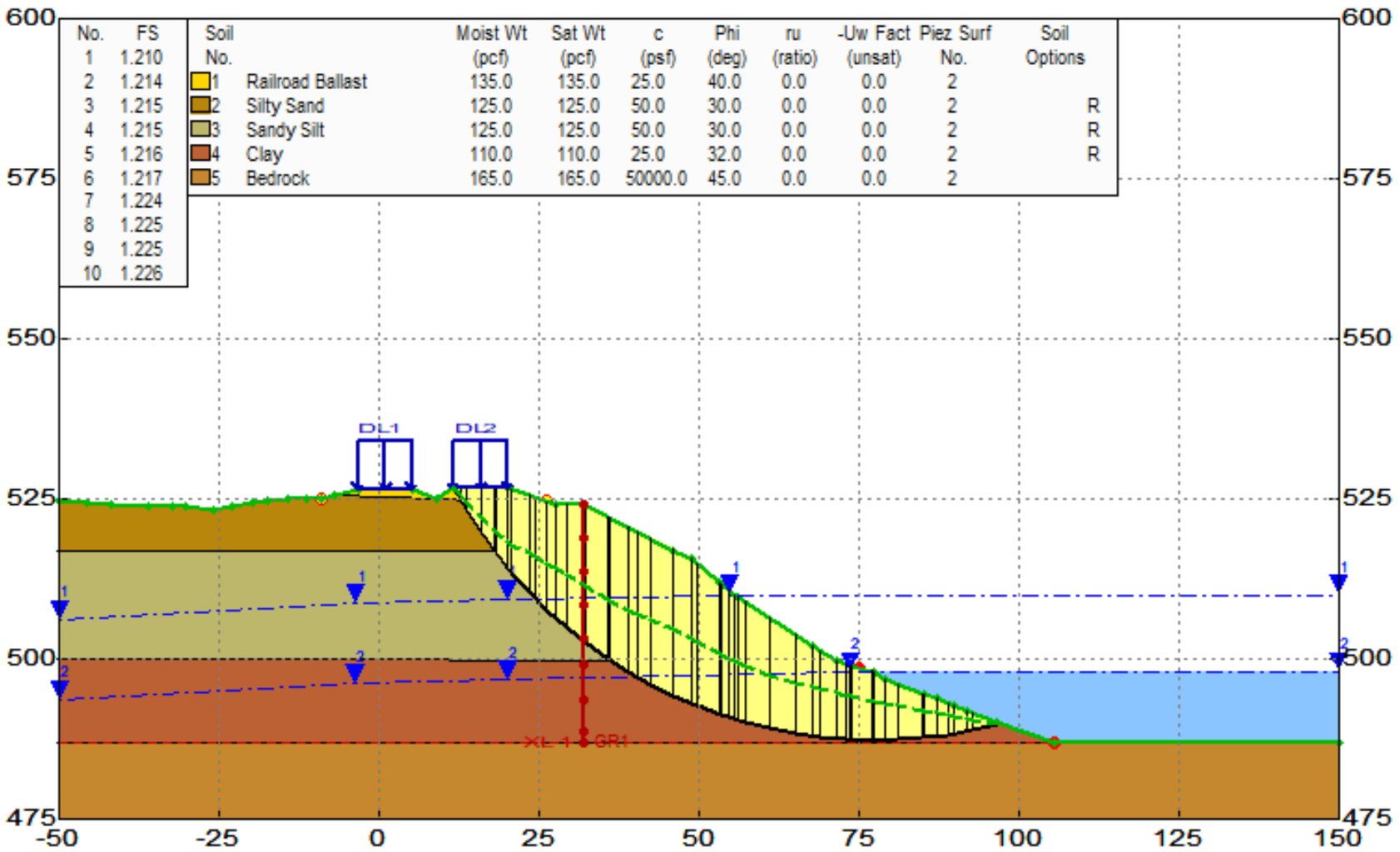
3-Stage Rapid Drawdown - Water Surfaces From FEM Analysis - Circular Search

GREGORY GEOTECHNICAL - GHG

\S3-2021-Initial-Deep-RD-B.gsd

No.	FS
1	1.210
2	1.214
3	1.215
4	1.215
5	1.216
6	1.217
7	1.224
8	1.225
9	1.225
10	1.226

Soil No.		Moist Wt (pcf)	Sat Wt (pcf)	c (psf)	Phi (deg)	ru (ratio)	-Uw Fact (unsat)	Piez Surf No.	Soil Options
1	Railroad Ballast	135.0	135.0	25.0	40.0	0.0	0.0	2	
2	Silty Sand	125.0	125.0	50.0	30.0	0.0	0.0	2	R
3	Sandy Silt	125.0	125.0	50.0	30.0	0.0	0.0	2	R
4	Clay	110.0	110.0	25.0	32.0	0.0	0.0	2	R
5	Bedrock	165.0	165.0	50000.0	45.0	0.0	0.0	2	



GEOSTASE FS = 1.210

Spencer Method

GEOSTASE
Slope Stability Analysis

GREGORY GEOTECHNICAL

GEOSTASE® by GREGORY GEOTECHNICAL SOFTWARE

PLATE S3-RD.2B

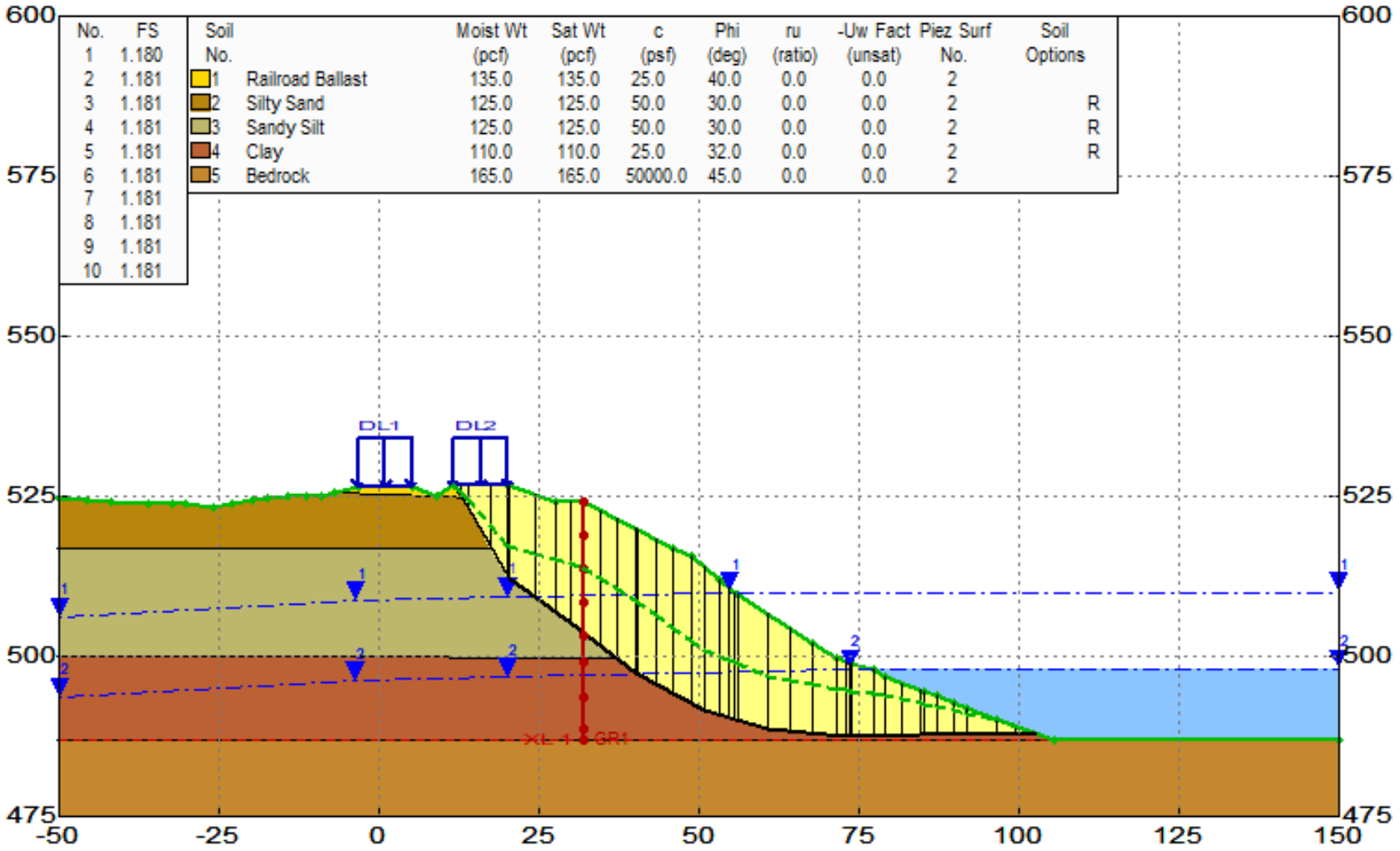
STATION 4598 - SLOPE STABILIZATION FOR TRACK EXPANSION

3-Stage Rapid Drawdown - Non-Circualr ZRSAUTO Search

GREGORY GEOTECHNICAL - GHG

\S3-2021-Initial-Deep-ZRSAUTO-RD.gsd

No.	FS	Soil No.		Moist Wt (pcf)	Sat Wt (pcf)	c (psf)	Phi (deg)	ru (ratio)	-Uw Fact (unsat)	Piez Surf No.	Soil Options
1	1.180										
2	1.181	1	Railroad Ballast	135.0	135.0	25.0	40.0	0.0	0.0	2	
3	1.181	2	Silty Sand	125.0	125.0	50.0	30.0	0.0	0.0	2	R
4	1.181	3	Sandy Silt	125.0	125.0	50.0	30.0	0.0	0.0	2	R
5	1.181	4	Clay	110.0	110.0	25.0	32.0	0.0	0.0	2	R
6	1.181	5	Bedrock	165.0	165.0	50000.0	45.0	0.0	0.0	2	
7	1.181										
8	1.181										
9	1.181										
10	1.181										



