SOFTWARE DISCUSSION INTRODUCTION AND PANEL

- Facilitator: Timothy Siegel, P.E., G.E., D.GE | Dan Brown and Associates, PC
- Garry Gregory, Ph.D., P. E., S.E., D.GE | Gregory Geotechnical & OSU
- Augusto Lucarelli | Itasca Consulting Group
- Jeff Lam, M.Eng., P. Eng. and Sina Javankhoshdel, Ph.D. | Rocscience



DAN BROWN AND ASSOCIATES

PROBLEM STATEMENT

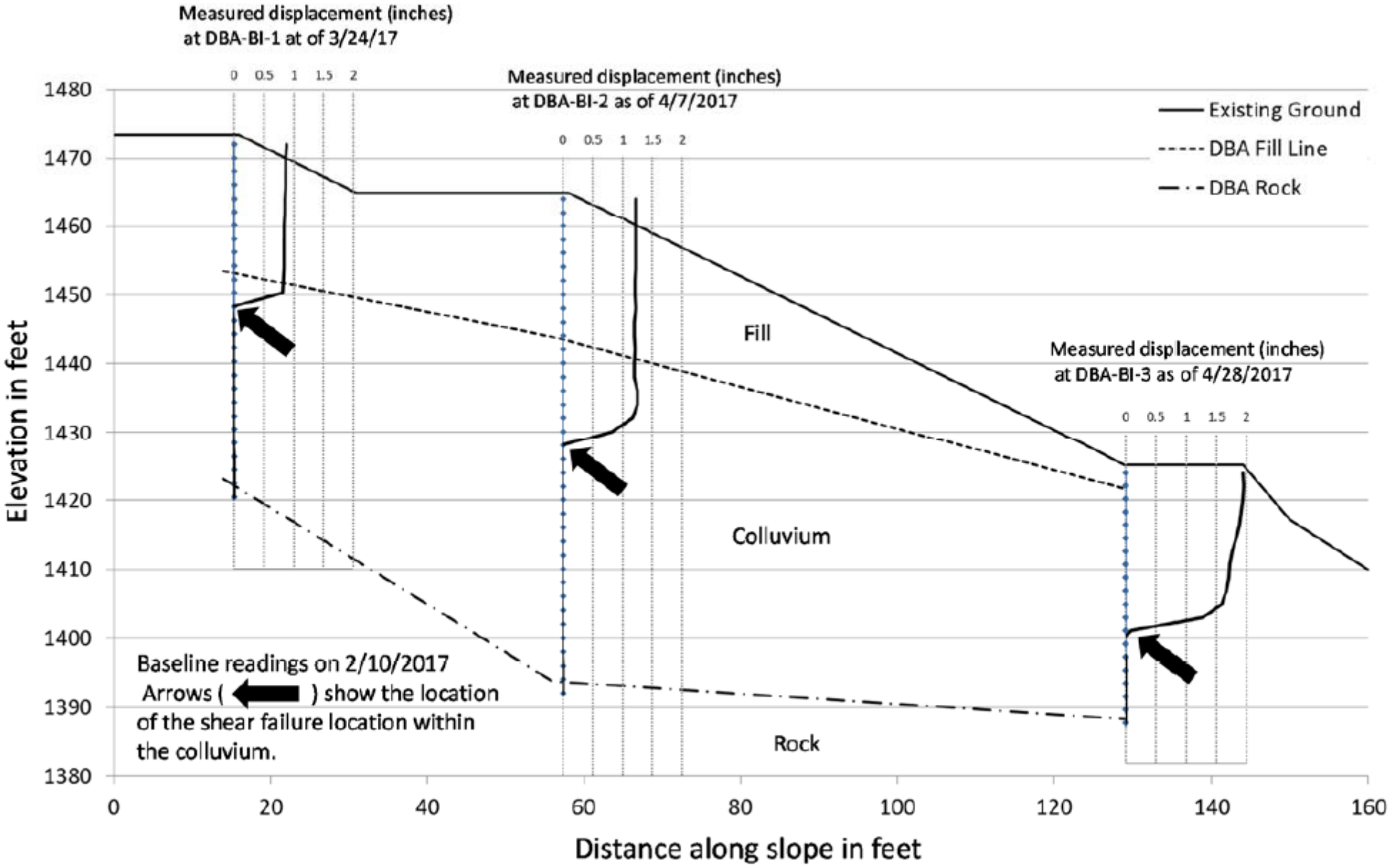


ACKNOWLEDGEMENTS

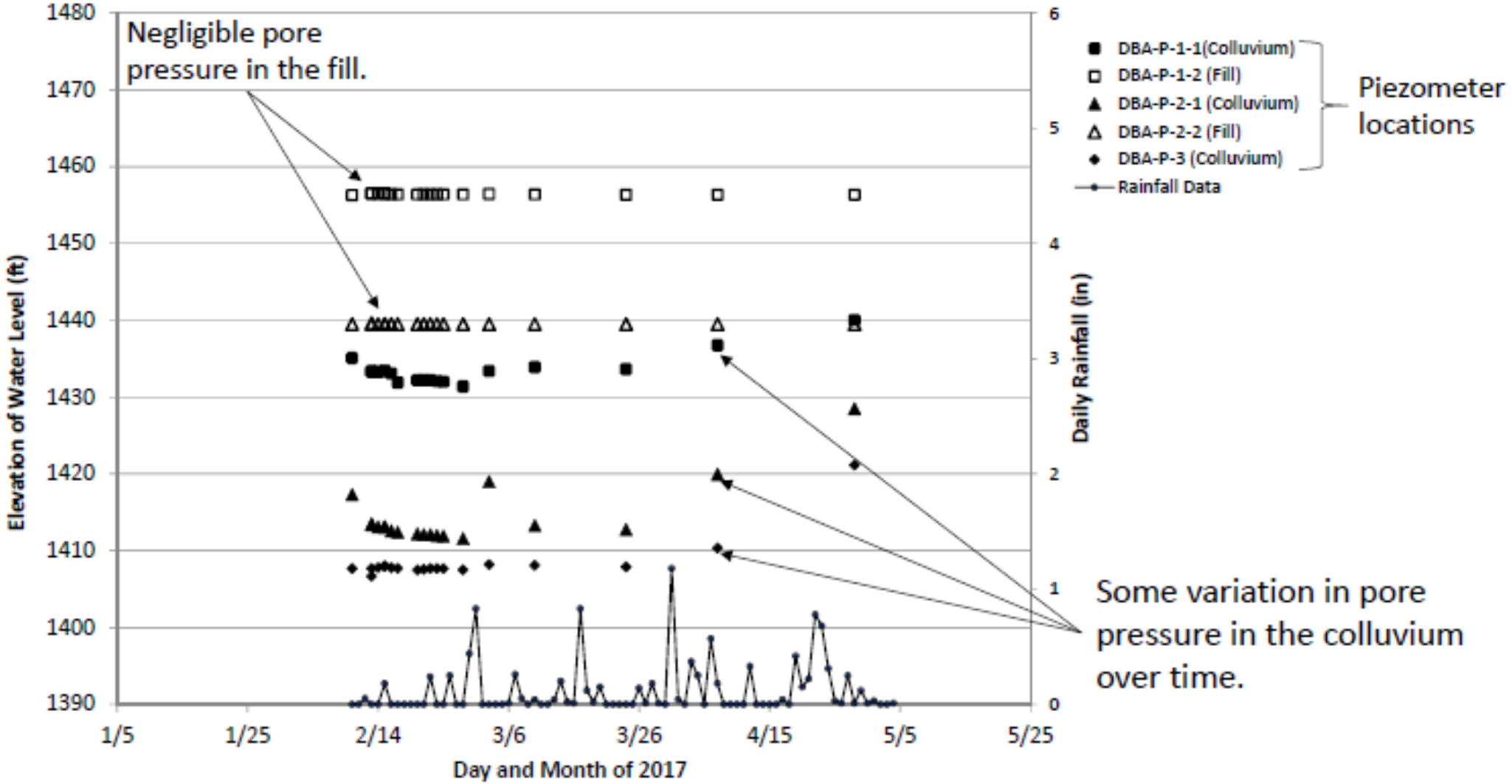
Mark Madgett, PE - Lead
Tayler Day, PE - Designer
Isaac Jeldes – Numerical Analysis
John Turner, PE PhD - Reviewer

- Highlight the frame action created
- Comment on the batter angles of the micropiles
- Comment on the structural forces on the cap

INCLINOMETER DATA

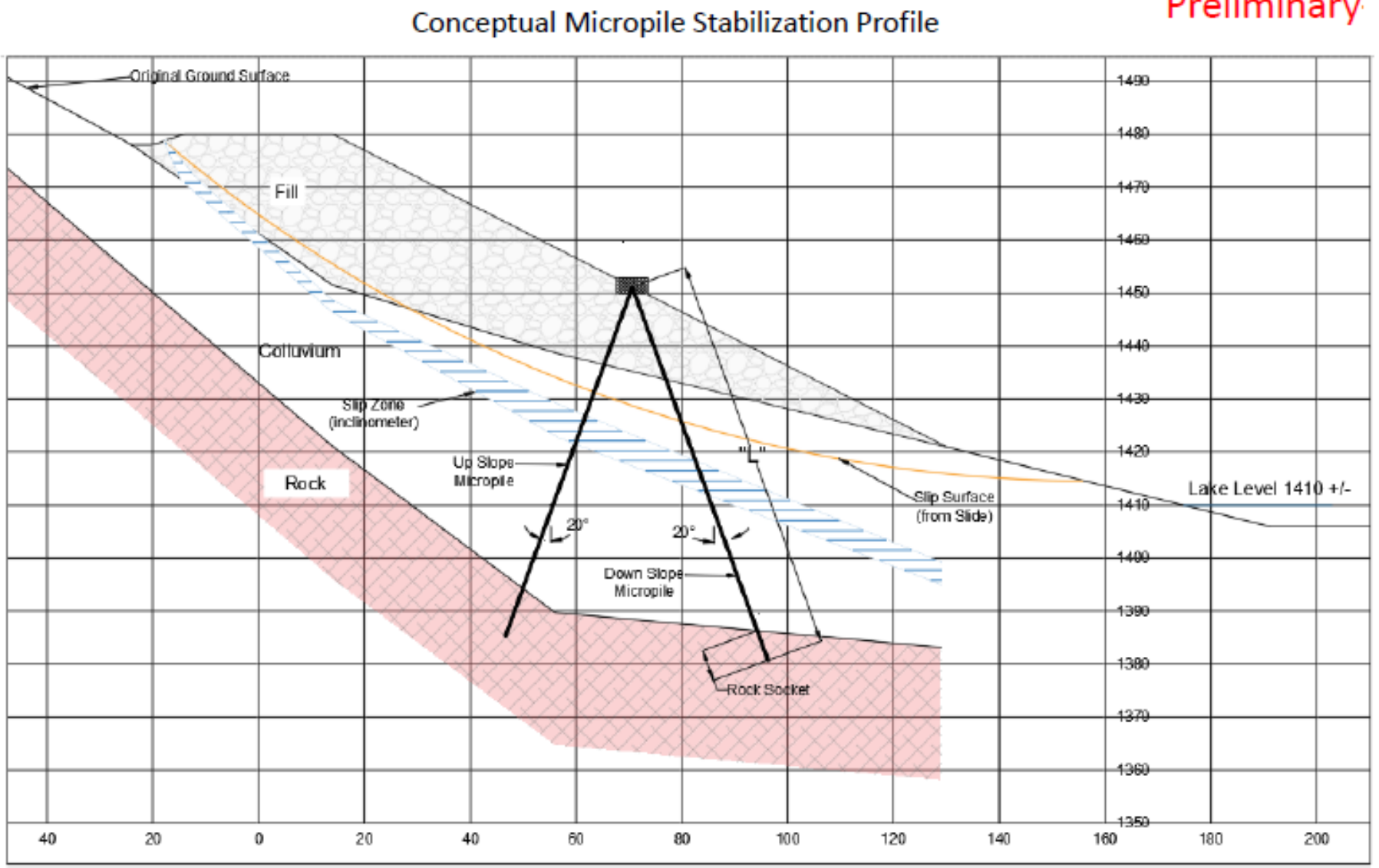


PIEZOMETER DATA



CONCEPT LEVEL DESIGN

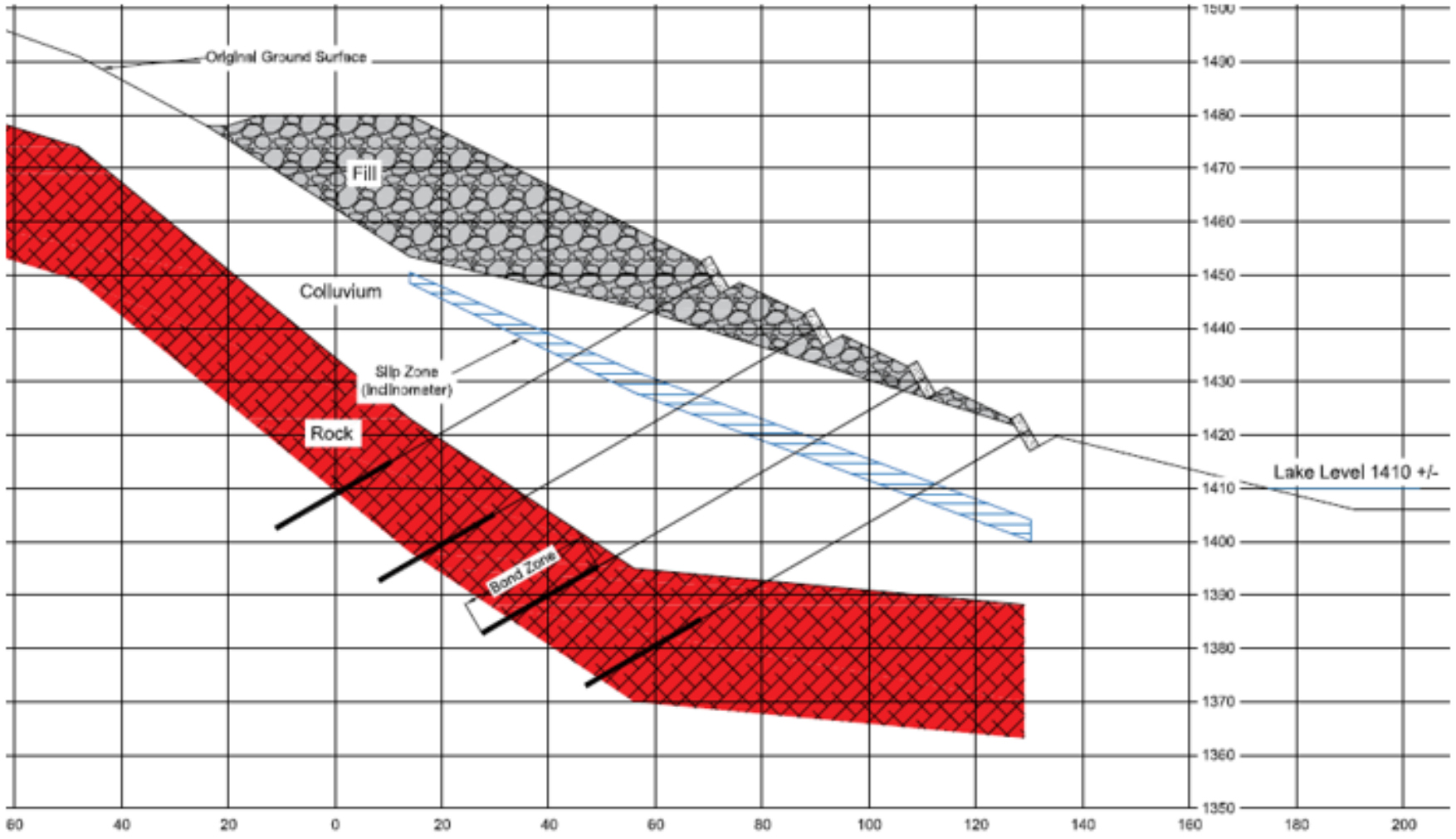
Preliminary



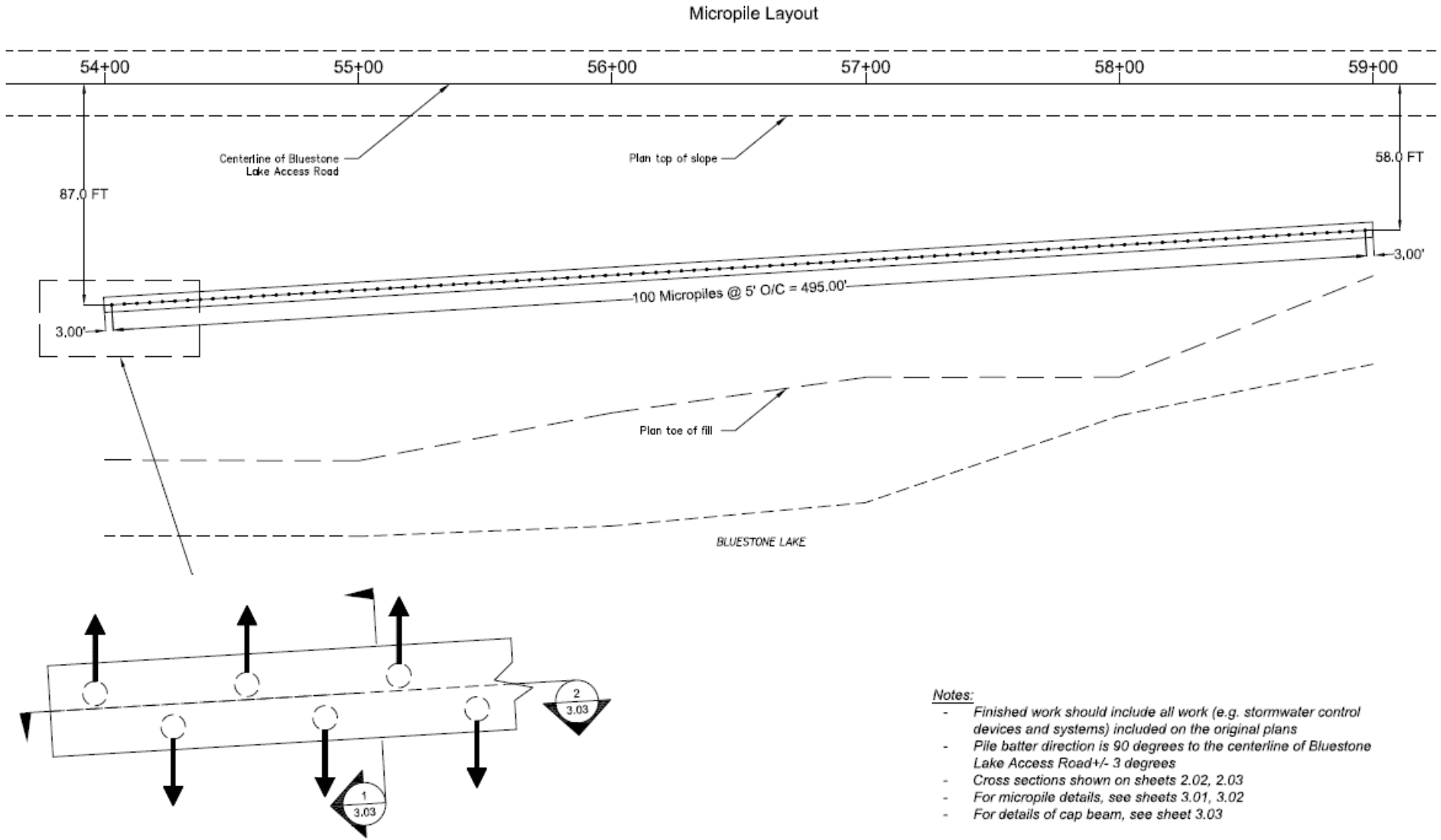
CONCEPT LEVEL DESIGN

Conceptual Reaction Block/Anchor Stabilization Plan and Details

Preliminary



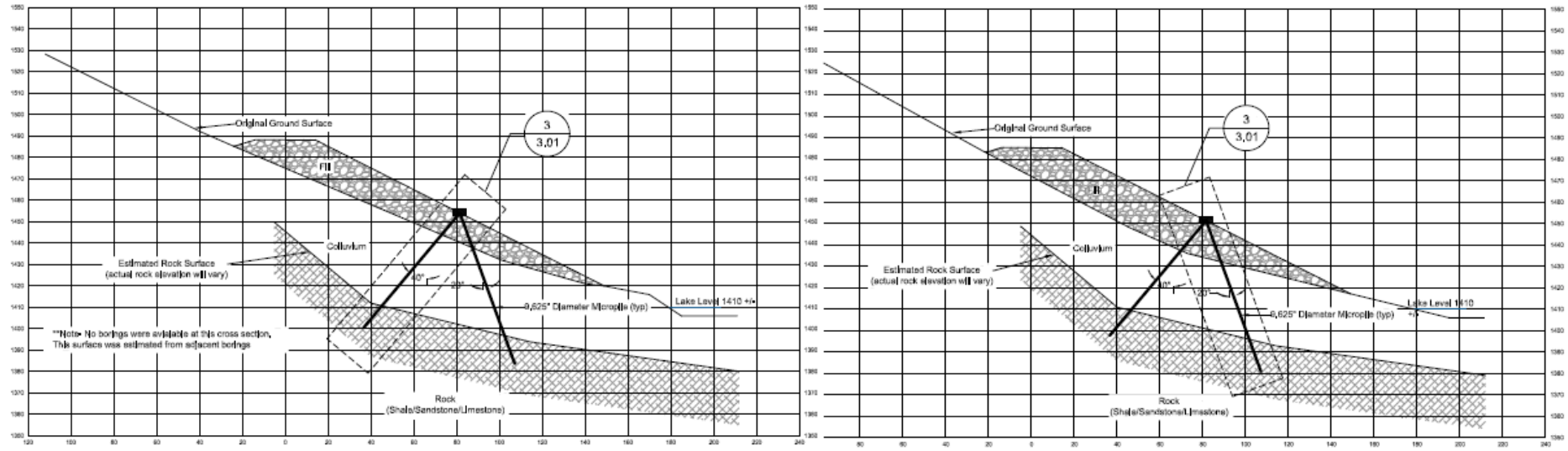
FINAL DESIGN PLAN

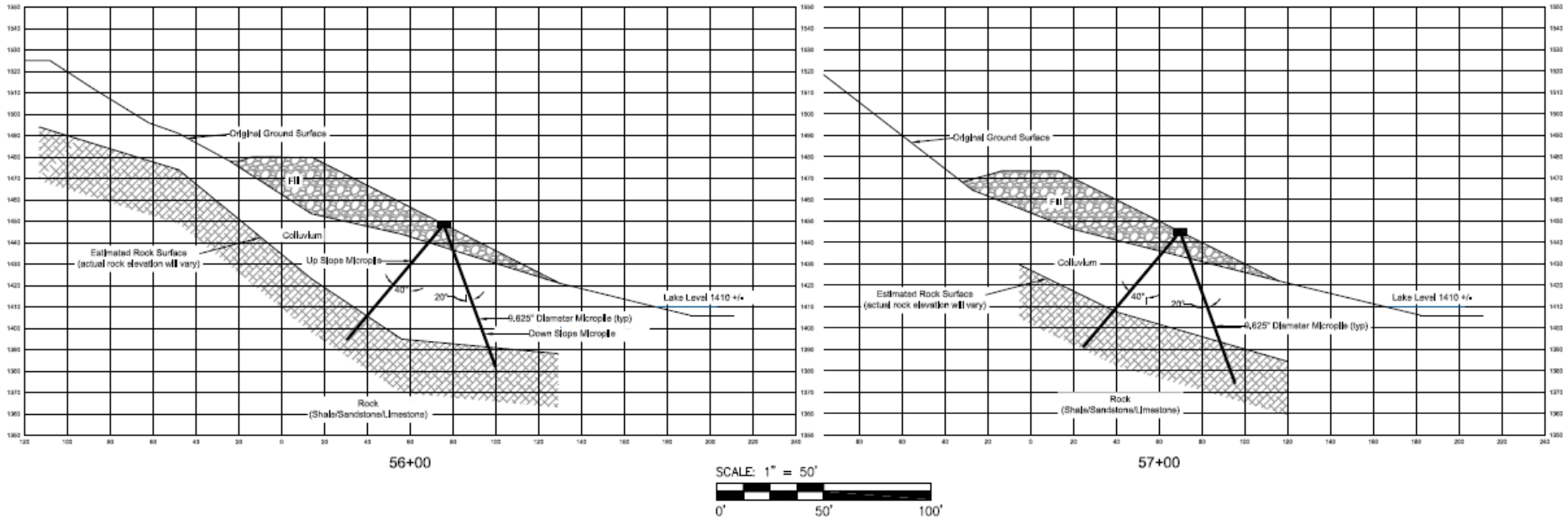


Notes:

- *Finished work should include all work (e.g. stormwater control devices and systems) included on the original plans*
- *Pile batter direction is 90 degrees to the centerline of Bluestone Lake Access Road+/- 3 degrees*
- *Cross sections shown on sheets 2.02, 2.03*
- *For micropile details, see sheets 3.01, 3.02*
- *For details of cap beam, see sheet 3.03*

FINAL DESIGN SECTIONS





DAN BROWN AND ASSOCIATES



SOFTWARE DISCUSSION
ANALYSIS OF HINTON WV LANDSLIDE
Using GEOSTASE and PLAXIS 2D

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

ggregory@gregeo.com

GREGORY GEOTECHNICAL

INTRODUCTION

The analyses included in this presentation were performed with GEOSTASE, the author's commercial 2D and 3D limit equilibrium method (LEM) software, and PLAXIS 2D finite element method (FEM) software developed by PLAXIS B.V., now a part of Bentley Systems, Inc. As previously presented in the Software Discussion Introduction by Tim Siegel, the example consists of stabilization of a landslide in Hinton, WV using "A-Frame" micropiles.

ANALYSES NOTES

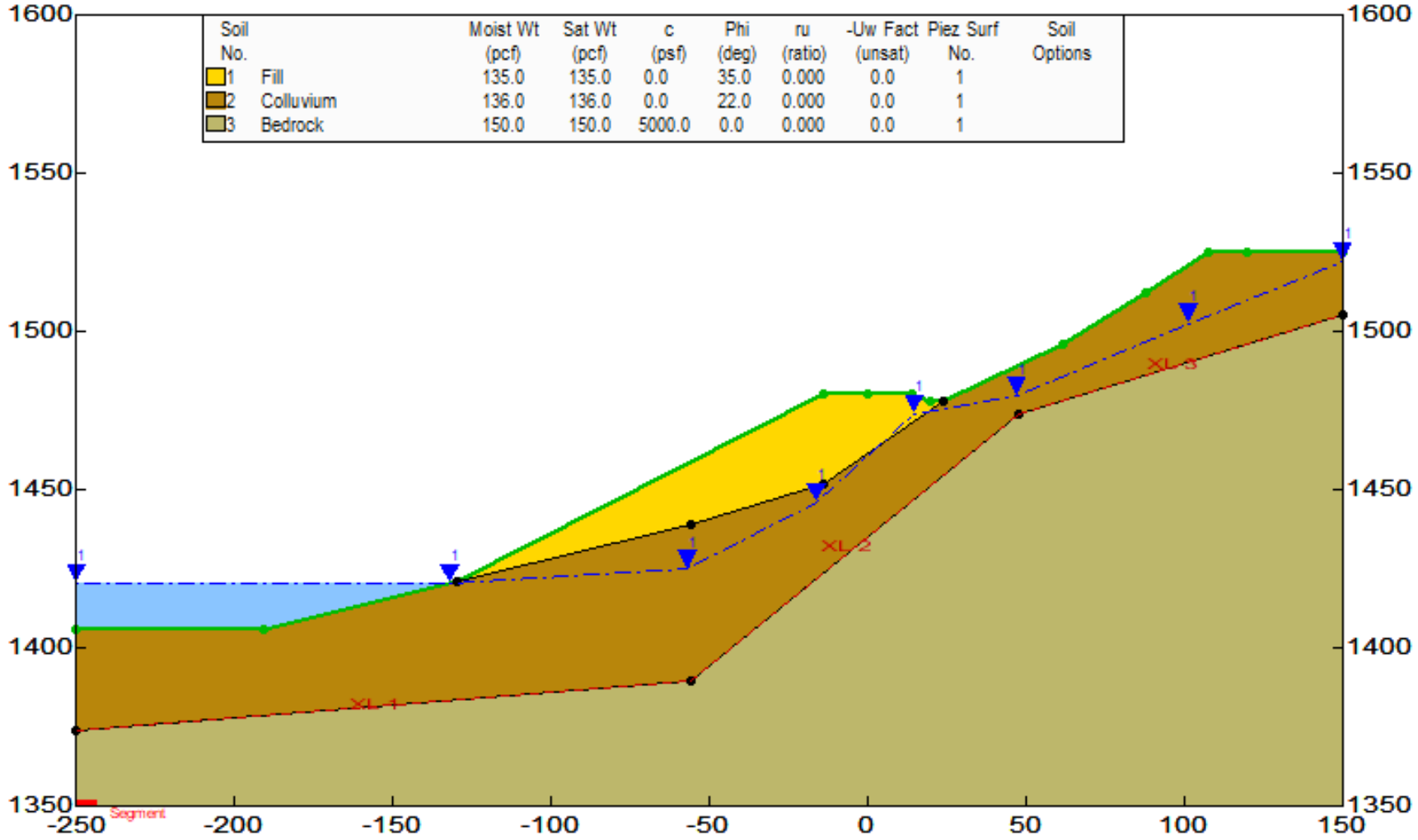
Factor of safety (FS) values are expressed to 3 decimal places to facilitate comparison among the various analyses. This does not imply that the analyses are accurate to 3 decimal places.

Due to the complex nature of the example and limited available data, various simplifying assumptions had to be made to facilitate the analyses.

S3-2022 - HINTON WV LANDSLIDE

Initial Condition Without Micropiles

\S3-2022-Hinton-1-PROFILE.gsd



GEOSTASE PROFILE PREVIEW

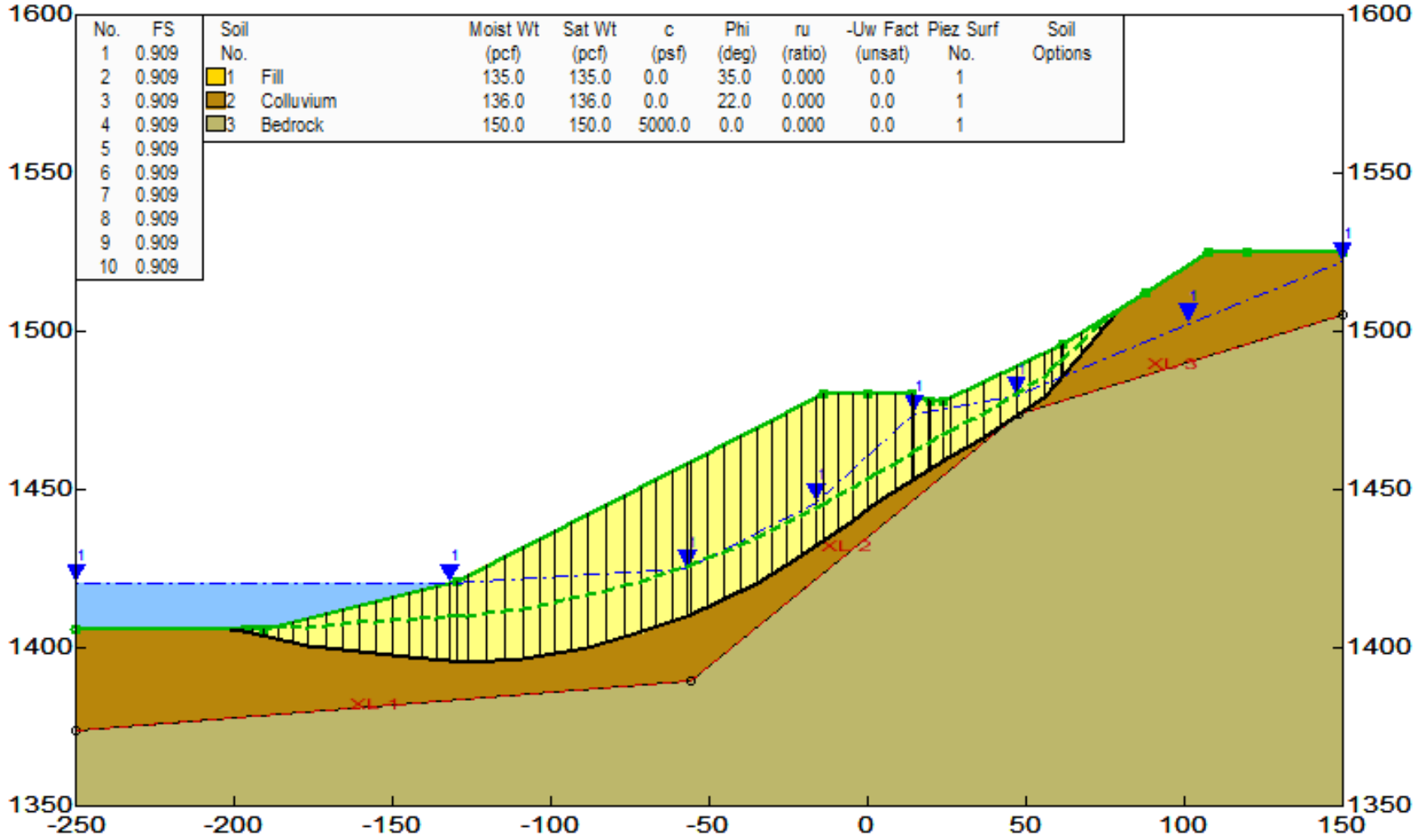
Spencer Method

GEOSTASE
Slope Stability Analysis

S3-2022 - HINTON WV LANDSLIDE

Initial Condition Without Micropiles - ZRSAUTO Search

\S3-2022-Hinton-1-ZRSAUTO.gsd



GEOSTASE FS = 0.909

Spencer Method

GEOSTASE
Slope Stability Analysis

GEOSTASE® v4.30.32 by GREGORY GEOTECHNICAL SOFTWARE

MODIFICATIONS TO THE DATA

Three modifications were made to the data provided.

(1) In the original data the reinforcing bars in the upslope micropiles were 2.25-inch diameter and in the downslope micropiles the bars were 1.75-inch diameter. Both bars were assumed to be 2.25-inch diameter since the micropile diameters were the same.

(2) Based on initial analyses, the rock socket depths were changed to 19 ft for the upslope micropiles and 12 ft for the downslope micropiles (original depths were 25 ft and 15 ft).

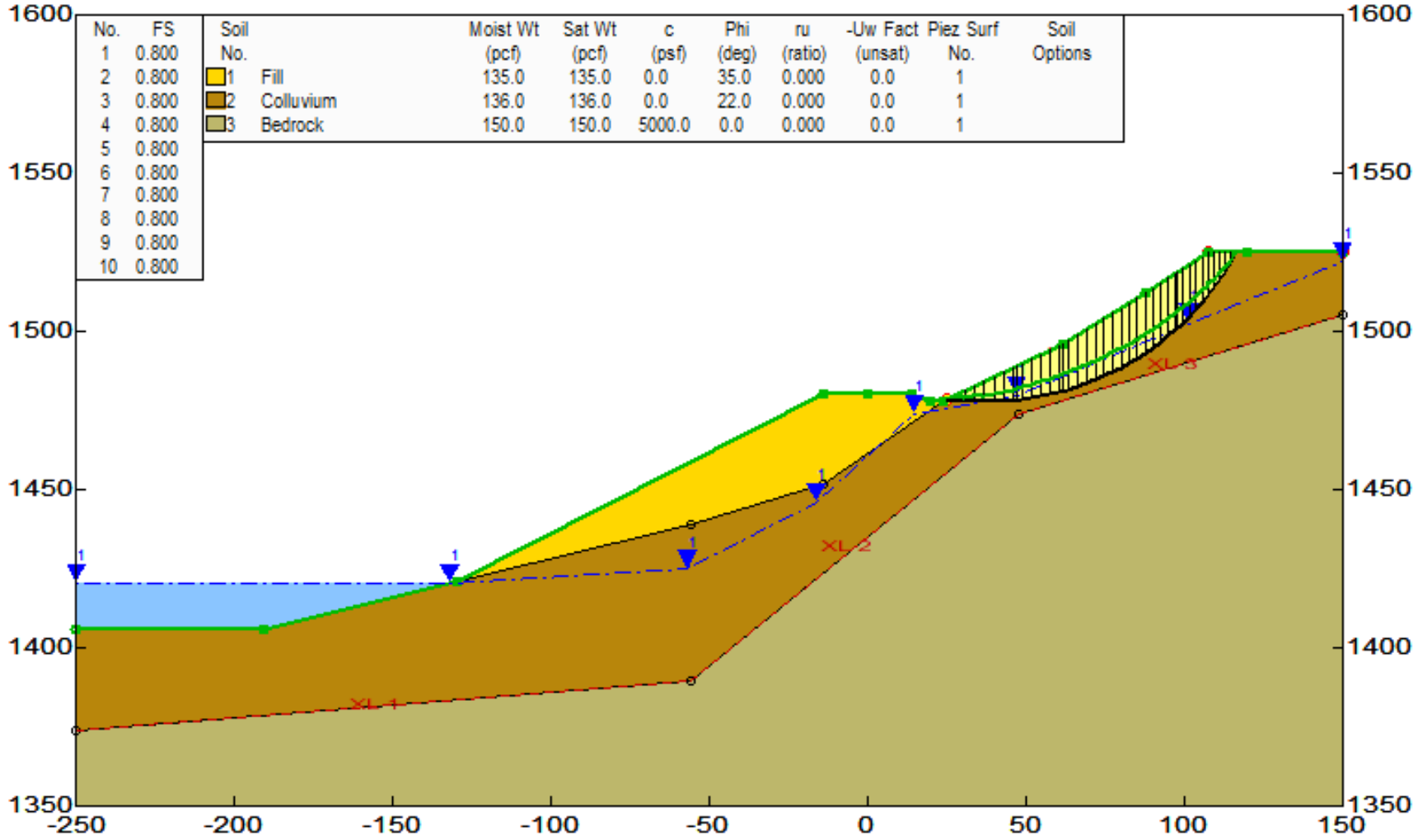
MODIFICATIONS TO THE DATA (CONT)

(3) When conducting the LEM search for the initial condition (unreinforced) it was discovered that the upper slope had a calculated FS of only 0.800 using the provided shear strength parameters of $\phi = 22$ degrees and $c = 0$ for the colluvium. Since the upper slope had apparently not failed, the shear strength parameters were likely higher. The ϕ and c values were iterated until a FS value slightly above unity was achieved. This resulted in $\phi = 24$ degrees and $c = 85$ psf. These parameters were used for the colluvium in the remainder of the analyses.

S3-2022 - HINTON WV LANDSLIDE

Initial Condition Without Micropiles - Upper Slope - Circular Search

\S3-2022-Hinton-1A.gsd



GEOSTASE FS = 0.800

Spencer Method

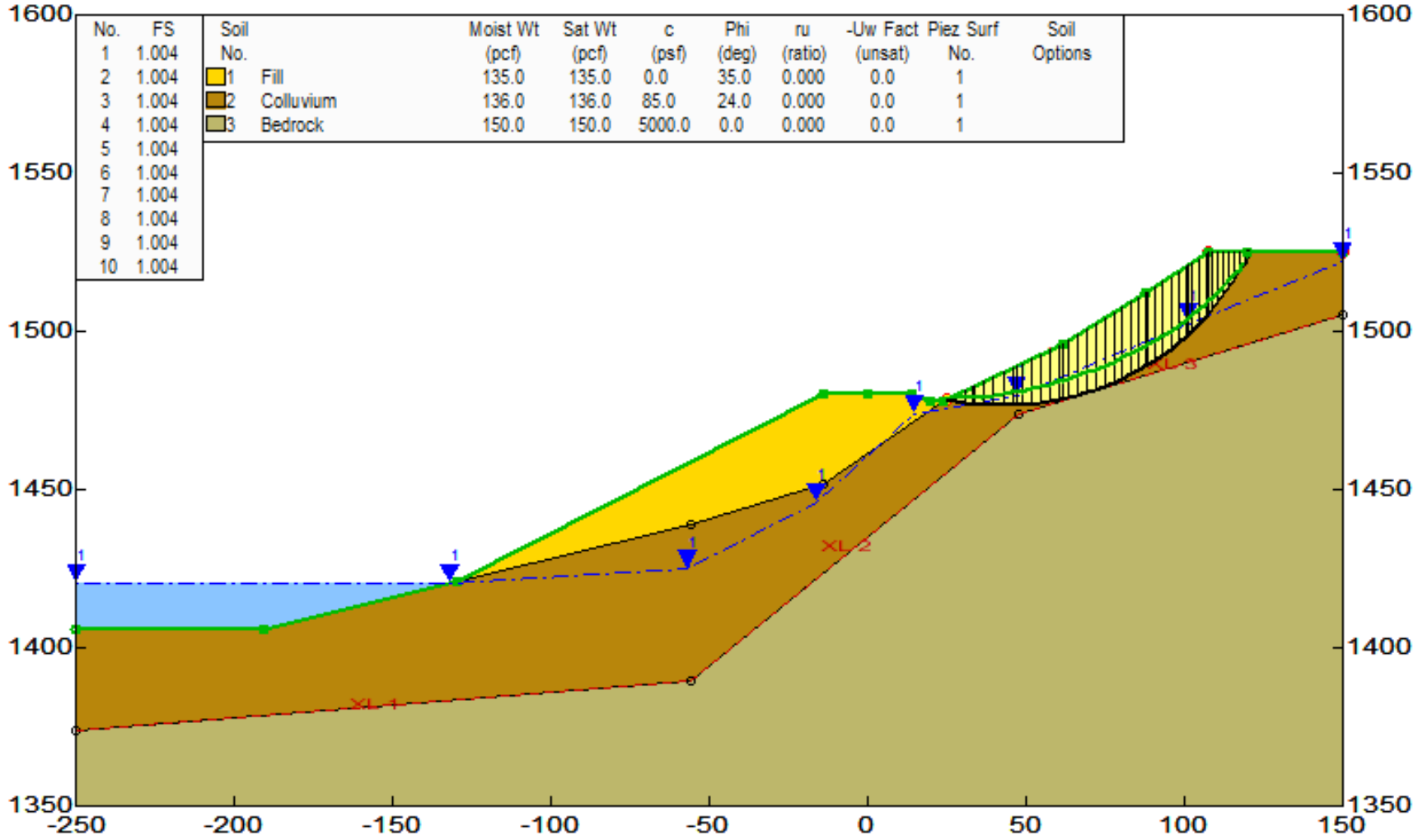
GEOSTASE
Slope Stability Analysis

GEOSTASE® v4.30.32 by GREGORY GEOTECHNICAL SOFTWARE

S3-2022 - HINTON WV LANDSLIDE

Initial Condition - Upper Slope -Increased Strength - Circular Search

\S3-2022-Hinton-1AB.gsd



GEOSTASE FS = 1.004

Spencer Method

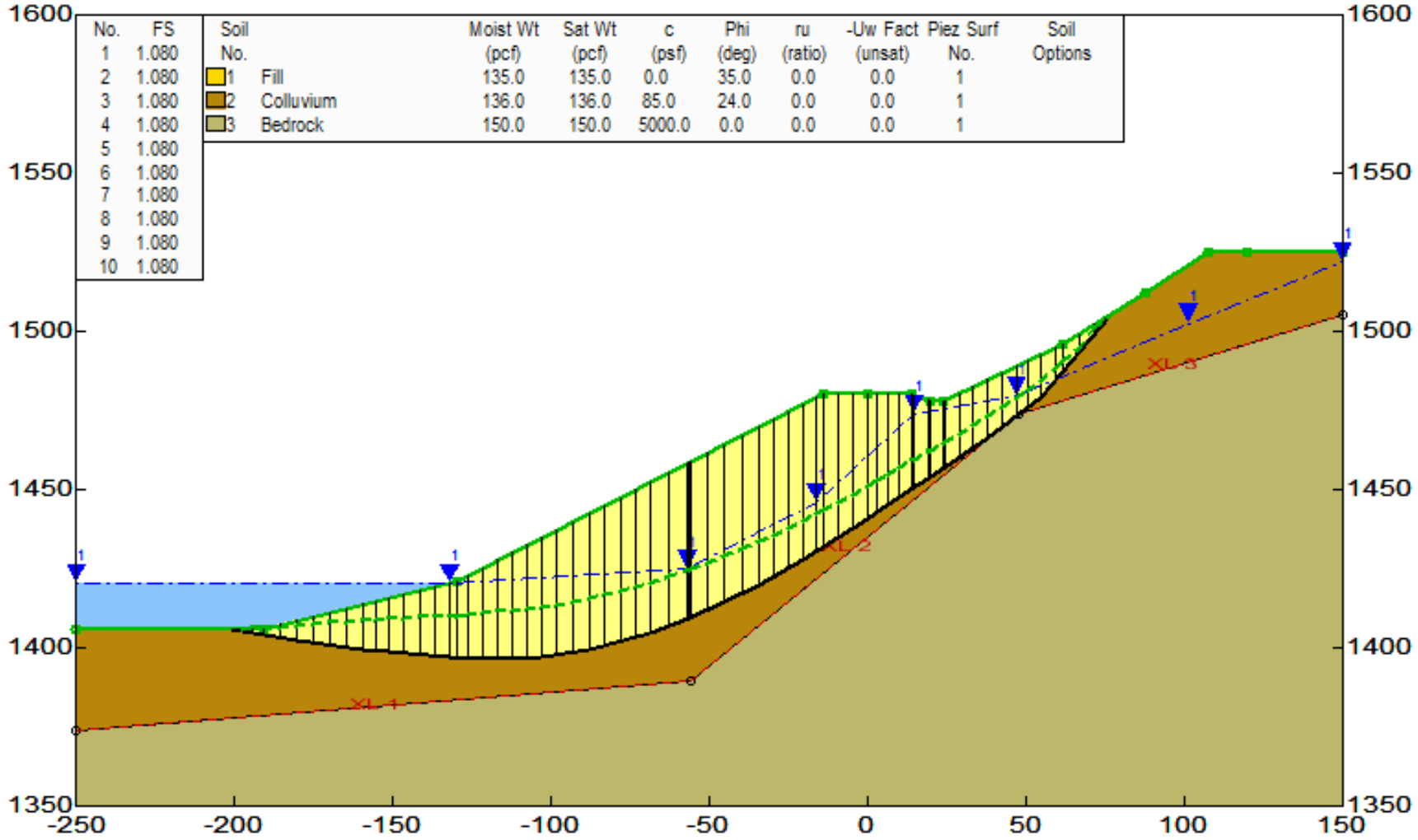
GEOSTASE
Slope Stability Analysis

GEOSTASE® v4.30.32 by GREGORY GEOTECHNICAL SOFTWARE

S3-2022 - HINTON WV LANDSLIDE

Initial Condition Without Micropiles - ZRSAUTO Search

\S3-2022-Hinton-1-ZRSAUTO-2.gsd



GEOSTASE FS = 1.080

Spencer Method

GEOSTASE
Slope Stability Analysis

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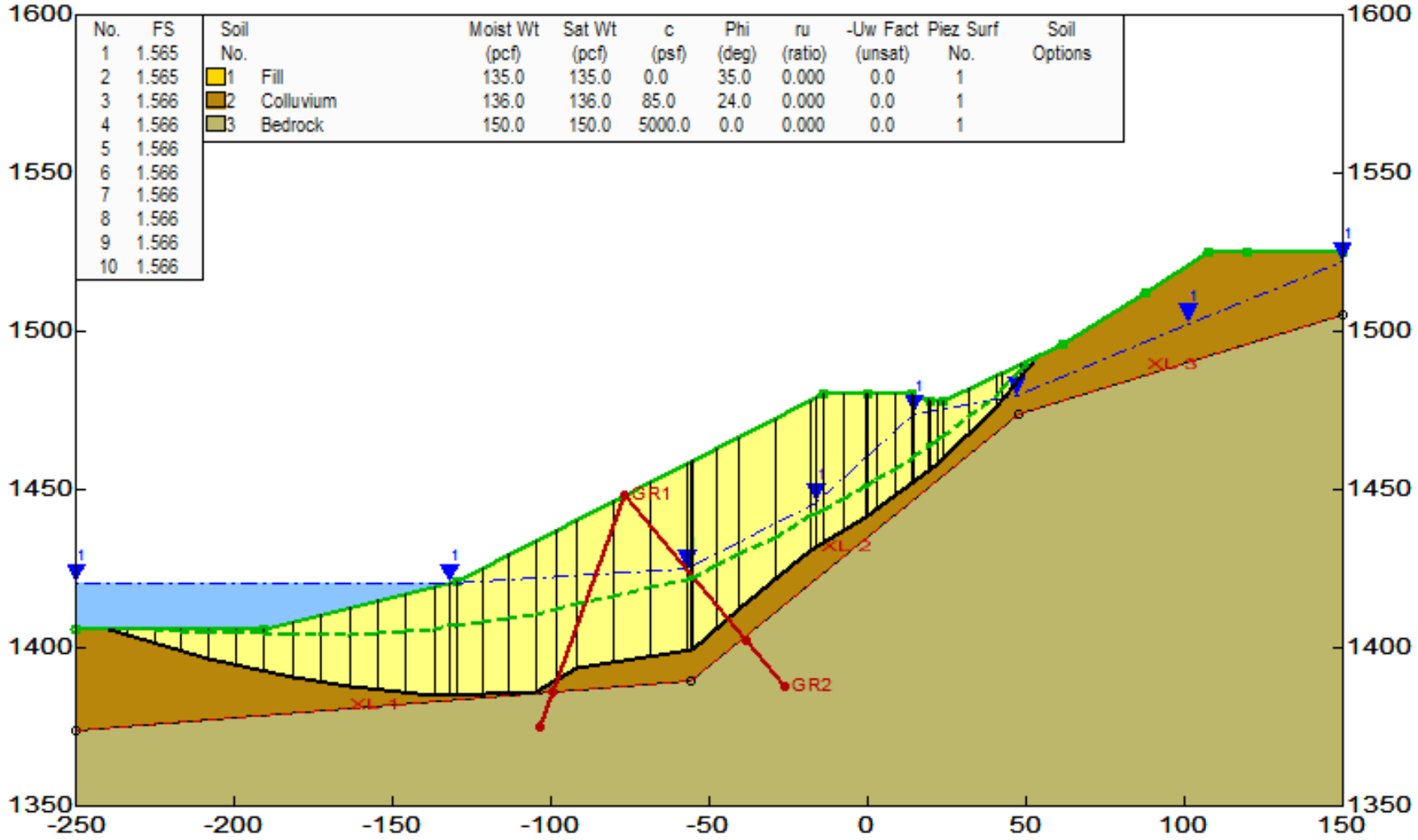
CREEP FAILURE vs. SHEAR STRESS RATIO

- Creep movements will typically occur in soil slopes when the shear stress ratio SR (mobilized shear stress divided by available strength) $$SR = \frac{\tau_{mobilized}}{\tau_{available}}$$ reaches about 70%.
- SR is the reciprocal of the FS. When SR reaches about 90% or greater (FS <= 1.1) the creep failure may progress more rapidly and cause larger slope movements or may eventually result in a catastrophic failure. Accordingly, the target FS for back-analysis of a creep failure is a little greater than unity (1.05 ~ 1.1). 1.08 is in this range!

S3-2022 - HINTON WV LANDSLIDE

Repaired Condition - Stabilized with Micropile A-Frames - ZRSAUTO Search

\S3-2022-Hinton-2R-ZRSAUTO.gsd



GEOSTASE FS = 1.565

Spencer Method

GEOSTASE
Slope Stability Analysis

GEOSTASE® v4.30.32 by GREGORY GEOTECHNICAL SOFTWARE

SIMPLIFIED 3D ANALYSIS

- Analyzed for static case
- Assume 2 different lengths along the slope
- L/D = 2.0 (172.1 ft)
- L/D = 5.81 (500 ft = Micropile beam length)
- Simplified 3D is an “Extruded” section.

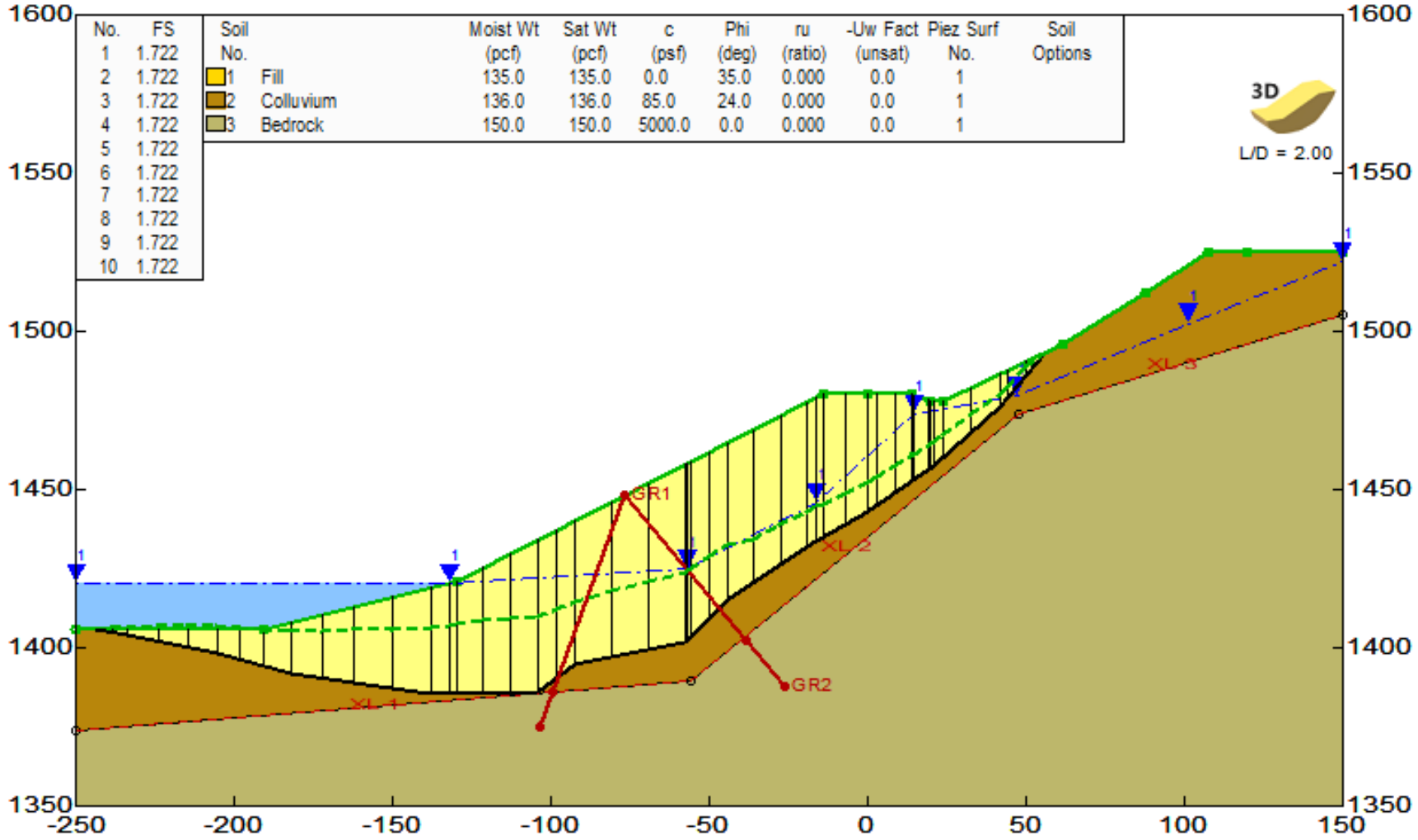
L/D:

- L = failure length in the out of plane direction
- D = difference in elevation between ends of slip surface

S3-2022 - HINTON WV LANDSLIDE

Repaired Condition - with Micropiles - ZRSAUTO - Simplified 3D

\S3-2022-Hinton-2R-ZRSAUTO-3D.gsd



GEOSTASE FS = 1.722

Spencer Method

GEOSTASE
Slope Stability Analysis

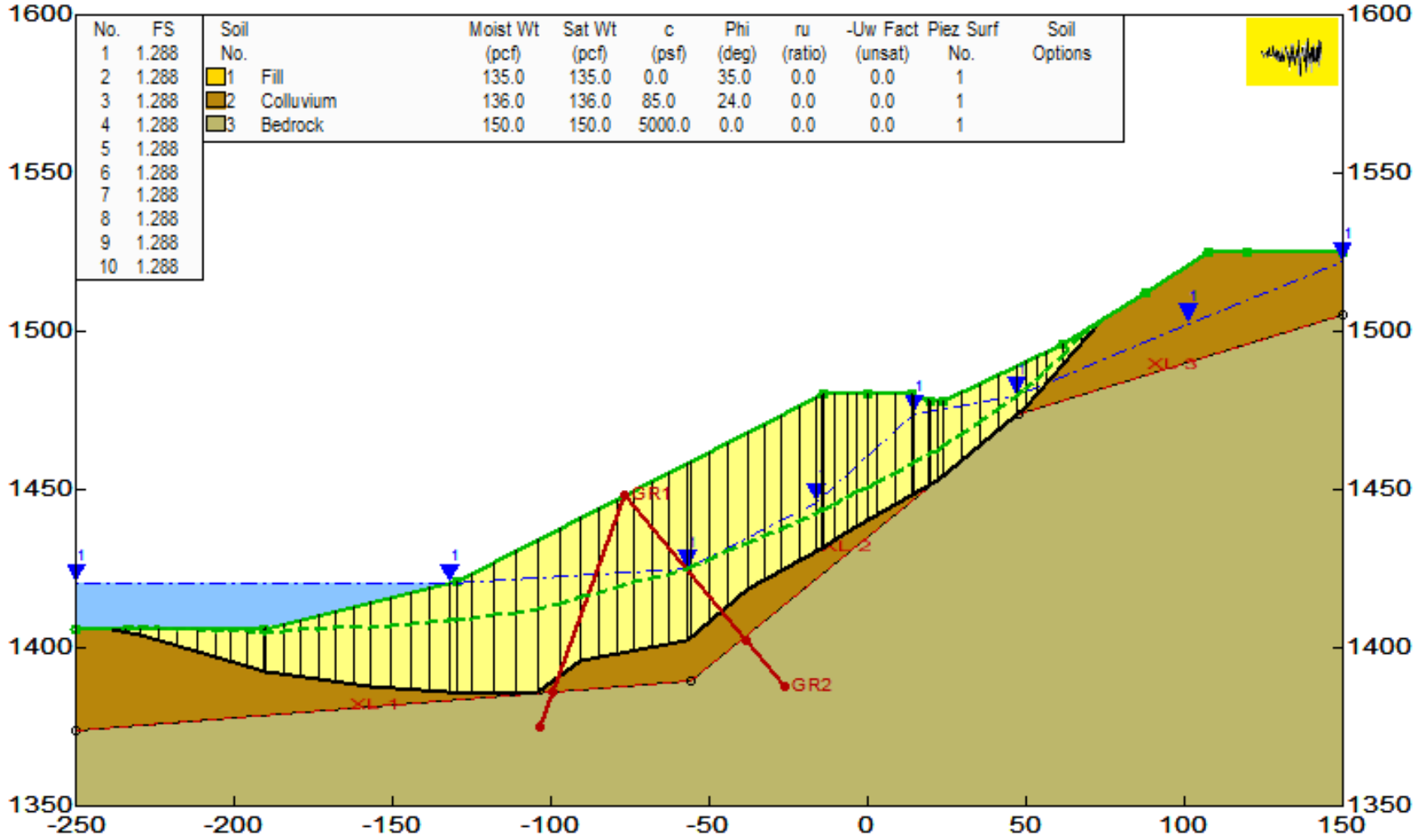
SIMPLIFIED 3D ANALYSIS RESULTS

- L/D = 2.0 (172.1 ft): FS = 1.722 => 10% > than 2D
- L/D = 5.81 (500 ft): FS = 1.620 => 3.5% > than 2D
- Provides some additional “comfort” level with the 2D analyses.

S3-2022 - HINTON WV LANDSLIDE - SEISMIC - PGA = 0.07

Repaired Condition - Stabilized with Micropile A-Frames - ZRSAUTO Search

\S3-2022-Hinton-2R-ZRSAUTO-Seismic - PGA07.gsd



GEOSTASE FS = 1.288

Spencer Method

kh = 0.05000

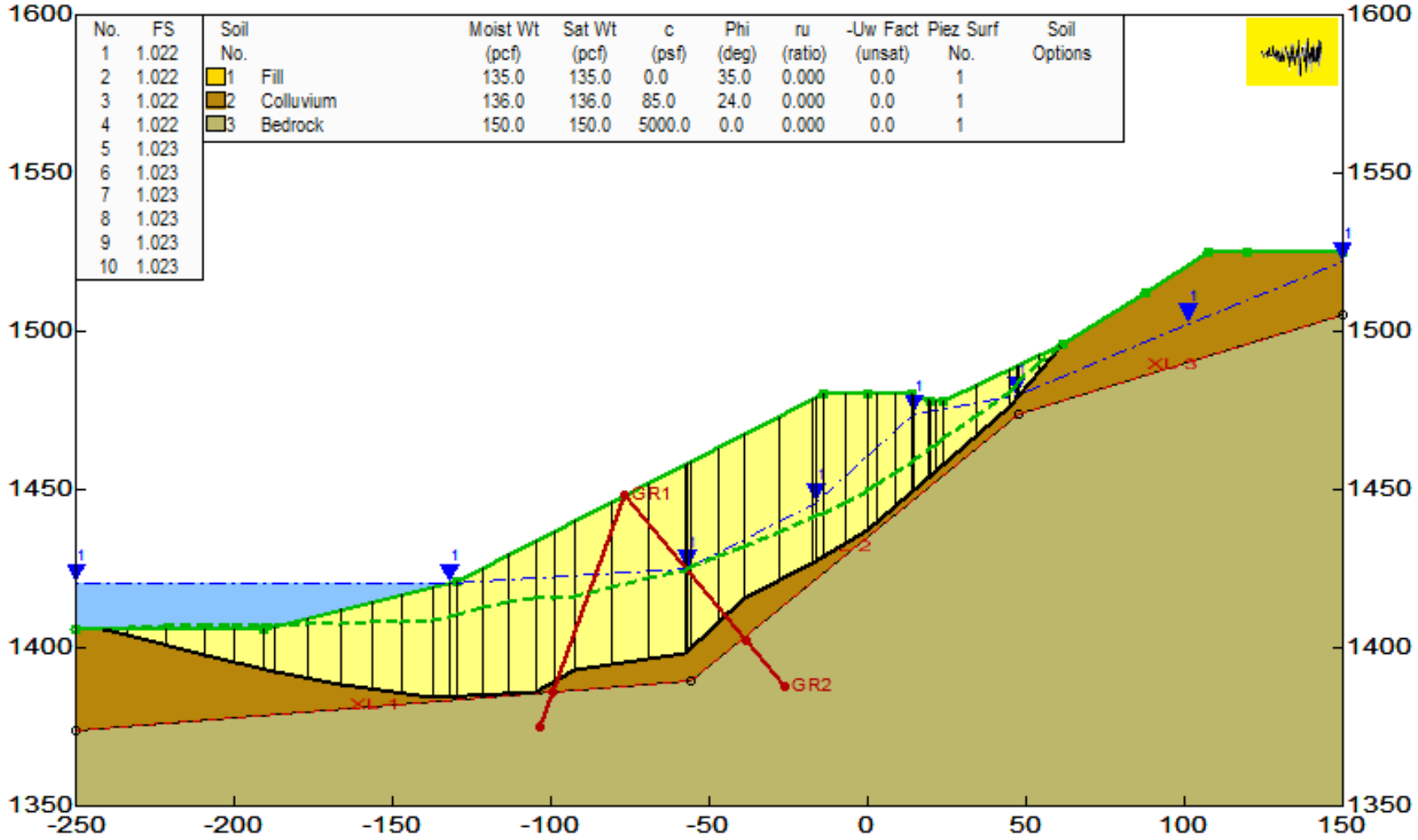
GEOSTASE Slope Stability Analysis

GEOSTASE® v4.30.32 by GREGORY GEOTECHNICAL SOFTWARE

S3-2022 - HINTON WV LANDSLIDE - SEISMIC - PGA = 0.35

Repaired Condition - Stabilized with Micropile A-Frames - ZRSAUTO Search

\S3-2022-Hinton-2R-ZRSAUTO-Seismic - PGA35.gsd



GEOSTASE FS = 1.022

Spencer Method

kh = 0.14000

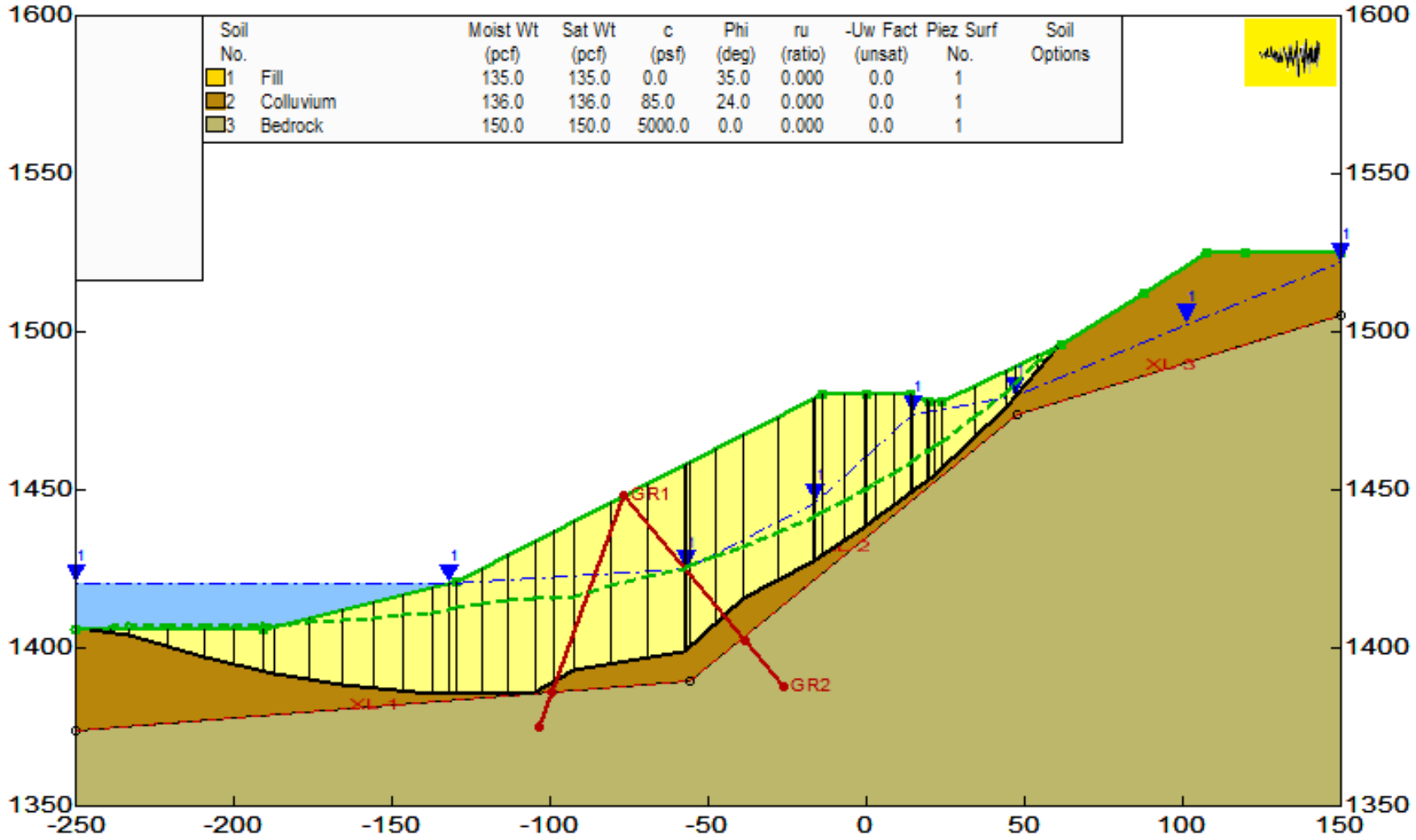
GEOSTASE Slope Stability Analysis

GEOSTASE® v4.30.32 by GREGORY GEOTECHNICAL SOFTWARE

S3-2022 - HINTON WV LANDSLIDE - SEISMIC - ky SEARCH

Repaired Condition - Stabilized with Micropile A-Frames - ZRSAUTO Search

\S3-2022-Hinton-2R-ZRSAUTO-Seismic - ky Search.gsd



GEOSTASE FS = 1.000

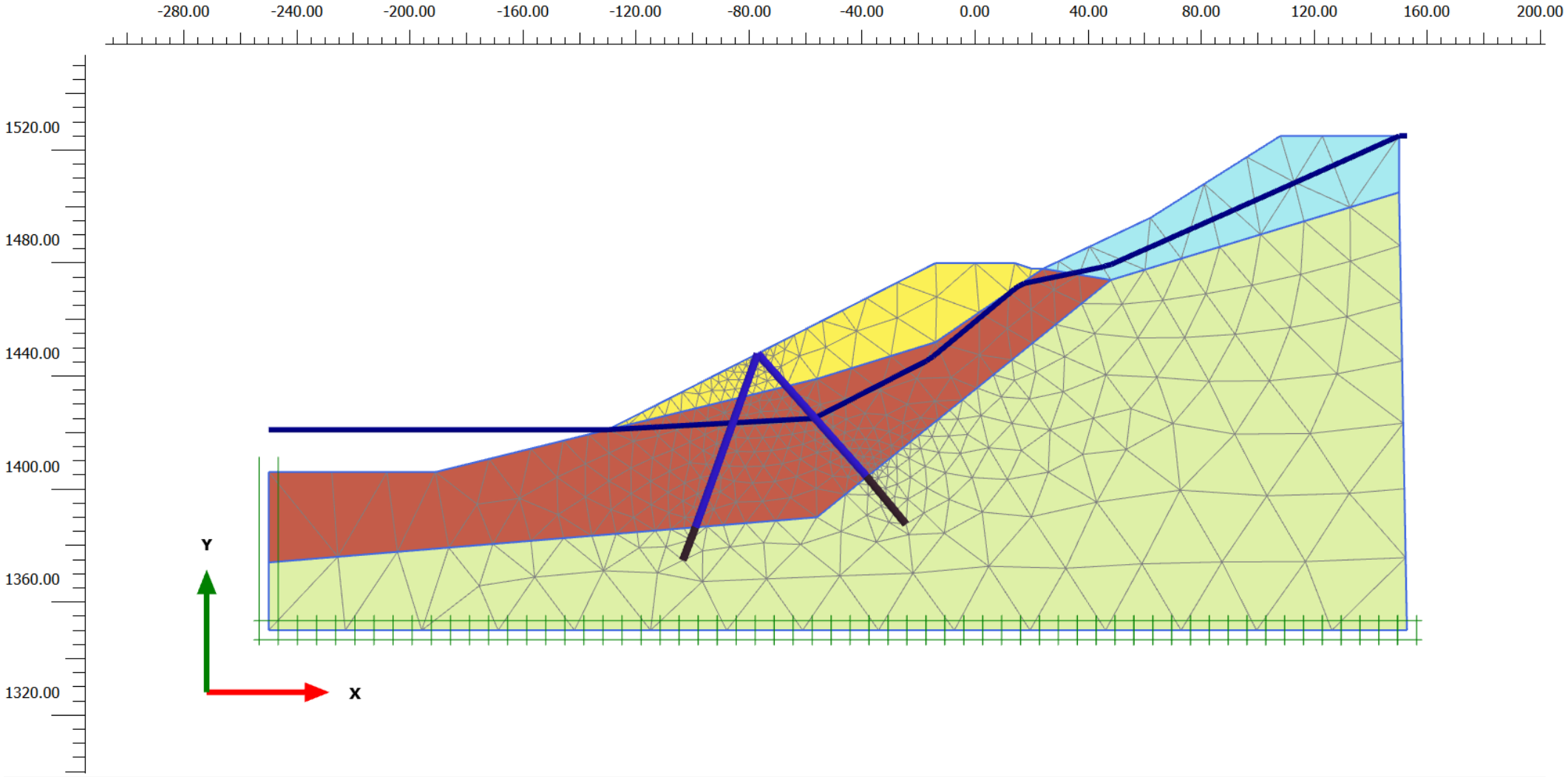
Spencer Method

ky = 0.14781

GEOSTASE Slope Stability Analysis

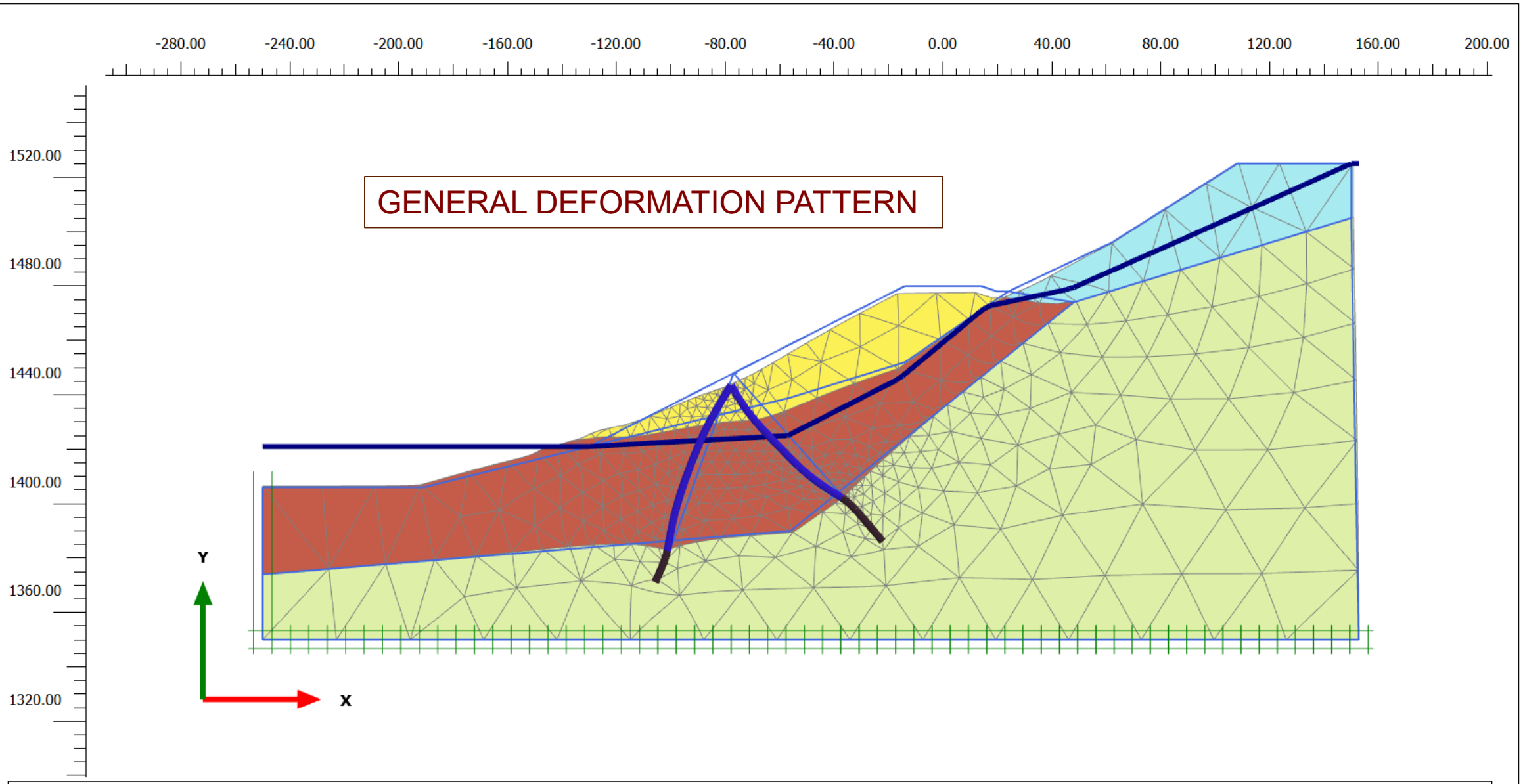
GEOSTASE® v4.30.32 by GREGORY GEOTECHNICAL SOFTWARE

Output Version 2019.0.0.0



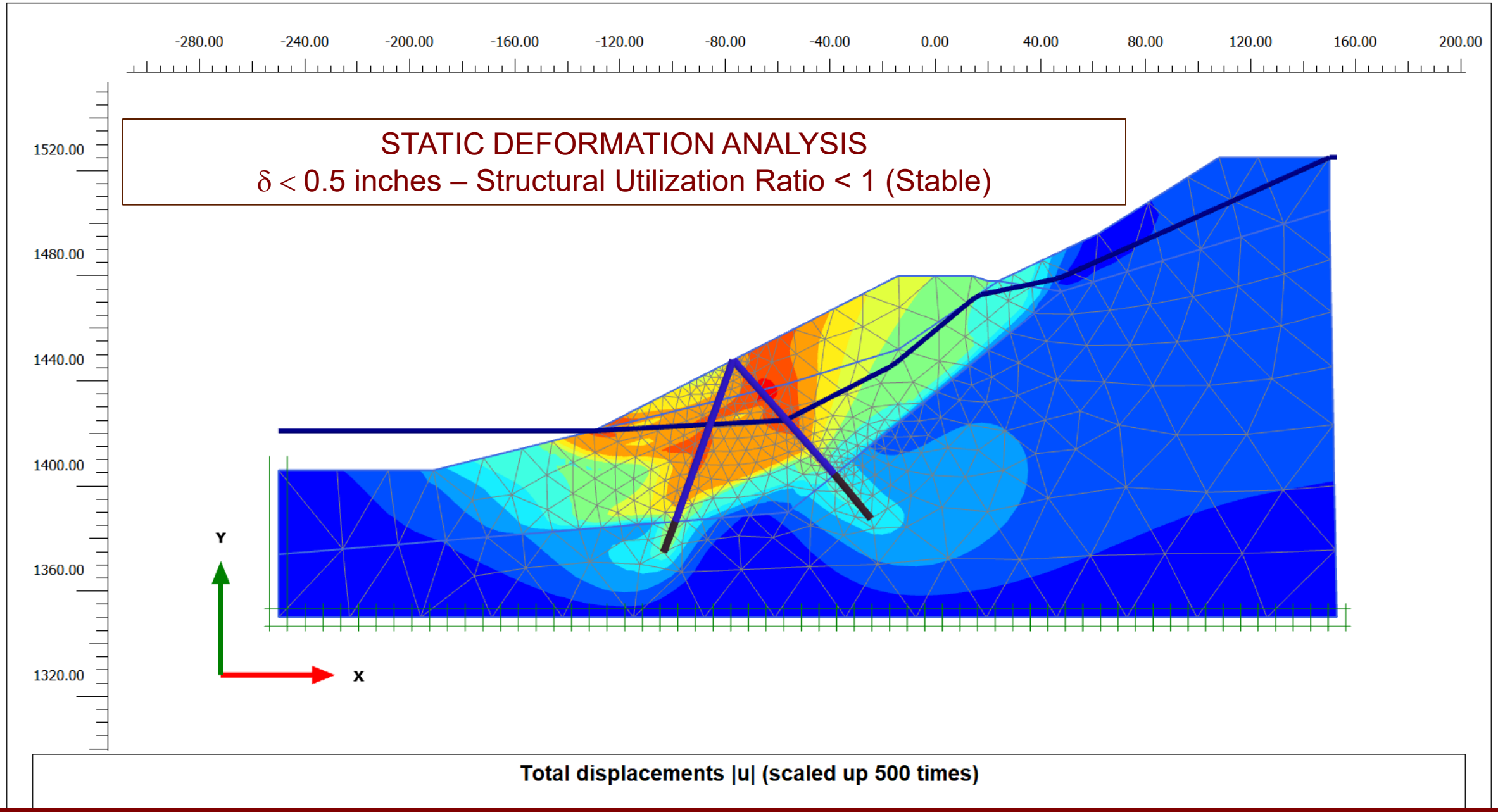
Connectivity plot

Output Version 2019.0.0.0

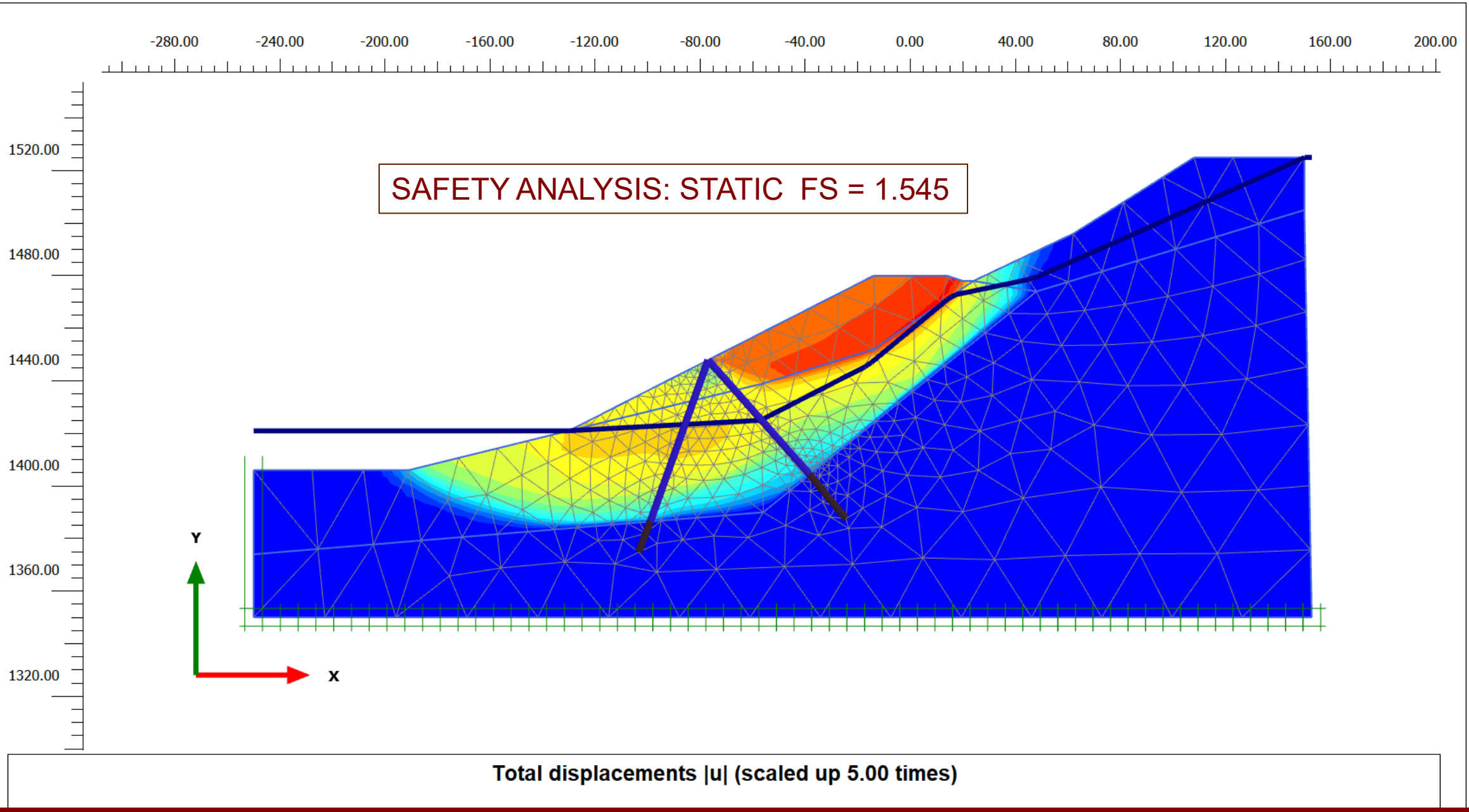


Deformed mesh |u| (scaled up 300 times)

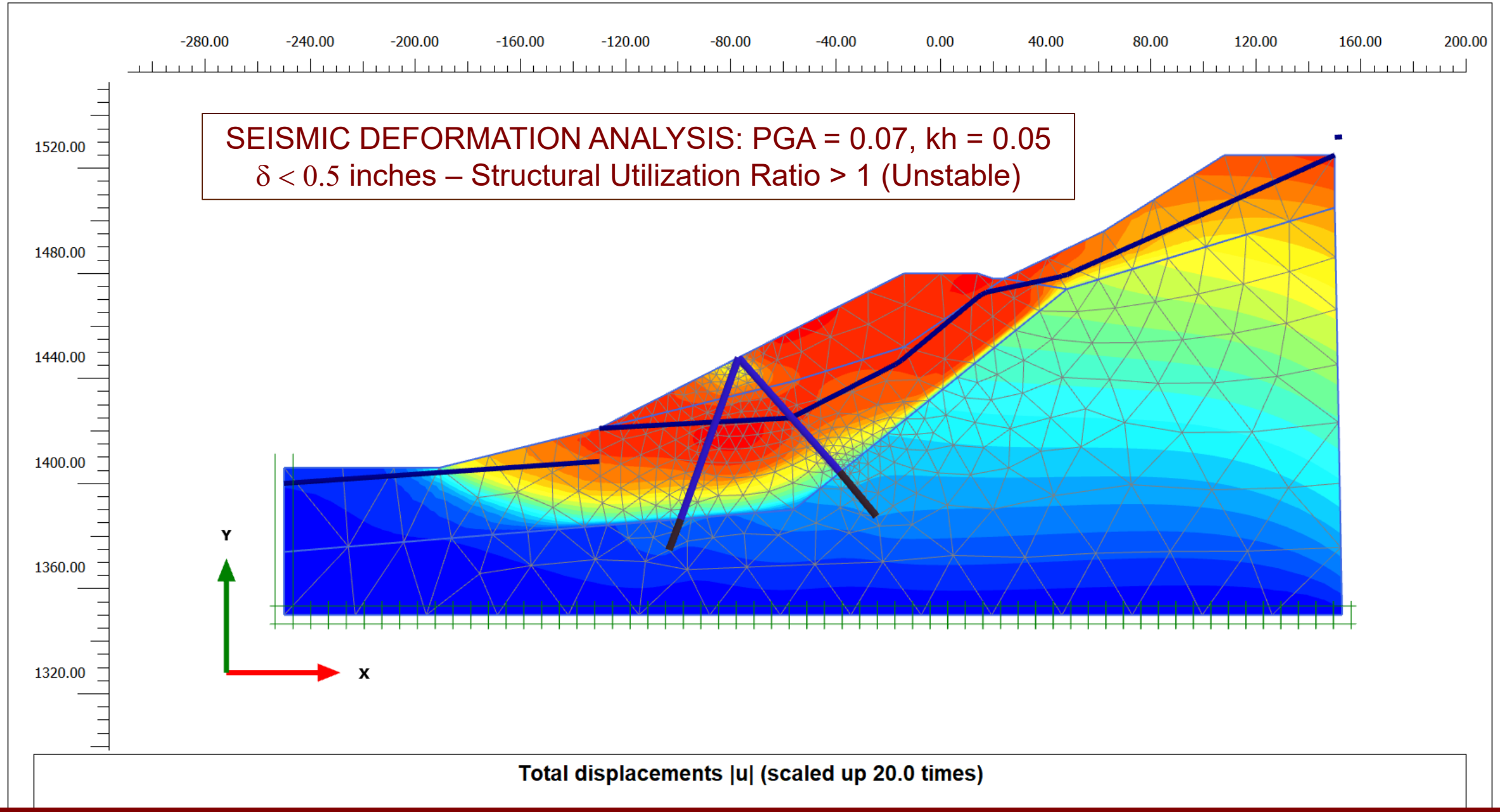
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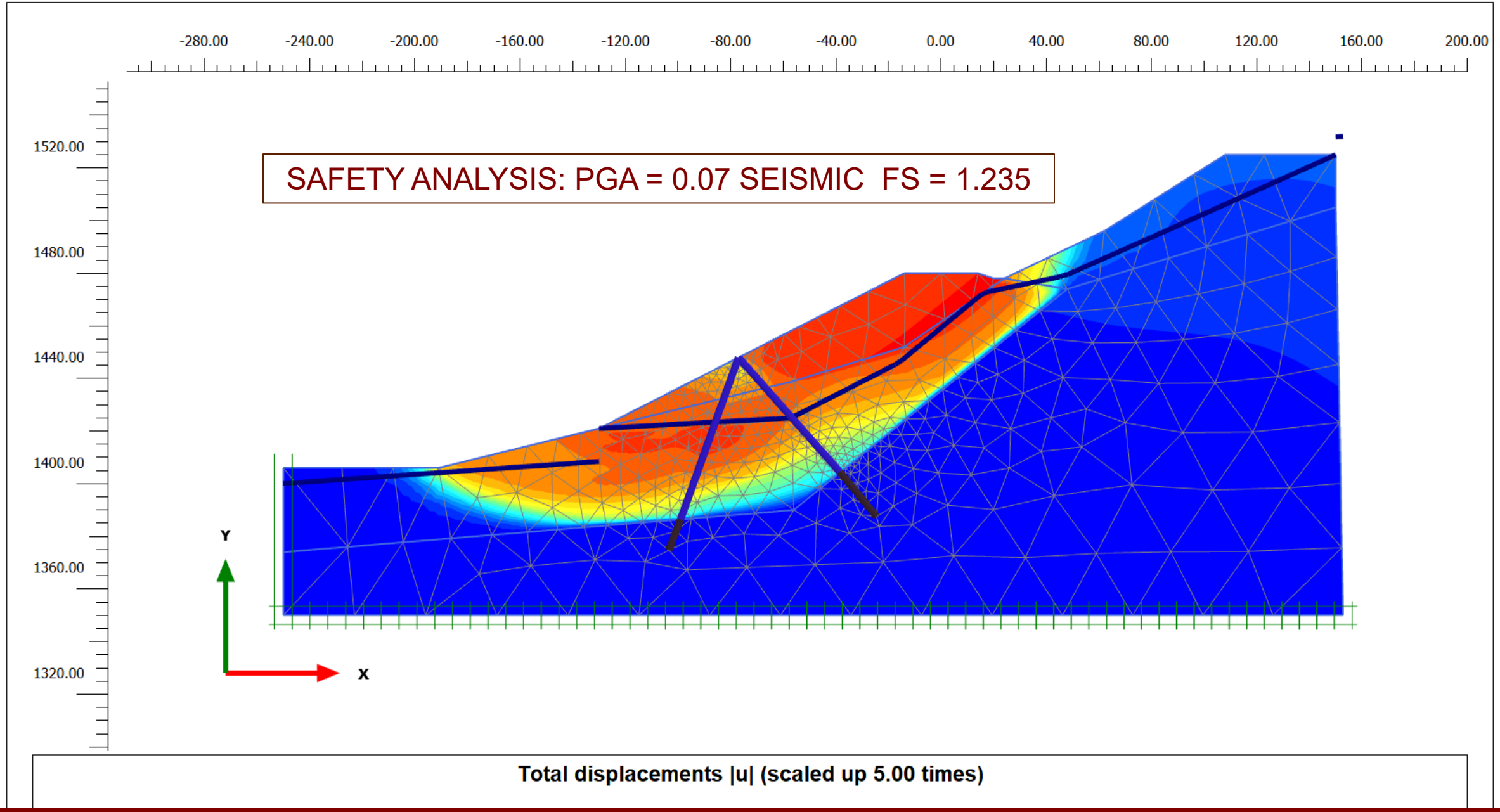
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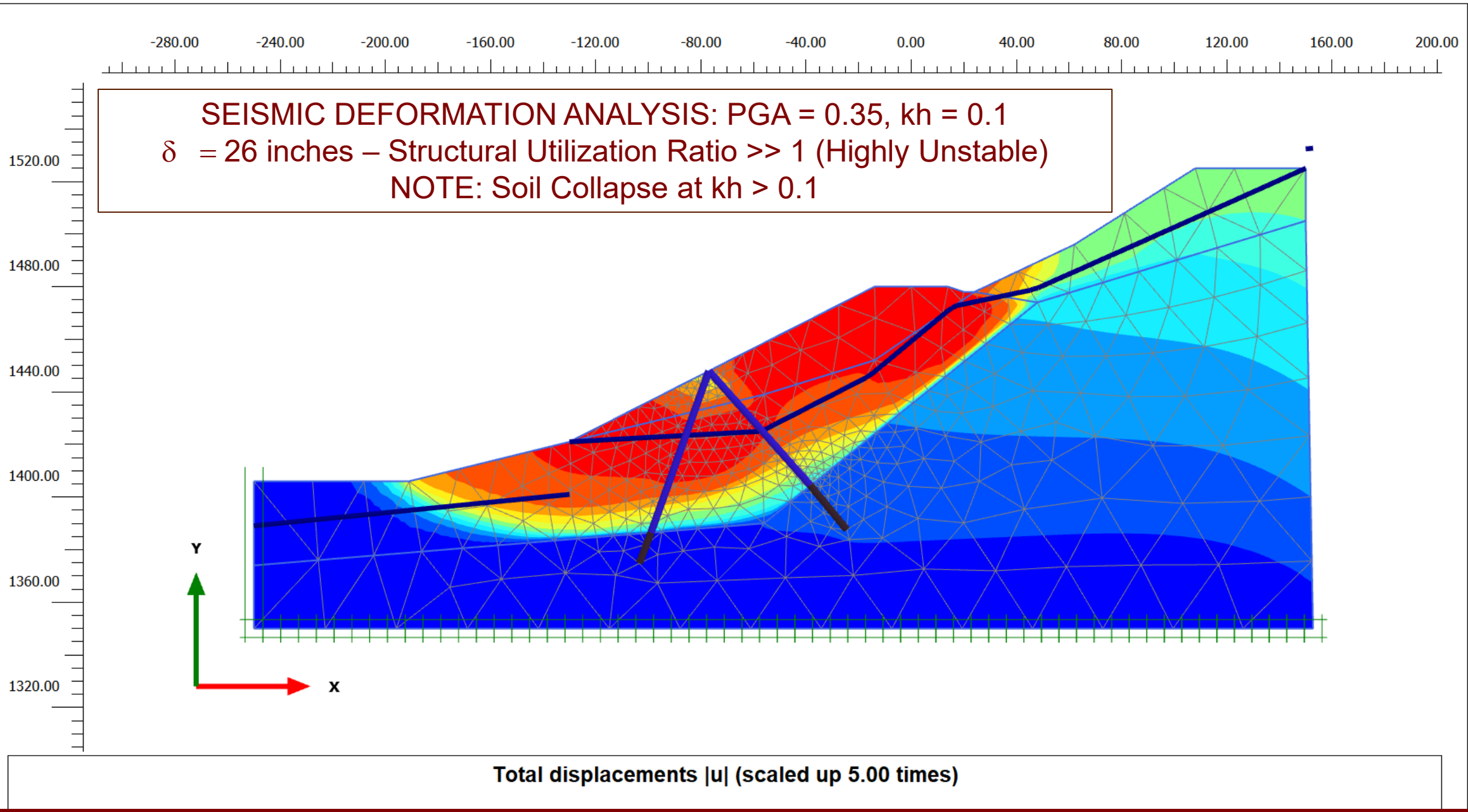
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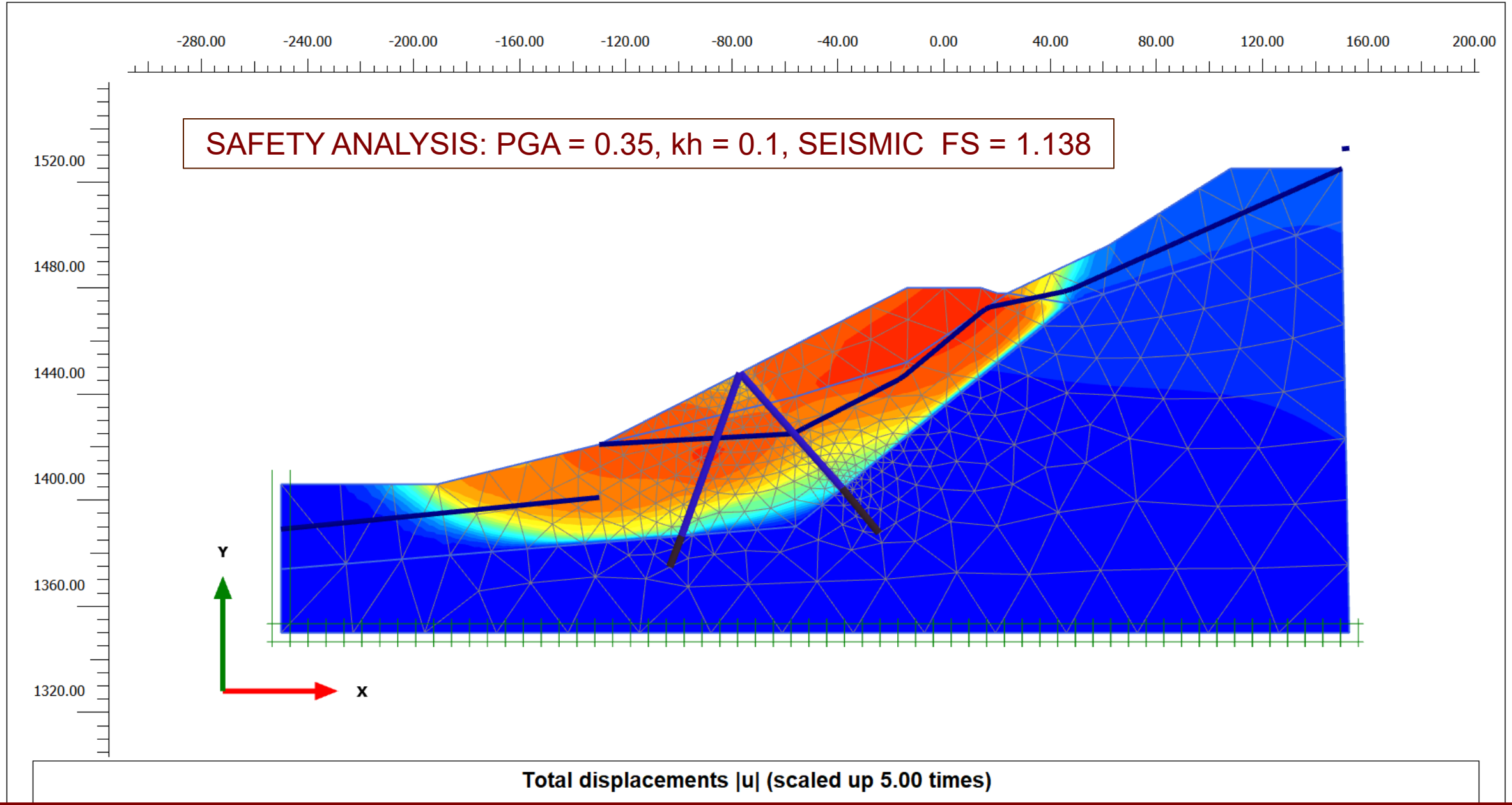
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Output Version 2019.0.0.0