GEOSTASE FS = 1.180

Spencer Method

GEOSTASE
Slope Stability Analysis

GREGORY GEOTECHNICAL

GEOSTASE® by GREGORY GEOTECHNICAL SOFTWARE

STATION 4598 - SLOPE STABILIZATION FOR TRACK EXPANSION

3-Stage Rapid Drawdown - Non-Circular ZRSAUTO Search - Curved Strength Envelope

GREGORY GEOTECHNICAL - GHG

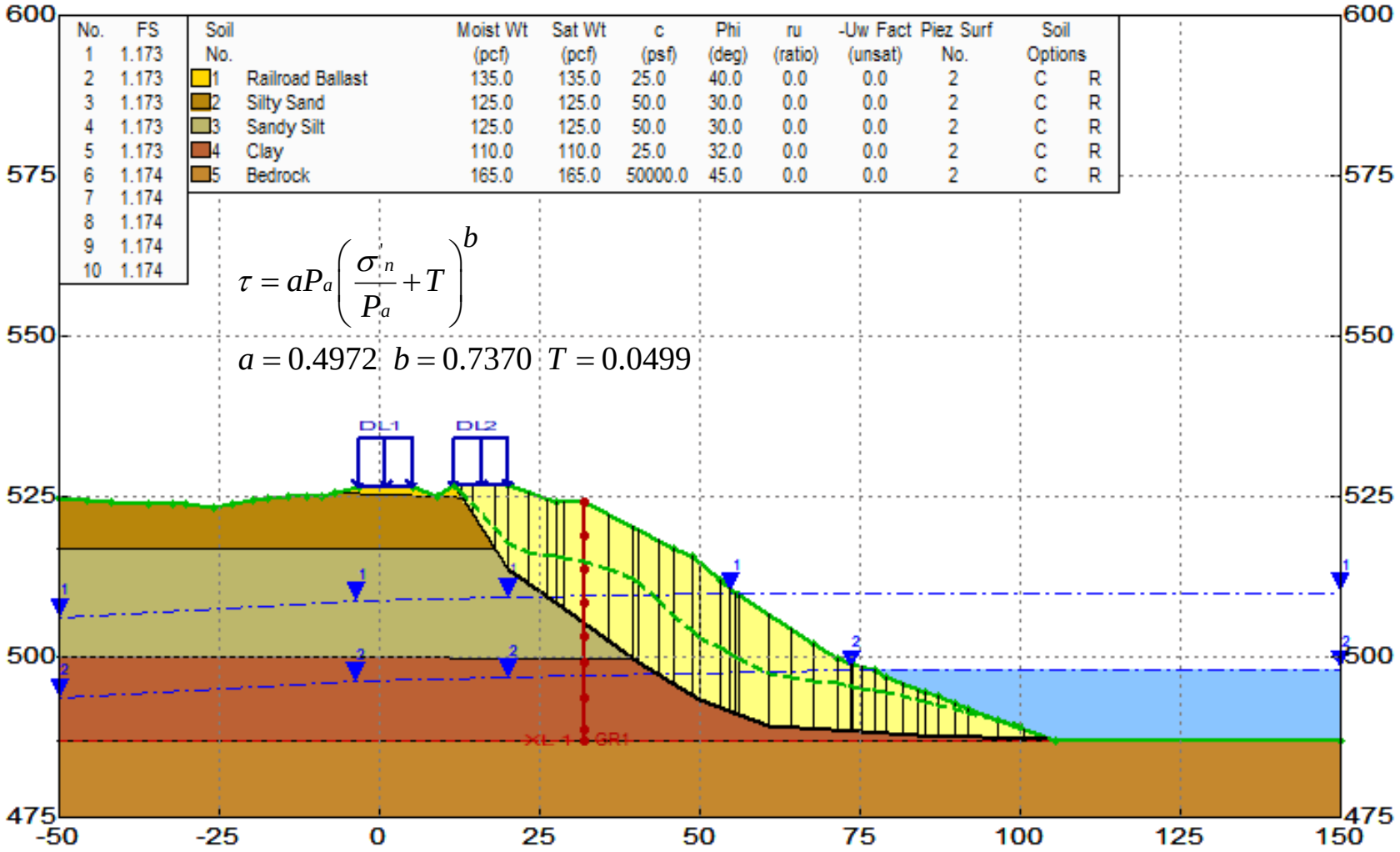
\S3-2021-Initial-Deep-ZRSAUTO-RD-C.gsd

No.	FS
1	1.173
2	1.173
3	1.173
4	1.173
5	1.173
6	1.174
7	1.174
8	1.174
9	1.174
10	1.174

Soil No.		Moist Wt (pcf)	Sat Wt (pcf)	c (psf)	Phi (deg)	ru (ratio)	-Uw Fact (unsat)	Piez Surf No.	Soil Options	
1	Railroad Ballast	135.0	135.0	25.0	40.0	0.0	0.0	2	C	R
2	Silty Sand	125.0	125.0	50.0	30.0	0.0	0.0	2	C	R
3	Sandy Silt	125.0	125.0	50.0	30.0	0.0	0.0	2	C	R
4	Clay	110.0	110.0	25.0	32.0	0.0	0.0	2	C	R
5	Bedrock	165.0	165.0	50000.0	45.0	0.0	0.0	2	C	R

$$\tau = aP_a\left(\frac{\sigma'_n}{P_a} + T\right)^b$$

$$a = 0.4972 \quad b = 0.7370 \quad T = 0.0499$$



GEOSTASE FS = 1.173

Spencer Method

GEOSTASE
Slope Stability Analysis

GREGORY GEOTECHNICAL

GEOSTASE® by GREGORY GEOTECHNICAL SOFTWARE

GEOSTASE Thrust Plot

GREGORY GEOTECHNICAL - GHG

\S3-2021-Initial-Deep-ZRSAUTO-RD-C.gsd

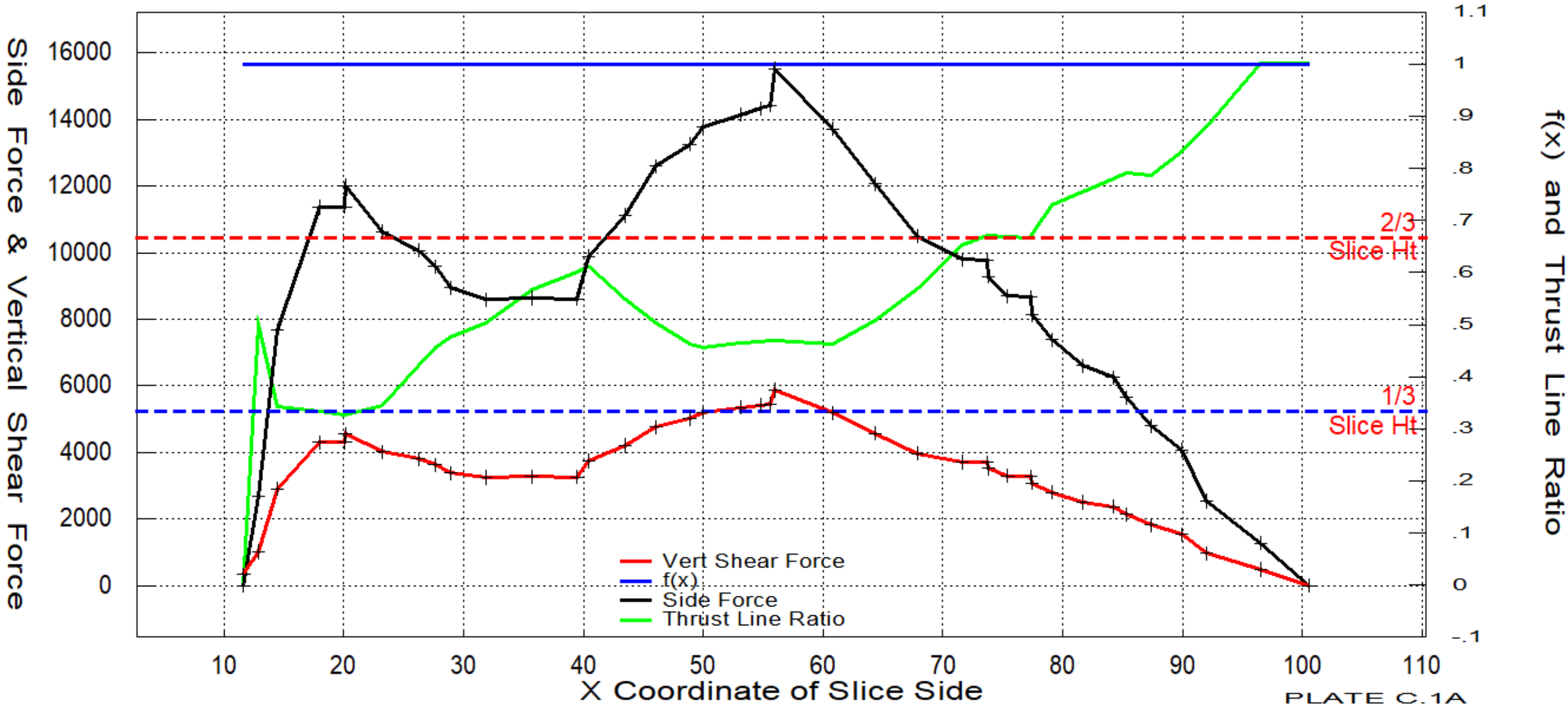


PLATE C.1A

GEOSTASE Stress Plot

GREGORY GEOTECHNICAL - GHG

\S3-2021-Initial-Deep-ZRSAUTO-RD-C.gsd

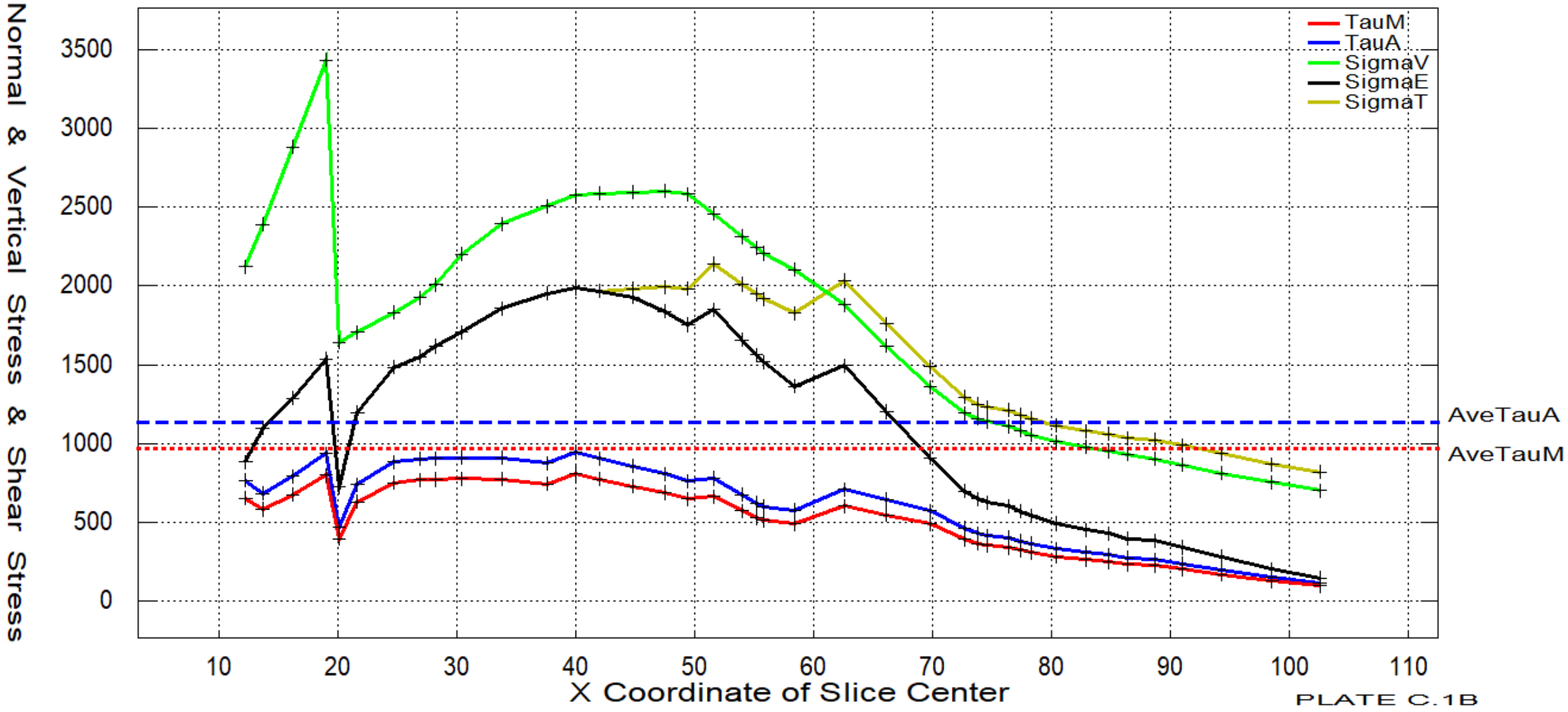


PLATE C.1B

STATION 4598 - SLOPE STABILIZATION FOR TRACK EXPANSION

3-Stage Rapid DD - Non-Circ. ZRSAUTO Search - Curved Strength Envelope - 3D

GREGORY GEOTECHNICAL - GHG

\S3-2021-Initial-Deep-ZRSAUTO-RD-C-3D.gsd

No.	FS
1	1.270
2	1.270
3	1.270
4	1.270
5	1.270
6	1.270
7	1.270
8	1.271
9	1.271
10	1.271

Soil No.		Moist Wt (pcf)	Sat Wt (pcf)	c (psf)	Phi (deg)	ru (ratio)	-Uw Fact (unsat)	Piez Surf No.	Soil Options	
1	Railroad Ballast	135.0	135.0	25.0	40.0	0.000	0.0	2	C	R
2	Silty Sand	125.0	125.0	50.0	30.0	0.000	0.0	2	C	R
3	Sandy Silt	125.0	125.0	50.0	30.0	0.000	0.0	2	C	R
4	Clay	110.0	110.0	25.0	32.0	0.000	0.0	2	C	R
5	Bedrock	165.0	165.0	50000.0	45.0	0.000	0.0	2	C	R

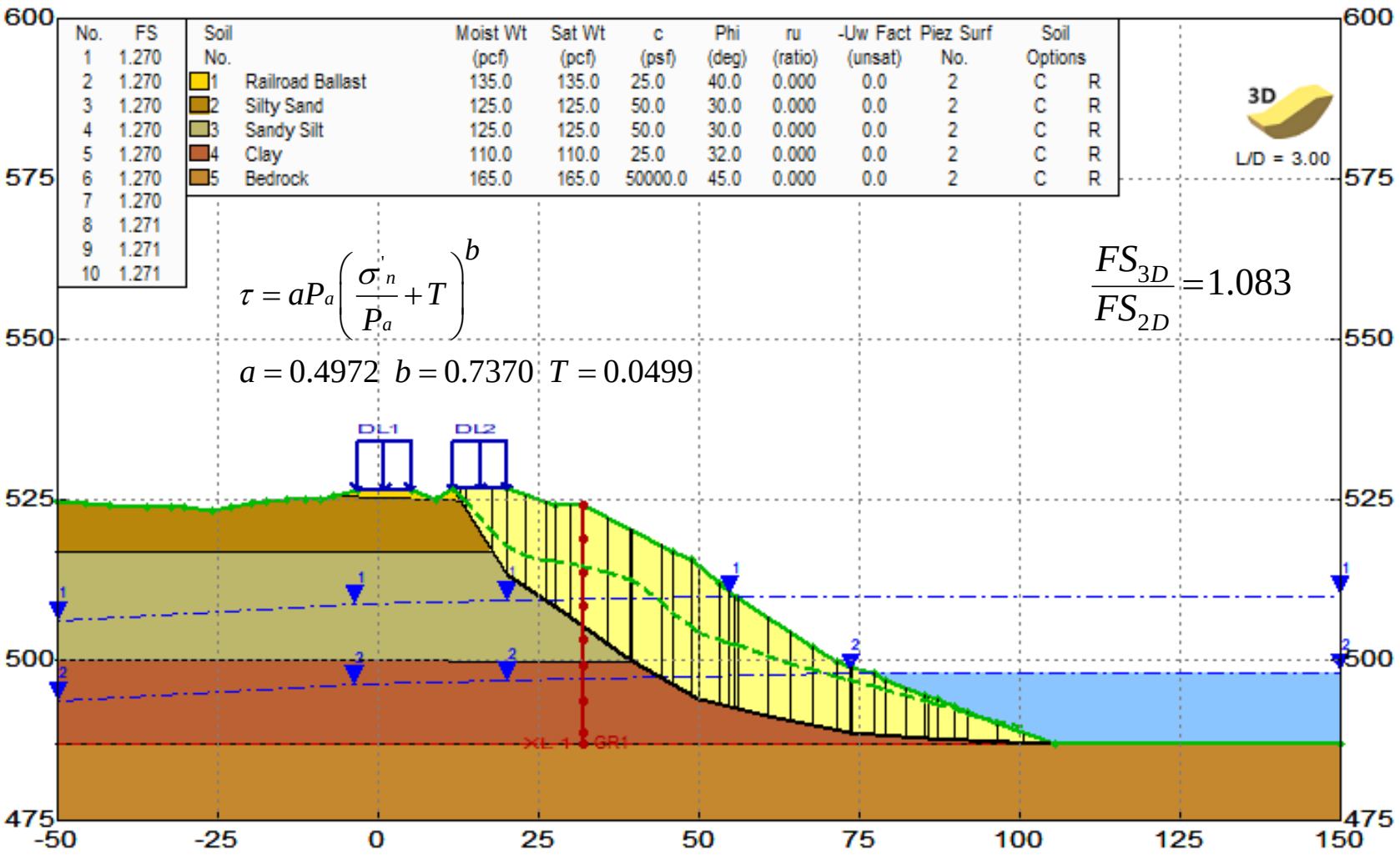
$$\tau = aP_a\left(\frac{\sigma'_n}{P_a} + T\right)^b$$

$$a = 0.4972 \quad b = 0.7370 \quad T = 0.0499$$

$$\frac{FS_{3D}}{FS_{2D}} = 1.083$$

3D

L/D = 3.00



GEOSTASE FS = 1.270

Spencer Method

GEOSTASE
Slope Stability Analysis

GREGORY GEOTECHNICAL

GEOSTASE® by GREGORY GEOTECHNICAL SOFTWARE

PLATE S3-RD-ZRSC-3D

CALCULATED FS SUMMARY	
Analysis Condition	**FS**
Steady State with Piles-Circular Search for Verification (Baseline FS = 1.48)	1.434
3-Stage RDD-Horizontal Water Surfaces-Circular Search	1.203
3-Stage RDD-Water Surfaces from FEM Analysis-Circular Search	1.210
3-Stage RDD-Non-Circular ZRSAUTO Search	1.180
3-Stage RDD-Non-Circular ZRSAUTO Search-Curved Strength Envelope	1.173
3-Stage RDD-Non-Circular ZRSAUTO Search-Curved Strength Envelope-3D	1.270
NOTE: Calculated FS values are expressed to 3 decimal places only for comparison among the various analyses. This does not imply actual accuracy to 3 decimal places.	

SUMMARY AND CONCLUSIONS

- Analyses with water surface configurations within the slope from the FEM Seepage Analyses produced a more accurate and somewhat higher FS value than the simplified assumption of horizontal water surfaces.
- The Duncan, Wright, and Wong (1990) 3-Stage Rapid Drawdown analyses take into account the pore pressures induced by shearing and whether the soils dilate or compress during shearing. This method uses an interpolated undrained shear strength value between the Kc = 1 and Kc = K_f envelopes for fine grained soils. The Kc = 1 envelope is calculated from the C_R and ϕ_R values from the “Total Stress” parameters from a CU triaxial test. The Kc = K_f envelope is the same as the drained strength envelope.
- The highly-refined non-circular ZRSAUTO search produced a lower FS value than the circular search.
- The ZRSAUTO search with curved strength envelope parameters for C_R and ϕ_R using a 3-parameter power curve produced the lowest FS value.
- The simplified 3D analysis produced a FS value approximately 8% higher than 2D.



STATION 4598 - SLOPE STABILIZATION FOR TRACK EXPANSION

Stabilization with H Piles

Limit Equilibrium: 3-Stage Rapid Drawdown

Finite Element Method: Steady State Seepage Analyses

Software: GEOSTASE & PLAXIS

Dr. Garry H. Gregory, PhD, PE, SE, D.GE

GREGORY GEOTECHNICAL



Rapid Drawdown Analysis

Murray Fredlund, Mohammed Siddiquee
Bentley Software Inc.

Bentley
Advancing Infrastructure

© 2021 Bentley Systems, Incorporated

Introduction



Dr. Murray Fredlund, Ph.D., P.Eng.
Senior Strategic Advisor, Geotechnical
Bentley Systems Inc.



Dr. Mohammed Siddiquee, Ph.D.
User Success Manager, Virtuosity, Bentley Systems Inc.

Bentley®

Bentley Geotechnical Engineering

Efficiently model, analyze, and report on any geoengineering project with Bentley's comprehensive geotechnical engineering software.

Geotechnical Analysis



PLAXIS® LE
CONNECT Edition

Limit equilibrium analysis (previously SVSLOPE)