Output Version 2019.0.0.0



SUMMARY OF ANALYSES

DESCRIPTION	LEM - FS	FEM - FS	δ – inches LEM / FEM	STRUCTURAL STABILITY
INITIAL CONDITION – NO MICROPILES (ϕ = 22, c = 0)	0.909	NA	--	--
UPPER SLOPE (ϕ = 22, c = 0)	0.800	NA	--	--
UPPER SLOPE (ϕ = 24, c = 85) ★	1.004	NA	--	--
INITIAL CONDITION – NO MICROPILES (ϕ = 24, c = 85)	1.080	NA	--	--
STATIC – WITH MICROPILES (w/MP)	1.565	1.545	< 0.5	Stable
SEISMIC: PGA = 0.07, kh = 0.05 (w/MP)	1.288	1.235	<0.5 / <0.5	Unstable
SEISMIC: PGA = 0.35, kh: LEM = 0.14, FEM = 0.10 (w/MP)	1.022	1.138	27 / 26	Highly Unstable
SEISMIC: LEM Search for ky and Calculate δ (ky = 0.14781)	1.000	NA	30 (LEM)	--

CONCLUSIONS

- LEM and FEM analyses are in good agreement.
- Using the same size bars in upslope and downslope micropiles and using the back-calculated strength parameters (ϕ = 24 degrees and c = 85 psf) for the colluvium, calculated slope movements are < 0.5 inches and the A-Frame micropile system is stable for the static case.
- The calculated FS for the seismic case with PGA = 0.07 and kh = 0.05 is > 1.2 and slope displaces are very small, but the micropile system is unstable.
- The calculated FS is slightly above unity for the PGA = 0.35 case, but the micropile system is highly unstable and slope movements are > 2 feet.



SOFTWARE DISCUSSION
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GREGORY GEOTECHNICAL

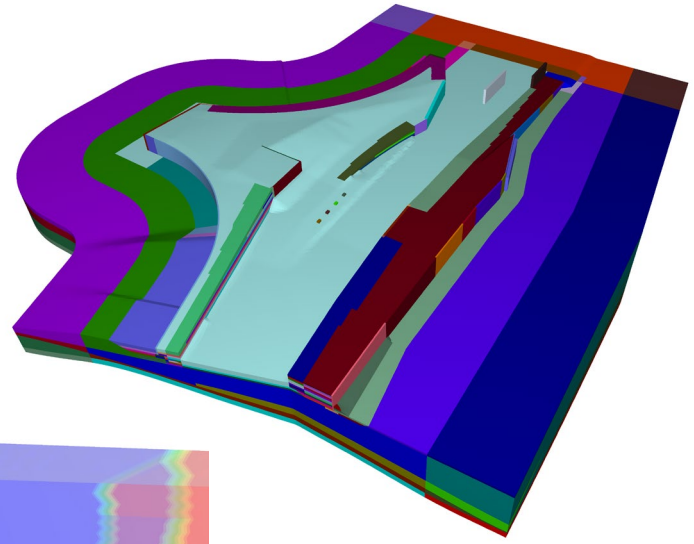
S3: Virtual Slope Stabilization

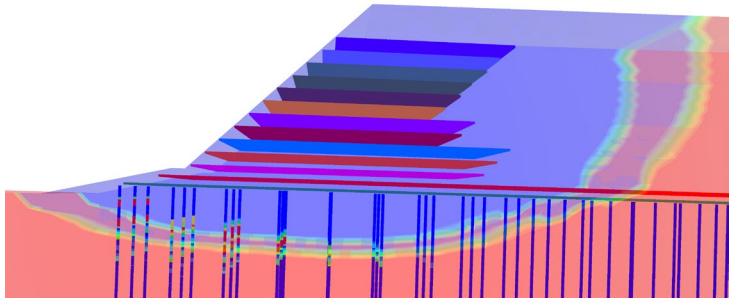
Reference Example: Slope stabilization using A-frame micropiles

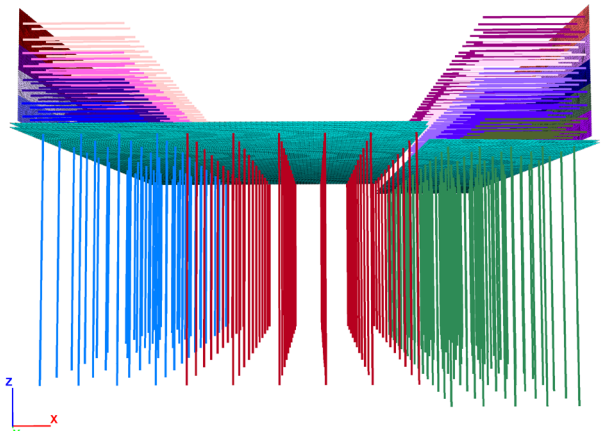
A. Lucarelli

Brief Description of *FLAC3D*

- Numerical modeling software for geomechanical analyses of soil, rock mass, ground support, and groundwater.
- Analyses may include engineering design, factor of safety prediction, service- and ultimate-limit states (displacements), parametric analysis, and back-analysis of failure.
- Using interfaces, can simulate discontinuities such as faults, joints, bedding planes, and engineered constructs.
- Captures the mechanism of complex behaviors of soils and rock masses consisting of multiple construction stages and ground support.
- *FLAC2D*, a 2D version of *FLAC3D*, pre-releases in 2022.

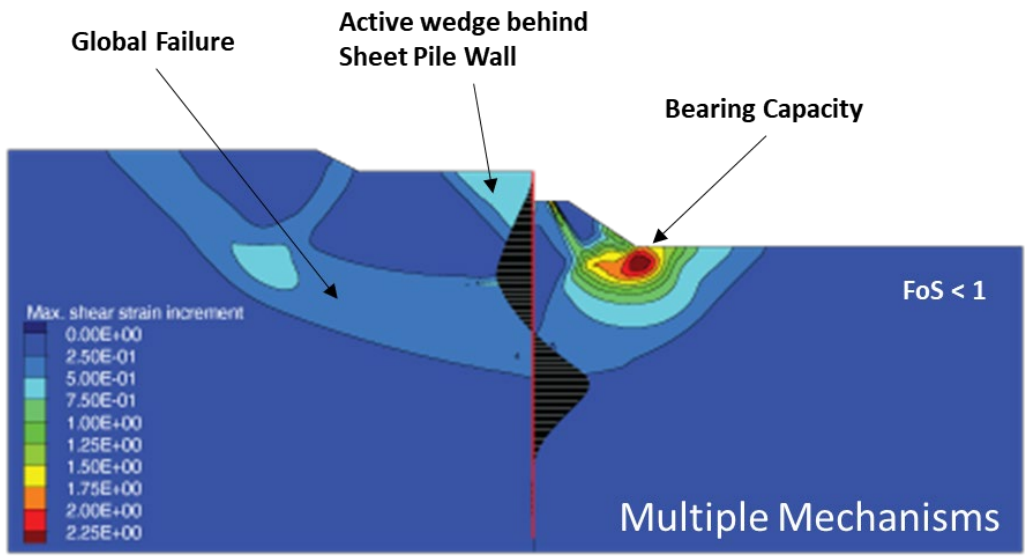






Shear Strength Reduction (SSR) Method Solution Approach

- Progressively reduce shear strength of materials (cohesion and friction coefficient) until excavation failure occurs.
- May reduce soil/rock tensile strength as well as ground support strength properties.



PROS

Produces mechanics-based failure mechanisms:

- Follows evolution of failure(s), including multiple mechanisms.
- Can model more complex ground behavior (e.g., stress-dependent material behavior, soil saturation, groundwater flow).
- Enhanced judgment from seeing realistic mechanisms.

Observe displacement progression:

- Deformations at the “failure state” are kinematically valid.
- Is the Service Limit State more critical than the Ultimate Limit State?

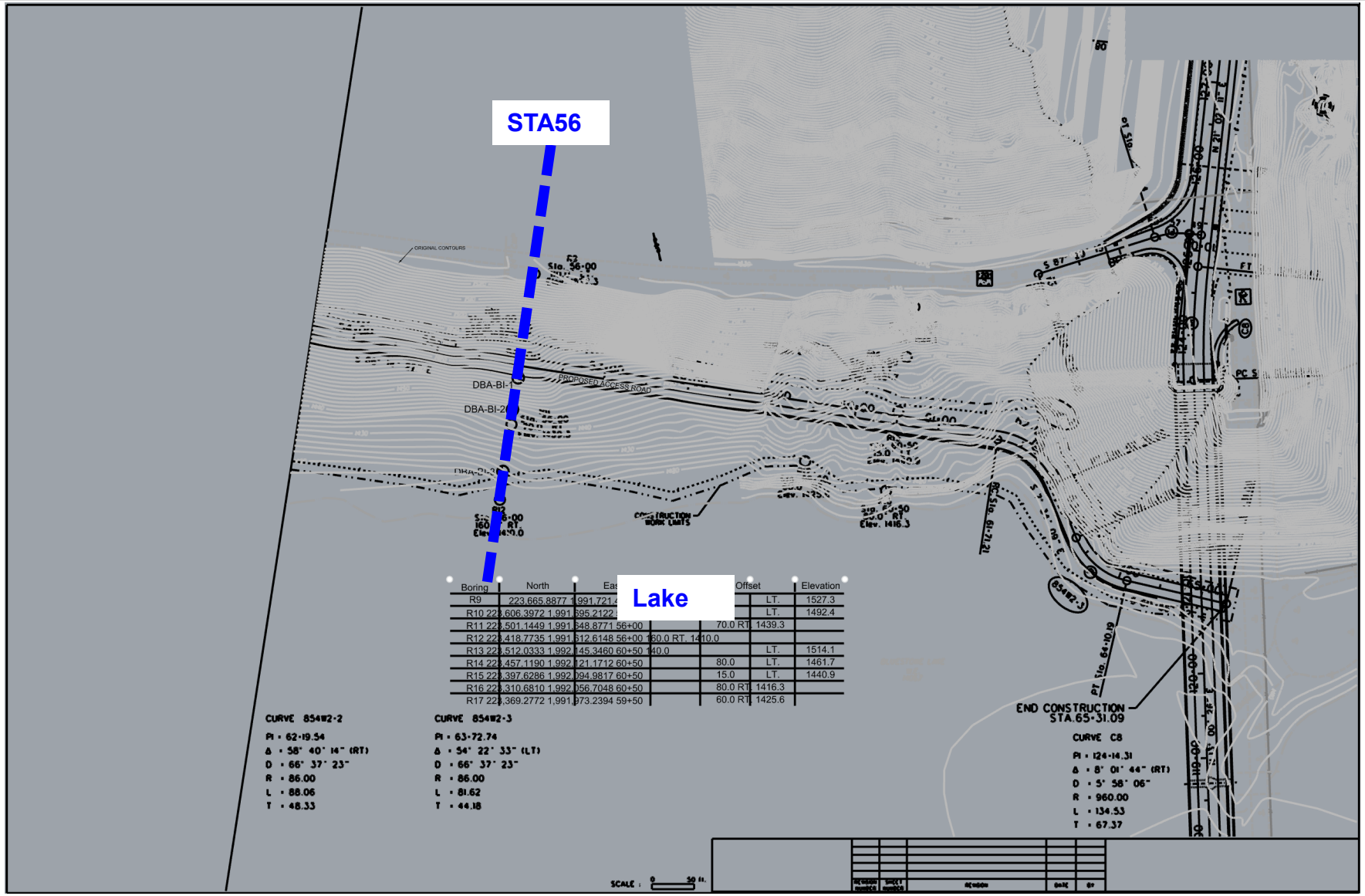
Incorporate ground support correctly:

- Full soil-structure interaction (beams, sheet pile walls, piles, liners, anchors, etc.).
- Structural reactions are not “wished-in-place”.

CONS

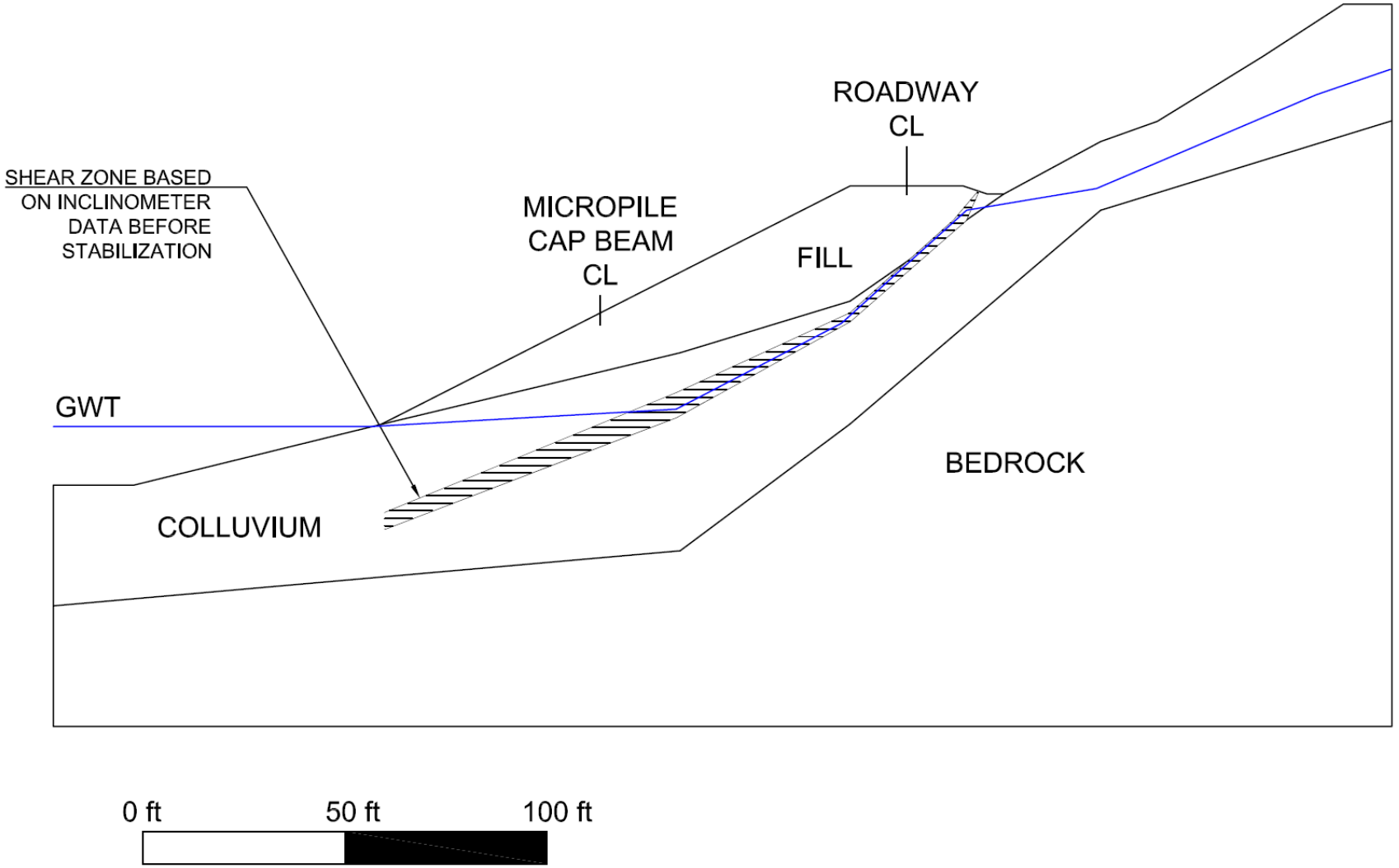
Solution time can take minutes to hours or more, increasing with grid refinement.

General site view

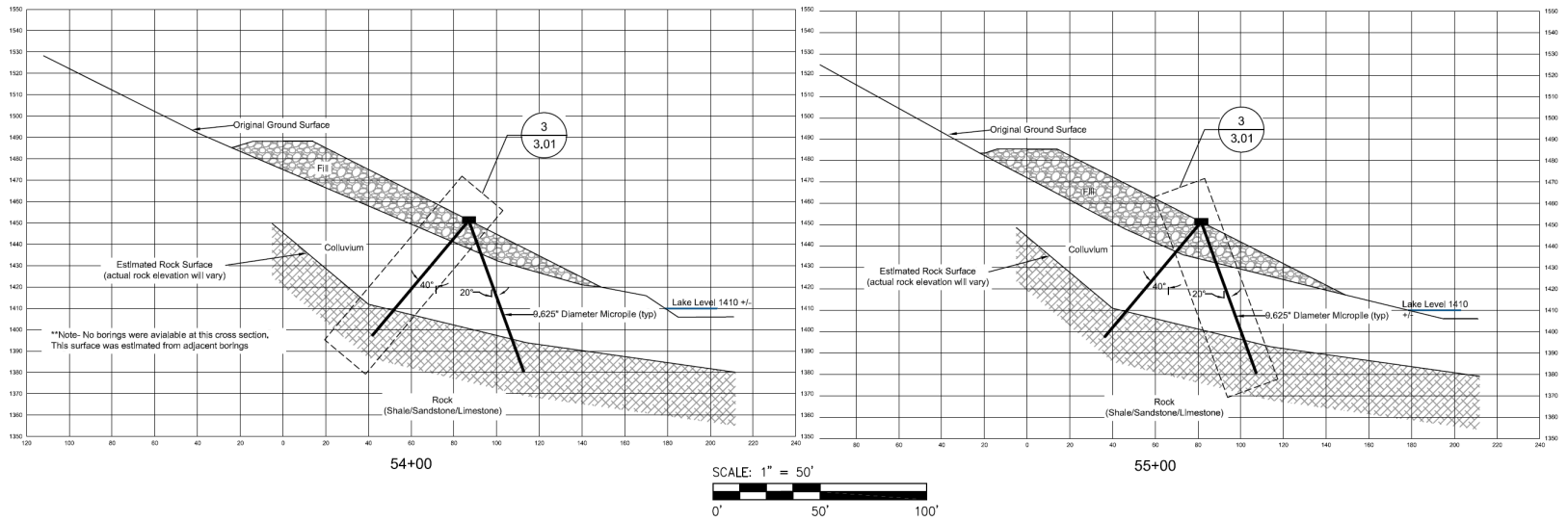


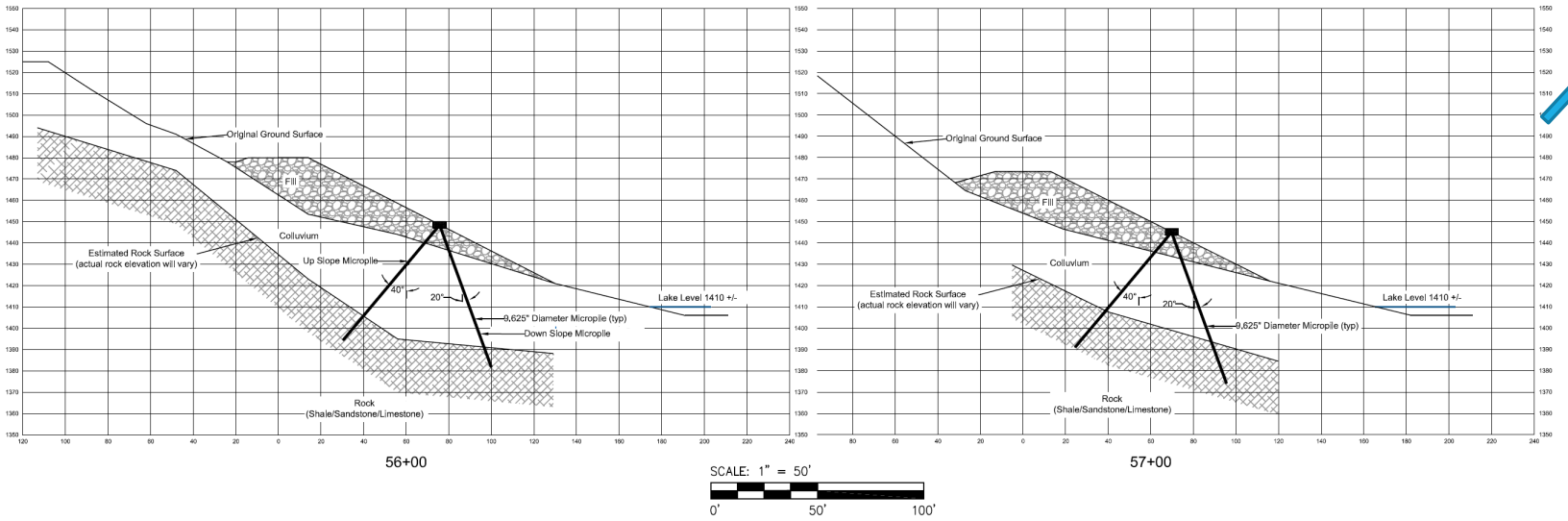
Boring	North	East	Offset		Elevation
R9	223,665.8877	1,991,721.4		LT.	1527.3
R10	223,606.3972	1,991,695.2122		LT.	1492.4
R11	223,501.1449	1,991,648.8771	56+00	70.0 RT	1439.3
R12	223,418.7735	1,991,612.6148	56+00	160.0 RT.	1410.0
R13	223,512.0333	1,992,145.3460	60+50	140.0 LT.	1514.1
R14	223,457.1190	1,992,121.1712	60+50	80.0 LT.	1461.7
R15	223,397.6286	1,992,094.9817	60+50	15.0 LT.	1440.9
R16	223,310.6810	1,992,056.7048	60+50	80.0 RT	1416.3
R17	223,369.2772	1,991,973.2394	59+50	60.0 RT	1425.6

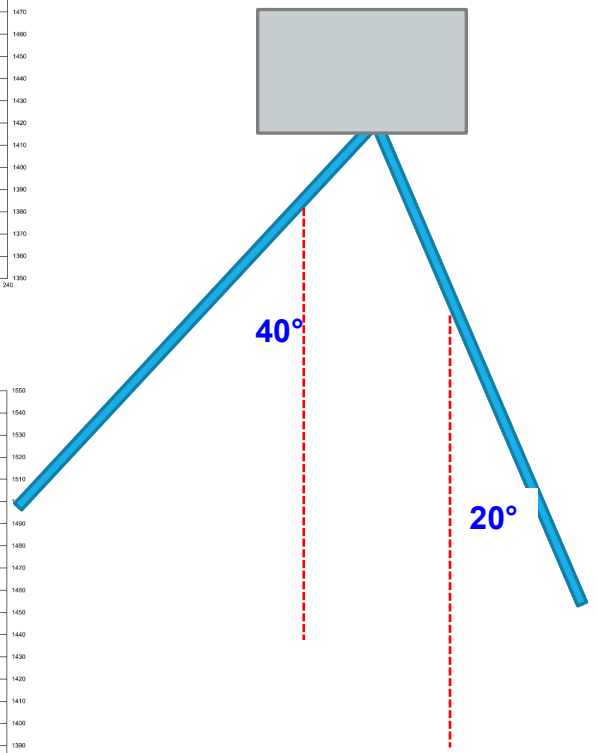
STA56 – reference geometry – stratigraphy



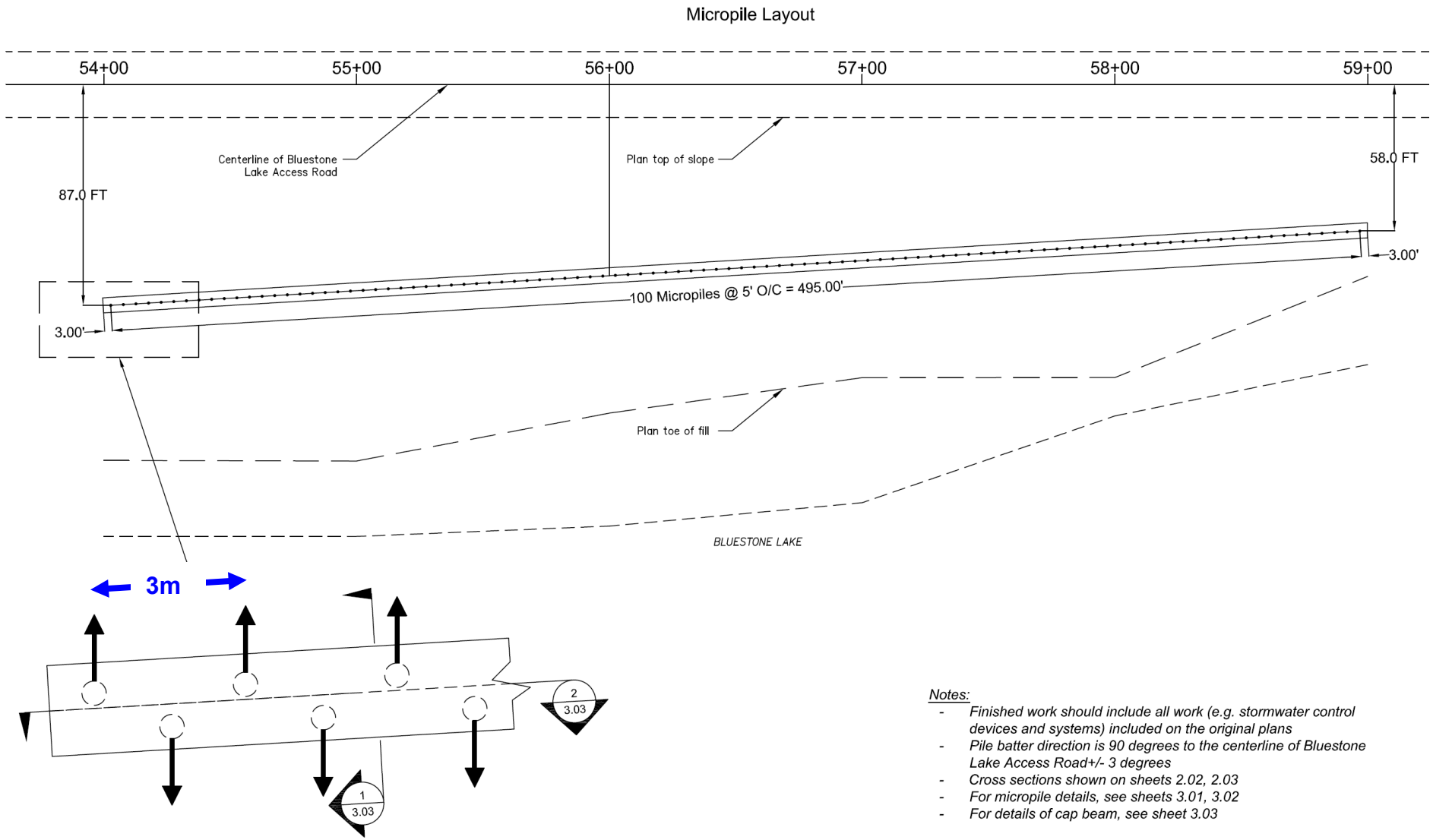
Cross-sections







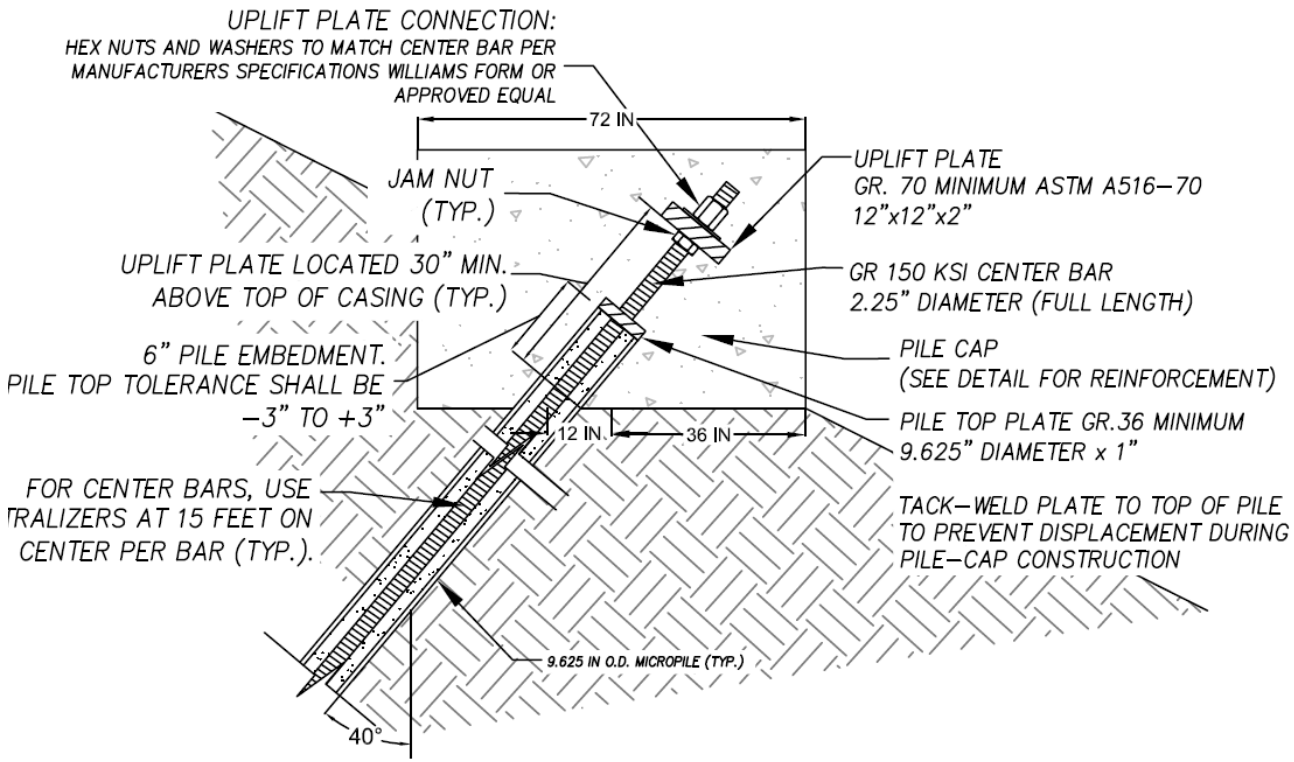
Plan view – micropile layout

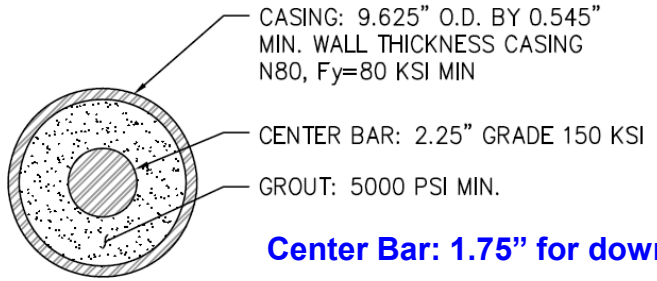


Notes:

- *Finished work should include all work (e.g. stormwater control devices and systems) included on the original plans*
- *Pile batter direction is 90 degrees to the centerline of Bluestone Lake Access Road+/- 3 degrees*
- *Cross sections shown on sheets 2.02, 2.03*
- *For micropile details, see sheets 3.01, 3.02*
- *For details of cap beam, see sheet 3.03*

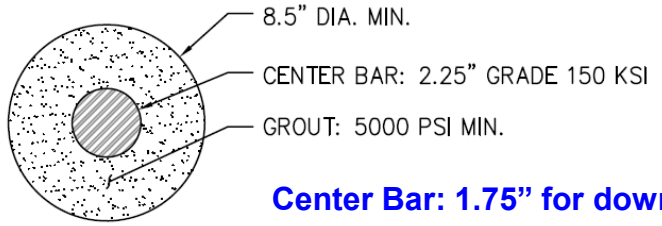
Micropile structural layout – composite system





Center Bar: 1.75" for downhill

3
3.01
UPSLOPE MICROPILE SECTION DETAILS
NO SCALE



Center Bar: 1.75" for downhill

Uphill: bar 2.25"; uplift plate 12x12x2.0
Downhill: bar 1.75" uplift plate 6x5x1.5

Modeling the micropiles

FLAC3D 9.00

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Each pile in the model is composed of:

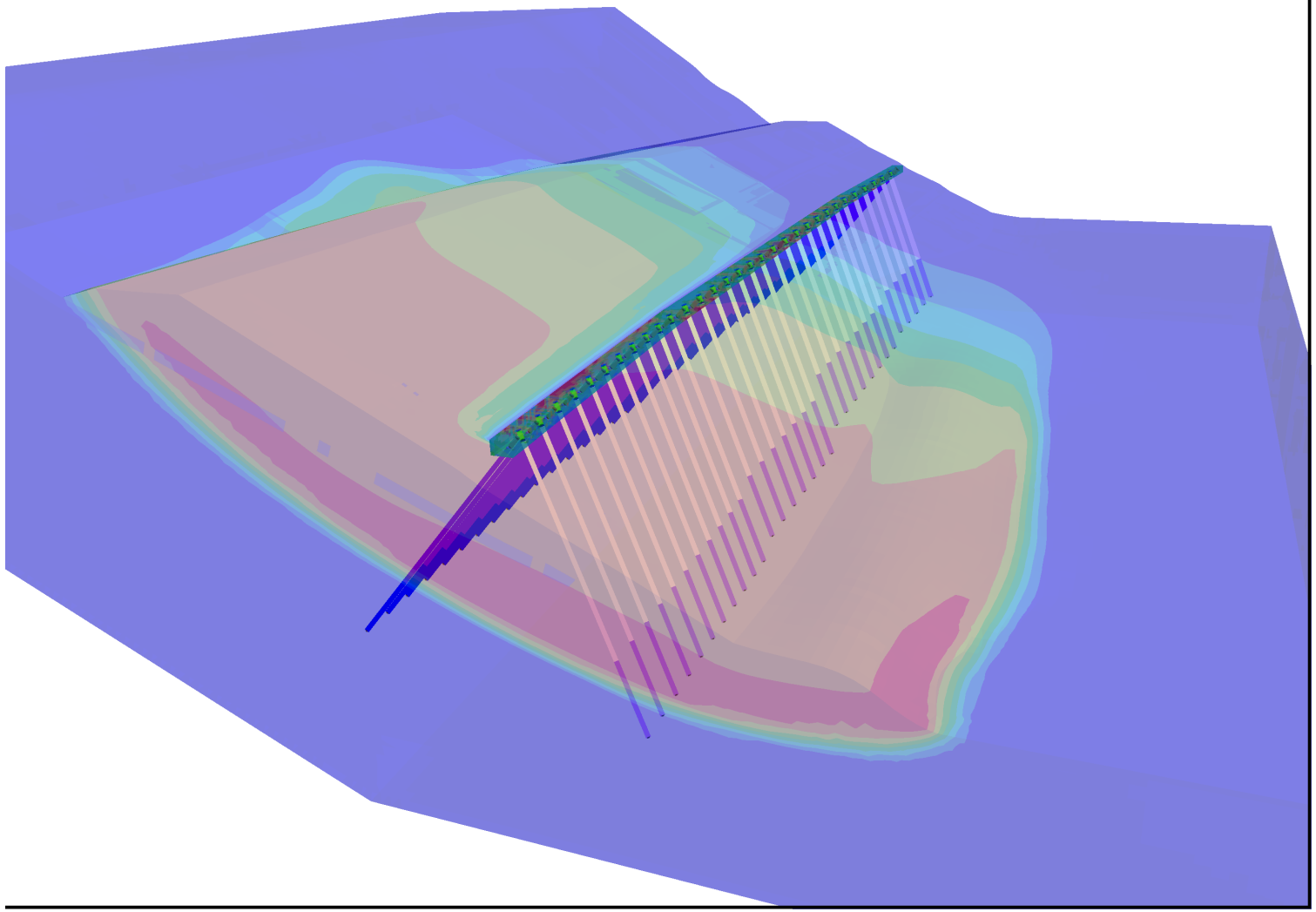
- **Central bar: 2.25”–1.75”**
- **Grout 5000 PSI**
- **Casing**

Each element has its own T-B curve and shear capacity.

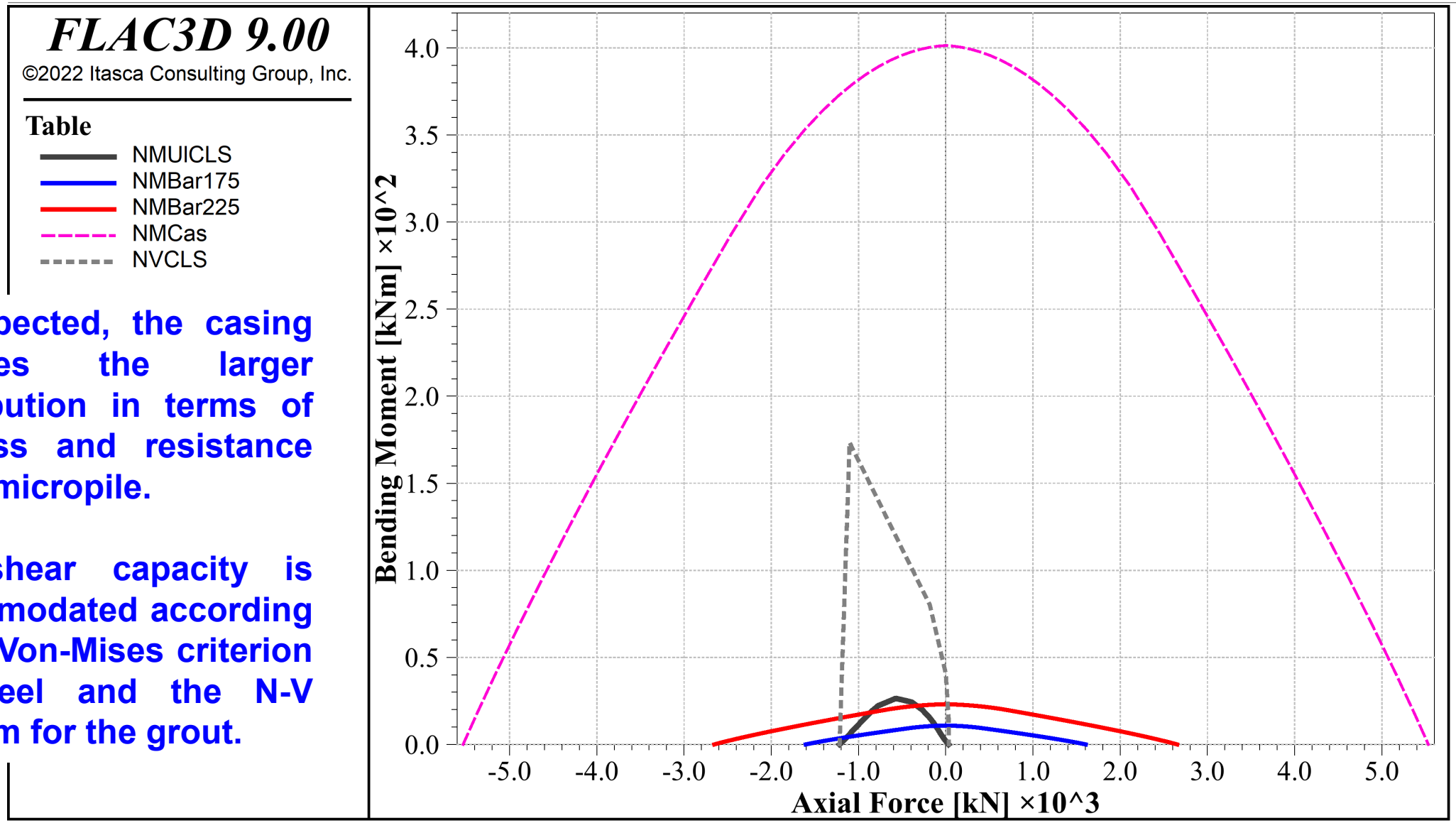
The interaction with the soil develops on the casing element surfaces and on the grout surface if the casing is not present.