PLAXIS® 3D
CONNECT Edition

Finite element analysis



PLAXIS® 2D
CONNECT Edition

Finite element analysis



PLAXIS® Designer
CONNECT Edition

Conceptual modeling

Geotechnical Information



gINT
CONNECT Edition

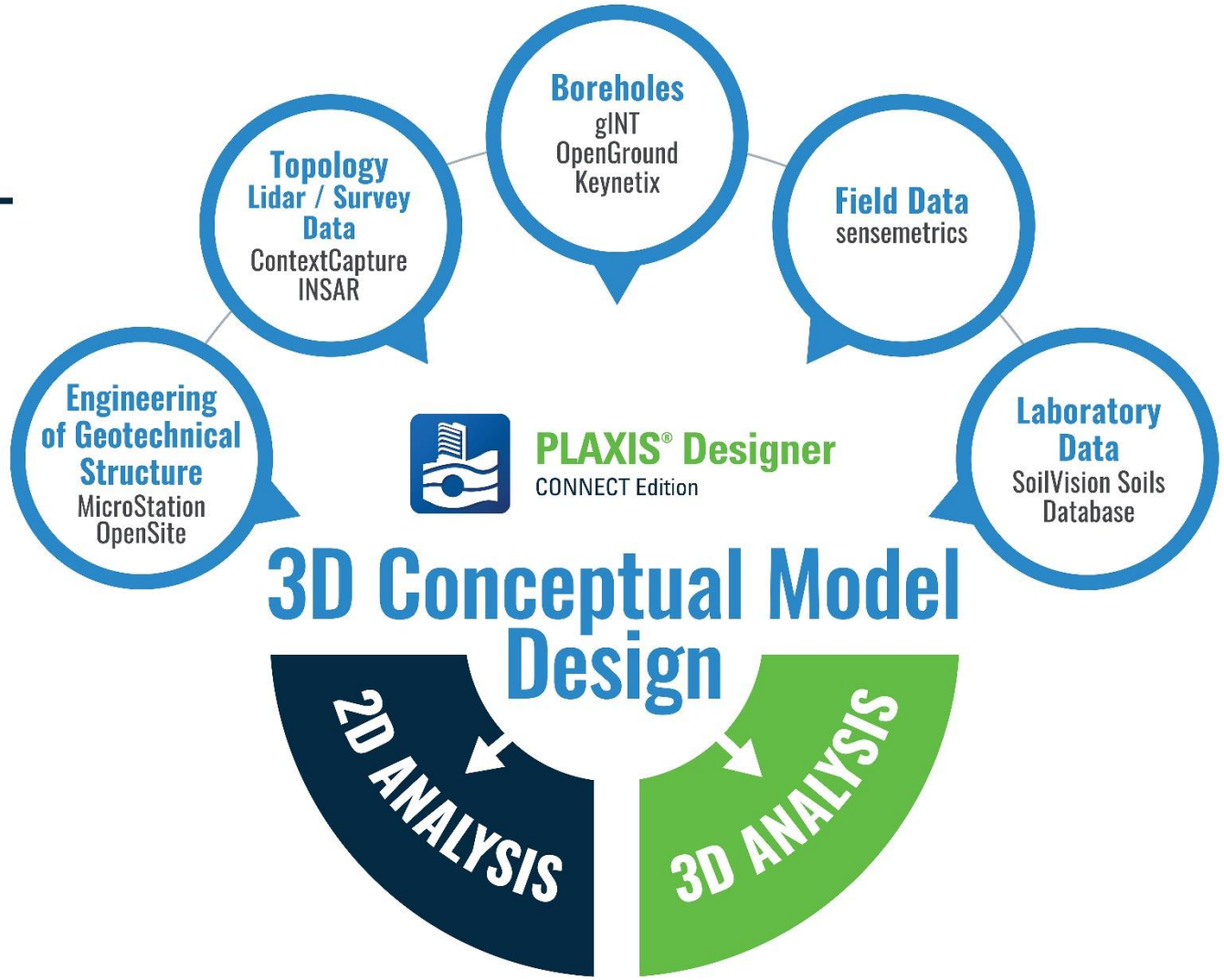


OpenGround® Cloud
CONNECT Edition



Keynetix

INTEGRATED GEOTECHNICAL WORKFLOW



 © 2021 Bentley Systems, Incorporated

Bentley

OUTLINE

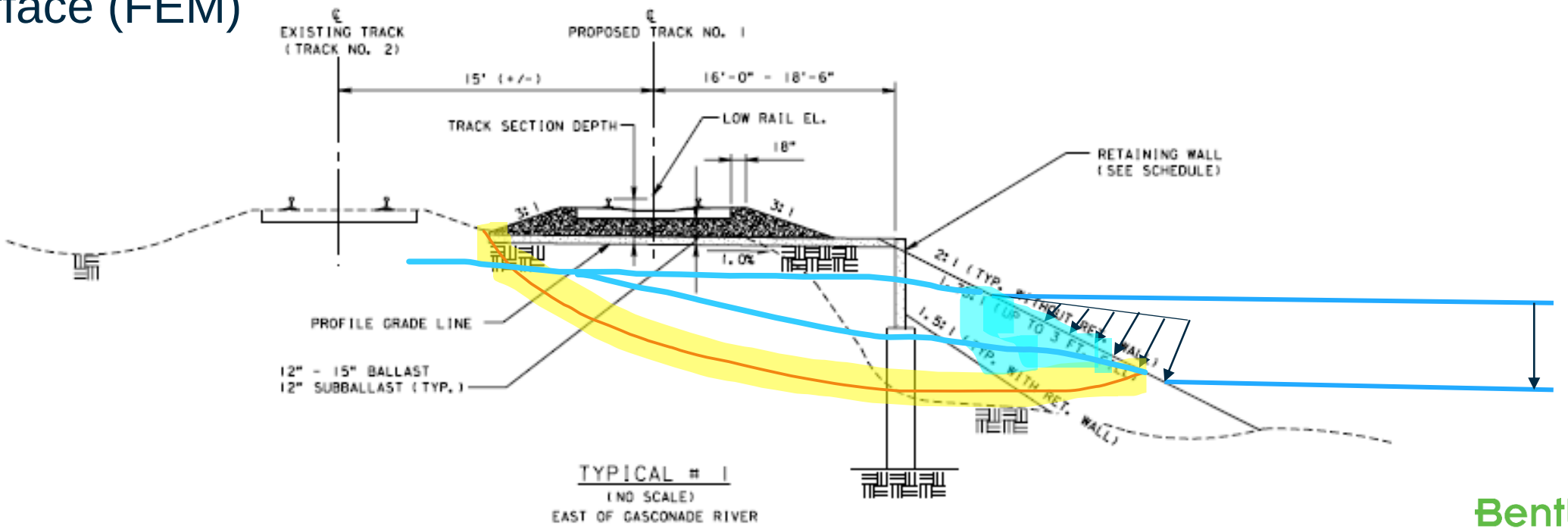
- Uncertainty & Variability
- Rapid drawdown
  - 2D/3D LEM Duncan method
  - LEM Coupled seepage FEM
  - FEM-SSR
- Summary

- Scenarios
  - Multi-layer
  - Double track
  - Without / with H-pile
  - 2D / 3D

Bentley®

MODELING ISSUES

- Static stability (LEM & FEM)
- Rapid drawdown
  - Pore-water pressures (LEM & FEM)
  - Removal of water load (FEM)
  - Dilation/compression & pore-water pressure change due to shear along slip surface (FEM)



Bentley

UNCERTAINTY

- “Why don’t we all get the same answer?”
- Uncertainty sources
  - Model uncertainty (focus)
  - Parameter uncertainty
  - Human uncertainty
- Modeling uncertainty
  - Software implementation
  - Method (Spencer/MP/GLE)
  - Circular vs. Non-circular
  - Pile representation
  - Pore-water pressure representation (Duncan, FEM combined, fully coupled)
  - FEM vs. LEM

Bentley®

Differences Between Software Implementations

- Table 7 presents a summary of the comparison between PLAXIS LE and SLIDE or SLOPE/W using a larger dataset
- In this comparison grid and tangent searching methods along with circular slip surfaces were used in the analysis.
- The deviations of the methods between different software packages are within **+/- 2% (Spencer, M-P, GLE)**

Table 7 Summary of software comparison

Methods	Number of Models	Max Diff (%)
Ordinary	41	1.93
Bishop Simplified	93	1.93
Janbu Simplified	59	2.80
Corps#1	17	0.47
Corps#2	17	0.505
L-K	21	11.32
Spencer	70	-2.14
M-P	30	0.48
GLE	46	2.19

Difference =(SVSLOPE-SLIDE)/SVSLOPE (%) or
Difference =(SVSLOPE-SLOPE/W)/SVSLOPE (%)

 © 2021 Bentley Systems, Incorporated

Bentley

Differences Between Analysis Methods

- Possible to quantify expected differences in the FOS between method
- Sample group of hundreds of models
- Difference of averages between GLE and Spencer/M-P methods is **3-10%**

Fully Specified

Row Labels	Average of FOS Moment	Average of FOS Force	Count of Model	Difference of Averages
Fully Specified	**1.731**	**1.360**	**113**	
Bishop	2.283		27	60.1%
Corps#1		1.432	6	0.5%
Corps#2		1.393	6	-2.3%
GLE	1.426	1.426	14	
Janbu Simplified		1.113	19	-21.9%
Lowe-Karafiath		1.445	5	1.4%
M-P	1.439	1.439	10	1.0%
Ordinary	1.361		8	-4.5%
Spencer	1.467	1.467	18	2.9%

Block Search

Row Labels	Average of FOS Moment	Average of FOS Force	Count of Model	Difference of Averages
Block	**0.983**	**1.036**	**22**	
Bishop	1.065		1	8.5%
Corps#1		1.223	1	24.6%
Corps#2		1.267	1	29.1%
GLE	0.982	0.982	9	
Janbu Simplified		1.092	3	11.2%
Lowe-Karafiath		1.276	1	30.0%
M-P	1.077	1.077	1	9.7%
Ordinary	0.974		1	-0.8%
Spencer	0.942	0.941	4	-4.1%

Grid & Tangent Search

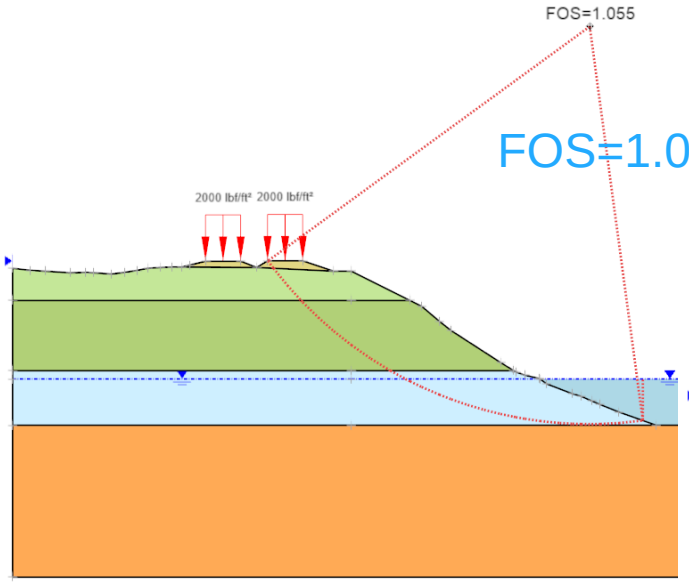
Row Labels	Average of FOS Moment	Average of FOS Force	Count of Model	Difference of Averages
Grid and Tangent	**1.394**	**1.397**	**243**	
Bishop	1.416		64	2.4%
Corps#1		1.441	11	4.2%
Corps#2		1.459	11	5.5%
GLE	1.383	1.382	23	
Janbu Simplified		1.298	29	-6.1%
Lowe-Karafiath		1.387	13	0.4%
M-P	1.447	1.447	19	4.7%
Ordinary	1.282		31	-7.3%
Spencer	1.426	1.426	42	3.2%

 © 2021 Bentley Systems, Incorporated

Bentley

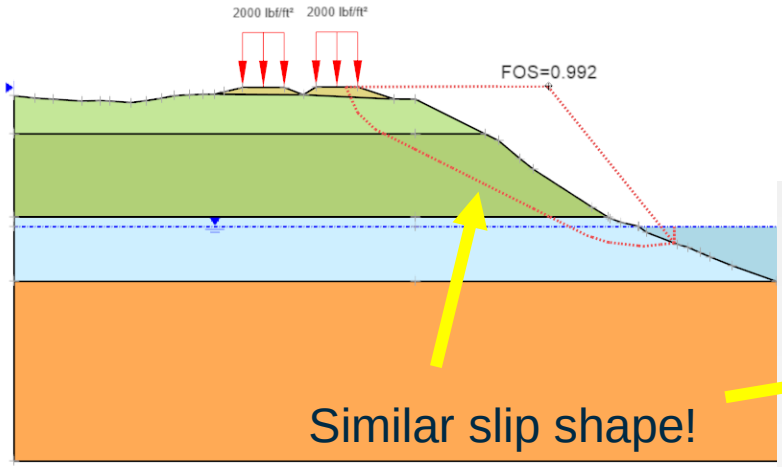
SEARCHING METHOD – w/o Piles

Circular (Cuckoo)



FOS=1.05

Non-circular (Cuckoo)



FOS=0.99

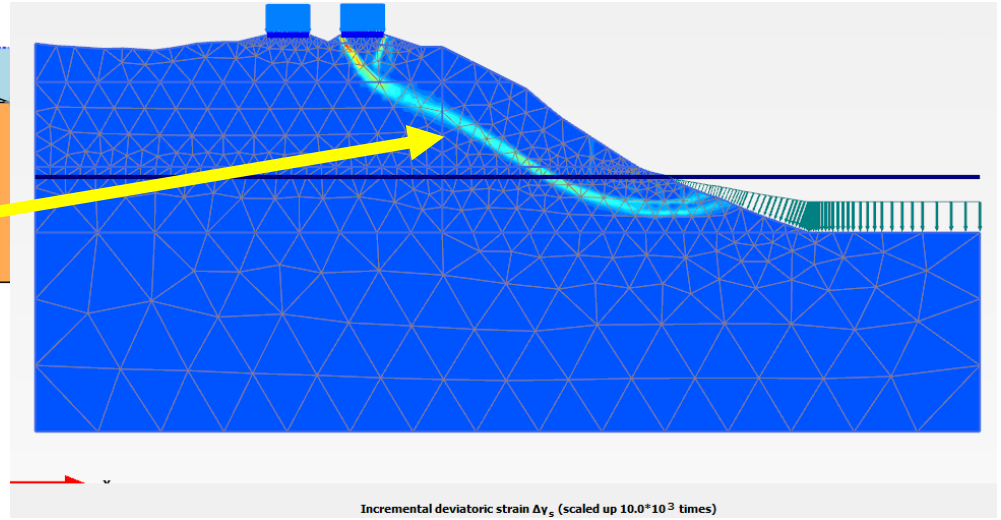
-6% difference

Similar slip shape!

FEM-SSR

FOS=1.06

+6.8% difference

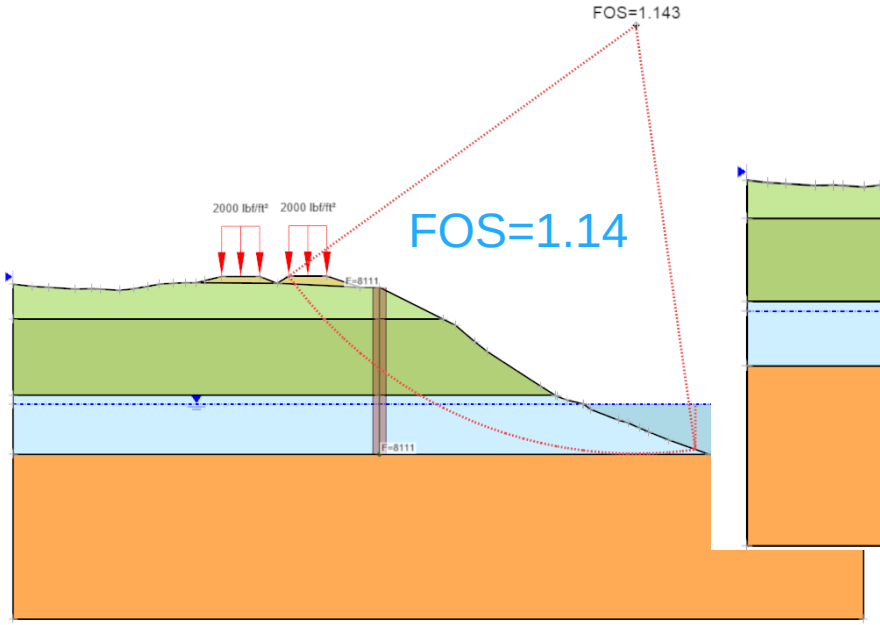


Note: LEM & FEM are both UPPER BOUND solutions!
One method will NOT always have a lower FOS

Bentley

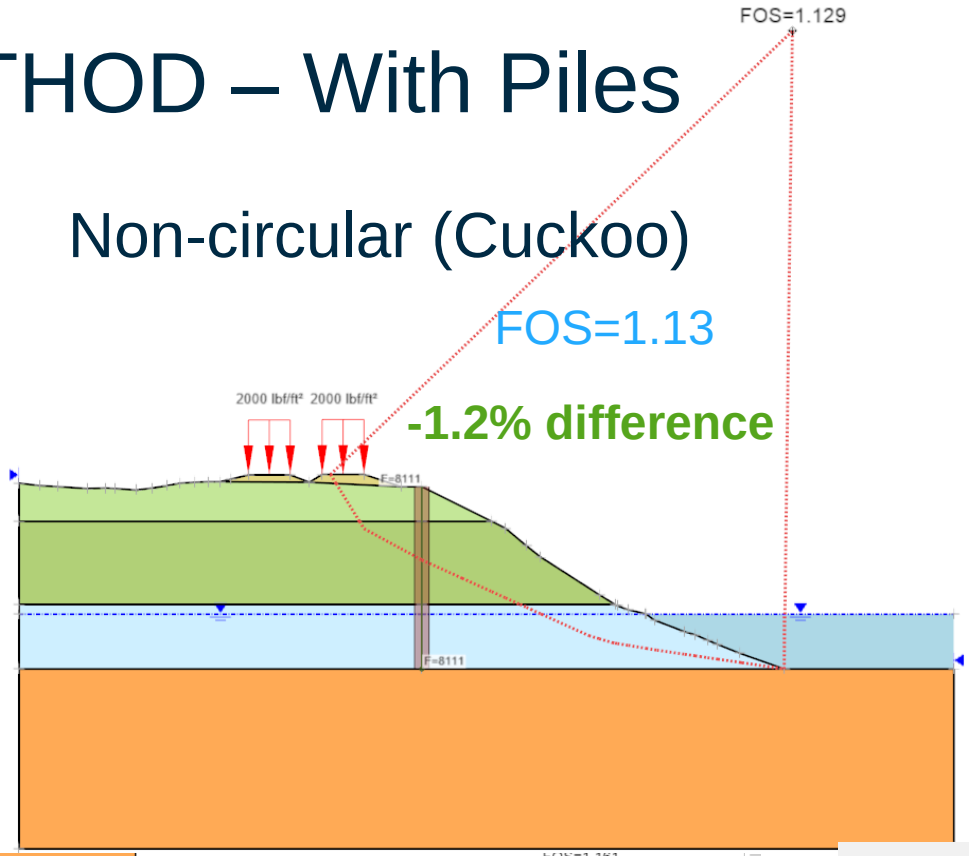
SEARCHING METHOD – With Piles

Circular (Cuckoo)



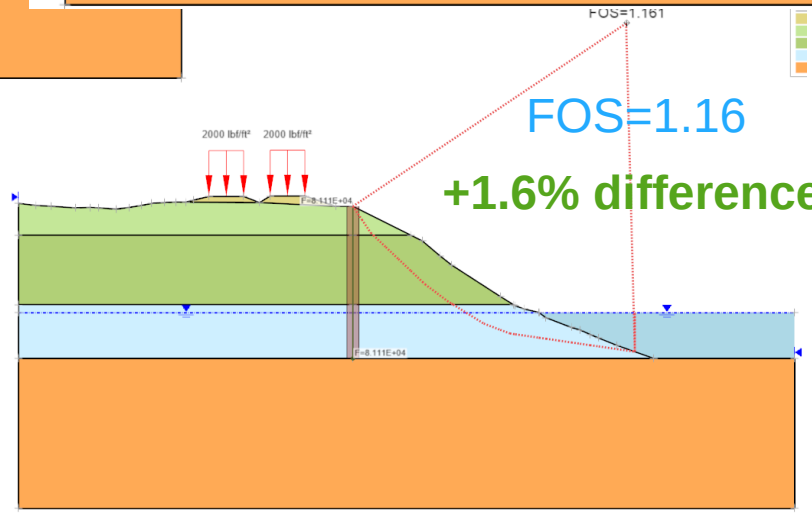
FOS=1.14

Non-circular (Cuckoo)



FOS=1.13

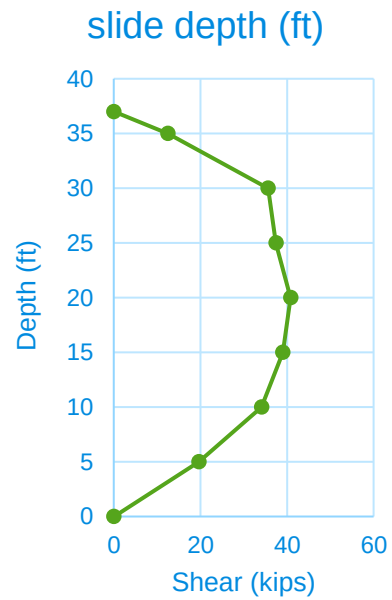
-1.2% difference



FOS=1.16

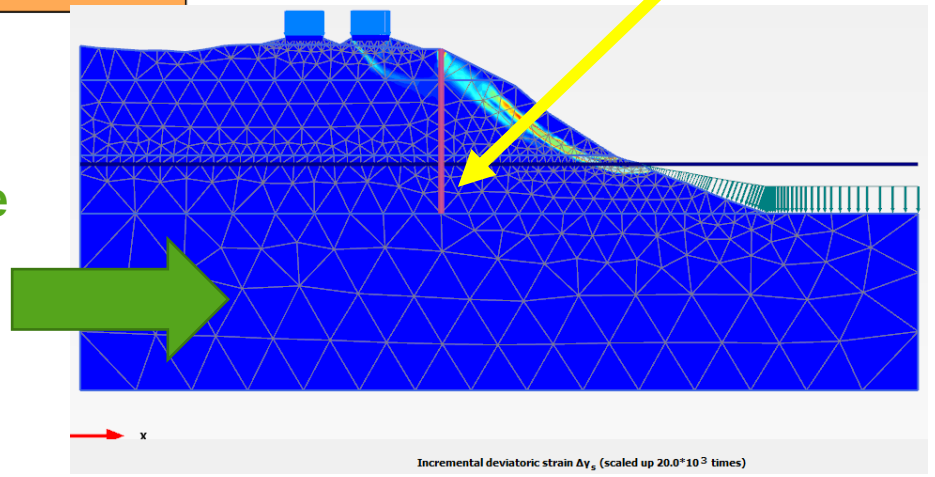
+1.6% difference

FEM-SSR



FOS=1.05

-9.5% difference



Bentley

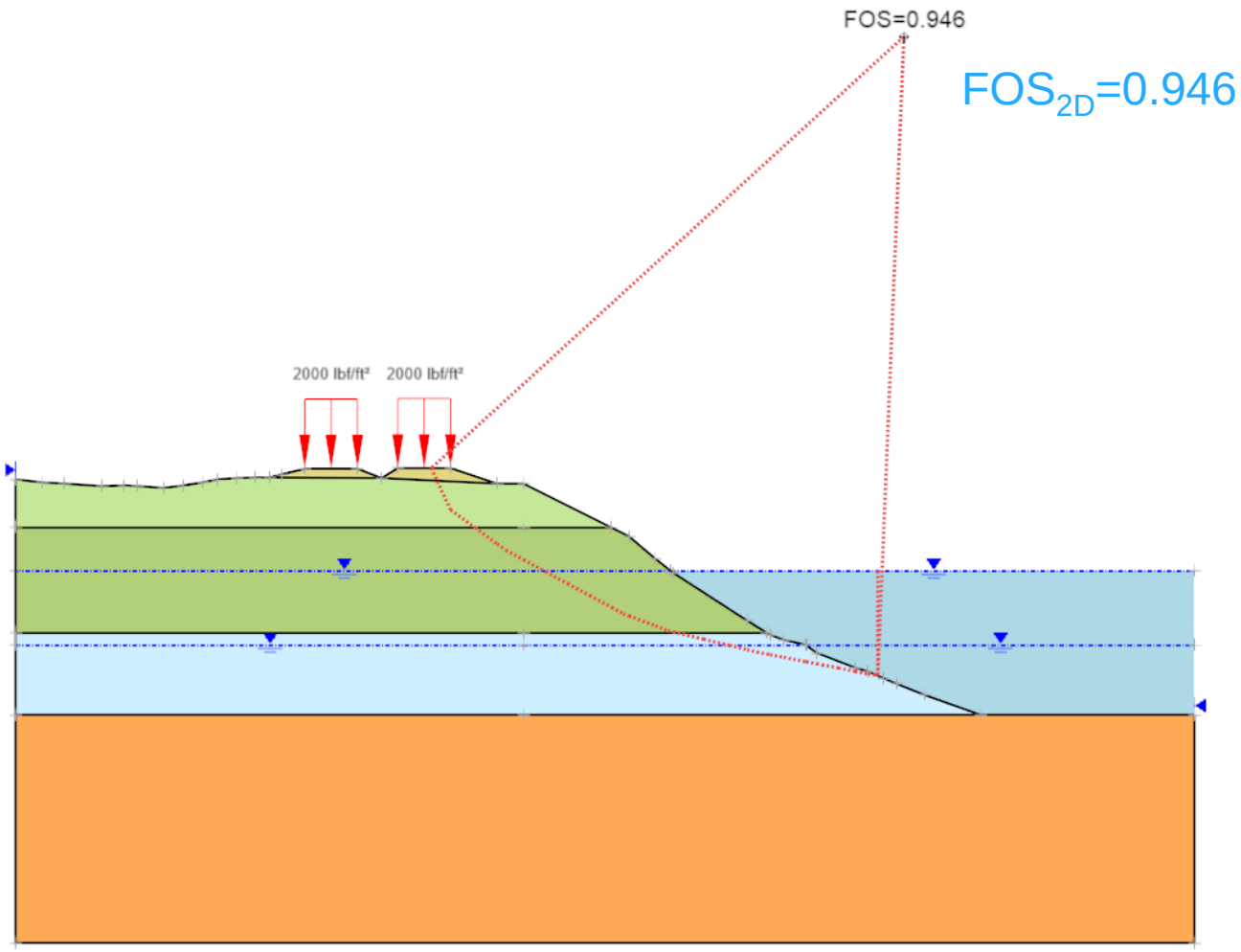
SEARCHING METHOD

- Circular vs. Non-circular
- Non-circular algorithms offer an improved method of finding a defensible factor of safety
  - Must be kinematically admissible!
  - Non-circular slips should be considered as they likely represent a more critical mechanism
- Searching method variability: 1.2 to 6% lower for this scenario
- FEM-SSR can be utilized to reinforce slip shape and FOS