In this way, it is possible to better capture:

- **the overall stiffness of the composite system**
- **the progressive failure**
- **localize the “weak link”**



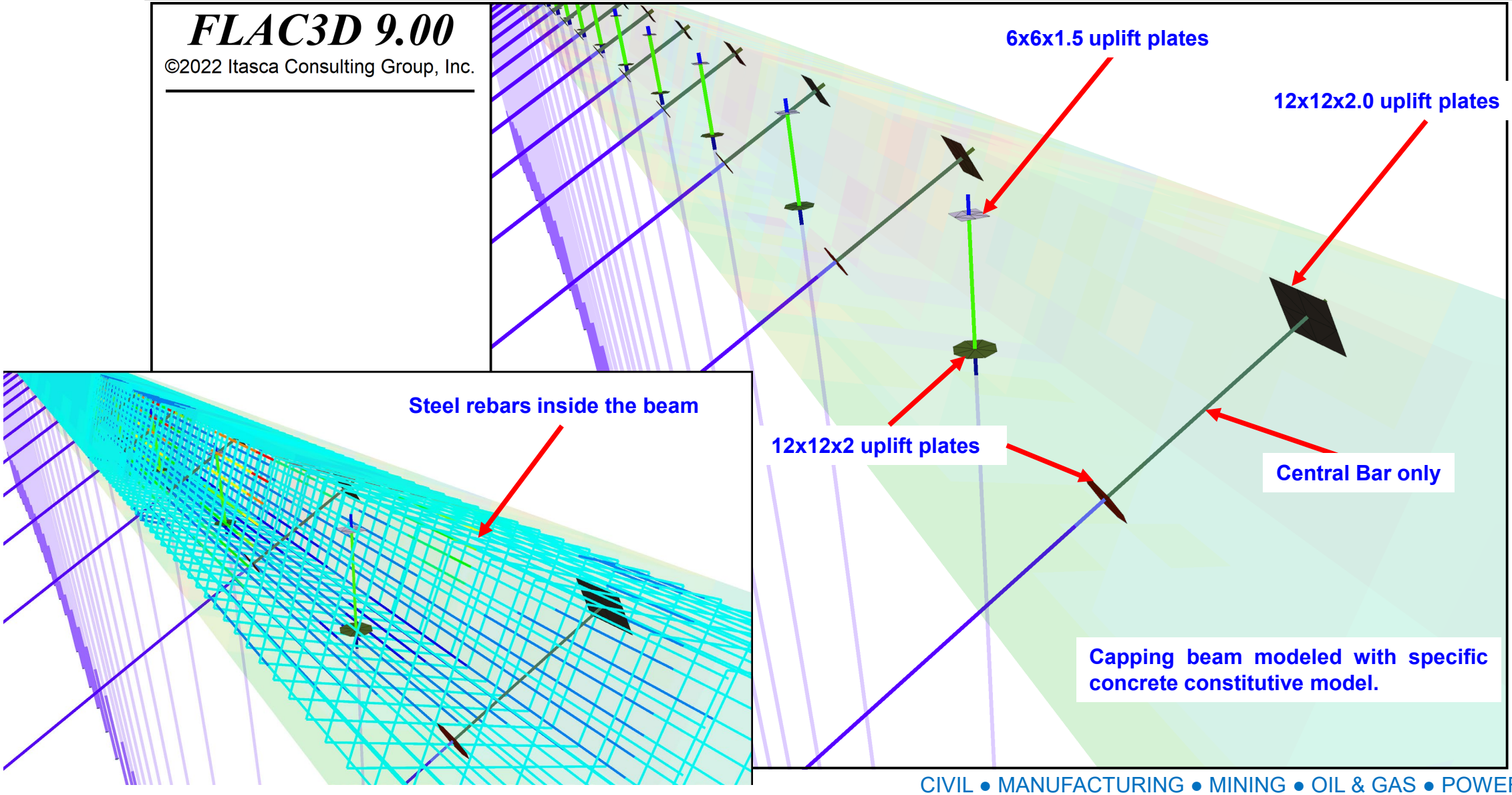
Thrust-bending diagrams



As expected, the casing provides the larger contribution in terms of stiffness and resistance to the micropile.

The shear capacity is accommodated according to the Von-Mises criterion for steel and the N-V diagram for the grout.

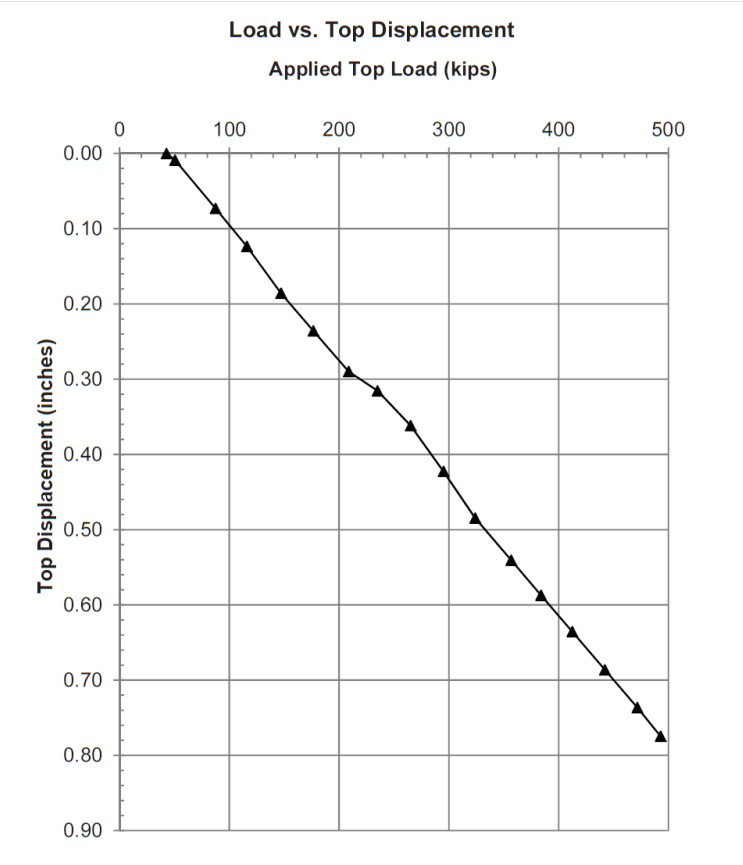
Micropile connection with the capping beam

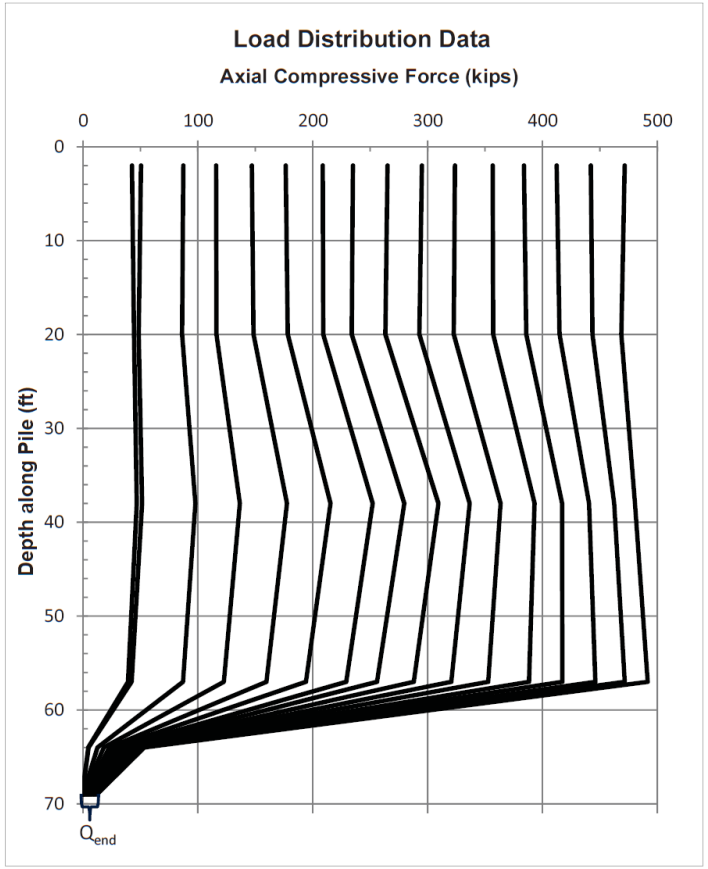


Micropile-soil interaction – Axial

DAN BROWN AND ASSOCIATES

TP1 at STA 56+00 (71 feet)





F_s=	22.8	ksf
Q_{end}=	12	kips

The shaft contribution in the colluvium material ranges from 50–100 kPa. This is important because it controls the axial load transfer from the sliding soil mass to the support system. For the design analyses, a max value of 80 kPa will be considered. The τ in the embedded portion is around 1100 kPa, but failure has not been detected. The load displacement curve is still linear.

A max value of 2000 kPa is considered for the embedded length in the bedrock.

The base is modeled adding a shell element that represents the size of the pile.

In summary, the following are considered for the shaft interaction:

τ_{lim_coll} = 0.45·s'v < 80 kPa

τ_{lim_rock} = 6.00·s'v < 80 kPa

Coupling spring stiffness

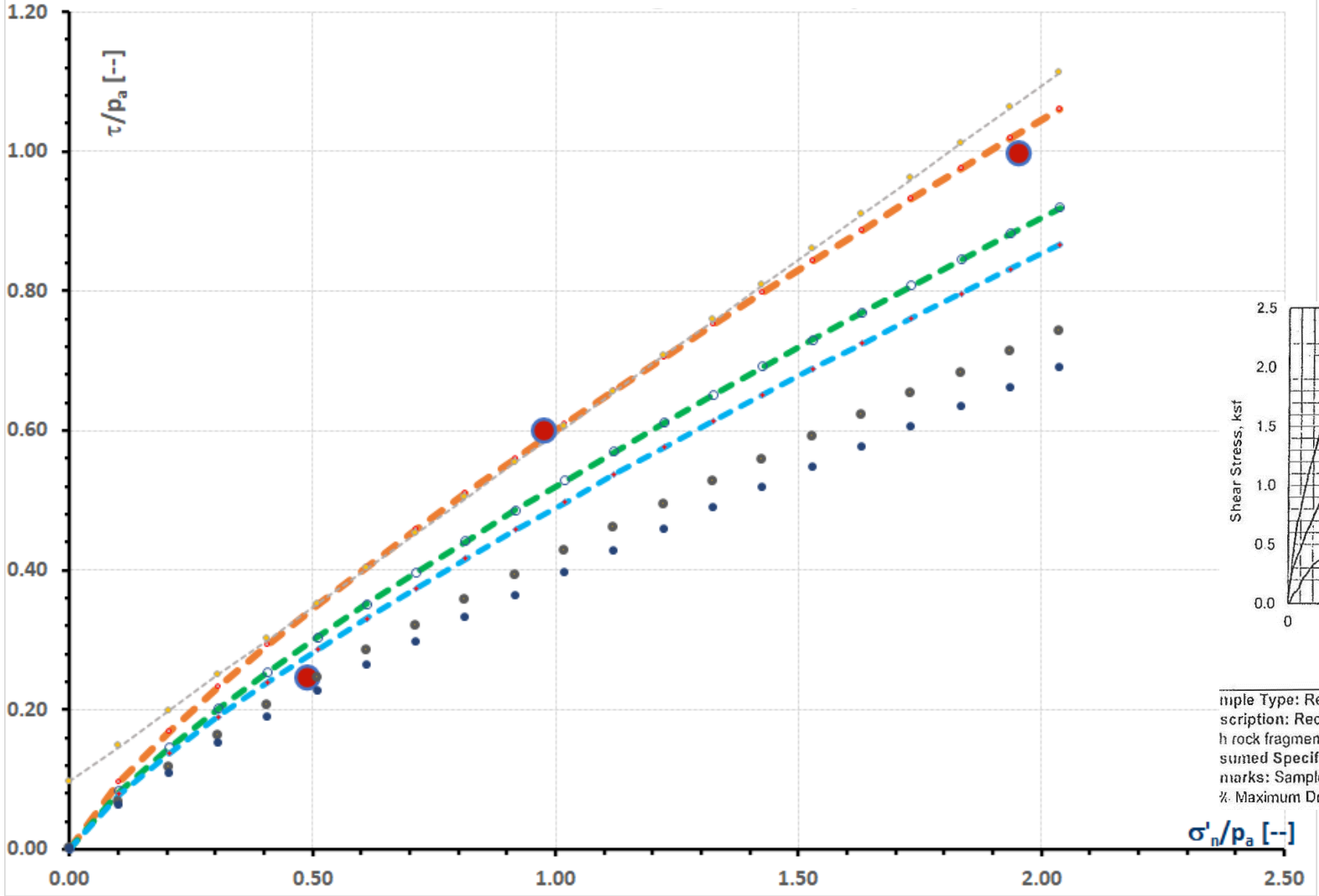
Kn = 10 · E'

Ks = 10 · E'

For normal interaction, a high strength of the coupling spring is considered. Potential plasticity will develop in the zones.

Colluvium – geotechnical properties – shear strength

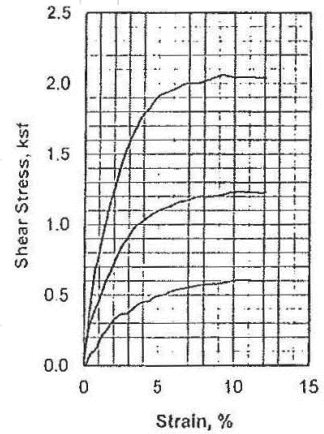
Shear Strength Envelops



$\tau = a \cdot p_a \cdot (\sigma'_n/p_a)^b$

a = 0.60	b = 0.80	Peak
a = 0.52-0.49	b = 0.80	FSS
a = 0.42-0.39	b = 0.80	RES

Note: The terminology FSS, RES is loosely used in this context. The *b* parameter usually also changes. For simplicity it is kept at the same value. The strength is reduced changing the *a* parameter only.

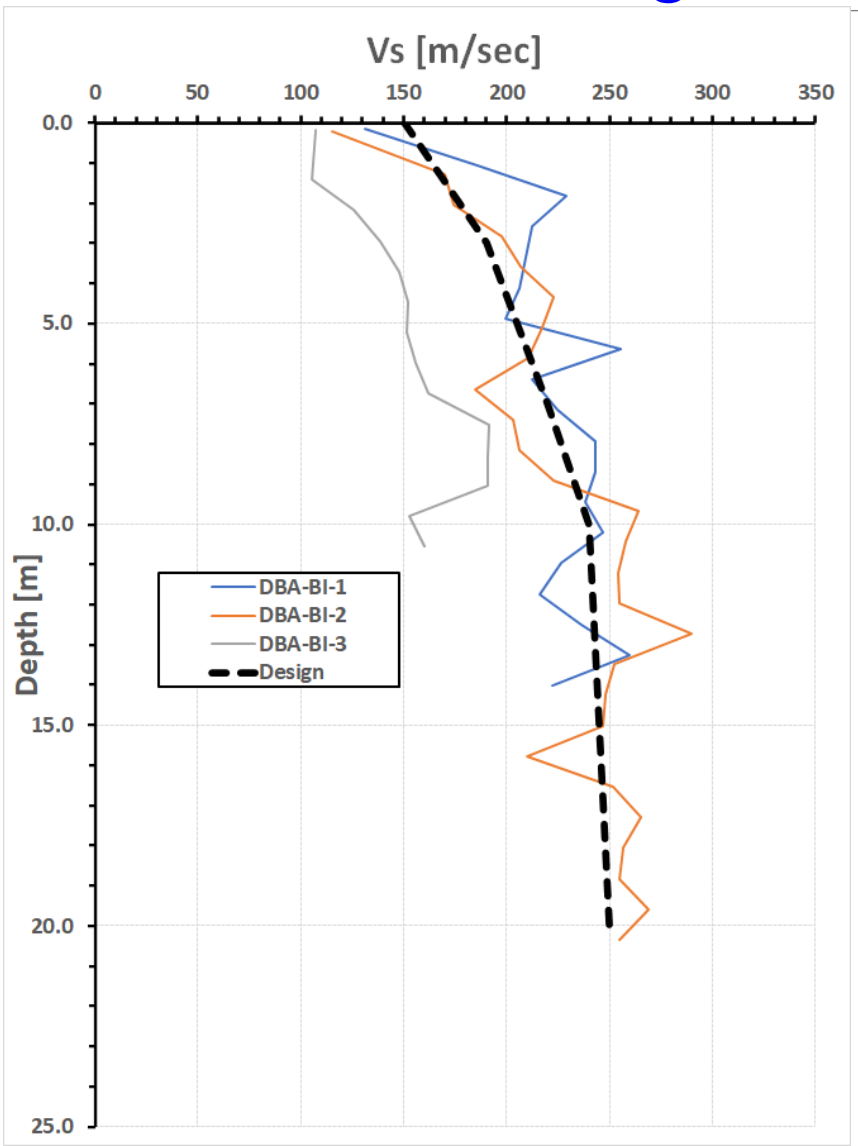


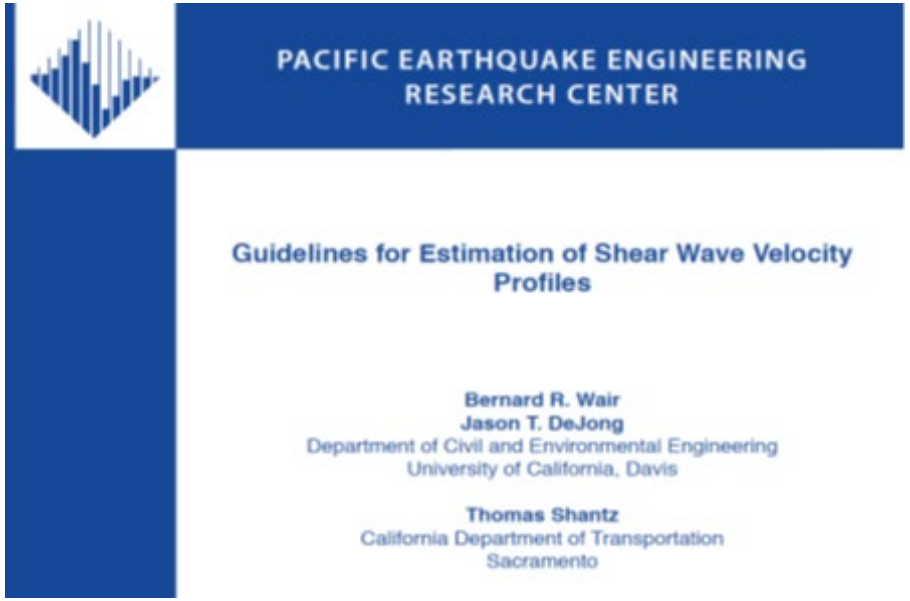
	Sample No.	1	2	3
Initial	Water Content, %	12.5	12.5	12.3
	Dry Density, pcf	100.5	100.0	100.2
	Saturation, %	51.2	50.7	50.2
	Void Ratio	0.6458	0.6538	0.6495
	Diameter, in.	2.50	2.50	2.50
	Height, in.	0.75	0.75	0.75
At Test	Water Content, %	18.1	17.2	14.9
	Dry Density, pcf	103.1	100.9	101.0
	Saturation, %	100.0	100.0	100.0
	Void Ratio	0.6041	0.6395	0.6379
	Diameter, in.	2.50	2.50	2.50
	Height, in.	0.73	0.74	0.74
Normal Stress, ksf		1.0000	2.0000	4.0000
Failure Stress, ksf		0.595	1.228	2.045
% Strain at Failure		9.7	9.7	8.7
Strain Rate, in./min.		0.00238	0.00238	0.00238

mple Type: Remolded
scription: Reddish brown SANDY CLAY
h rock fragments
sumed Specific Gravity = 2.65
marks: Sample remolded to
% Maximum Dry Density as determined by

Tested By: DLS
Checked By: SJG
Sample Source: Composite of all jars and tubes
Depth: Na
Project No.: 04-14-0075 Date Sampled: 3/17/14

Colluvium – geotechnical properties – deformability



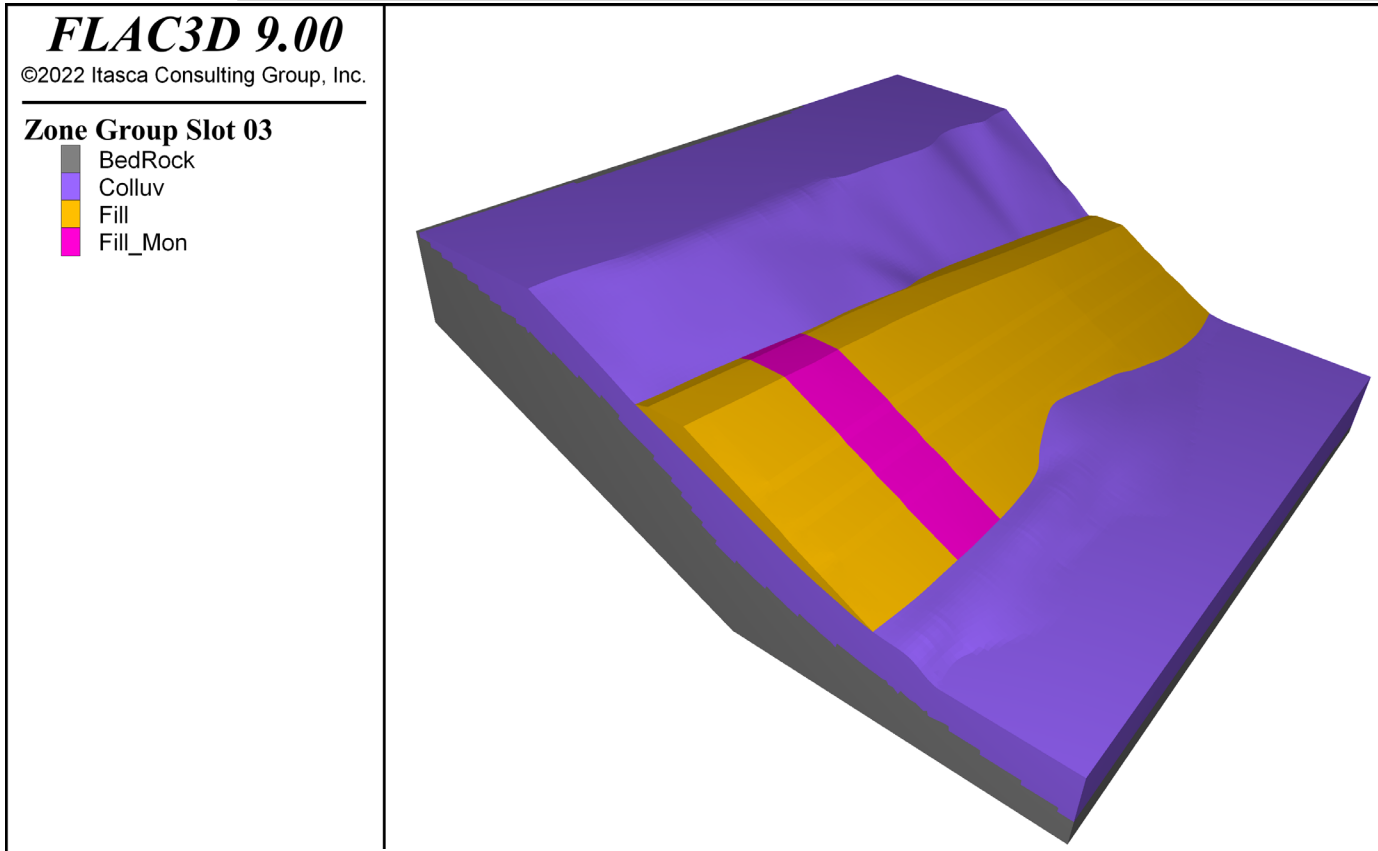


Darendeli's equation for clay

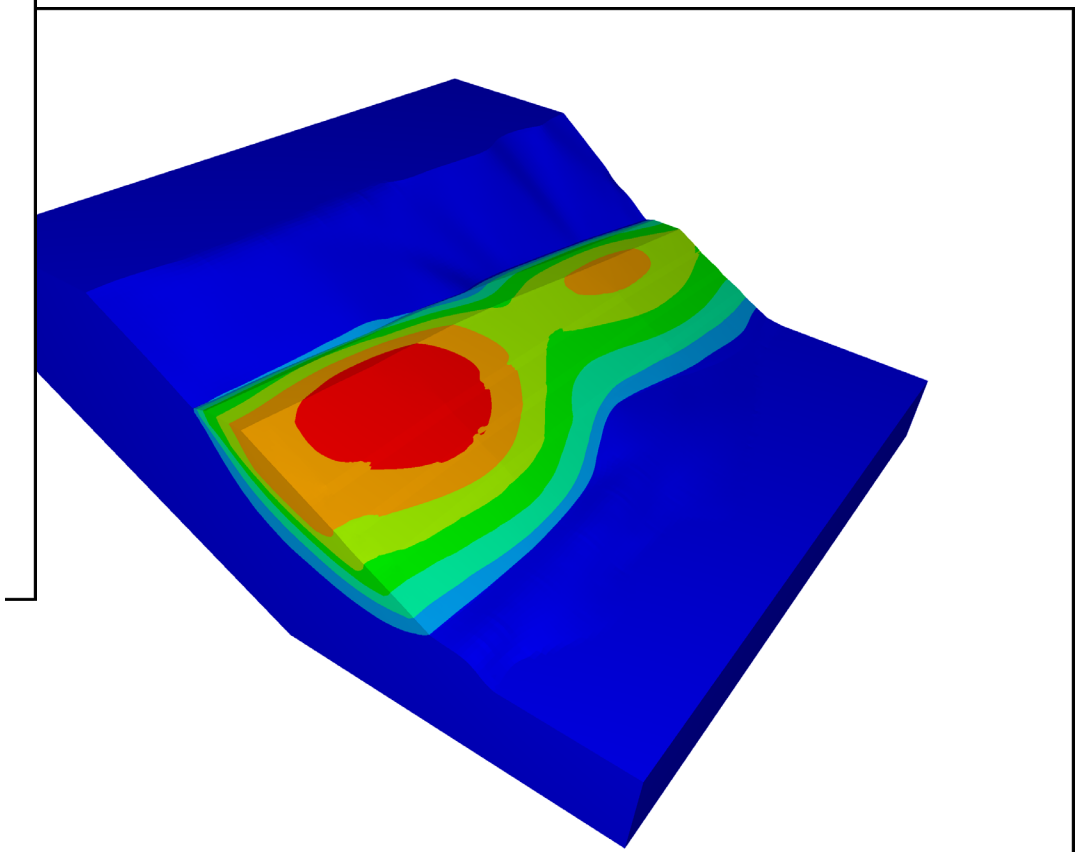
- **OCR = 3**
- **IP = 15**

```
.....................................
        if SoilType = 'Clay' then
           g07 = ((1.25e-2+3.7e-4*IP*OCR^0.3)*(pprime/pref)^0.35)/100.
           zone.extra(zp,zEx_g07) = g07*mulg07
        endif
.....................................
```

Modeling approach

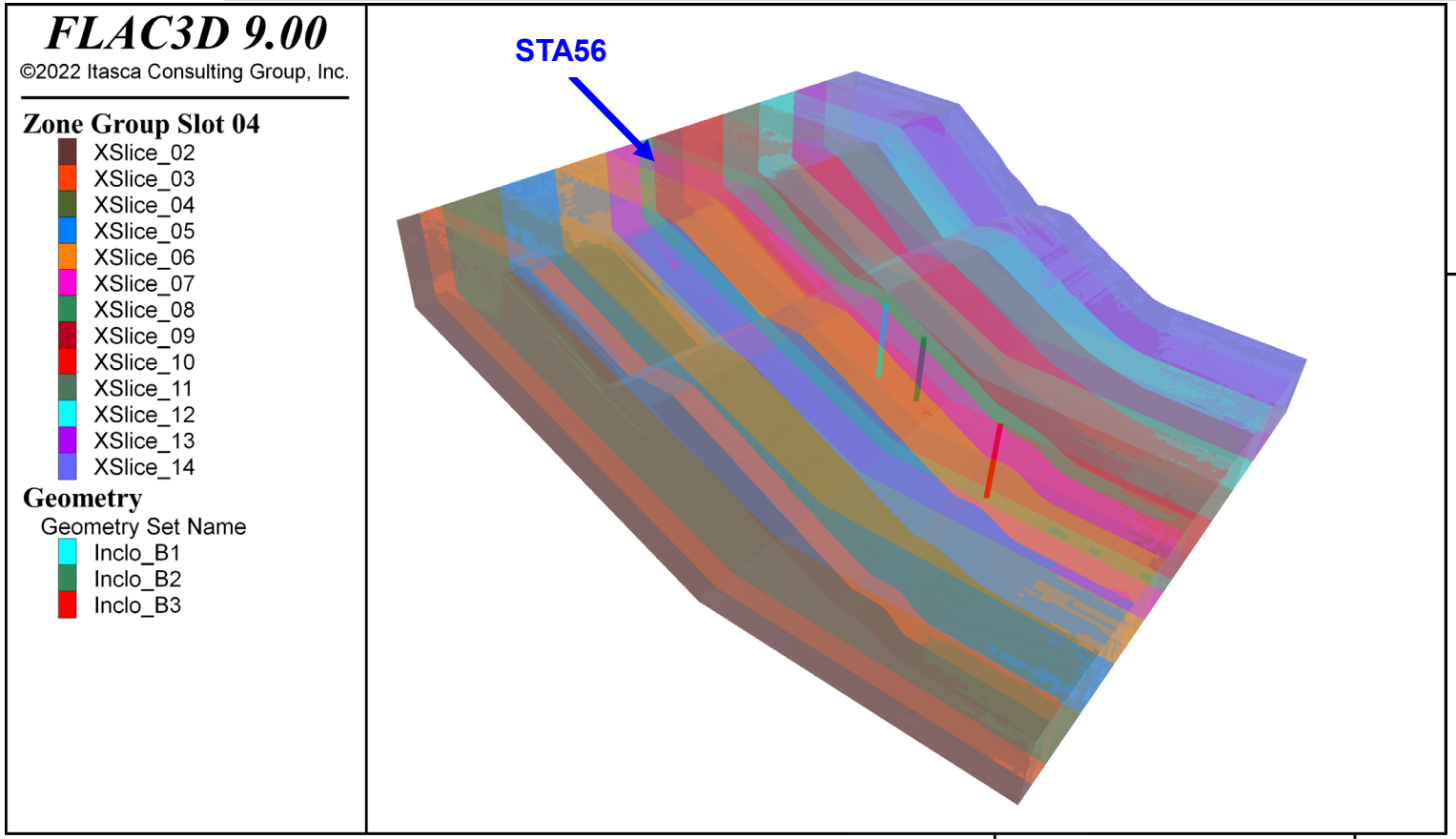


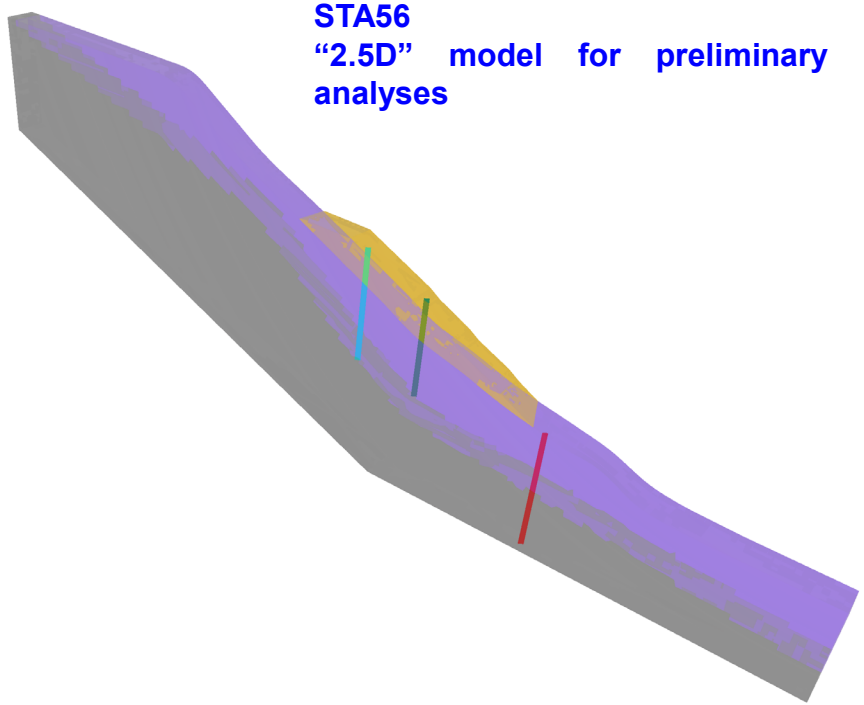
The 3D model is generated using *Rhino* as a geometry management tool, and the mesh is generated using *Griddle*, a *Rhino* add-in for generating surface meshes and volume meshes. *Griddle* generated a data file that is then imported into *FLAC3D*.



The model is then initialized in terms of stress and the fill is placed. The shear strength of the colluvium is such that the model can reach equilibrium (Peak). The strength of the colluvium is gradually reduced until metastable conditions are reached. At this point the micropiles are installed.
The process is initially simulated considering station STA56 by extracting a "2.5D" model from the general 3D model.

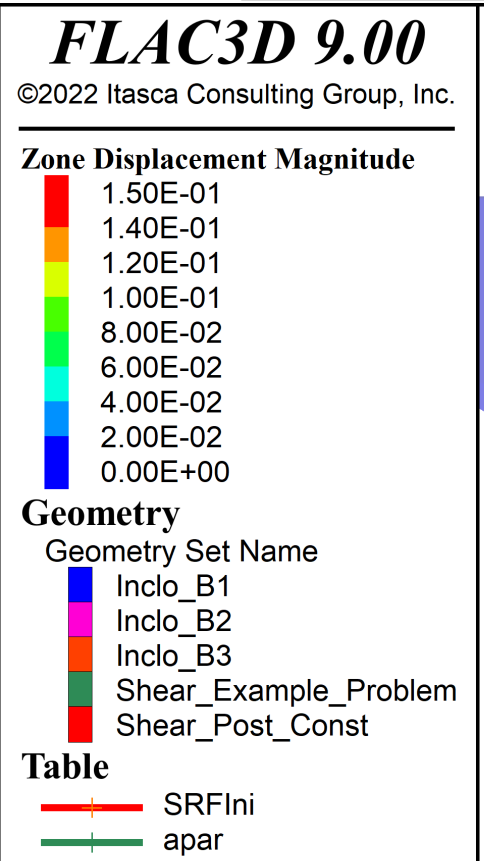
STA56 extracted from the general 3D model



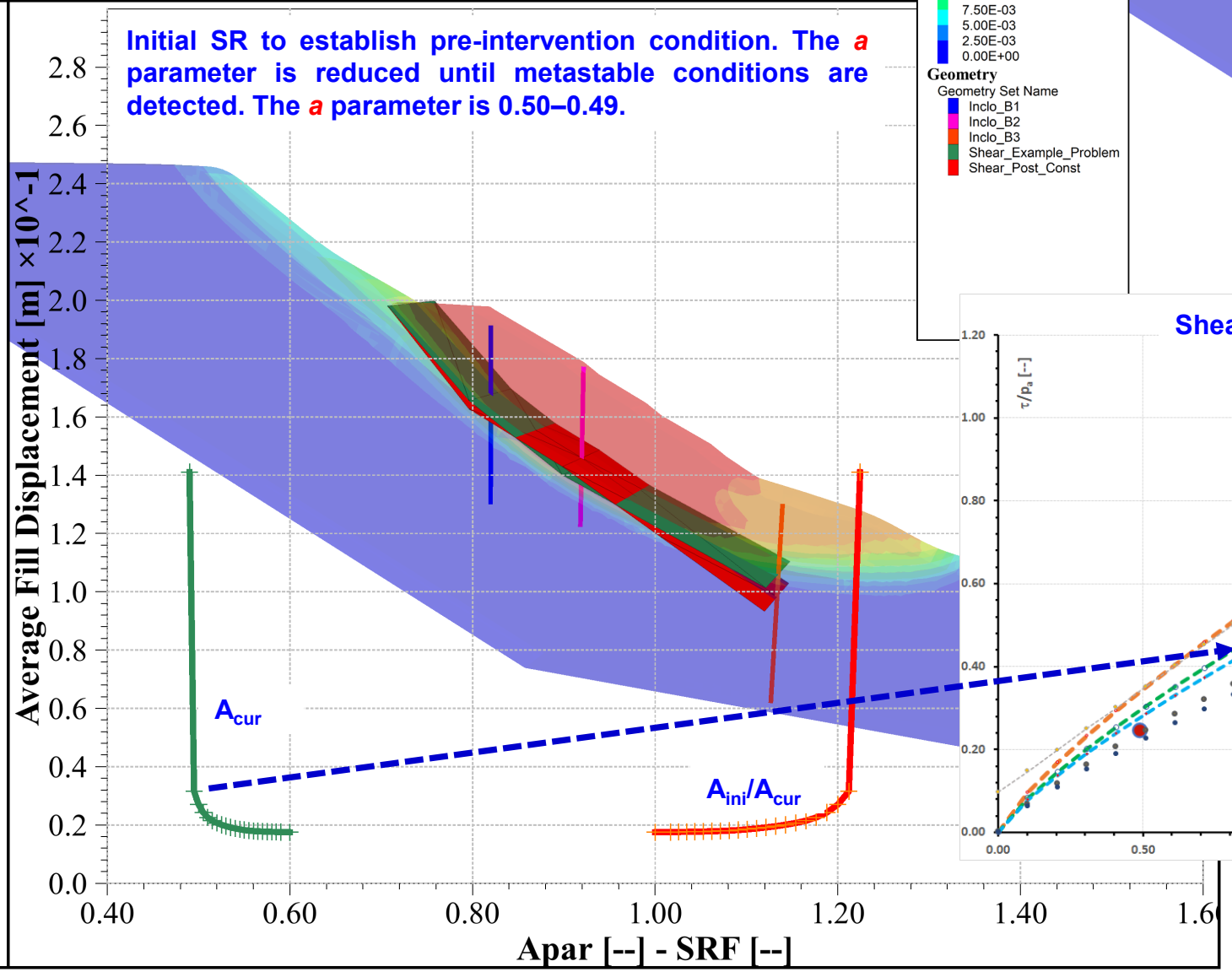


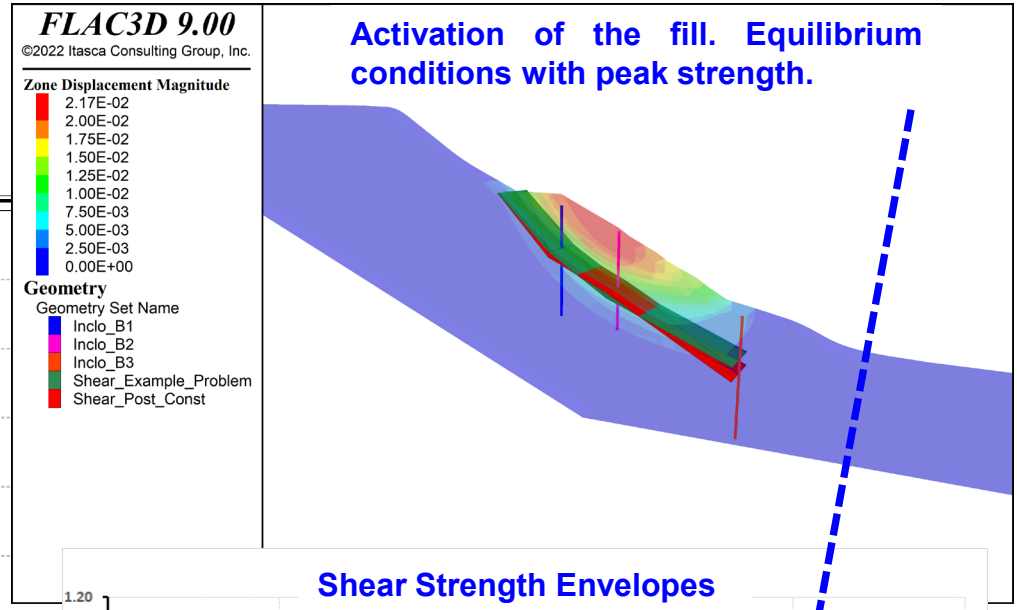
Extract from the full 3D model: STA56
"2.5D" model for preliminary analyses

STA56 analysis – pre-intervention

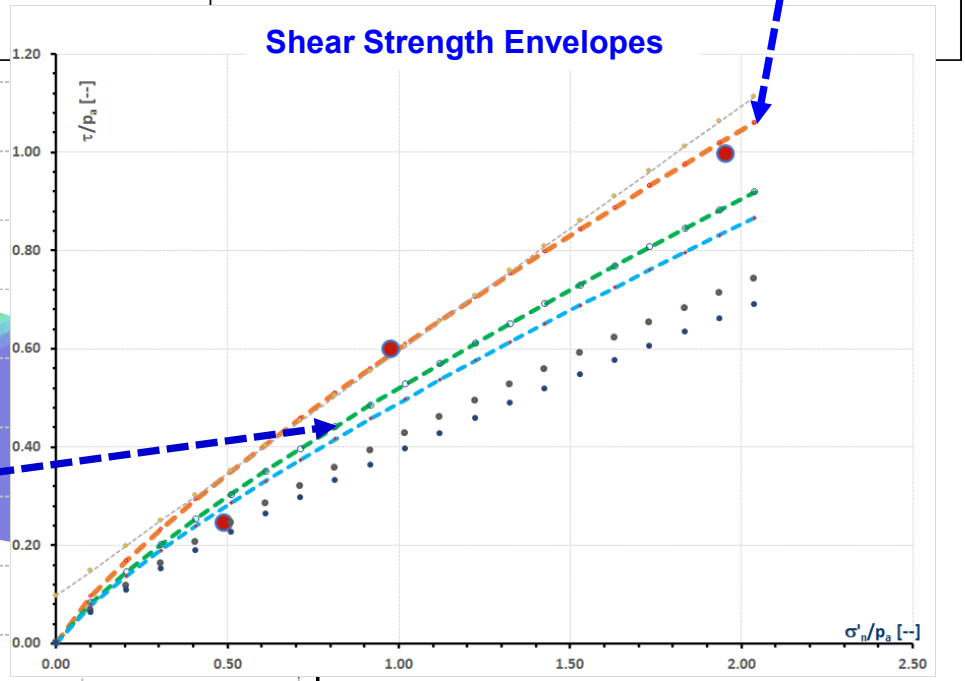


Initial SR to establish pre-intervention condition. The *a* parameter is reduced until metastable conditions are detected. The *a* parameter is 0.50–0.49.