Bentley®

RAPID DRAWDOWN – Duncan w/o Piles

- Use Duncan 3-stage procedure
- Non-circular



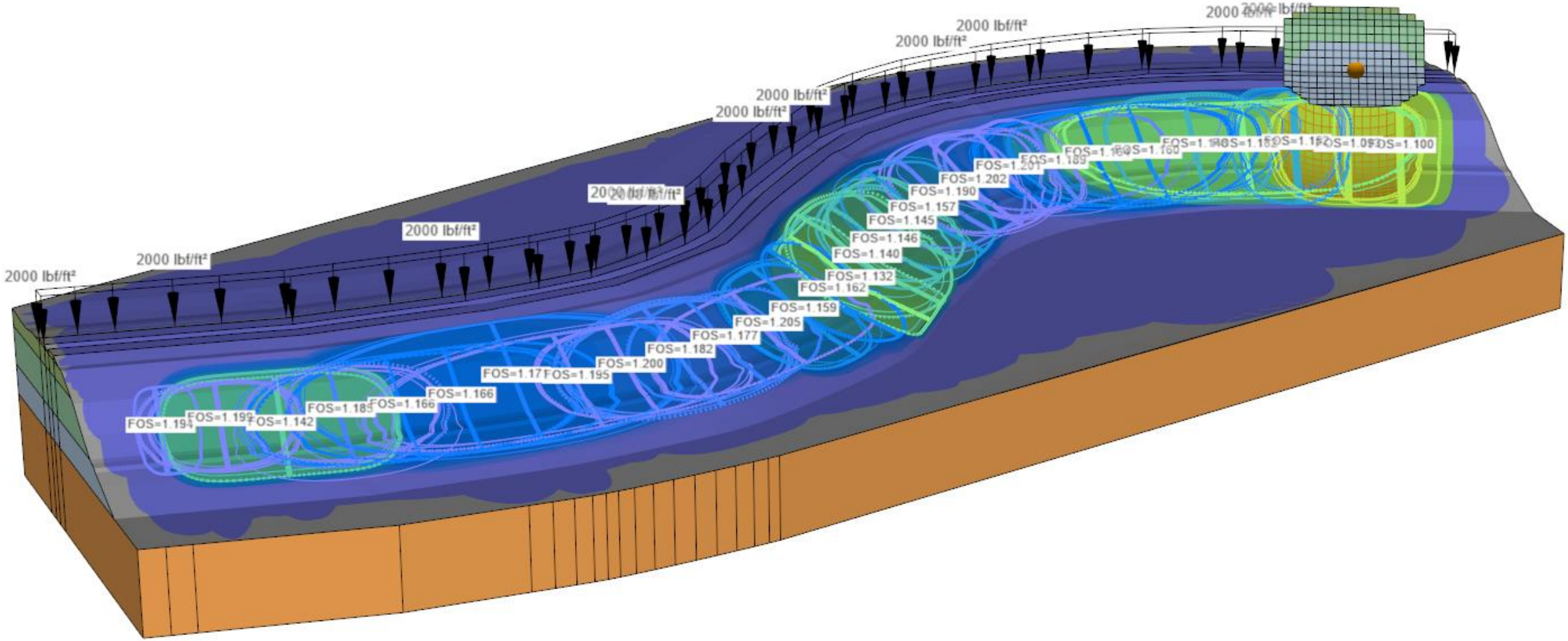
FOS_{2D}=0.946

Bentley

RAPID DRAWDOWN – 3D Duncan 3-Stage Analysis

- LEM spatial analysis without piles

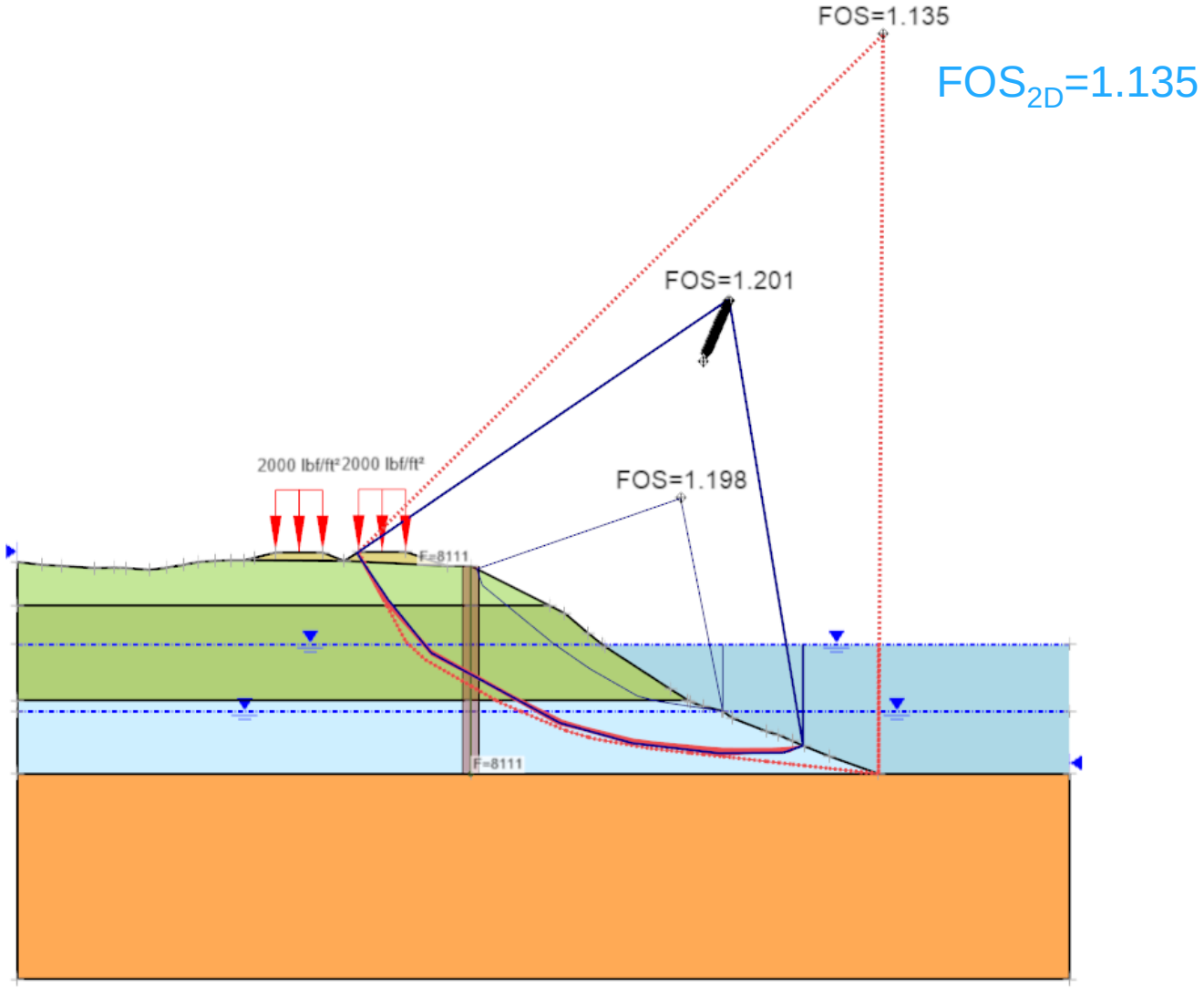
FOS_{3D}=1.093 (15.5% increase over 2D)



Bentley

RAPID DRAWDOWN – Duncan with Piles

- Use Duncan & Wright 3-stage procedure
- Non-circular



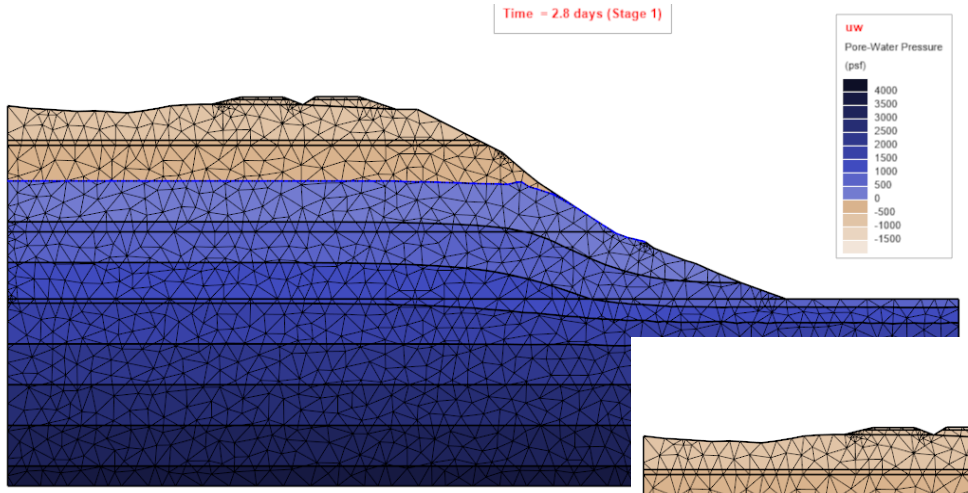
FOS_{2D}=1.135

Bentley®

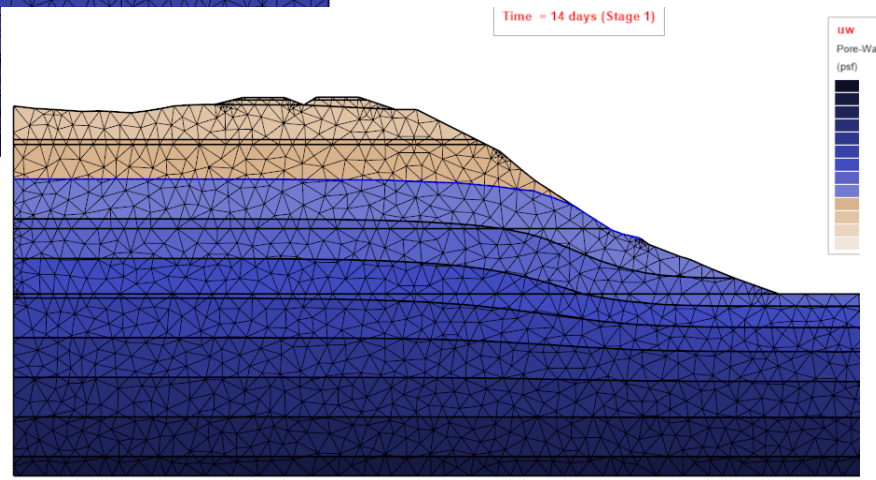
RAPID DRAWDOWN – Combined FEM Seepage

- LEM + FEM Seepage

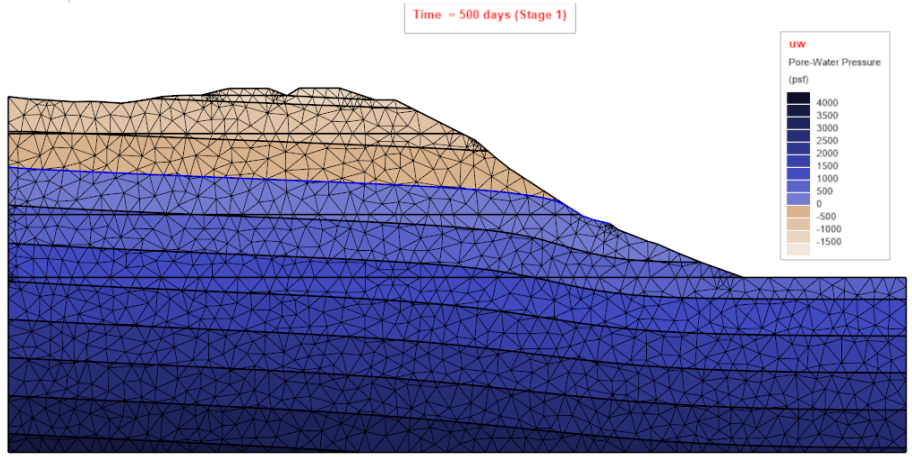
2.8 Days



14 Days



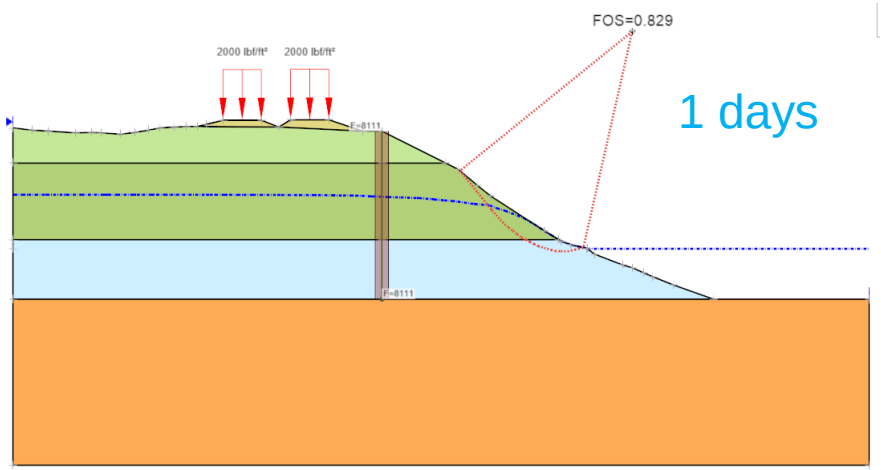
500 Days



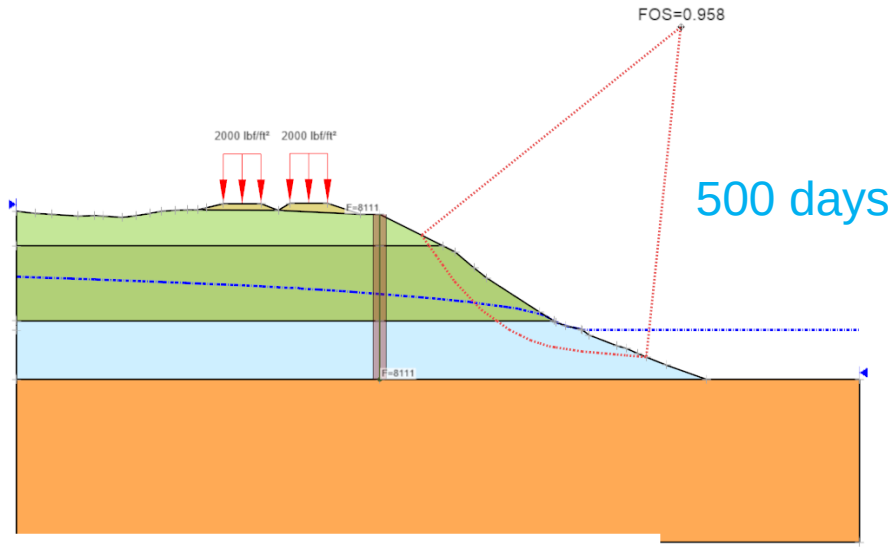
Bentley

RAPID DRAWDOWN – Combined FEM Seepage

- LEM + FEM Seepage

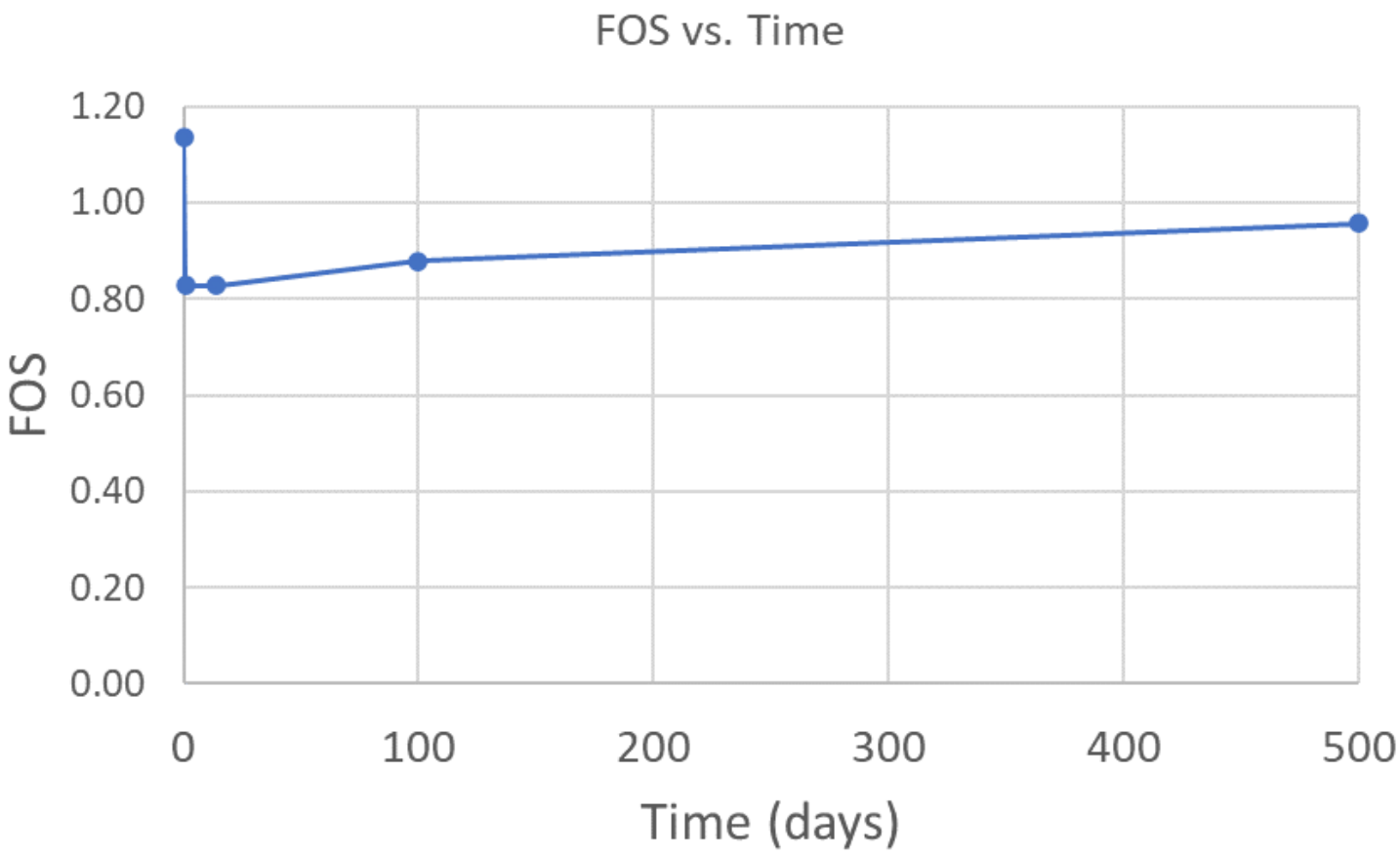


1 days



500 days

Critical FOS=0.83 (drop of 27% from Duncan)



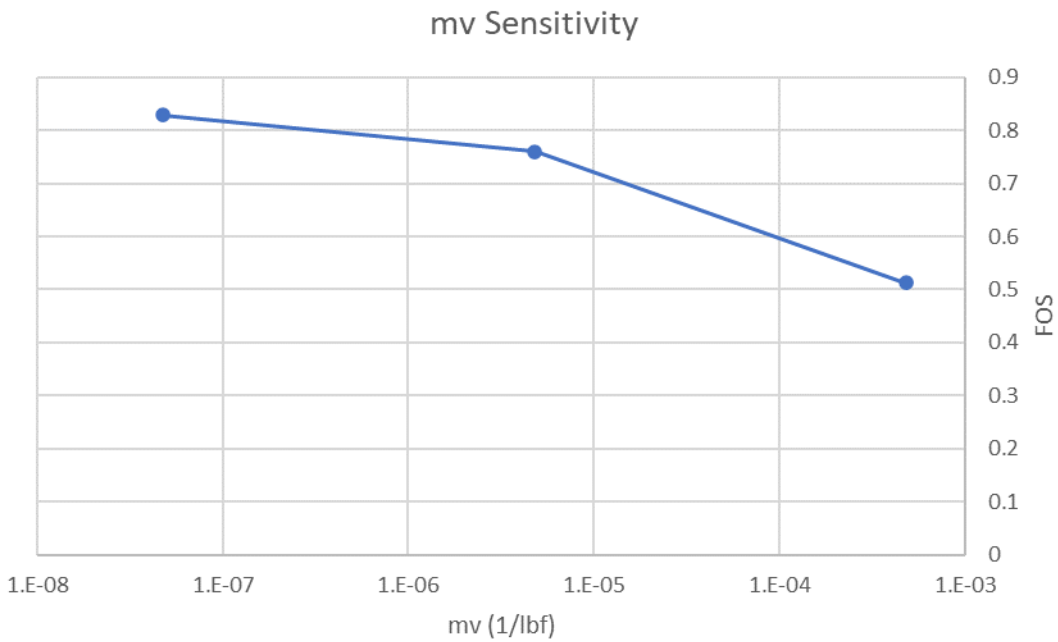
Bentley

RAPID DRAWDOWN – Combined FEM Seepage

- m_v sensitivity noted in previous studies
- Sensitivity to FOS at 14 days is plotted

Table 2-1. Typical values of k_s (after USACE 1986 and Benson and Trast 1995), c_v (after Duncan et al. 1990), and m_v (calculated) for common embankment soil types.