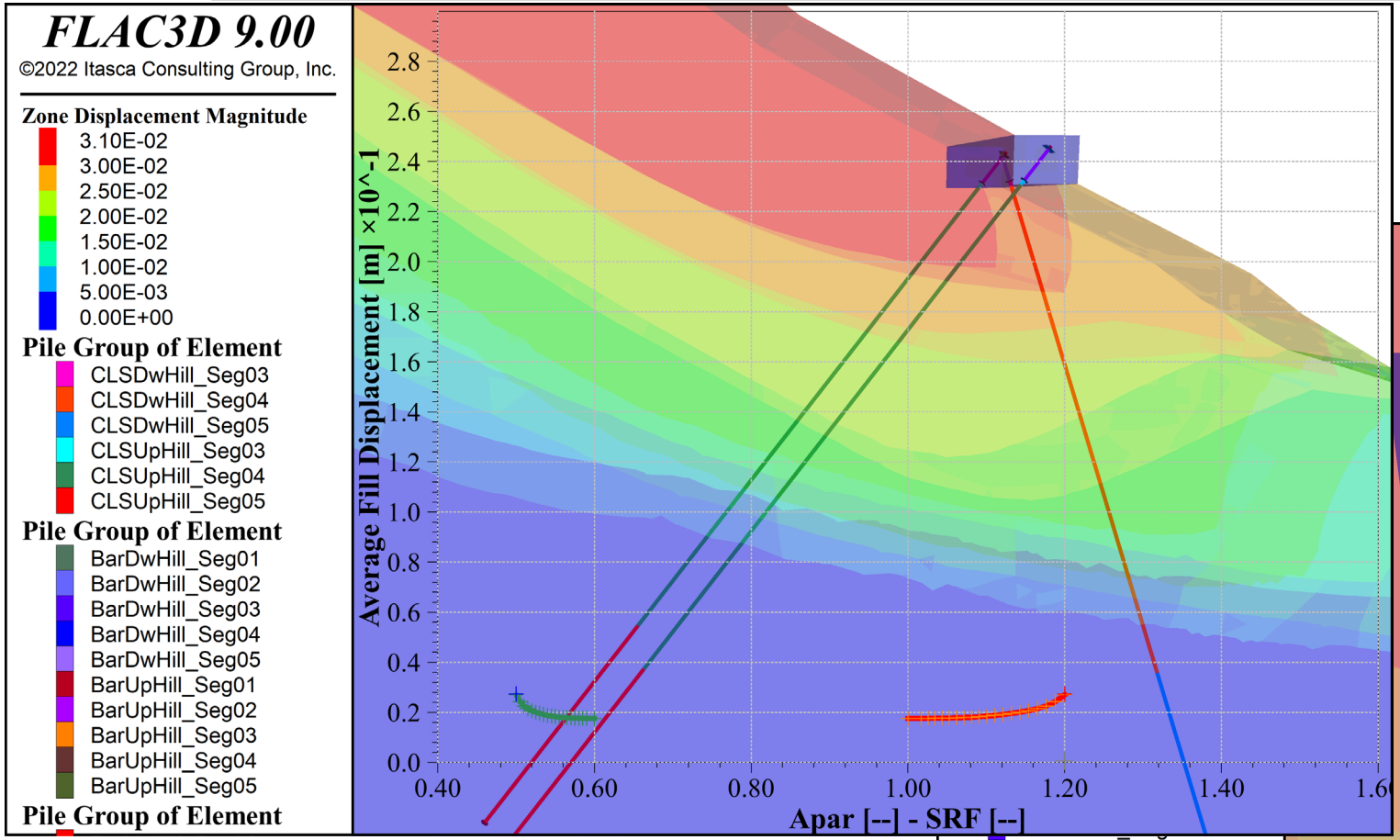


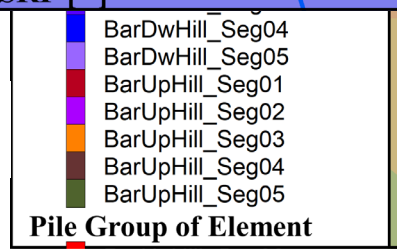


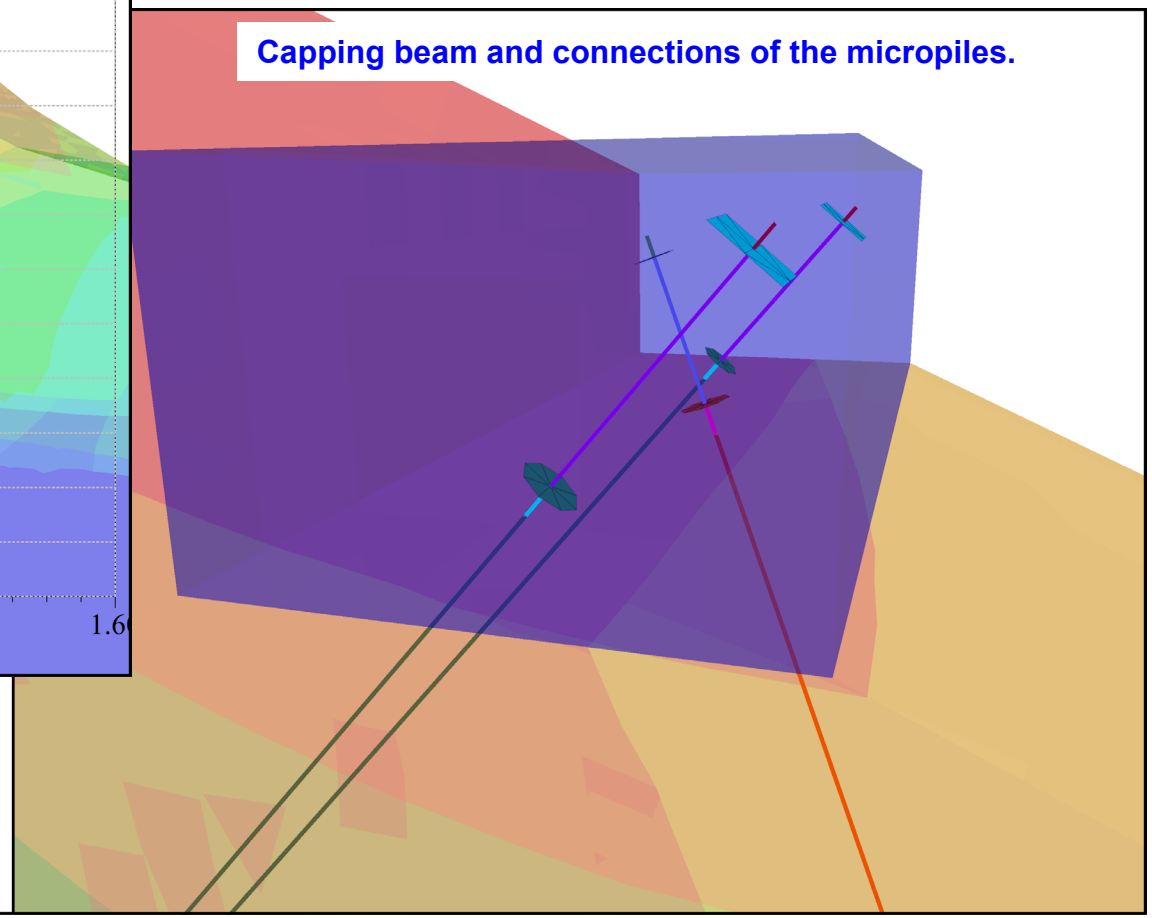
Activation of the fill. Equilibrium conditions with peak strength.



STA56 – micropile and capping beam installation (as designed)

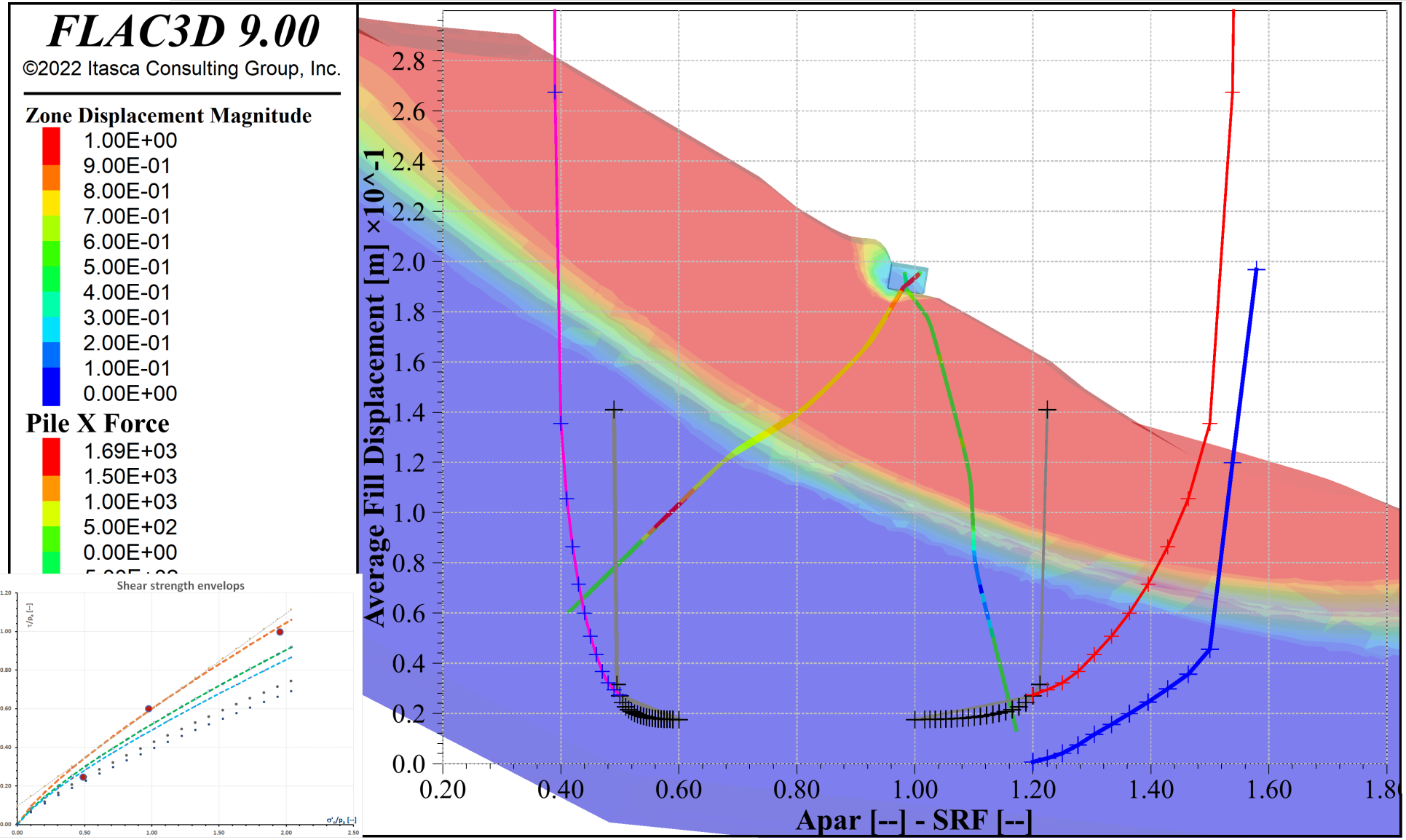






Each micropile is comprised of a central bar, grout, and casing, each component with its own strength and deformability.

STA56 – SR with intervention



After installation of the support, the strength is reduced until failure is detected. In this case multiple failure mechanisms develop: 1) passive geotechnical failure at the level of the capping beam; and 2) bending and shear failure of the central bar and casing at different locations. The first bending failure of the central bar develops inside the capping beam just outside of the contact with the casing. There is also plastic flow of the soil in between the piles.

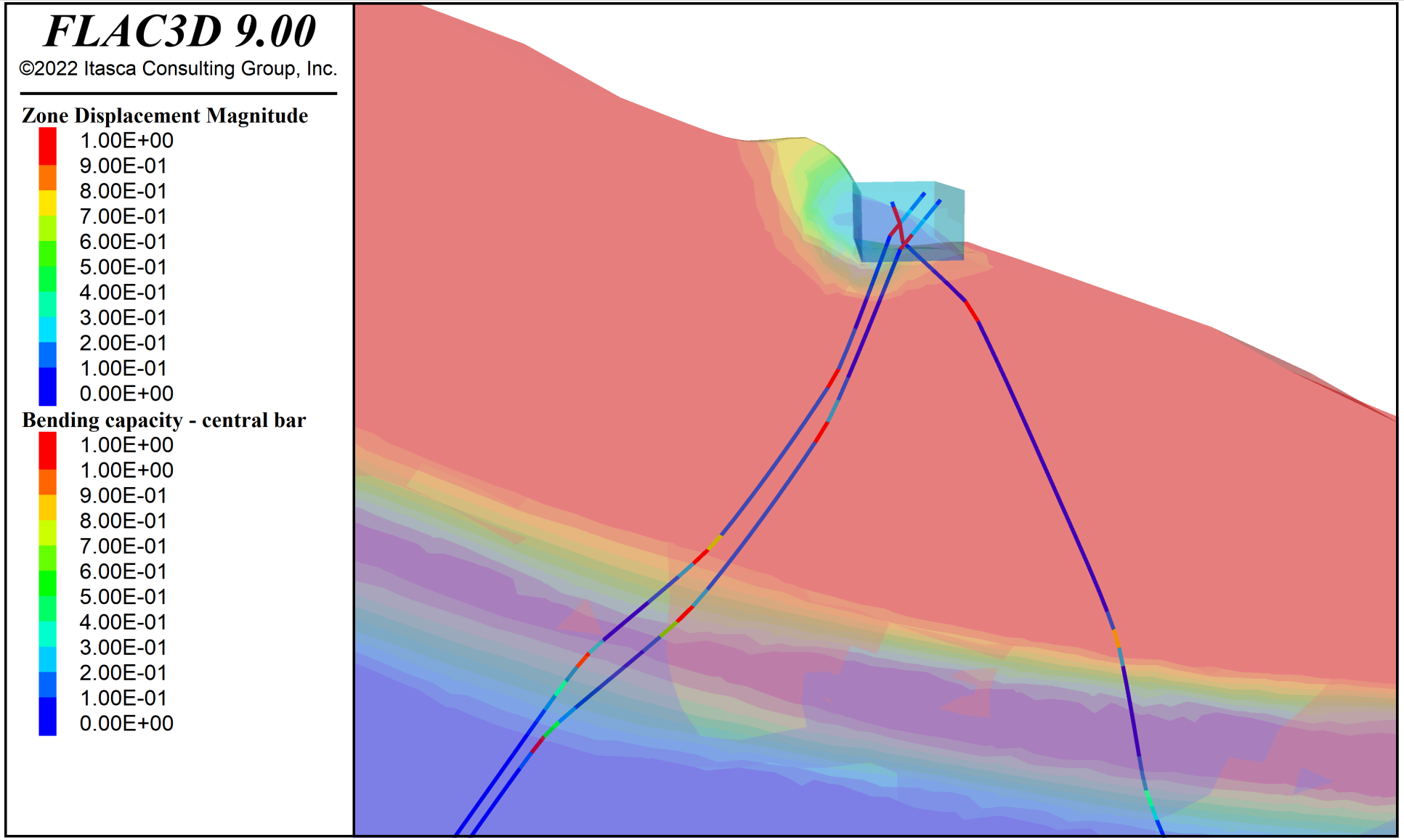
The axial capacity of the micropile on the geotechnical and structural side is not the limit factor in this case.

The model converges up to the "residual" strength (0.40–0.39) of the colluvial with a global FoS = 1.5/1.2 = 1.25.

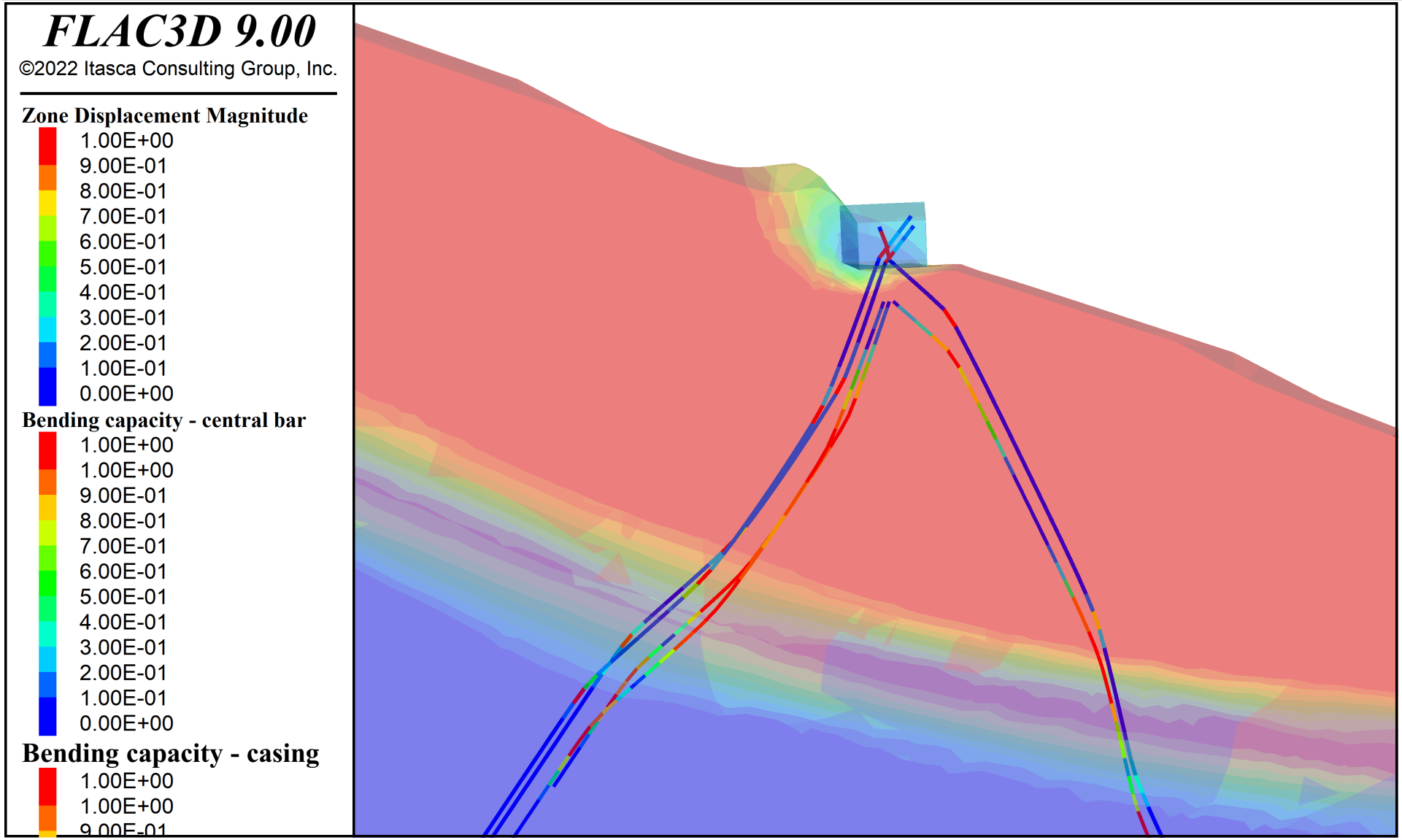
Note:

There is no physical reason to reduce the strength below residual, and therefore it does not make much sense to "impose" a global FoS disconnected from the realistic residual strength of the soil we want to support.

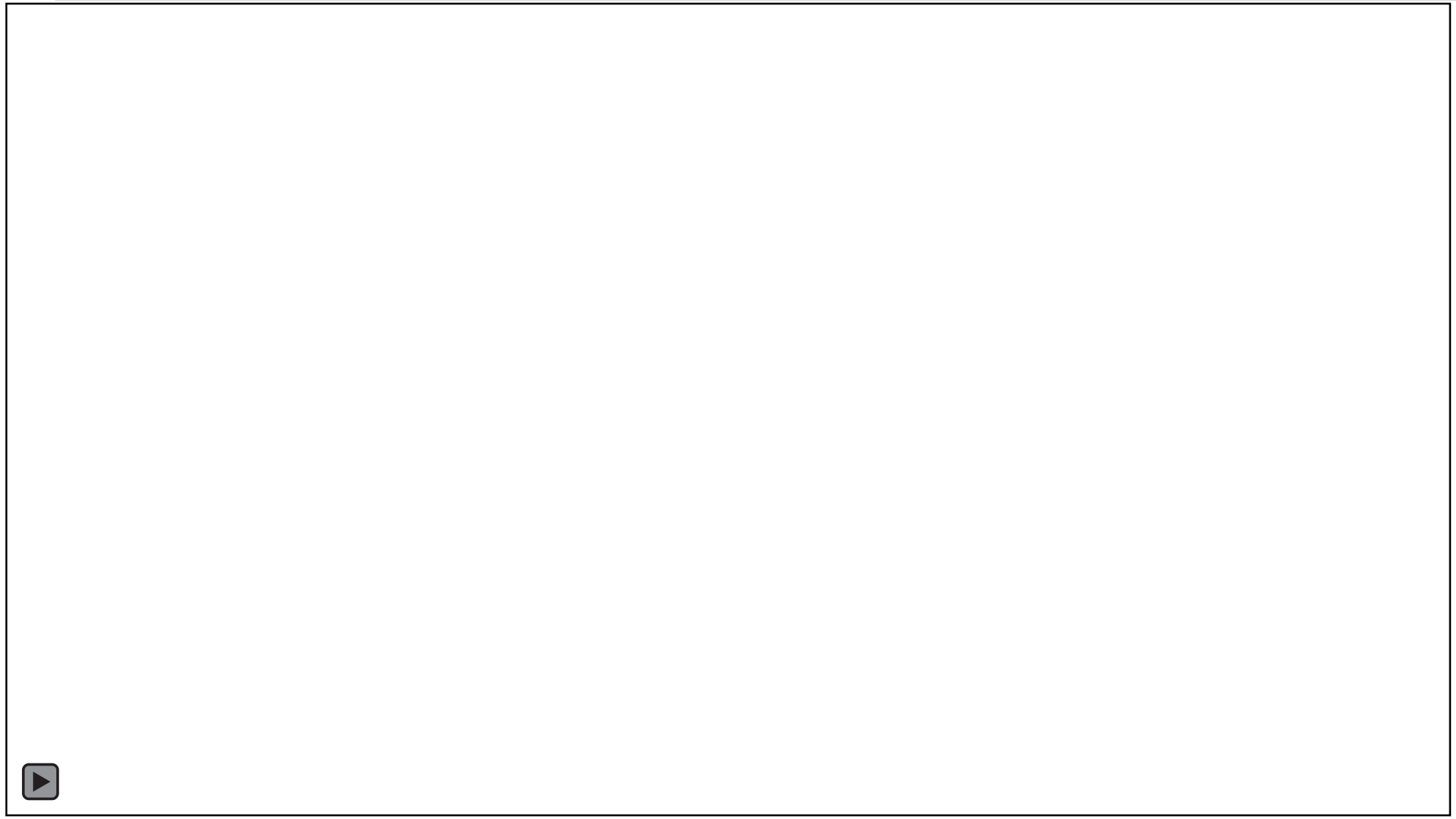
STA56 – Bending failure of the central bar



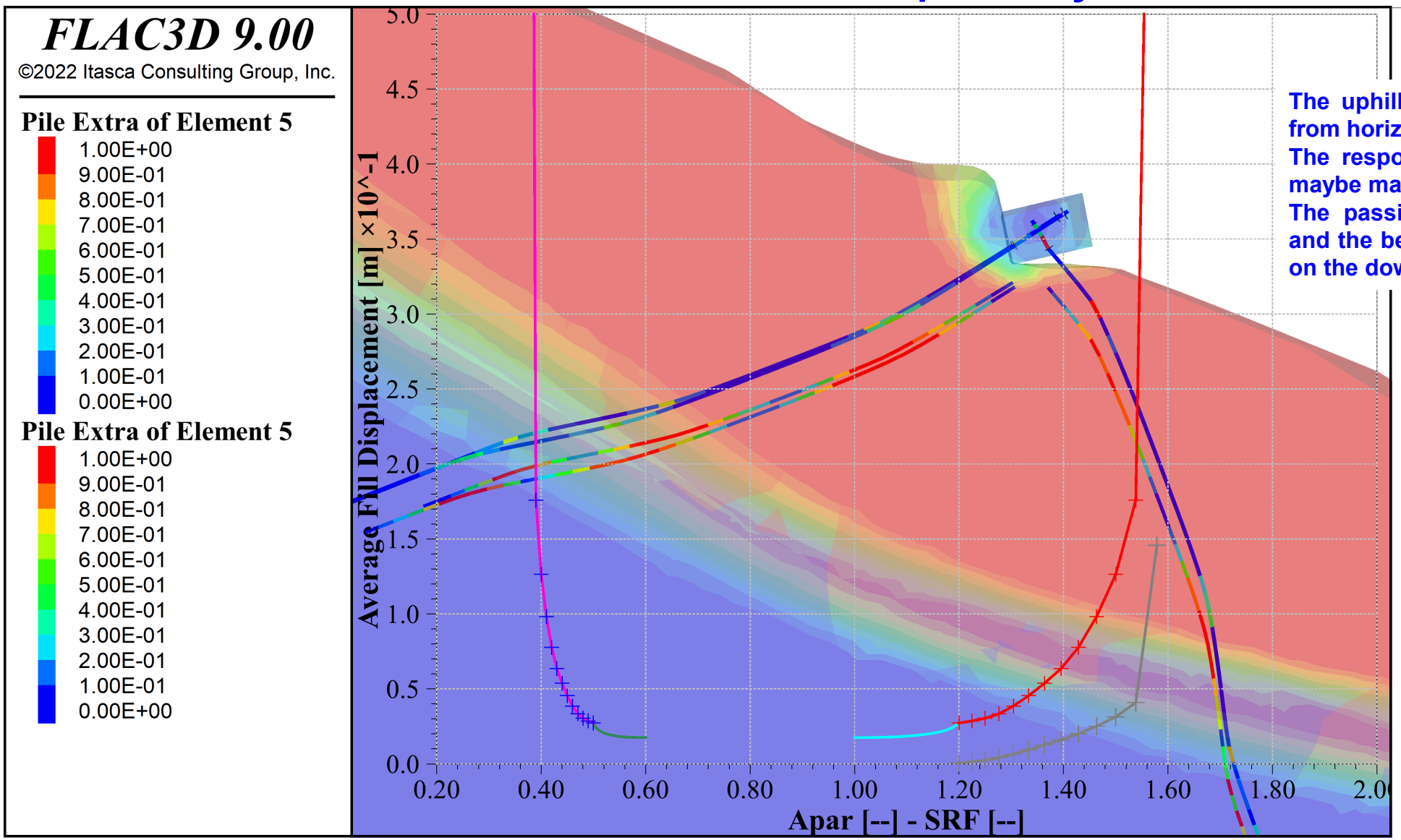
STA56 – Bending failure of the central bar and casing



STA56 – Failure mechanism progression – Movie

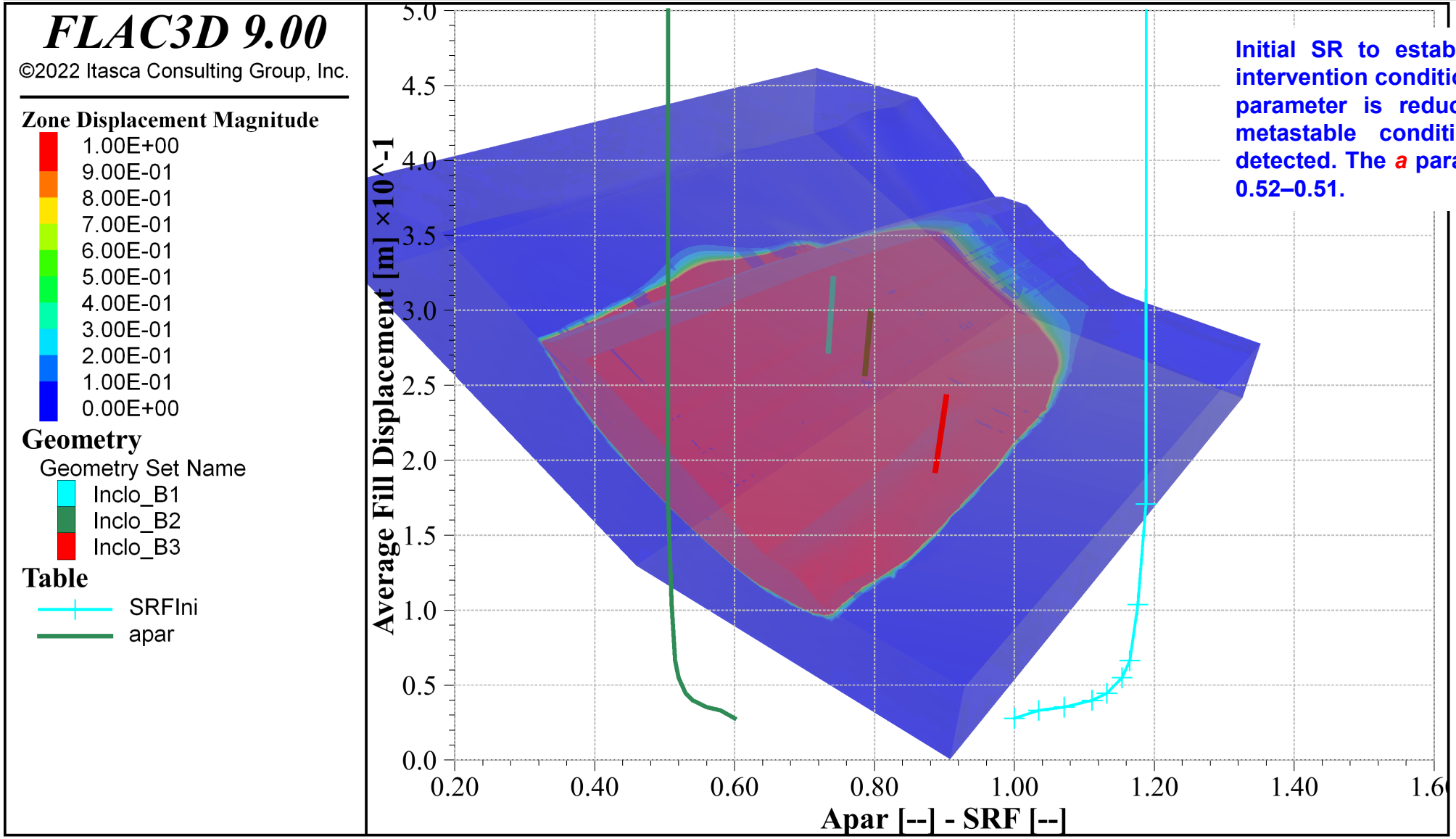


What about a different micropile layout?



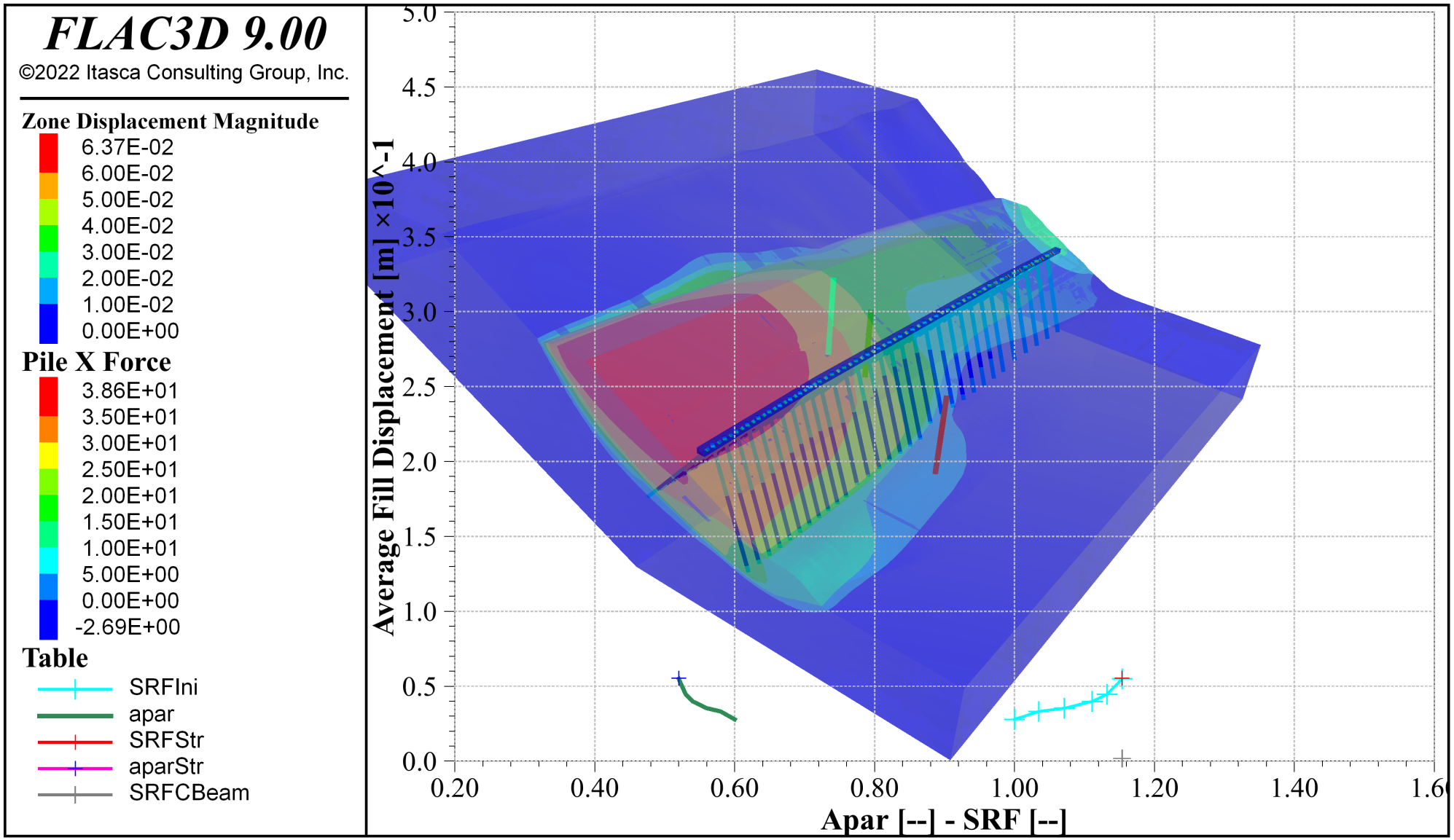
The uphill micropiles are inclined 20 degrees from horizontal.
The response of the support is quite similar, maybe marginally better.
The passive wedge failure around the beam and the bending failure of the central bar (only on the downhill side) are controlling the failure.

3D model results – pre-intervention conditions

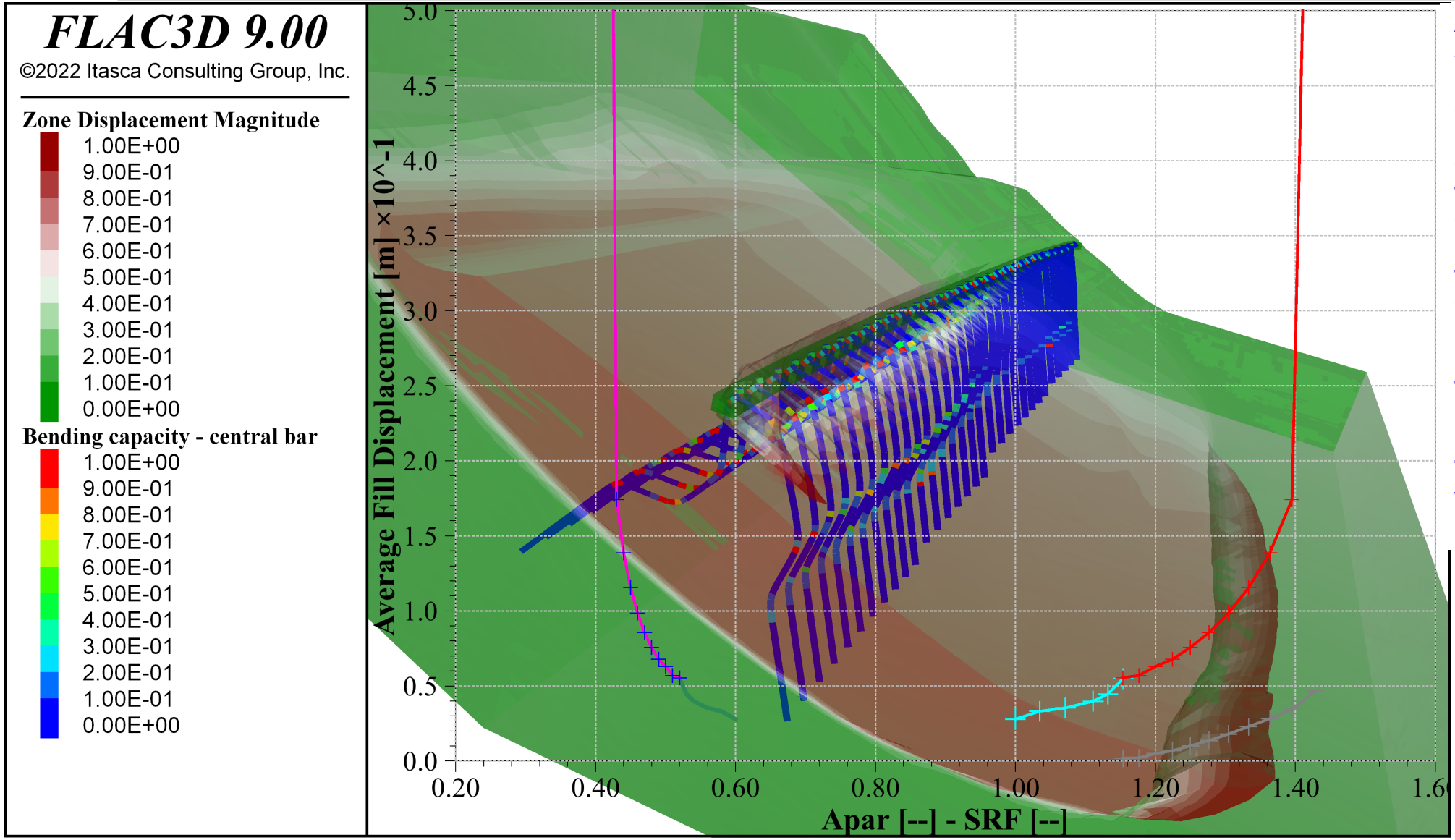


Initial SR to establish pre-intervention condition. The *a* parameter is reduced until metastable conditions are detected. The *a* parameter is 0.52–0.51.

3D model results – installation of the micropiles



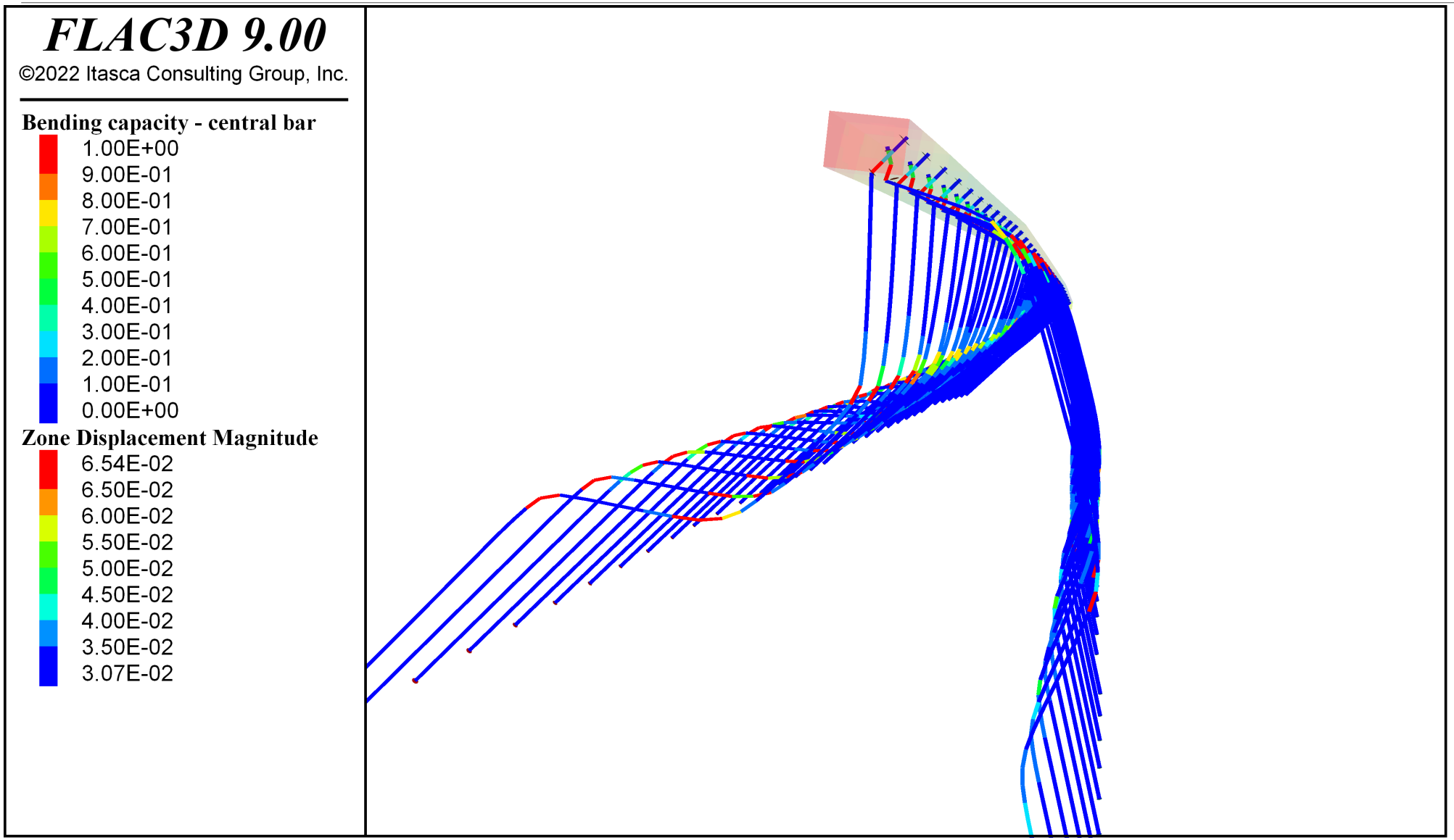
3D model results – SR with intervention



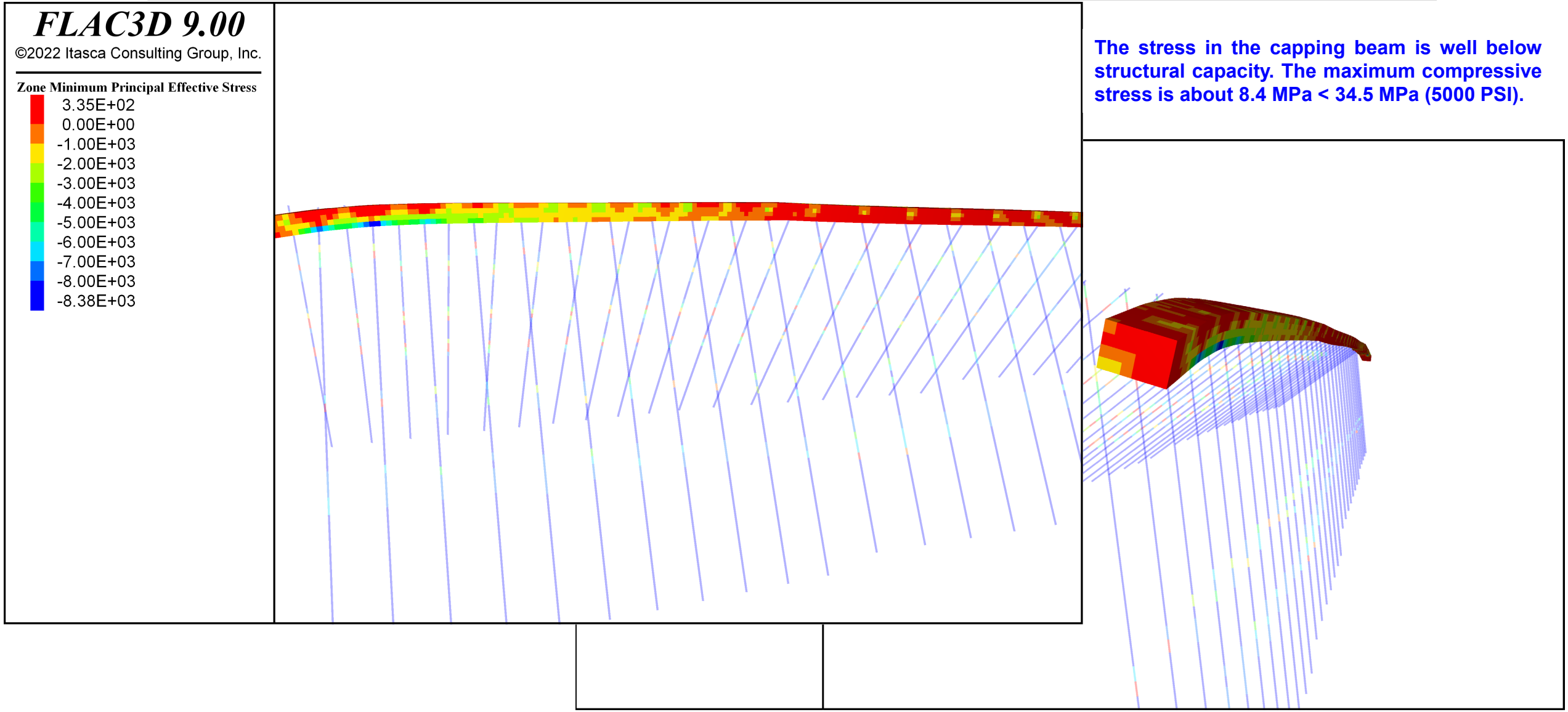
After installation of the support, the strength is reduced until failure is detected. In this case, multiple failure mechanisms develop: 1) passive geo-technical failure at the level of the capping beam; and 2) bending and shear failure of the central bar and casing at different locations. The model converges up to the residual strength (0.42) of the colluvial with a global FoS = 1.4/1.2 = 1.15.

The 3D model provides a worse response than the 2.5 D slice at STa56.

3D model results – structural failure mechanism

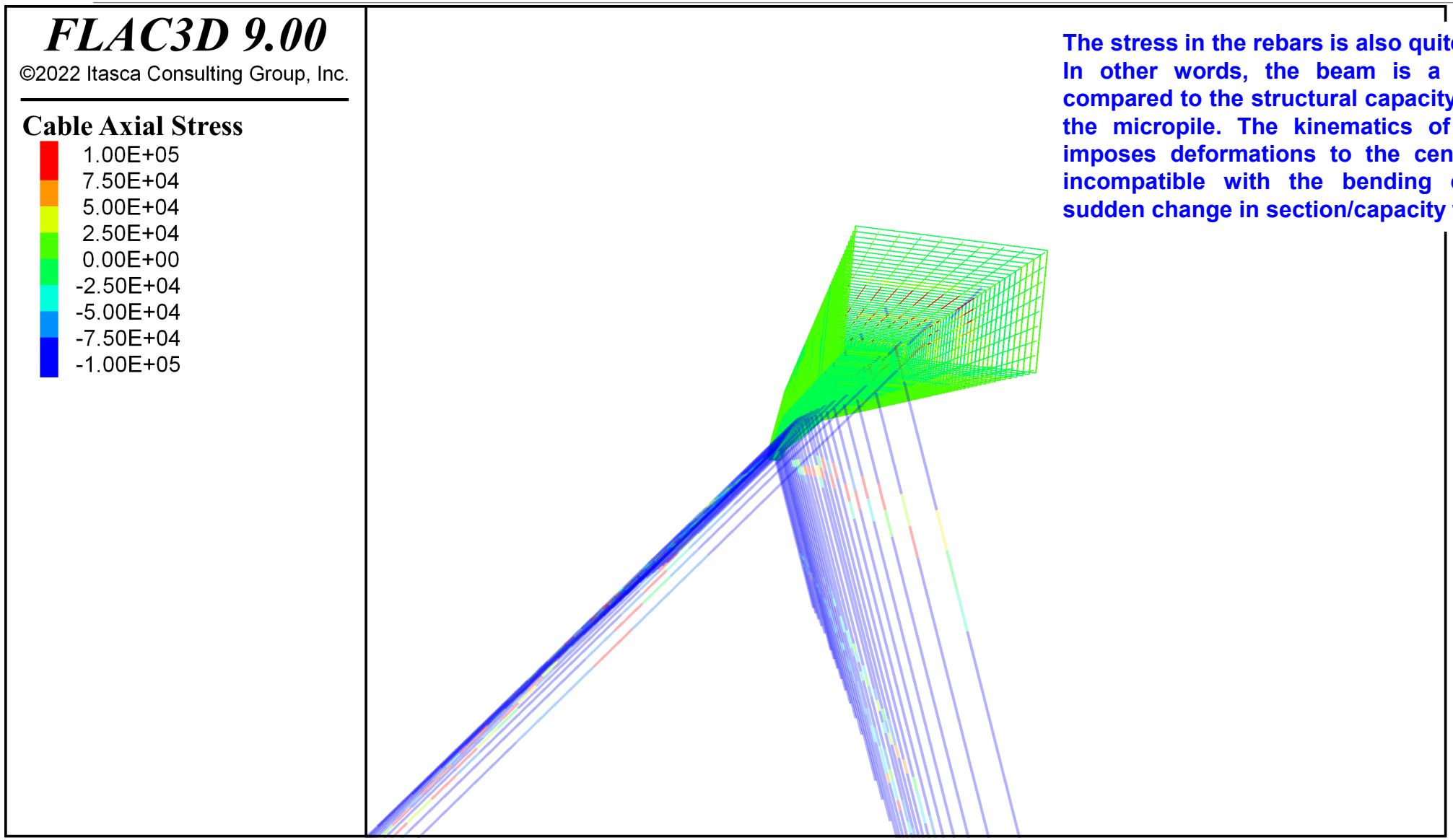


3D model results – compressive stress in the beam



The stress in the capping beam is well below structural capacity. The maximum compressive stress is about 8.4 MPa < 34.5 MPa (5000 PSI).