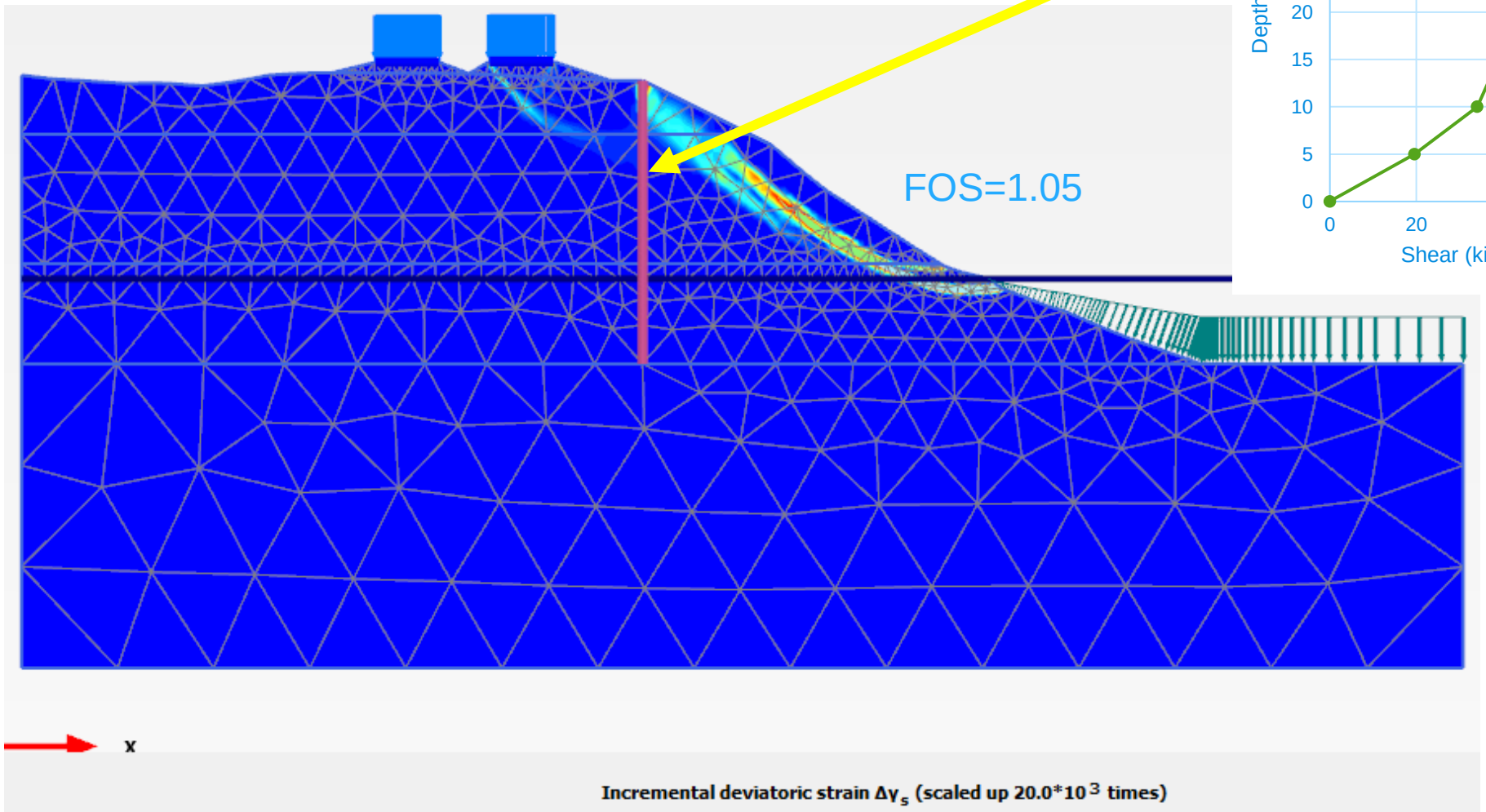
	Soil Type	Coefficient of Hyd. Conductivity, k_s, (ft/day)	Coefficient of Consolidation, c_v, (ft^2/day)	Coefficient of Volume Compressibility, m_v, (1/psf)
English units	Coarse Sand	30 – 3000	10,000 – 100,000	5×10^{-6} – 5×10^{-4}
	Fine Sand	0.3 – 30	100 – 10,000	5×10^{-6} – 5×10^{-4}
	Silty Sand	0.03 – 3	10 – 1000	5×10^{-6} – 5×10^{-4}
	Silt	3×10^{-4} – 3×10^{-2}	0.5 – 100	5×10^{-7} –5×10^{-5}
	Soft Clay	3×10^{-6} – 3×10^{-4}	0.002 – 0.2	2×10^{-6} – 2×10^{-4}
	Compacted Clay	3×10^{-6} – 3×10^{-2}	0.05 – 5	9×10^{-8} – 9×10^{-4}



Bentley

RAPID DRAWDOWN – FEM Analysis

- FEM Seepage + FEM-SSR

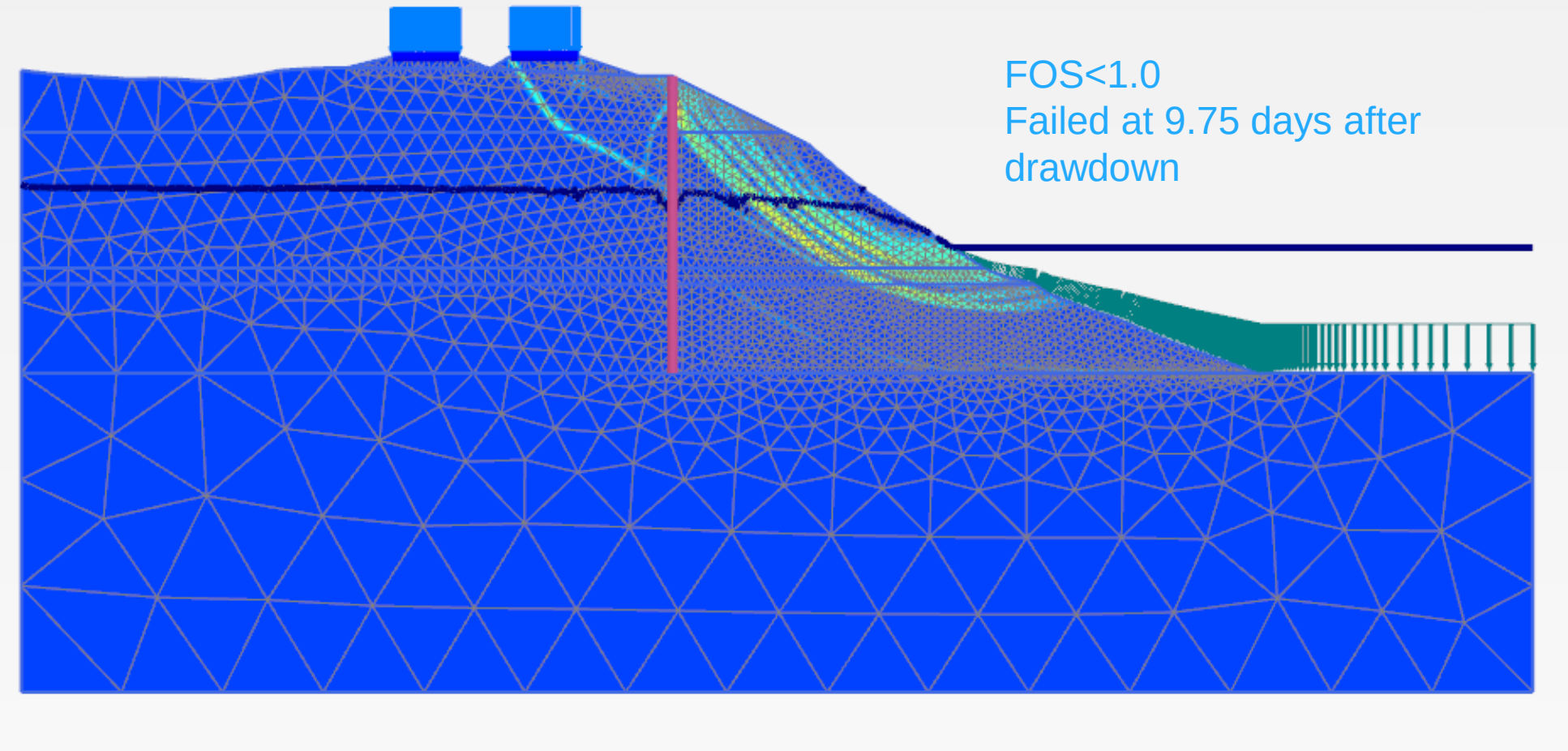




Bentley

RAPID DRAWDOWN – FEM Analysis

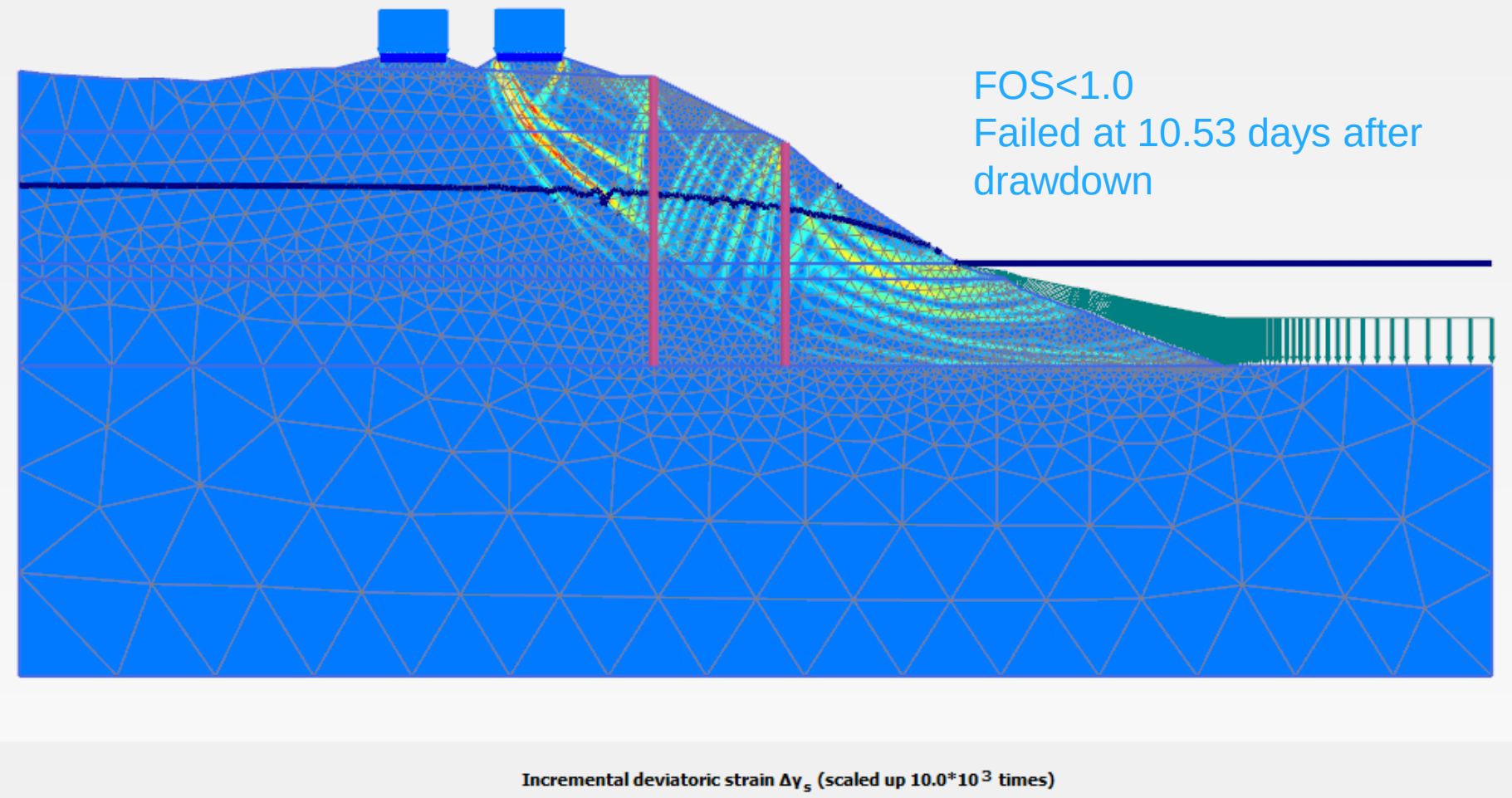
- FEM Seepage + FEM-SSR



Bentley

RAPID DRAWDOWN – FEM Analysis

FEM Seepage + FEM-SSR + 2 Piles



 © 2021 Bentley Systems, Incorporated

Bentley

SUMMARY

- Modeling uncertainty
  - LEM software implementation: 2% difference
  - Method (Spencer/MP/GLE): 3 to10% difference
  - Circular vs. Non-circular: reduction of up to 6% with non-circular in this case
  - Pile representation: (unknown due to pile placement)
  - Rapid drawdown
    - Duncan: FOS=1.14
    - LEM/FEM transient: FOS=0.83 (drop of 27% from Duncan)
    - FEM fully coupled: ?? (FOS drops below 1.0 – demonstrates failure)
  - FEM vs. LEM: -9.5% to +6.8%
  - 2D vs. 3D: 15% increase from 2D to 3D FOS

Bentley®

Thank you!

 © 2021 Bentley Systems, Incorporated