3D model results



The stress in the rebars is also quite low and not critical. In other words, the beam is a very strong element compared to the structural capacity of the central bars of the micropile. The kinematics of the potential failure imposes deformations to the central bar that become incompatible with the bending capacity due to the sudden change in section/capacity with the casing.

Summary

A-Frame micropile structures are a relatively common technique for improving slope performance/stability.

For this type of supports, the soil structure interaction aspect could be complex, kinematic dependent, and the interaction with the capping beam requires particular attention.

The structural components should be designed to achieve/guide the main failure mechanism as desired.

For example, a strong capping beam could lead to premature failure of the micropile.

In many of these cases, the axial capacity of the micropile is not controlling the performance. In fact, the kinematics of the slides impose a mostly shear/bending demand on the elements. It could be more informative/appropriate to perform horizontal load tests instead of axial load tests for the piles.

It is common practice to require a target global safety factor for these improvement systems. However, in several cases, the requirement could be disconnected from the soil properties in terms of minimum/residual strength.

Note:
In this case, a potential higher-performing solution could have been to add a second line of micropiles at a higher elevation and connecting the two rows. The multi-frame structure would have mitigated the local passive failure and reduced the local rotation of beam that leads to the central bar structural failure.

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rocscience

DFI S3 Conference Software Discussion

July 28, 2022

Rocscience session presented by:



Sina Javankhoshdel
Ph.D., P.Eng.



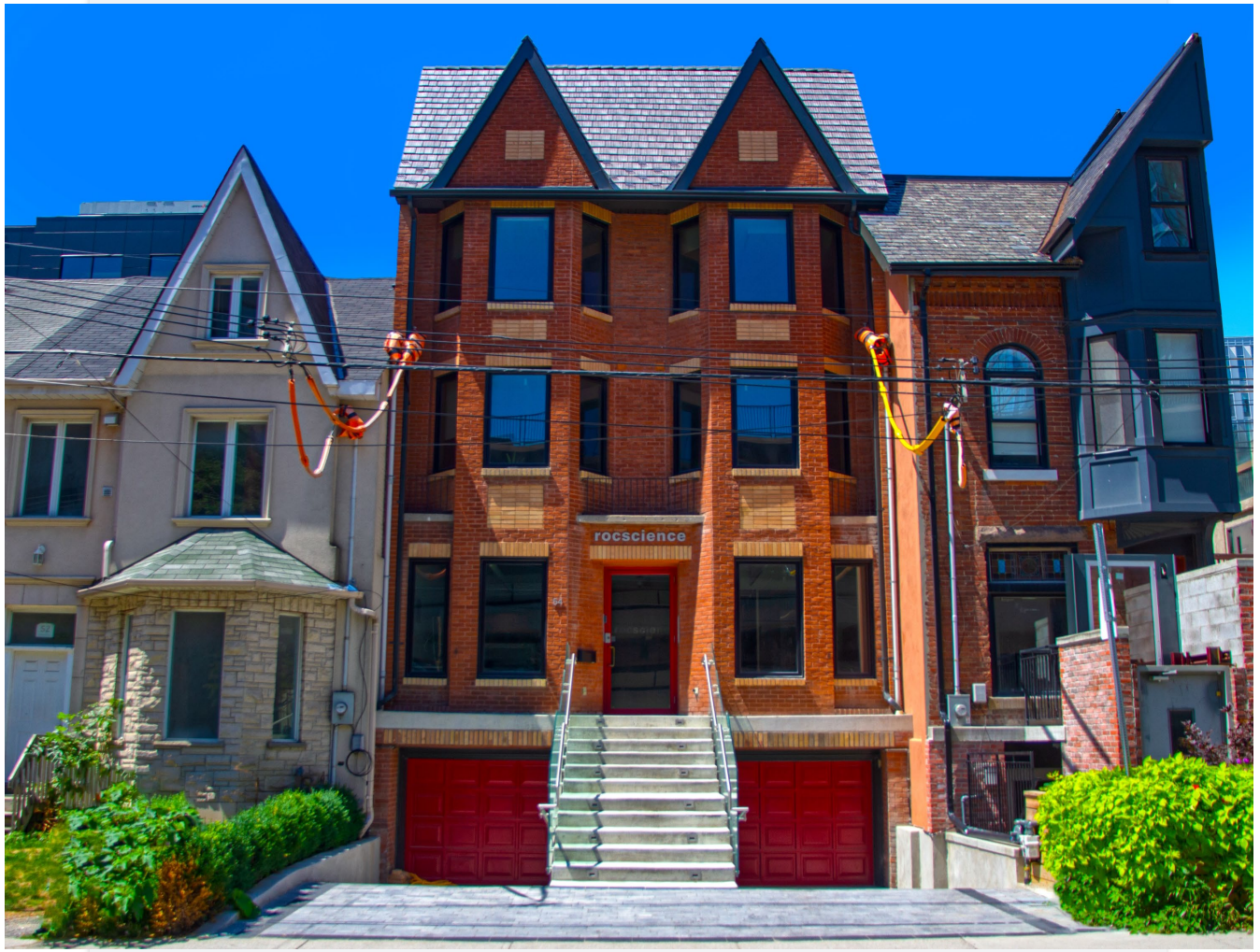
Jeff Lam
M.Eng., P.Eng.

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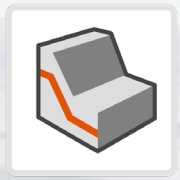


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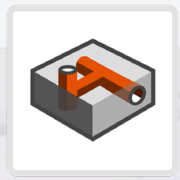
Rocscience Software Suite

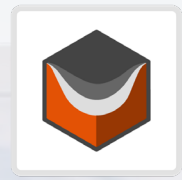

Slide2

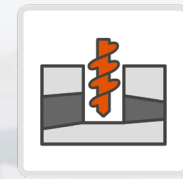

Slide3


RS2


RS3


EX3


Settle3


RSLog


RocFall2


RocFall3


SWedge

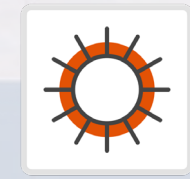

UnWedge


RSPile


RSData


Dips


RocPlane

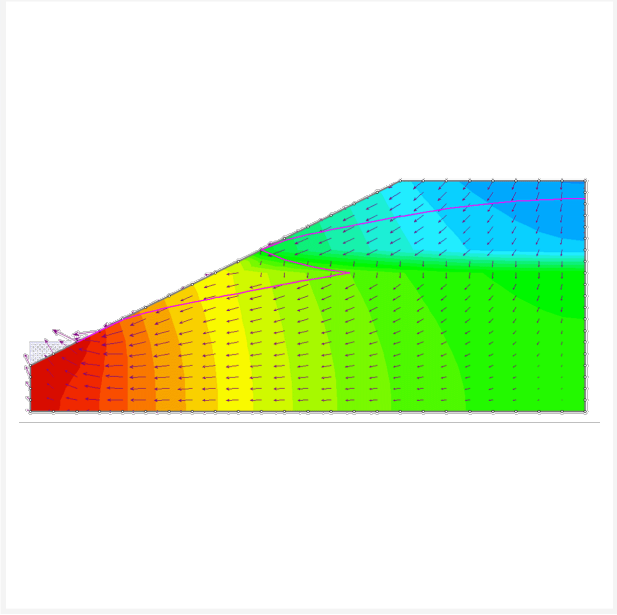

RocSupport


RocTopple

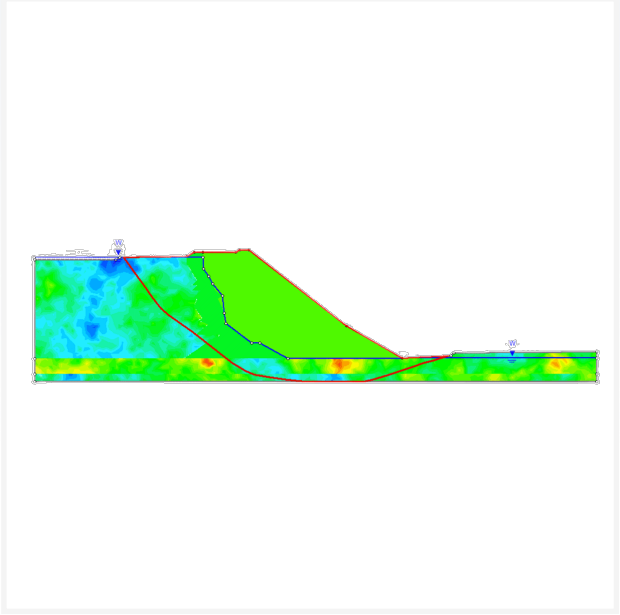

CPillar

Slide2

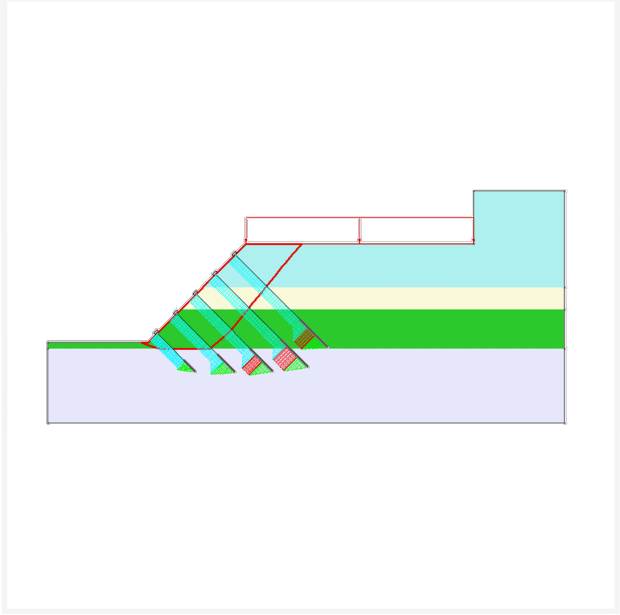
2D Limit Equilibrium Analysis for Slopes (with FEM seepage analysis)



Built-in Groundwater Seepage Analysis



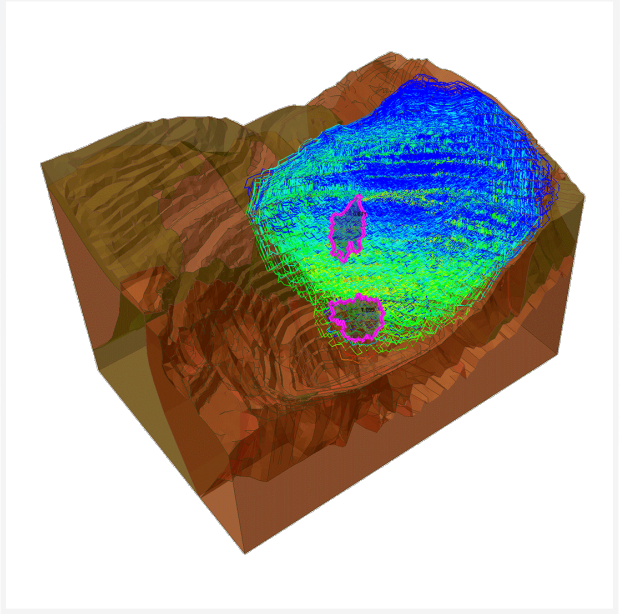
Probabilistic Analysis



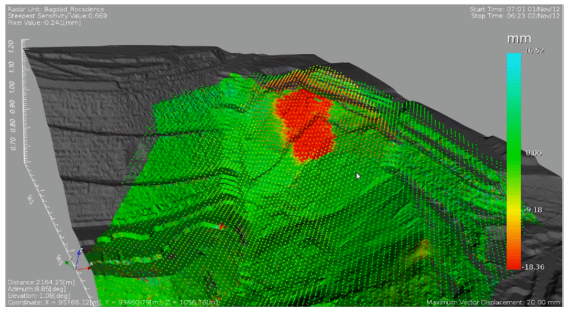
Supports

Slide3

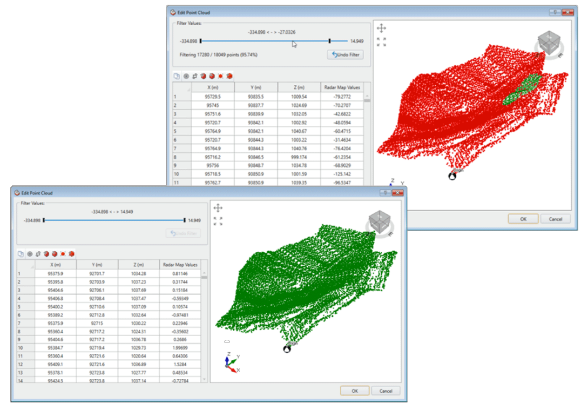
3D Limit Equilibrium Analysis for Slopes



Powerful Failure Surface Searching



Integration with Radar Data

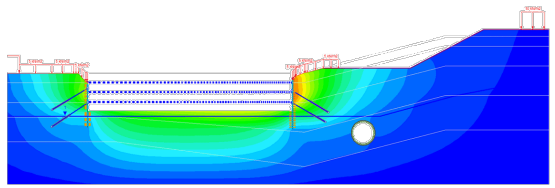


3D Model Creation – Point cloud, LiDAR, Leapfrog

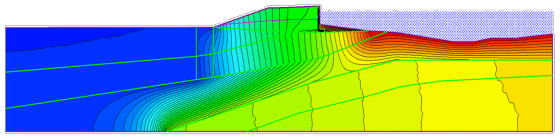
rocscience

RS2

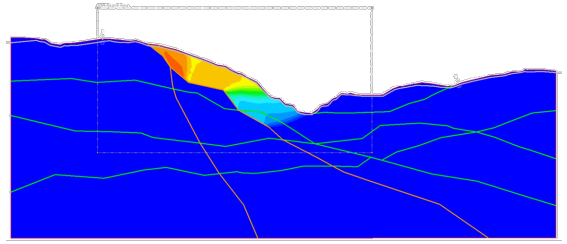
2D Finite Element Analysis



Surface & Underground Excavations



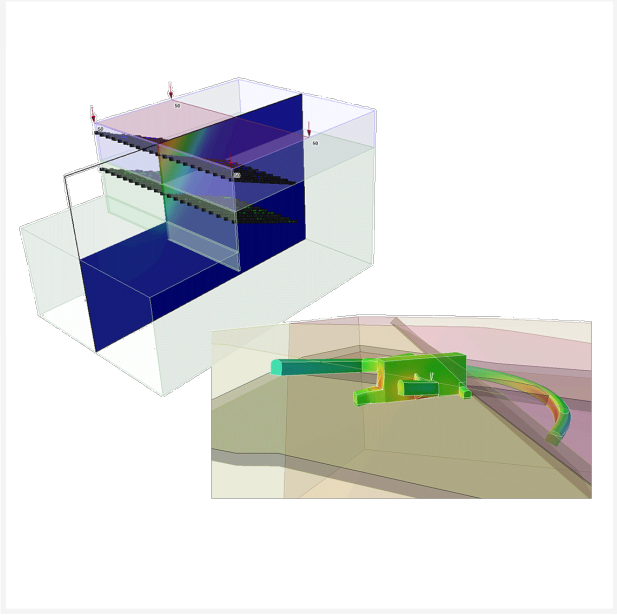
Groundwater Seepage Analysis



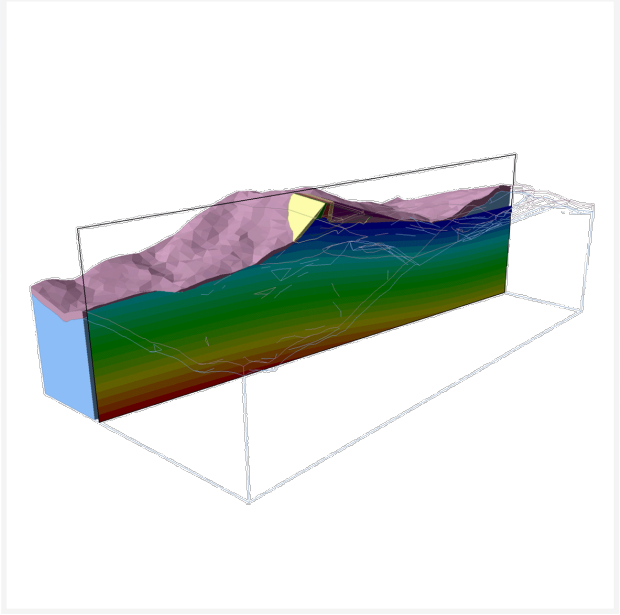
Shear Strength Reduction

RS3

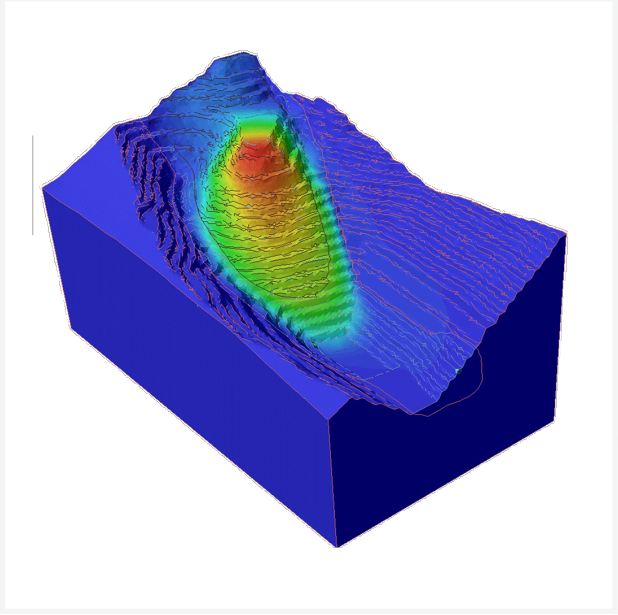
3D Finite Element Analysis



Surface & Underground Excavation



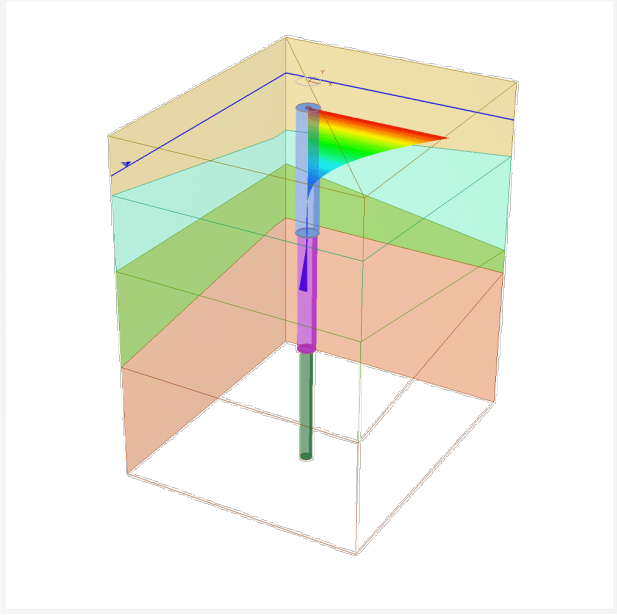
Groundwater Seepage



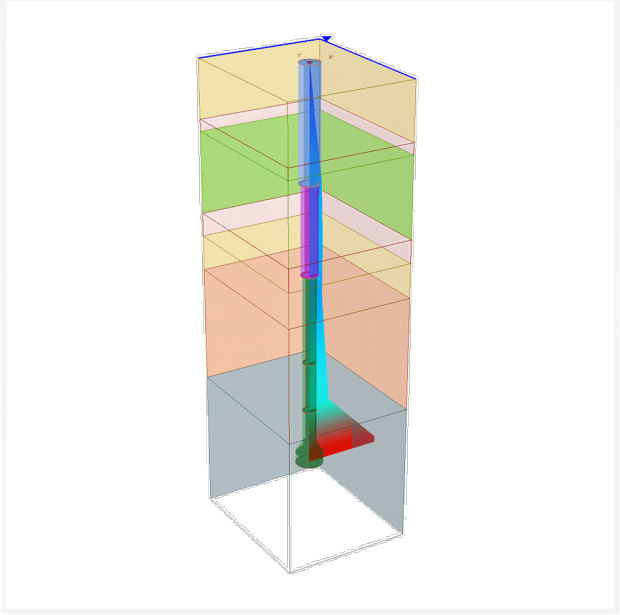
Shear Strength Reduction

RSPile

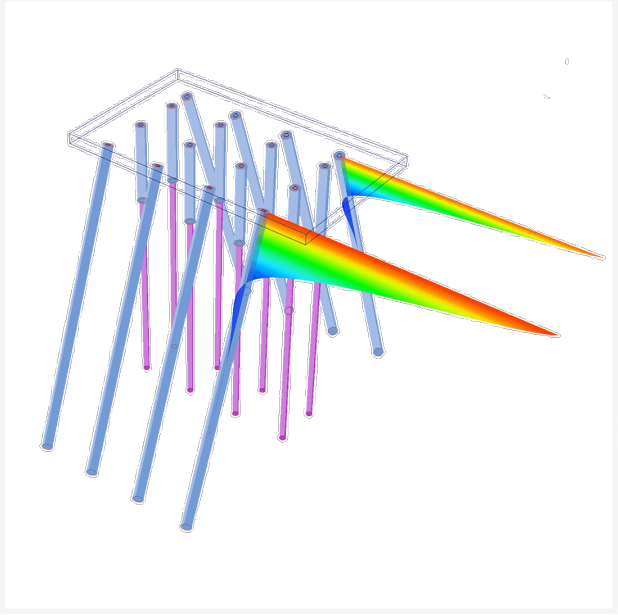
3D Pile Analysis



Driven, Lateral, and Axial Pile Analysis



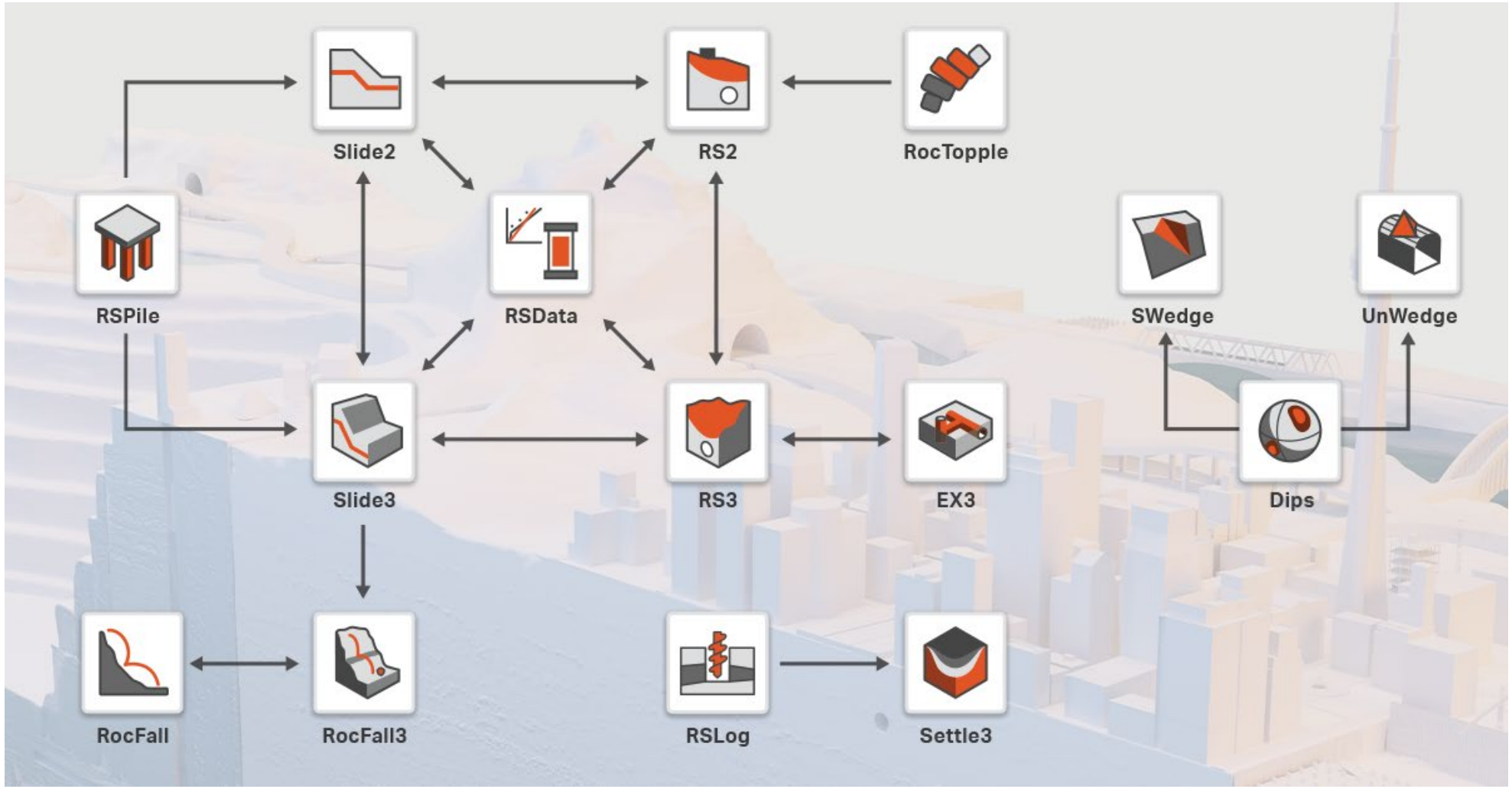
Pile Capacity Analysis



Grouped Pile Analysis

rocscience

Rocscience Software Integrations



Analysis Workflow

1. Obtain baseline FoS without supports at STA 56+00 using RS2 and Slide2.

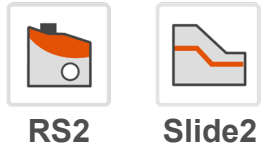


2. Obtain FoS with supports using a variety of methods.

2D Finite Element only
Model upper and lower pile in the same plane as pile cap.



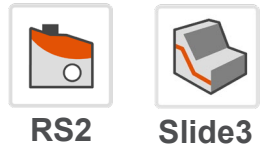
2D Finite Element and 2D Limit Equilibrium
Obtain pile forces from RS2 then apply pile forces to Slide2 model.



2D Finite Element and 2D Limit Equilibrium
Obtain pile displacement from RS2, obtain forces from RSPile, apply forces from RSPile to Slide2 model.



2D Finite Element and 3D Limit Equilibrium
Obtain pile forces from RS2 then apply pile forces to Slide3 model.



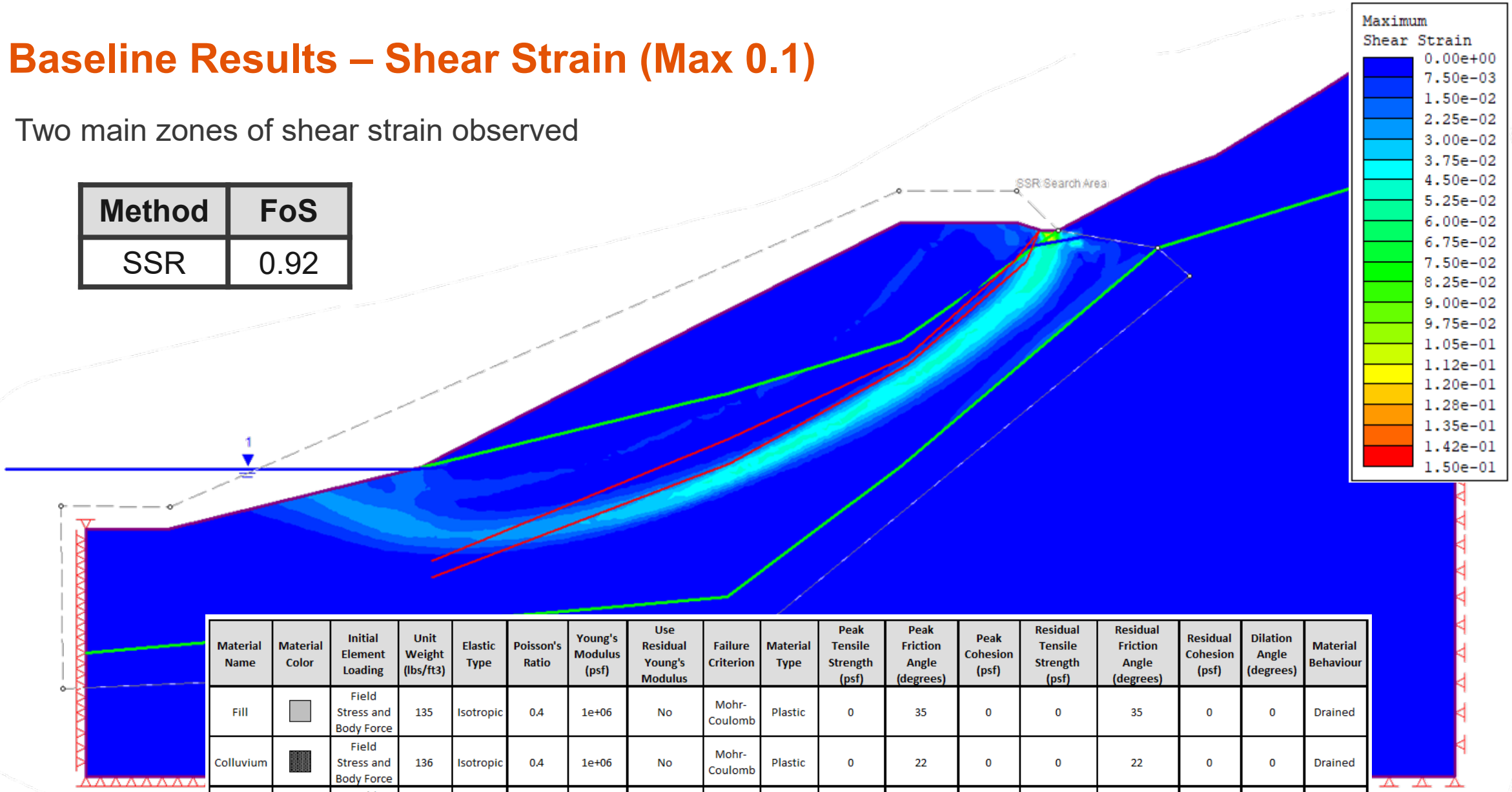
3D Finite Element Analysis
Model true 3D configuration and behavior of system.



Baseline Results – Shear Strain (Max 0.1)

Two main zones of shear strain observed

Method	FoS
SSR	0.92

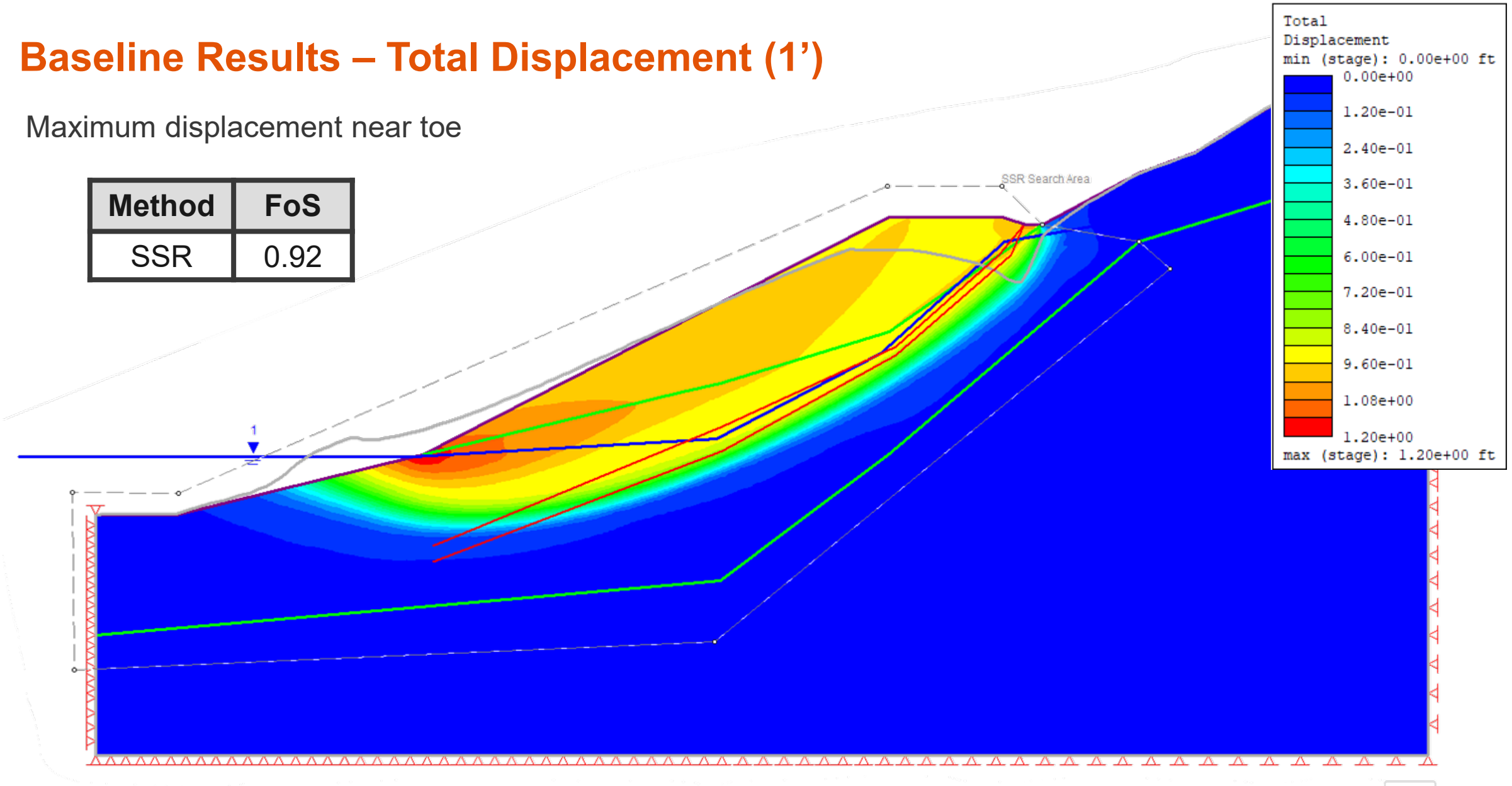


Material Name	Material Color	Initial Element Loading	Unit Weight (lbs/ft3)	Elastic Type	Poisson's Ratio	Young's Modulus (psf)	Use Residual Young's Modulus	Failure Criterion	Material Type	Peak Tensile Strength (psf)	Peak Friction Angle (degrees)	Peak Cohesion (psf)	Residual Tensile Strength (psf)	Residual Friction Angle (degrees)	Residual Cohesion (psf)	Dilation Angle (degrees)	Material Behaviour
Fill		Field Stress and Body Force	135	Isotropic	0.4	1e+06	No	Mohr-Coulomb	Plastic	0	35	0	0	35	0	0	Drained
Colluvium		Field Stress and Body Force	136	Isotropic	0.4	1e+06	No	Mohr-Coulomb	Plastic	0	22	0	0	22	0	0	Drained
Bedrock		Field Stress and Body Force	150	Isotropic	0.4	1e+06		Mohr-Coulomb	Elastic	0	35	219.3					Drained

Baseline Results – Total Displacement (1')

Maximum displacement near toe

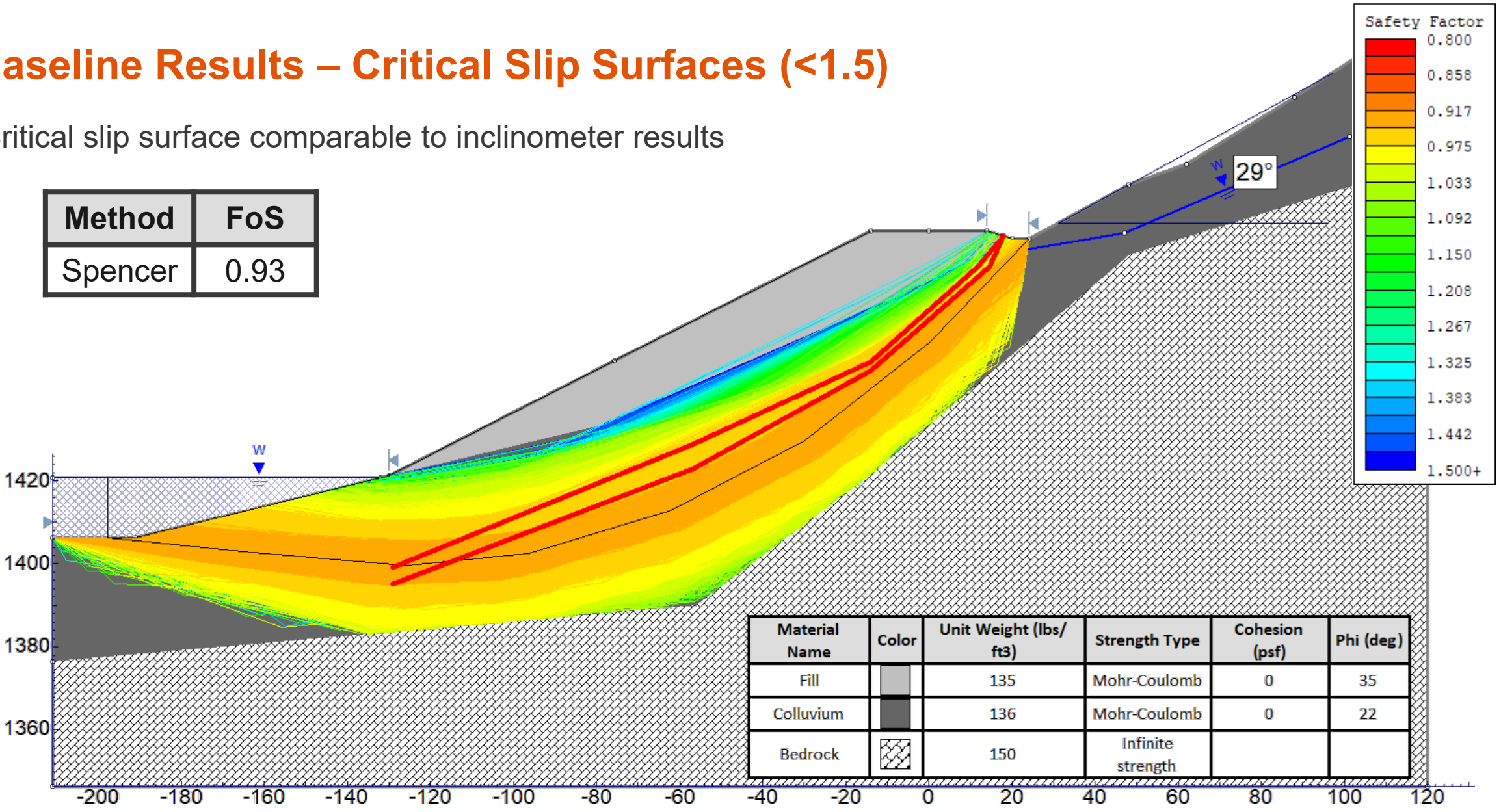
Method	FoS
SSR	0.92



Baseline Results – Critical Slip Surfaces (<1.5)

Critical slip surface comparable to inclinometer results

Method	FoS
Spencer	0.93

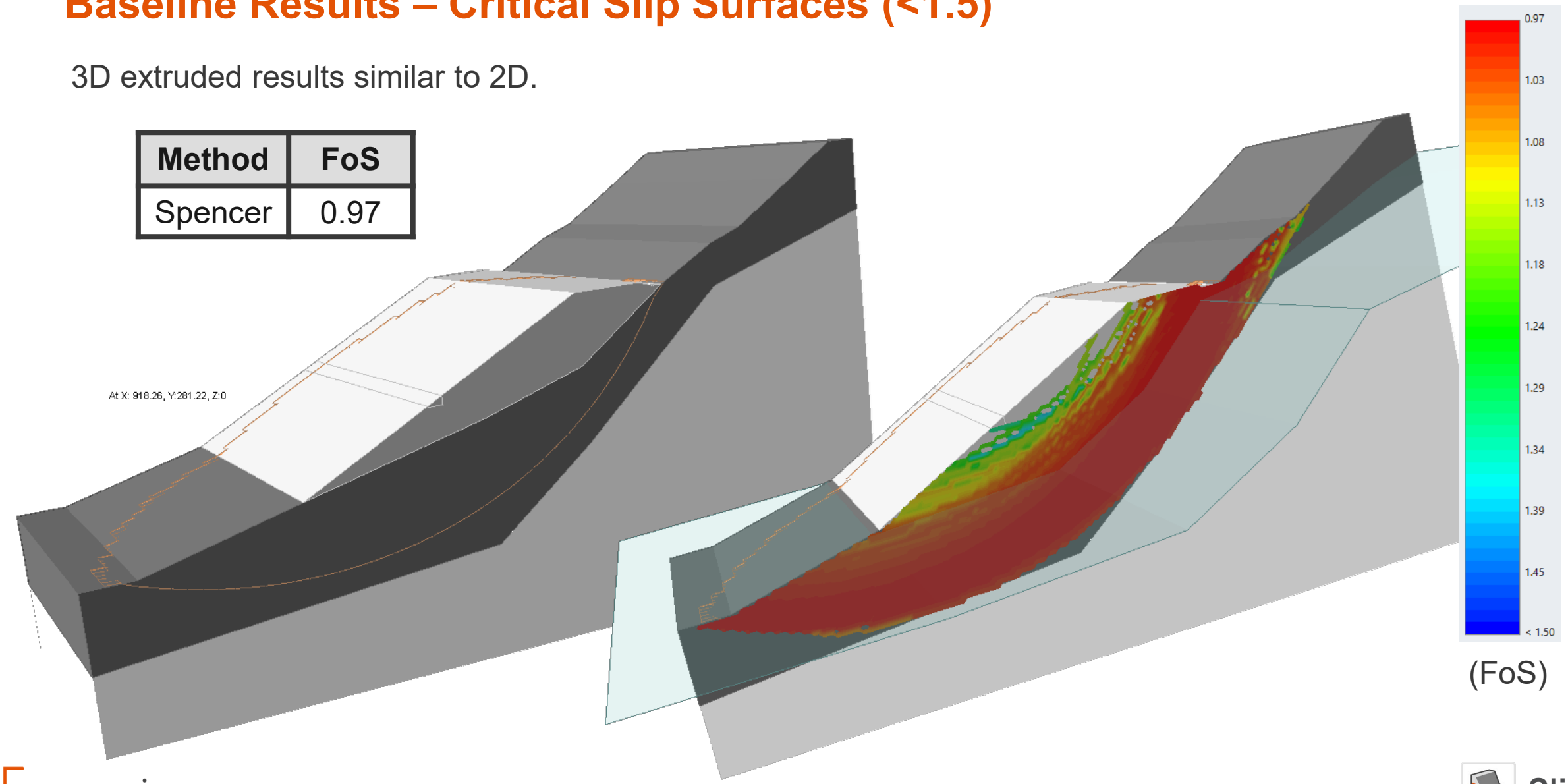


Material Name	Color	Unit Weight (lbs/ ft3)	Strength Type	Cohesion (psf)	Phi (deg)
Fill		135	Mohr-Coulomb	0	35
Colluvium		136	Mohr-Coulomb	0	22
Bedrock		150	Infinite strength		

Baseline Results – Critical Slip Surfaces (<1.5)

3D extruded results similar to 2D.

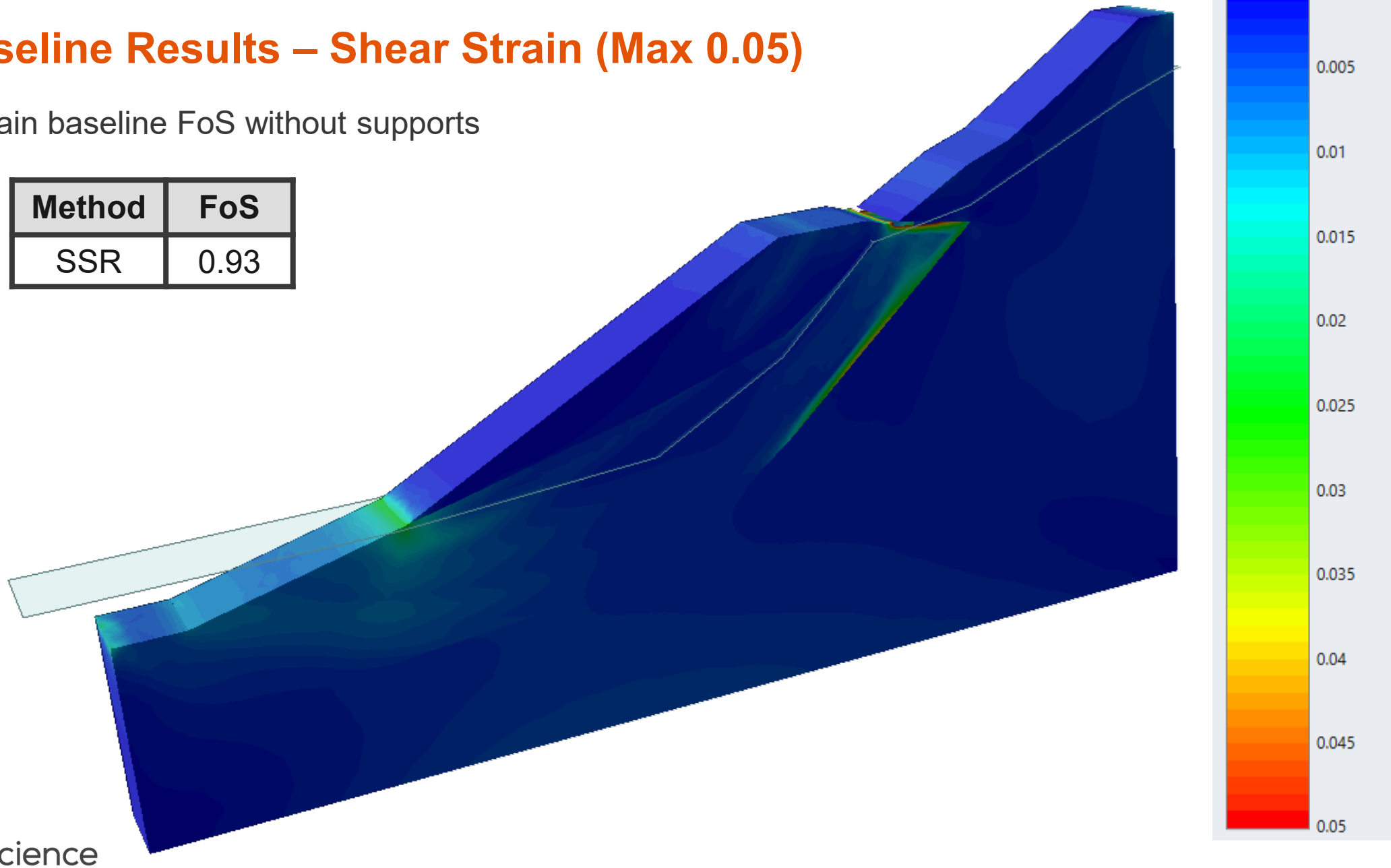
Method	FoS
Spencer	0.97



Baseline Results – Shear Strain (Max 0.05)

Obtain baseline FoS without supports

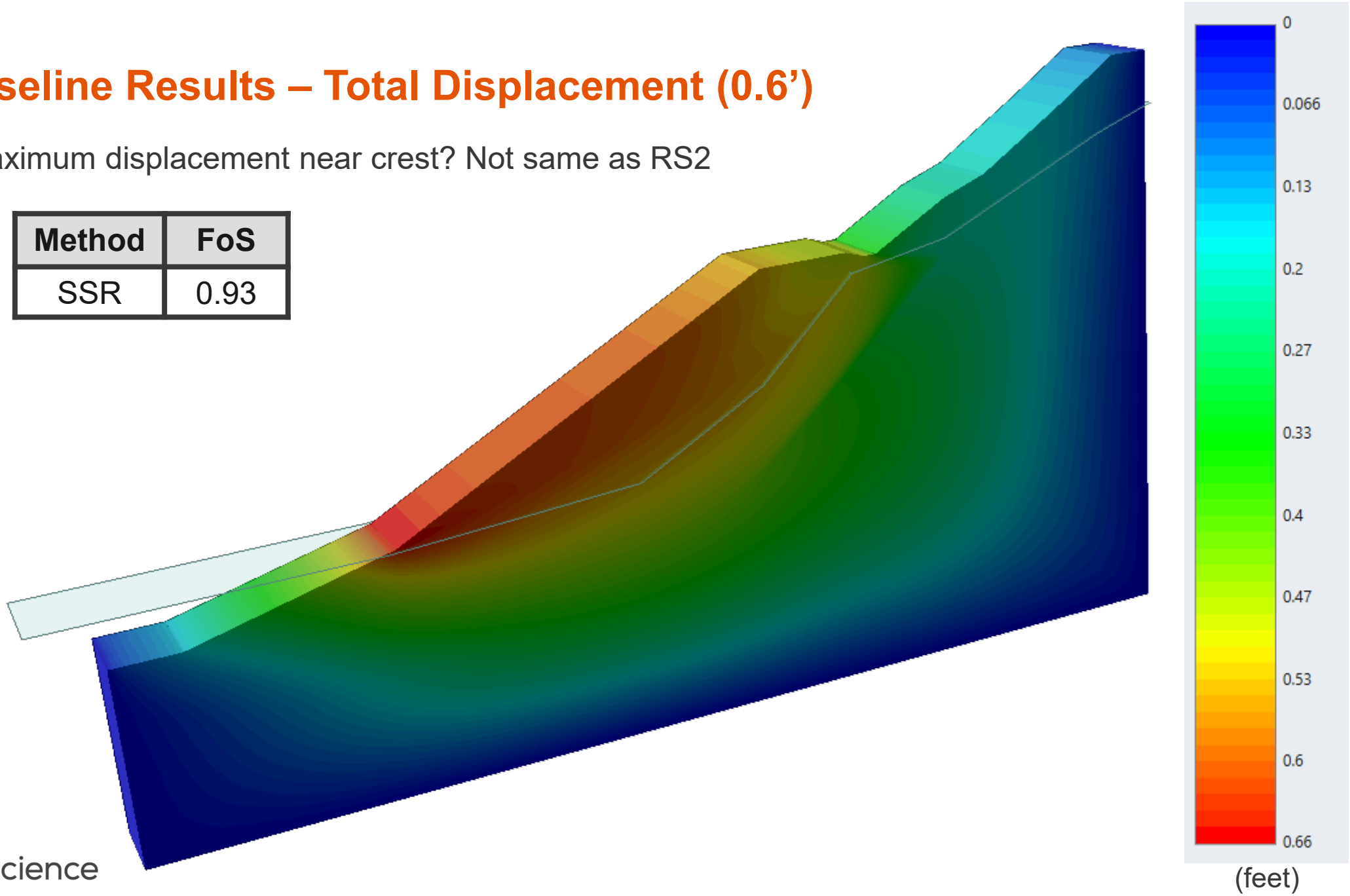
Method	FoS
SSR	0.93



Baseline Results – Total Displacement (0.6’)

*Maximum displacement near crest? Not same as RS2

Method	FoS
SSR	0.93

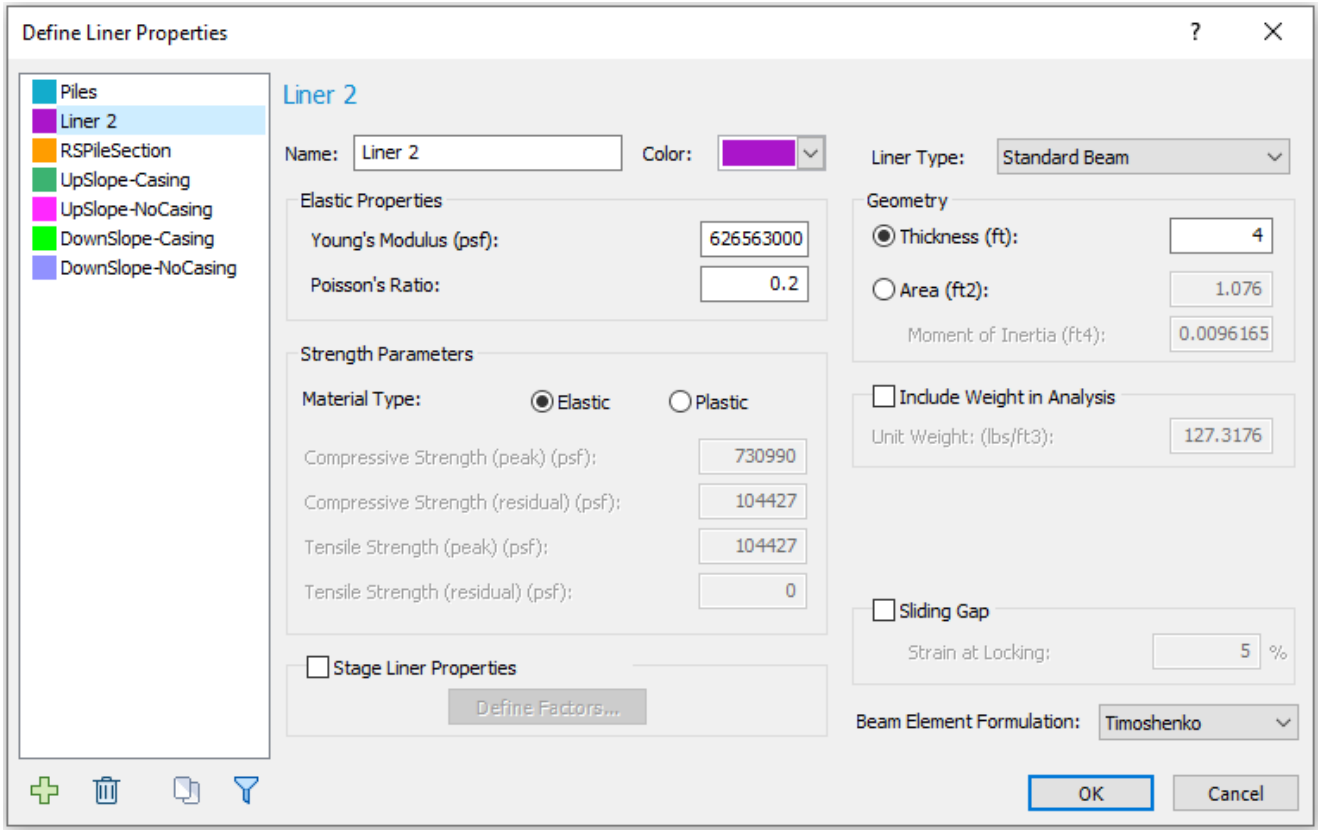


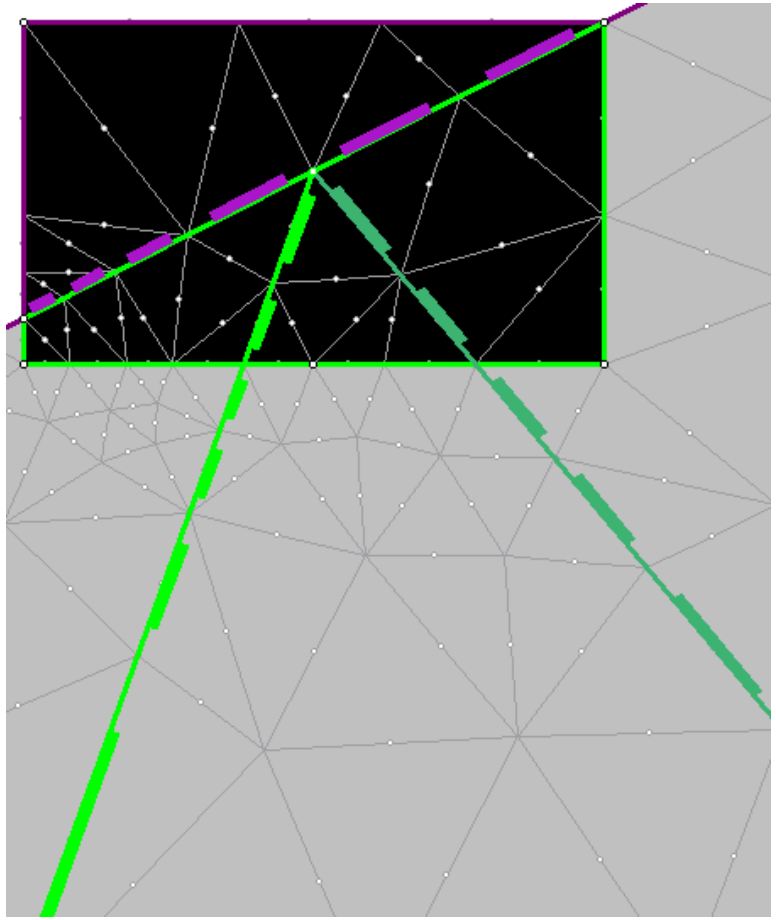
FoS Summary

Scenario	RS2	Slide2	Slide3	RS3	Target FoS
Baseline	0.92	0.93	0.97	0.93	-
With Supports					1.5

Modeling A-frame structure components

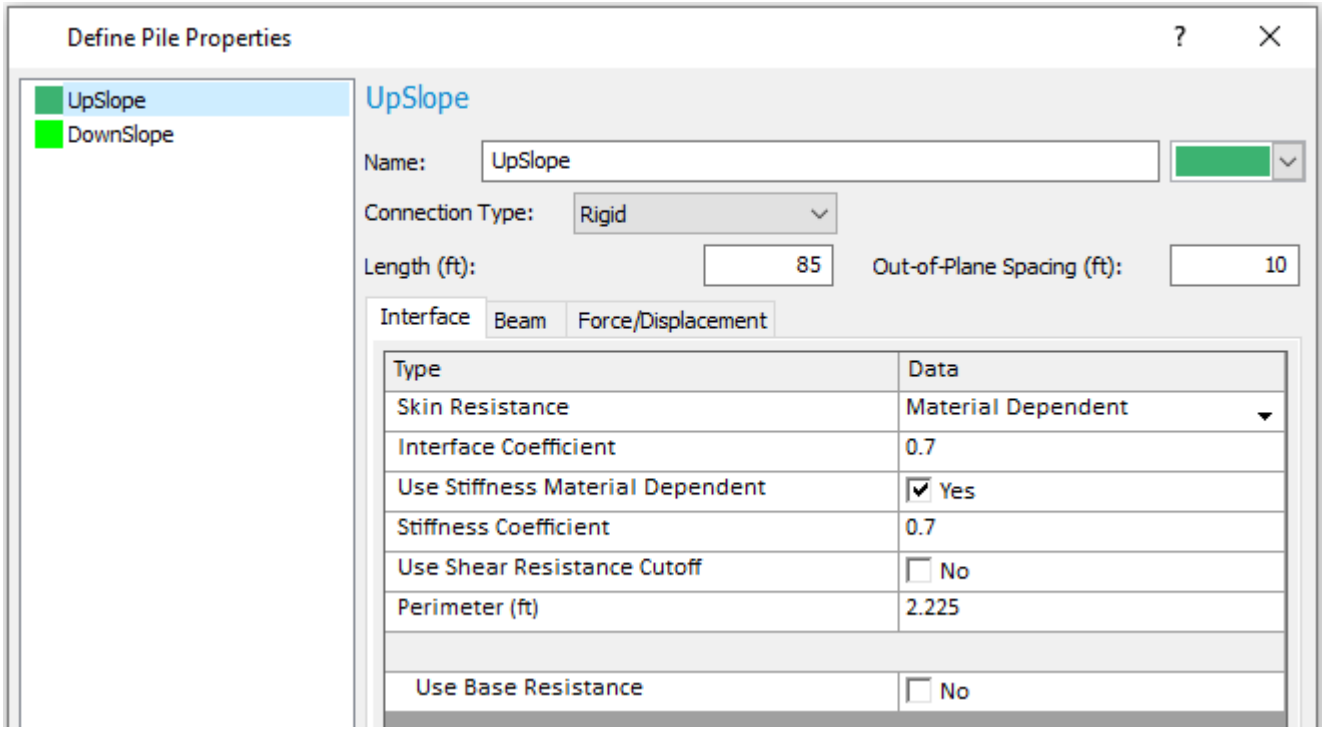
Set-up pile cap using liners in RS2

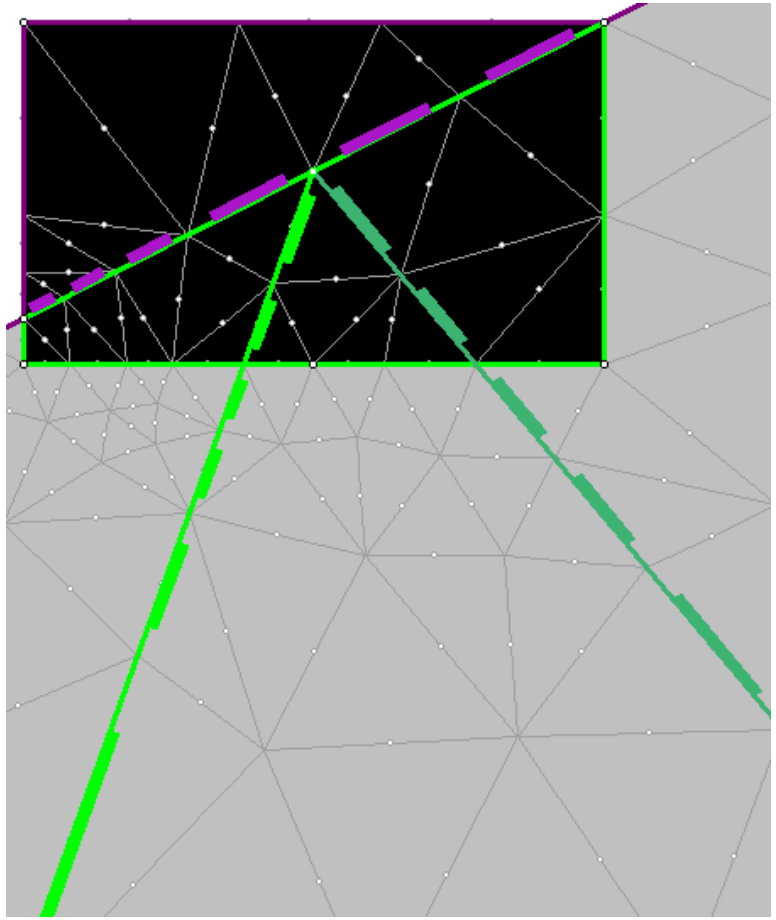




Modeling A-frame structure components

Set-up piles using pile support type in RS2

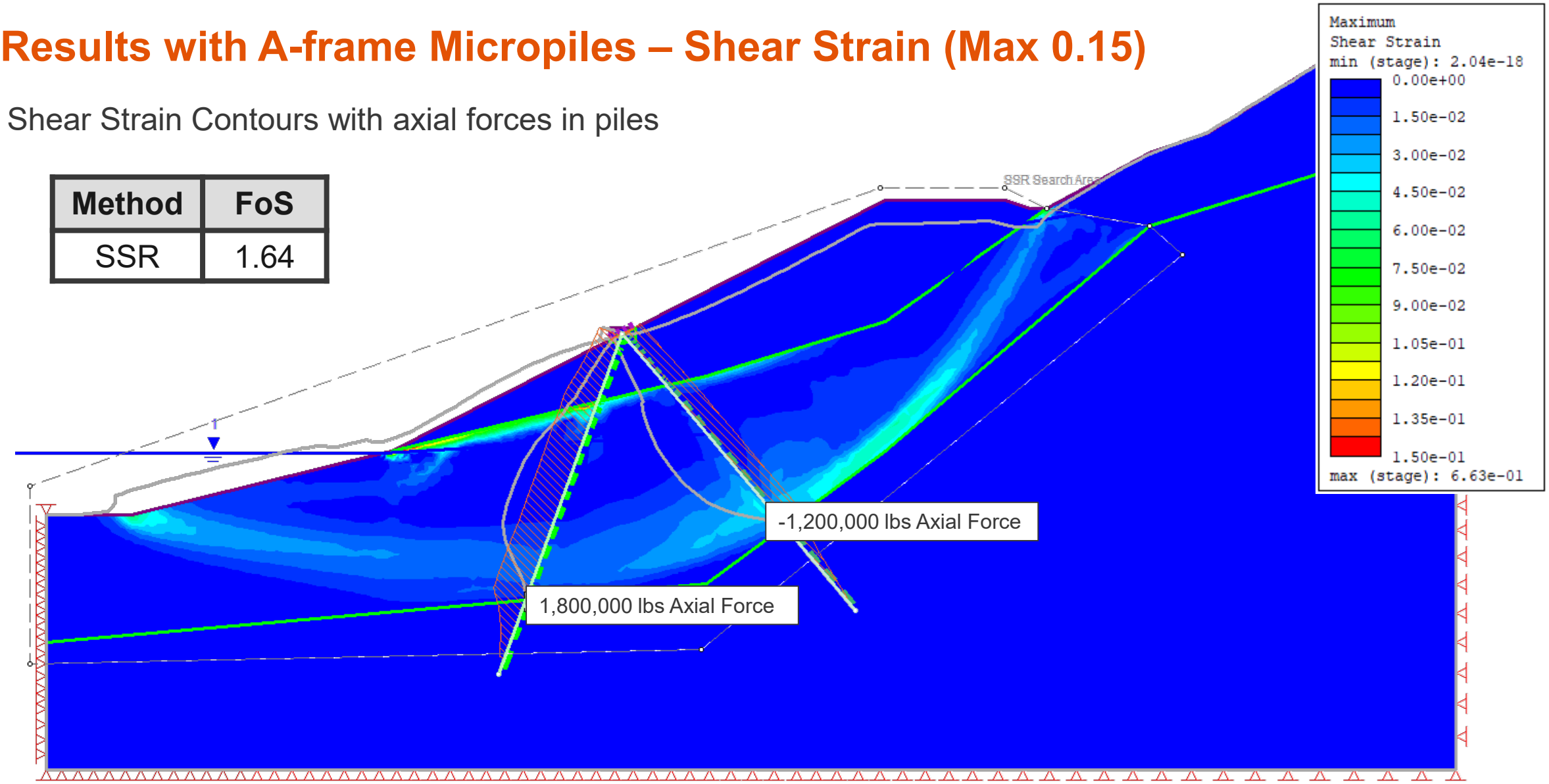




Results with A-frame Micropiles – Shear Strain (Max 0.15)

Shear Strain Contours with axial forces in piles

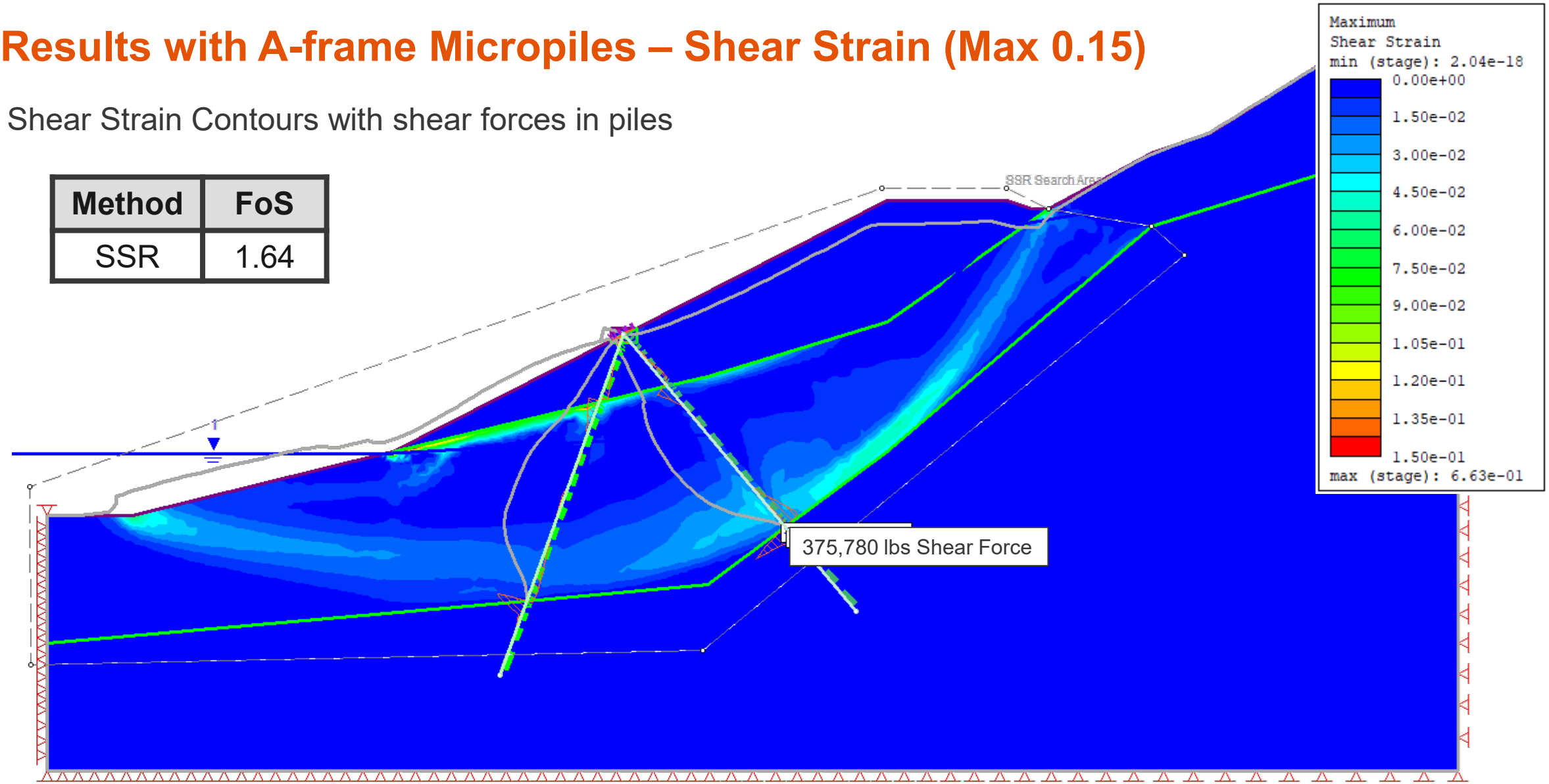
Method	FoS
SSR	1.64



Results with A-frame Micropiles – Shear Strain (Max 0.15)

Shear Strain Contours with shear forces in piles

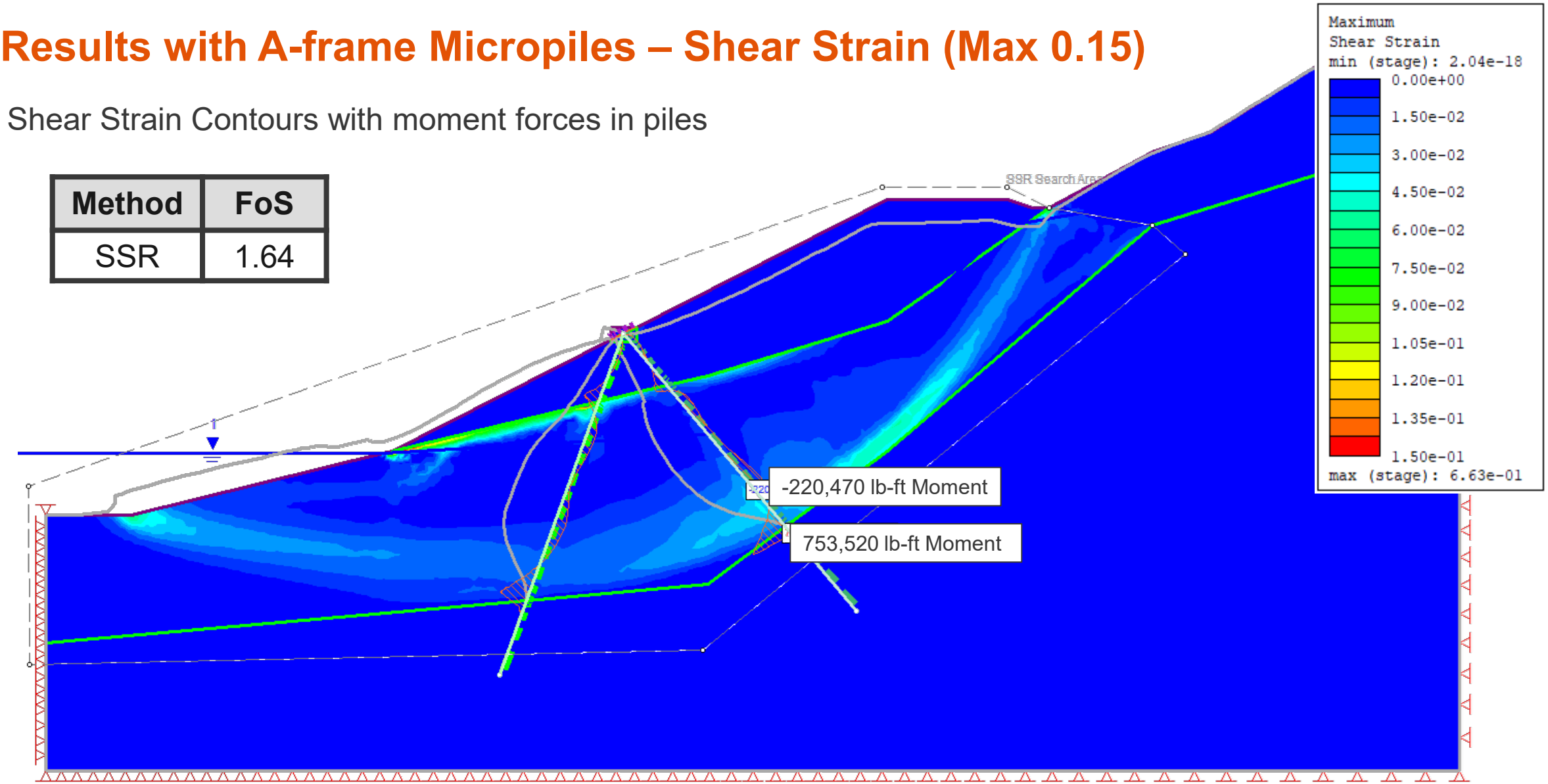
Method	FoS
SSR	1.64



Results with A-frame Micropiles – Shear Strain (Max 0.15)

Shear Strain Contours with moment forces in piles

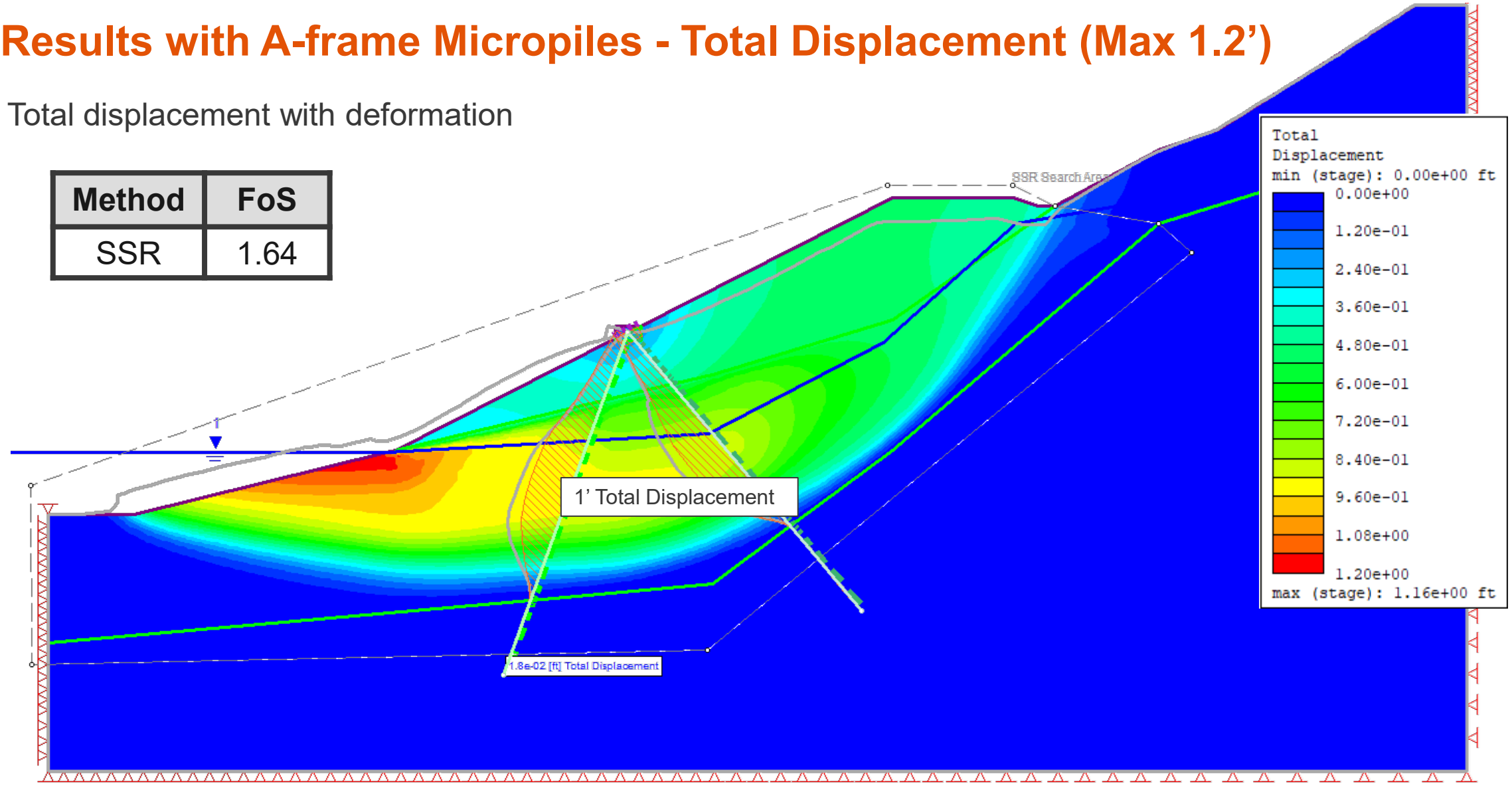
Method	FoS
SSR	1.64



Results with A-frame Micropiles - Total Displacement (Max 1.2')

Total displacement with deformation

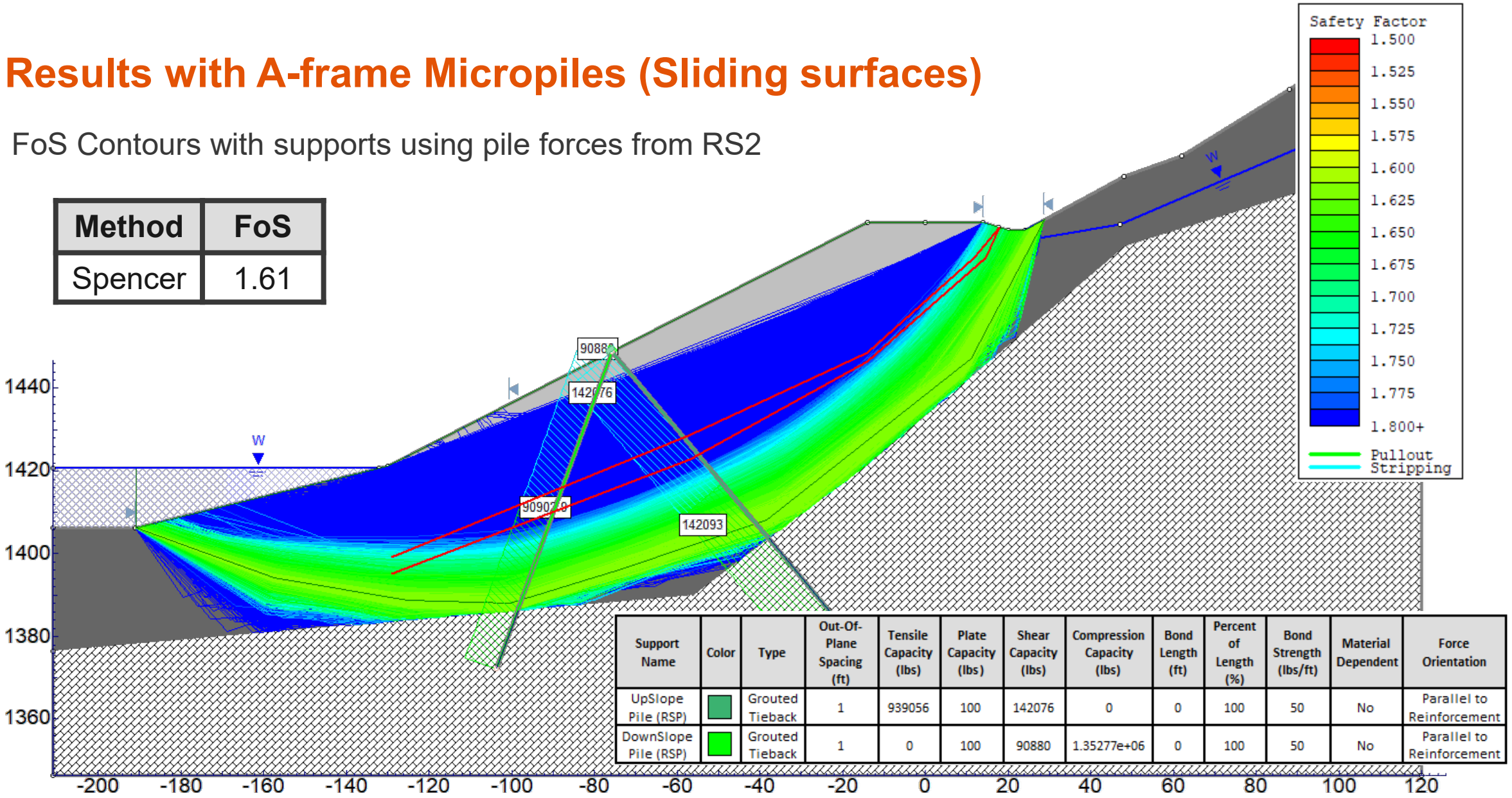
Method	FoS
SSR	1.64



Results with A-frame Micropiles (Sliding surfaces)

FoS Contours with supports using pile forces from RS2

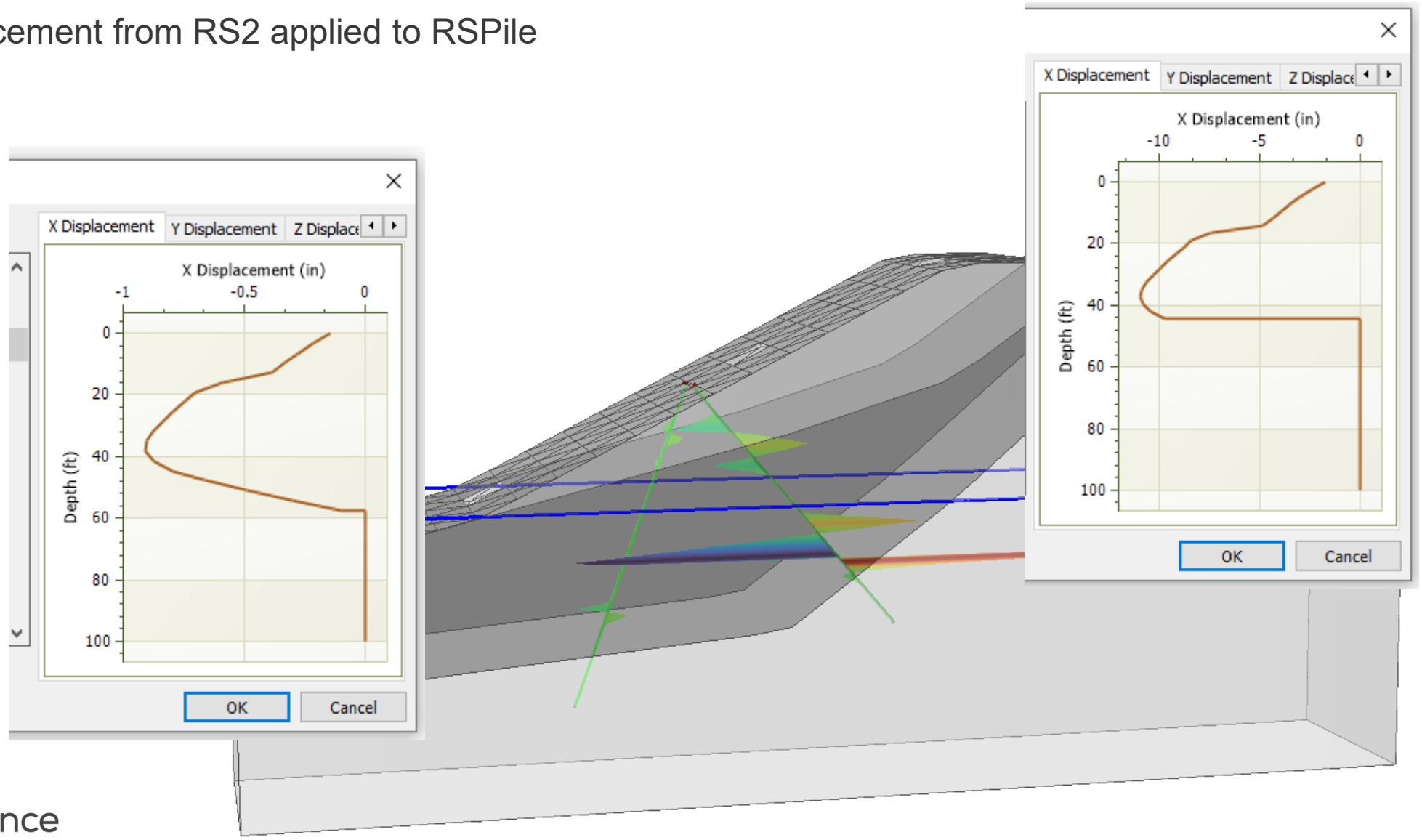
Method	FoS
Spencer	1.61



Support Name	Color	Type	Out-Of-Plane Spacing (ft)	Tensile Capacity (lbs)	Plate Capacity (lbs)	Shear Capacity (lbs)	Compression Capacity (lbs)	Bond Length (ft)	Percent of Length (%)	Bond Strength (lbs/ft)	Material Dependent	Force Orientation
UpSlope Pile (RSP)		Grouted Tieback	1	939056	100	142076	0	0	100	50	No	Parallel to Reinforcement
DownSlope Pile (RSP)		Grouted Tieback	1	0	100	90880	1.35277e+06	0	100	50	No	Parallel to Reinforcement

Results with A-frame Micropiles – RSPile Results

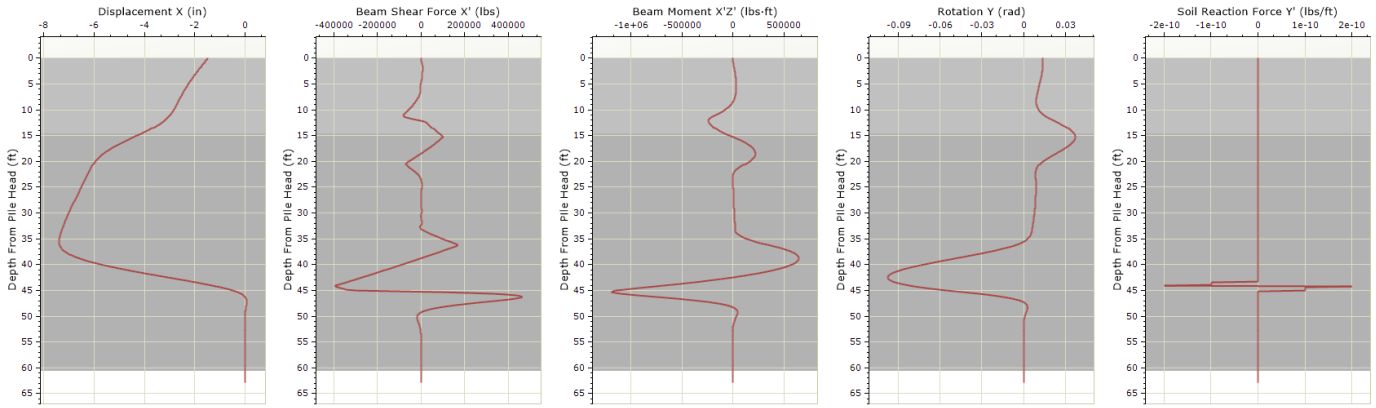
Displacement from RS2 applied to RSPile



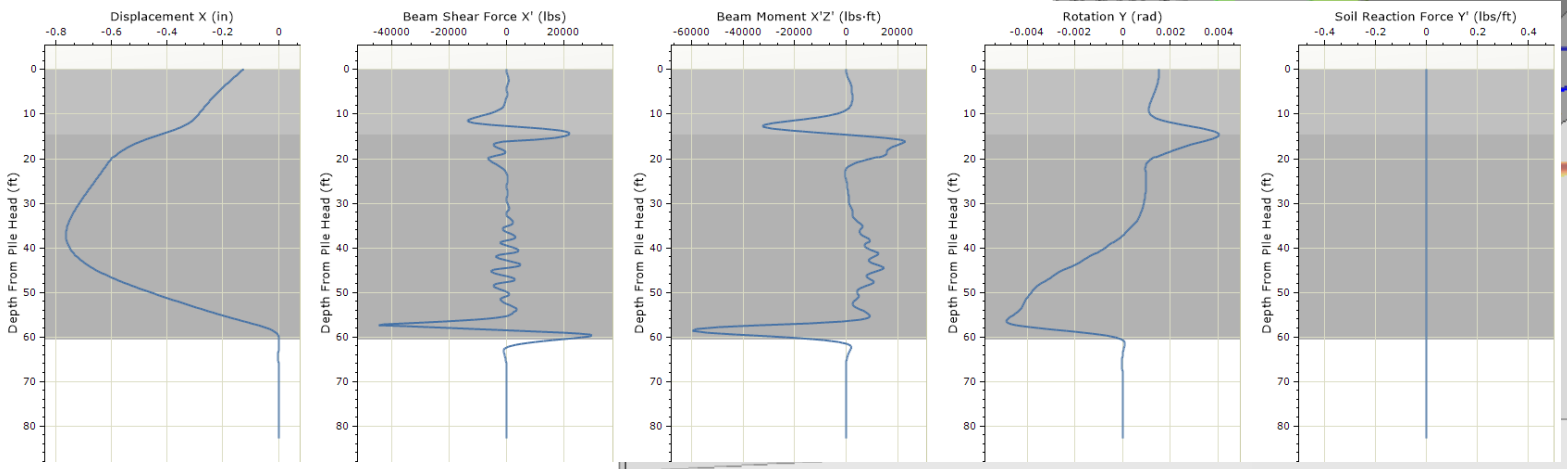
Results with A-frame Micropiles – RSPile Results

Displacement from RS2 applied to RSPile

197,000 lb



29,800 lb



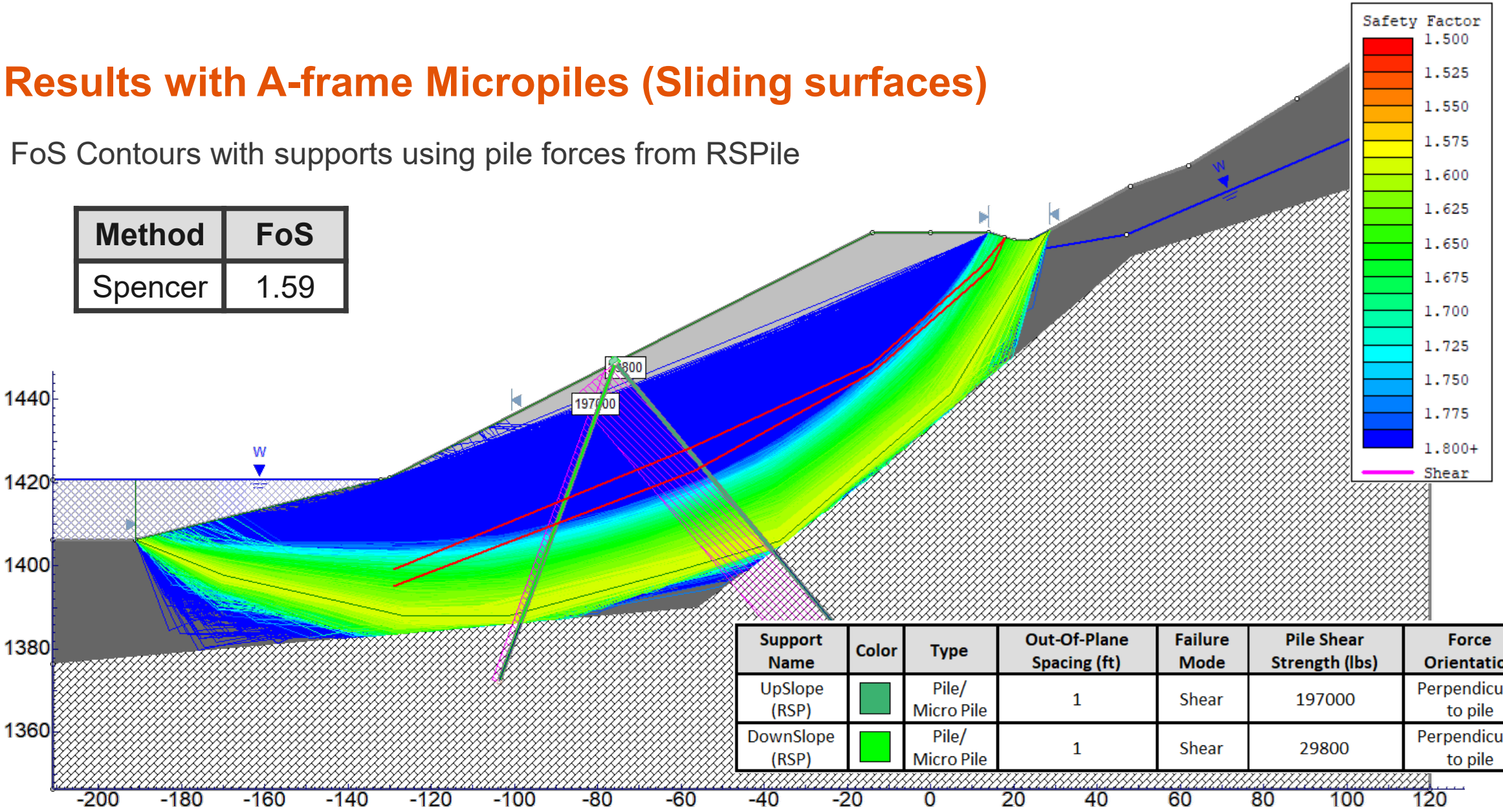
rocscience

RSPile

Results with A-frame Micropiles (Sliding surfaces)

FoS Contours with supports using pile forces from RSPile

Method	FoS
Spencer	1.59

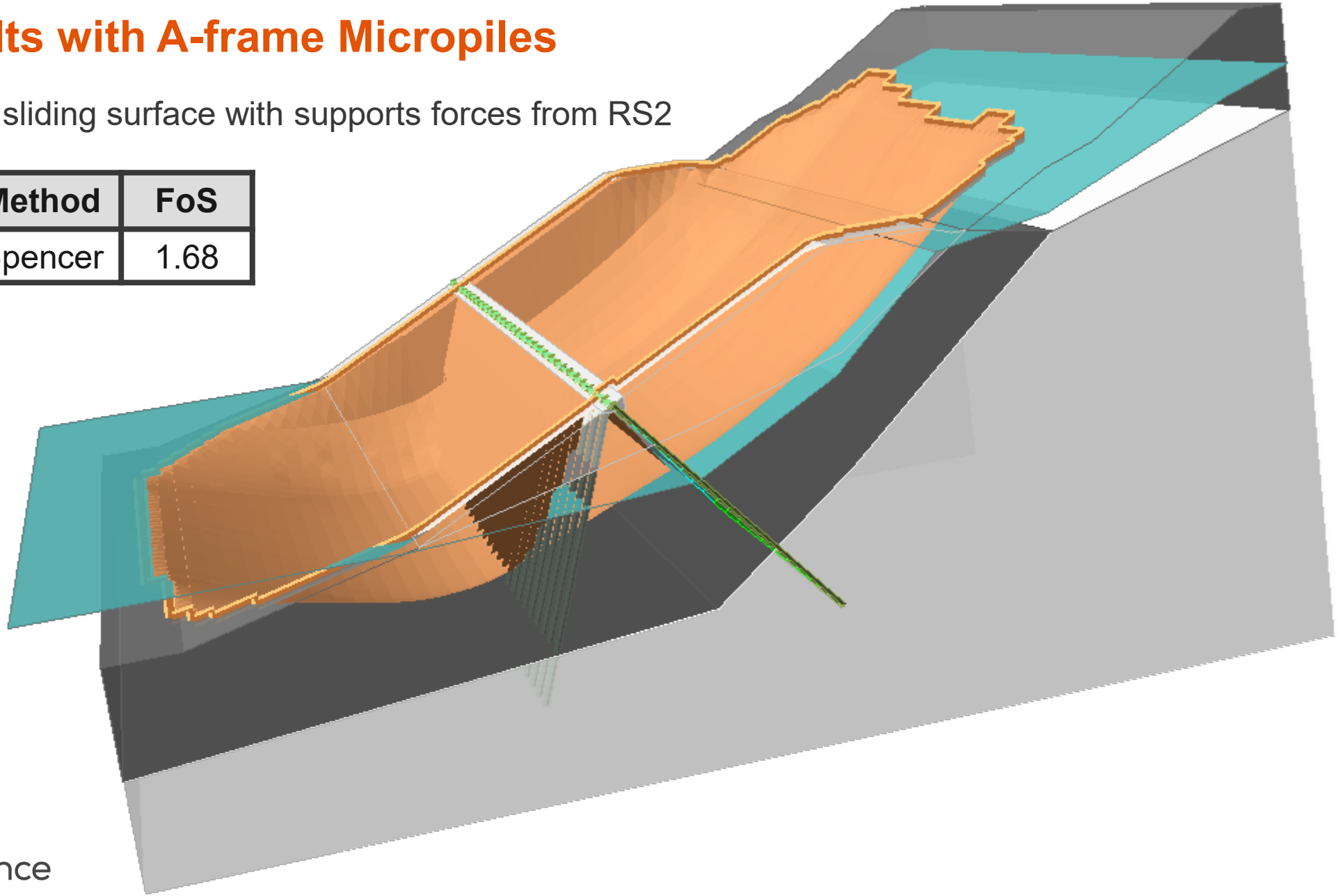


Support Name	Color	Type	Out-Of-Plane Spacing (ft)	Failure Mode	Pile Shear Strength (lbs)	Force Orientation
UpSlope (RSP)		Pile/ Micro Pile	1	Shear	197000	Perpendicular to pile
DownSlope (RSP)		Pile/ Micro Pile	1	Shear	29800	Perpendicular to pile

Results with A-frame Micropiles

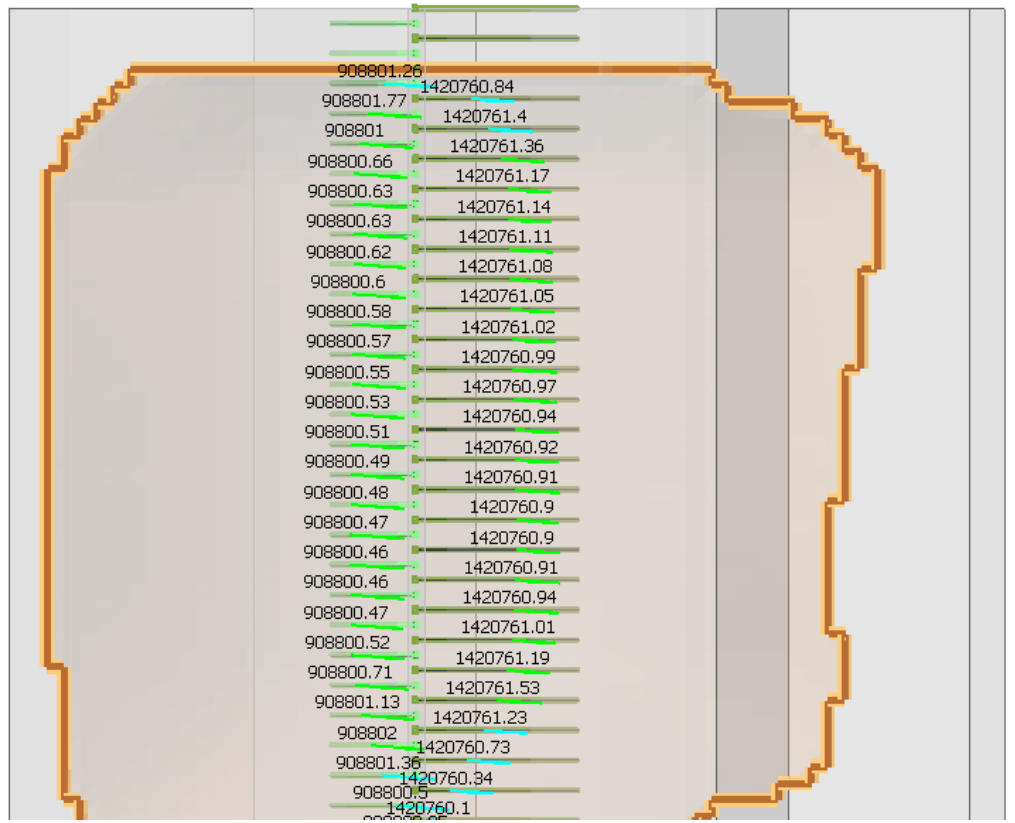
Critical sliding surface with supports forces from RS2

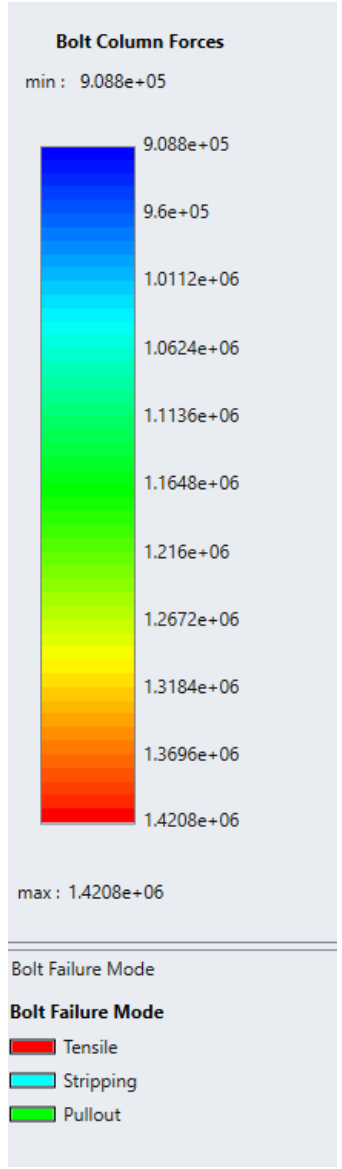
Method	FoS
Spencer	1.68



Results with A-frame Micropiles

Critical sliding surface with supports forces from RS2

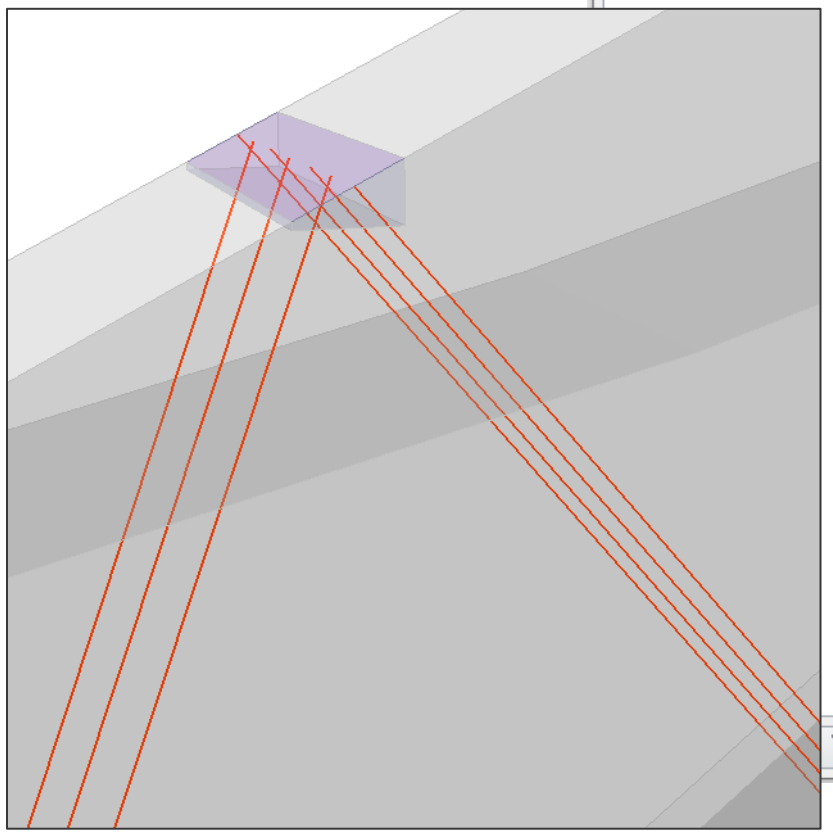


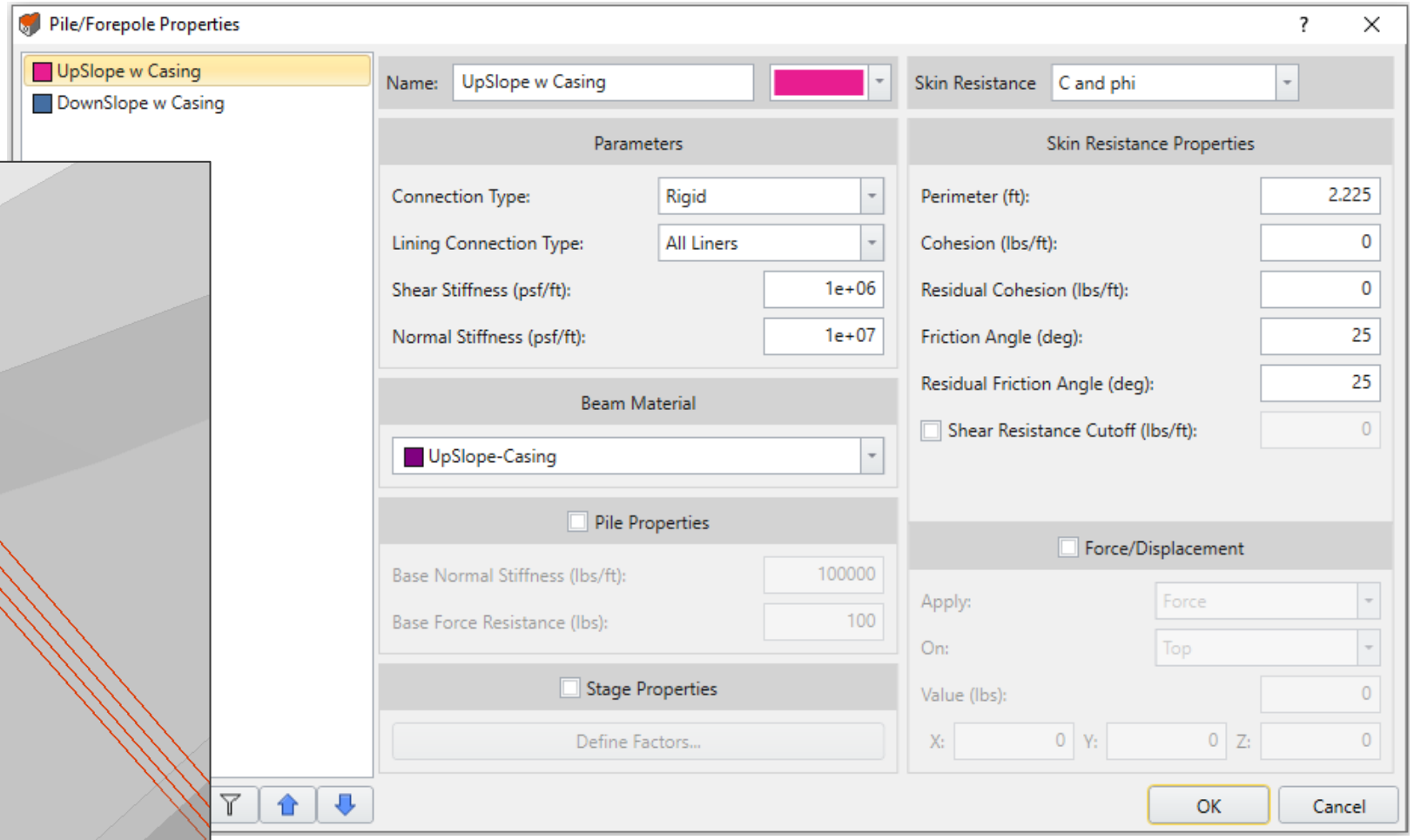


Name	Colour	Support Type	Force Orientation	Percent of Length (%)	Tensile Capacity (lbs)	Plate Capacity (lbs)	Shear Capacity (lbs)	Bond Strength (lbs/ft)	Material Dependent	Compression Capacity (lbs)
UpSlope Pile		Grouted Tieback	Parallel to Reinforcement	100	9390560	100	1420760	50	No	
DownSlope Pile		Grouted Tieback	Parallel to Reinforcement	100	0	100	908800	50	No	13527700

Modeling A-frame structure components

Set-up piles using pile support type in RS3

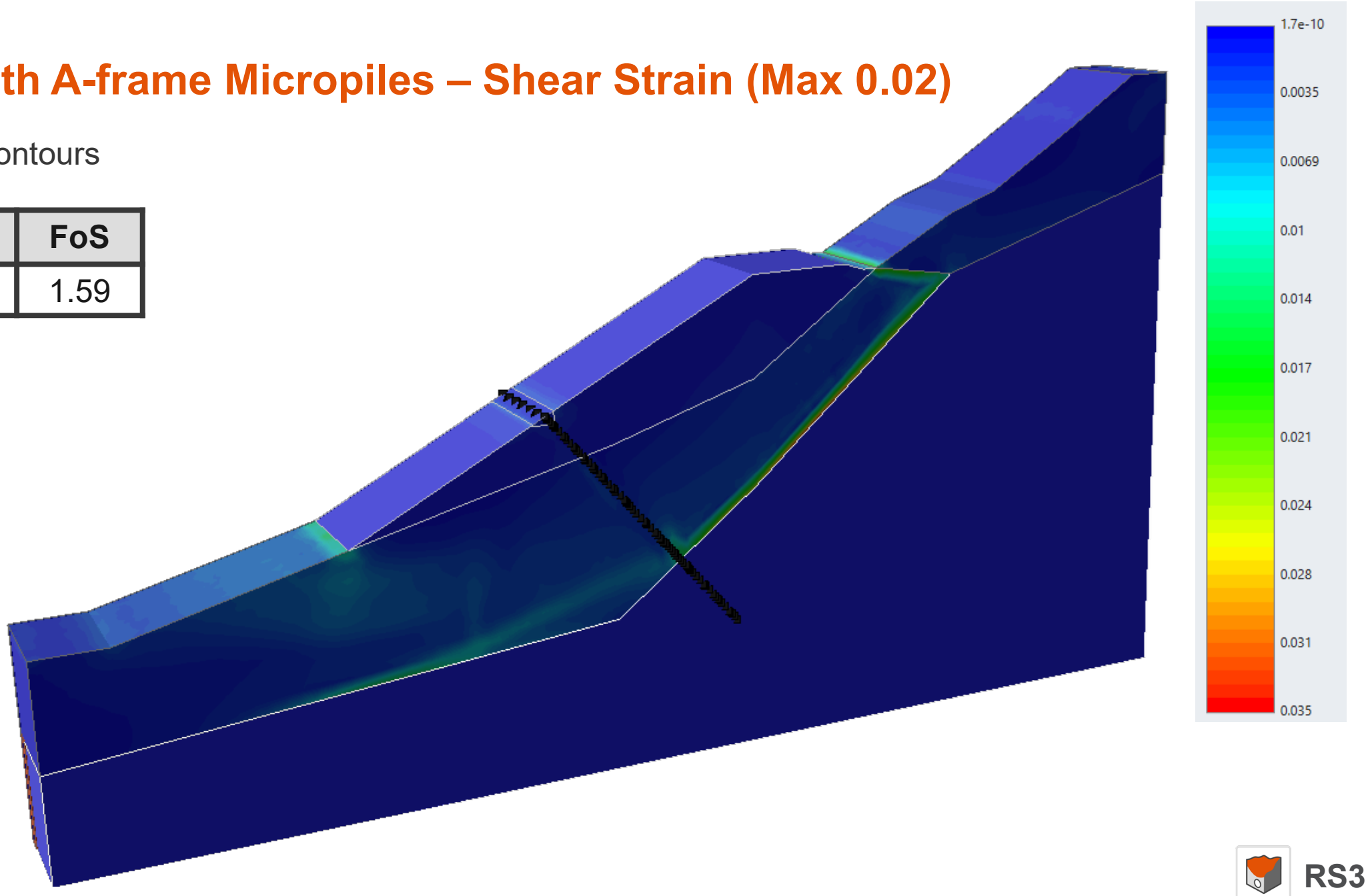




Results with A-frame Micropiles – Shear Strain (Max 0.02)

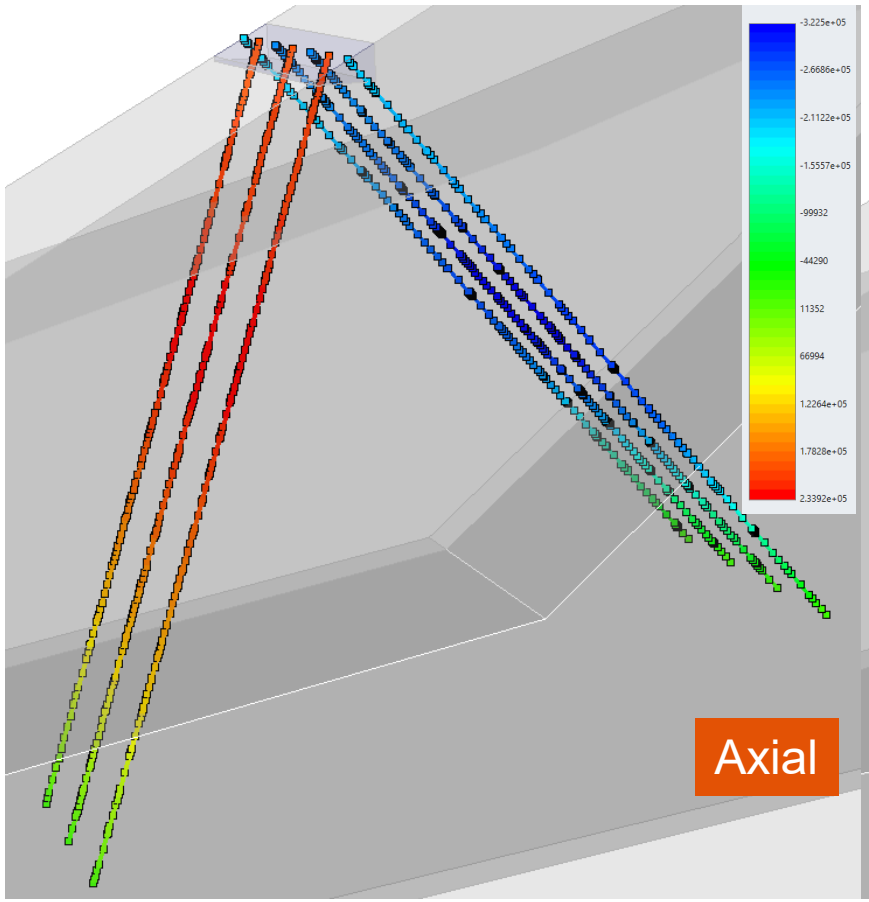
Shear strain contours

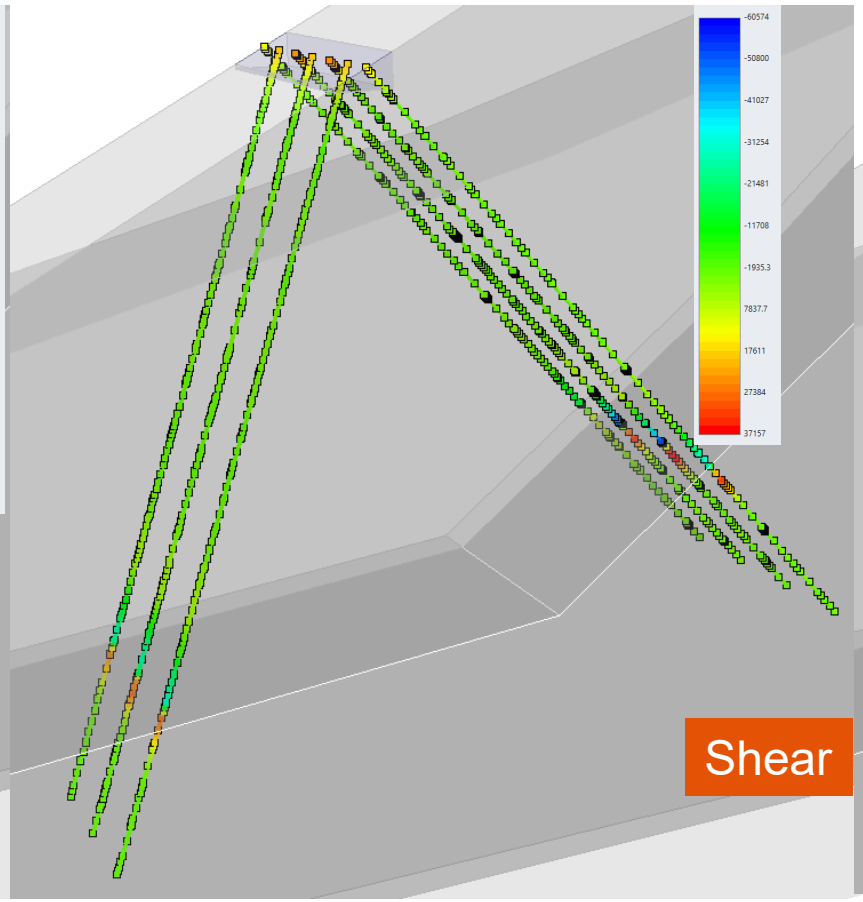
Method	FoS
SSR	1.59

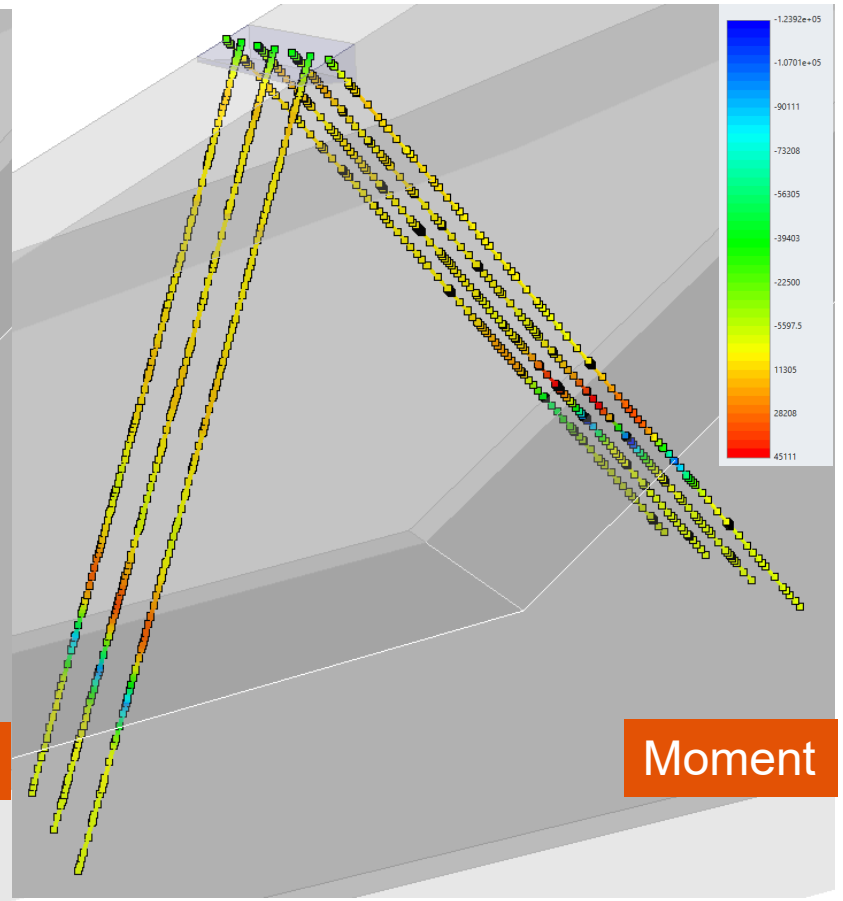


Results with A-frame Micropiles

Pile Forces (Axial, Shear, Moment)

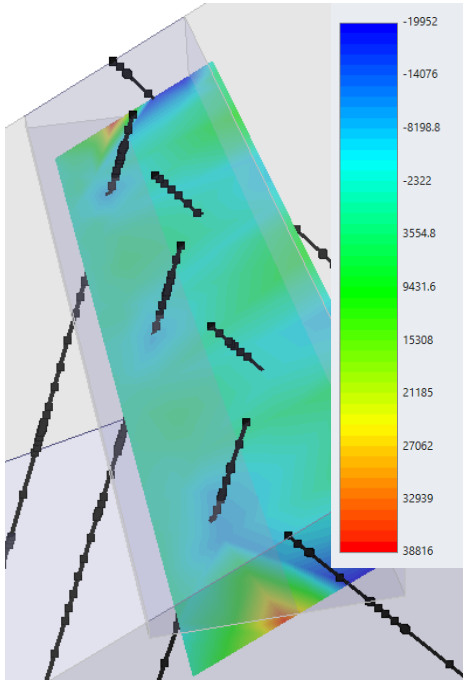




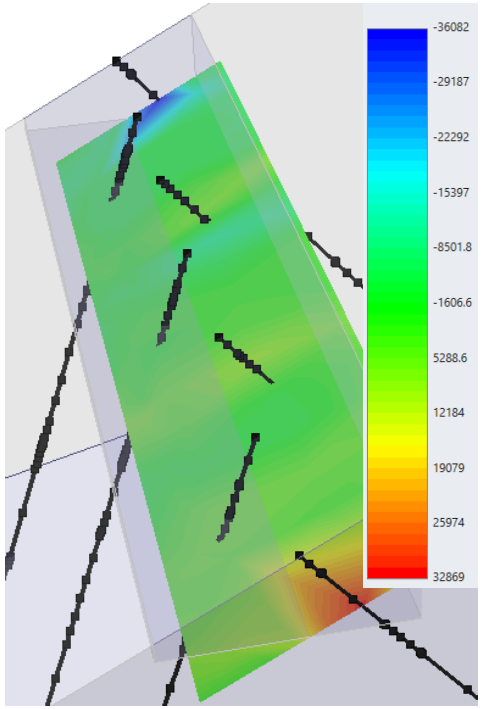


Results with A-frame Micropiles

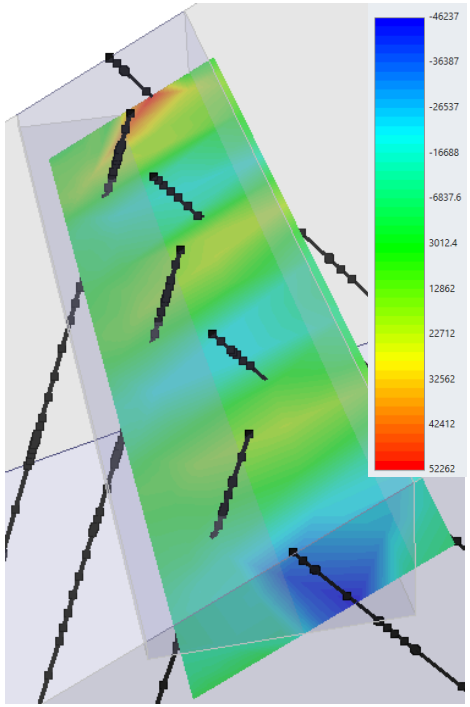
Cap Forces (Shear, Moment)



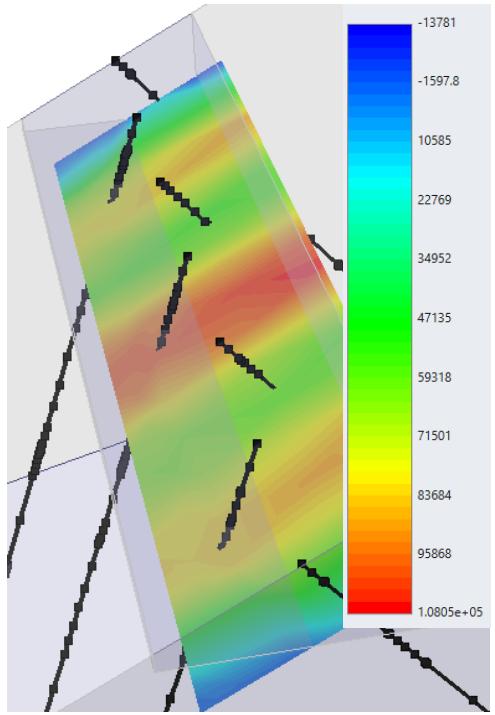
Fx XZ



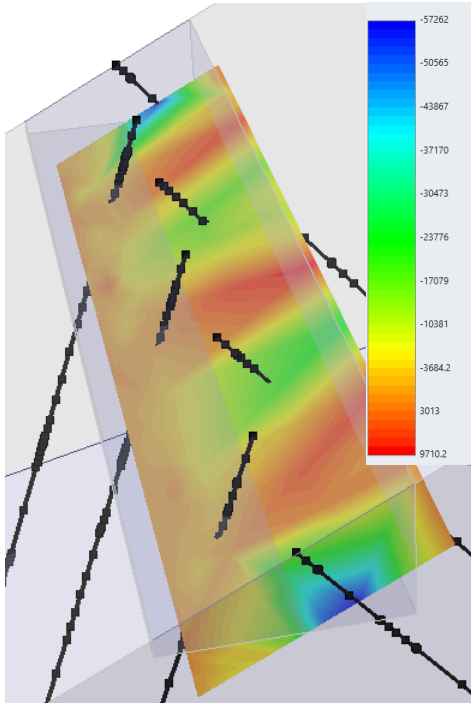
Fy XY



Fz YZ

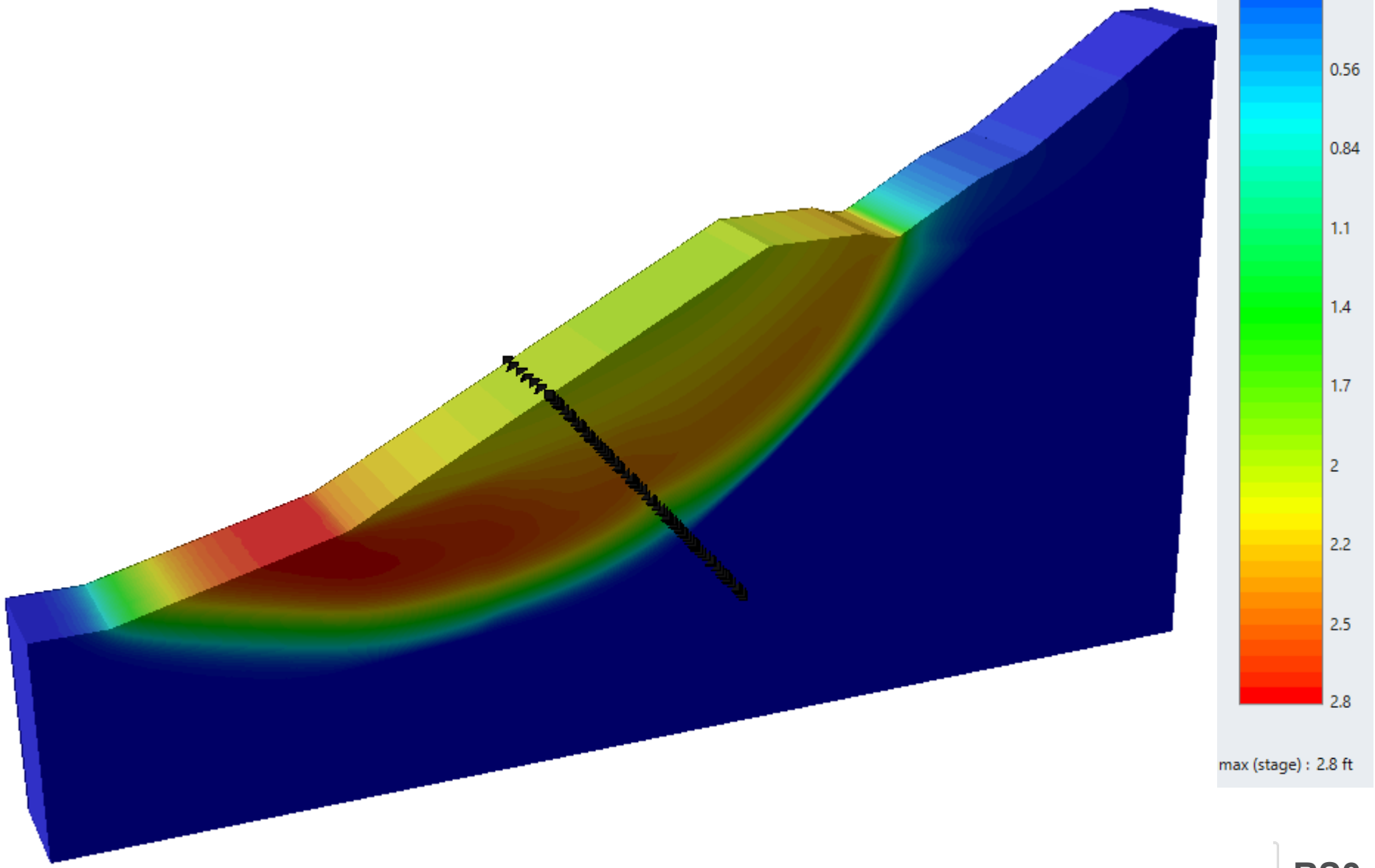


Mx

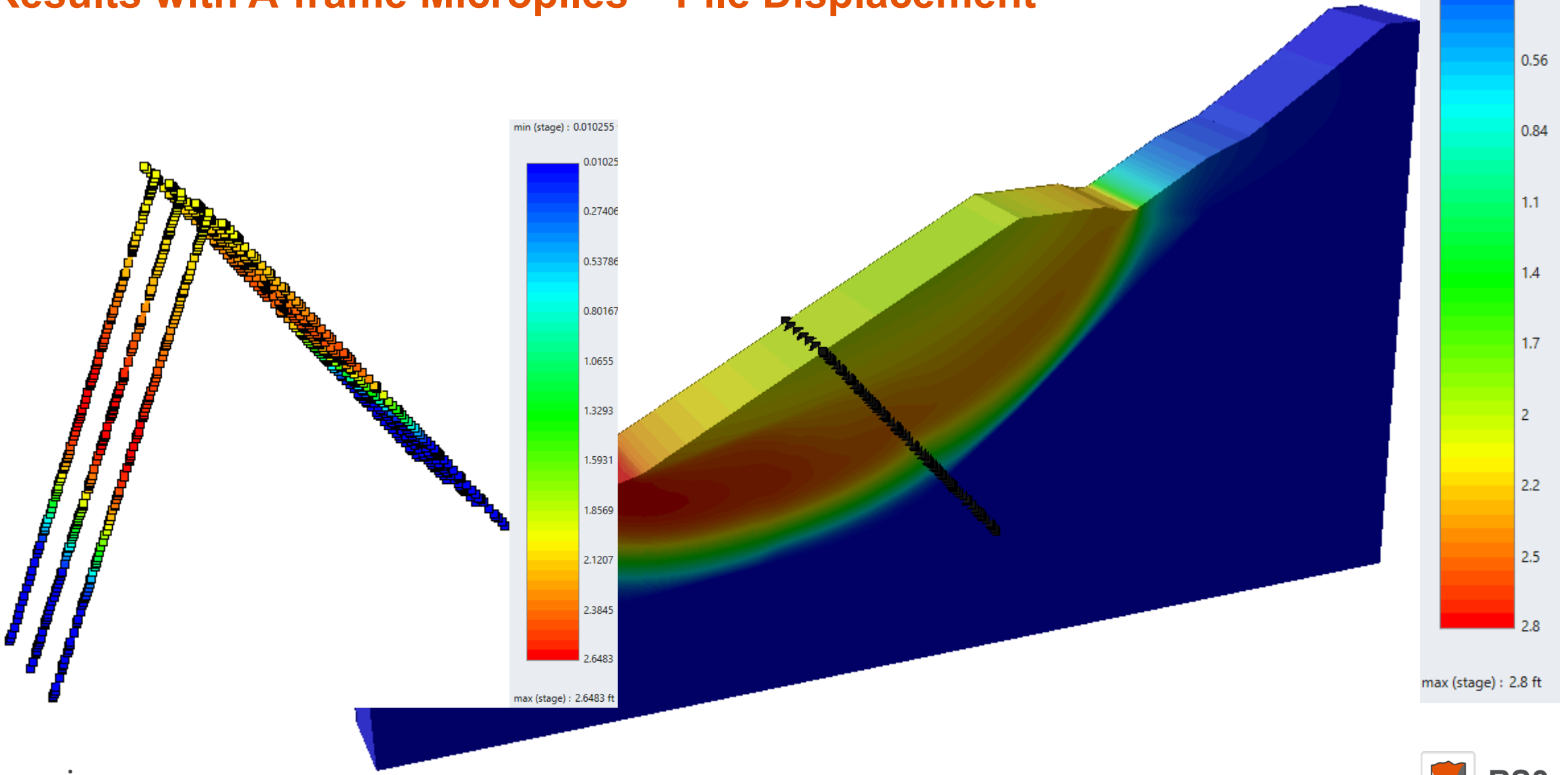


My

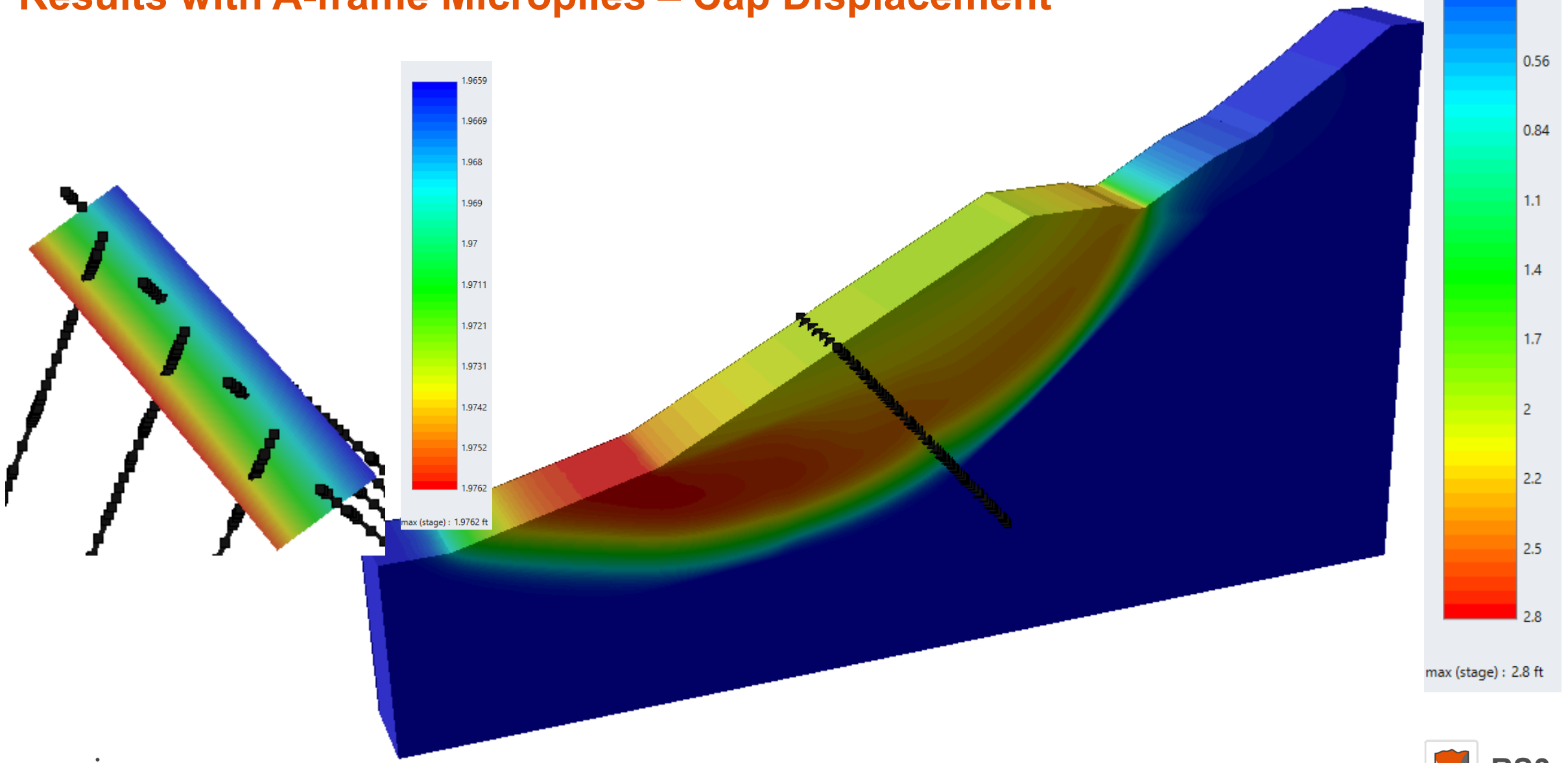
Results with A-frame Micropiles – Total Displacement



Results with A-frame Micropiles – Pile Displacement



Results with A-frame Micropiles – Cap Displacement



FoS Summary

Scenario	 RS2	 Slide2	 Slide3	 RS3	Target FoS
Baseline	0.92	0.93	0.97	0.93	-
With Supports	1.64	1.61	1.68	1.59	1.5