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TRANSPORTATION RESEARCH BOARD

Straight to Recording for All:

Benefits of Computational Modeling for Geotechnical Engineers

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Benefits of Computational Modeling for Geotechnical Engineers

Transportation Research Board Webinar

Lee Petersen, PhD, PE (CO IL MN MO VA)

Welcome and Introduction

- Welcome
- What is computational modeling?
  - The process of using a computer program to solve the partial differential equations of:
    - Stress and strain (mechanics)
    - Seepage and groundwater
    - Heat transfer
- What are simplified or traditional methods?
  - Analysis methods adapted to limited computational capabilities

Speakers

- Lee Petersen, PhD, PE (5 states), M. ASCE, Principal Engineer, Itasca Consulting Group
  - lpetersen@itascacg.com
- Derrick Dasenbrock, PE, F. ASCE, Senior Geomechanics/LRFD Engineer, MnDOT
  - derrick.dasenbrock@state.mn.us
- Varun, PhD, Senior Geomechanics Engineer, Itasca Consulting Group
  - varun@itascacg.com
- Augusto Lucarelli, MS, Principal Engineer, Itasca Consulting Group
  - alucarelli@itascacg.com

Five Learning Objectives

- Review of traditional, simplified analysis methods, and compare with computational modeling methods
- Identify limitations associated with traditional or simplified analysis methods that could adversely impact predictions of stability and performance
- Learn the benefits of numerical modeling with respect to assumptions, effort, project complexity, and risk and reliability
- Understand the steps involved in formulating and implementing a computation model for a geotechnical engineering problem to those using traditional methods
- Learn the costs and benefits of using numerical modeling as compared to traditional and limit equilibrium analysis approaches

Derrick Dasenbrock, MnDOT

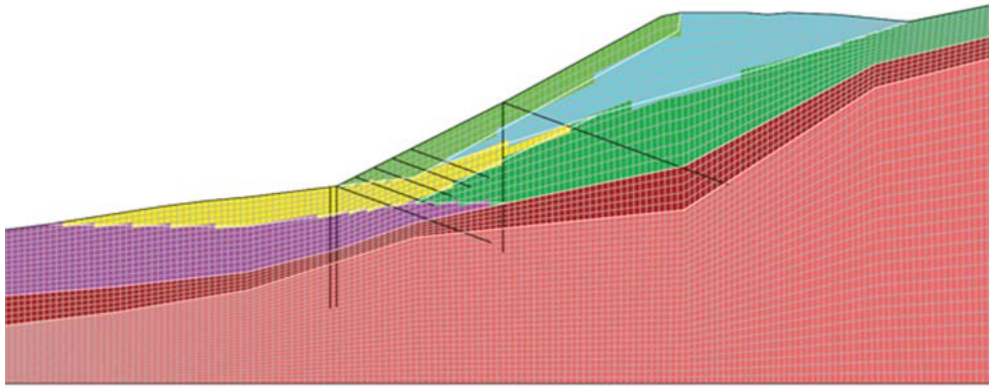
- Solving geotechnical design problems
  - DOT focus, value proposition
  - Benefits of the model, and the visualization
  - Overview of traditional methods: by hand, spreadsheet, software programs
- Numerical analysis tools:
  - Benefit from new field methods
  - More robust results
  - Accommodate complexity: strength, deformation, rate effects, permeability, reinforcement, structures
  - Beneficial graphics useful for communicating results to non-geotechnical engineers and project leaders

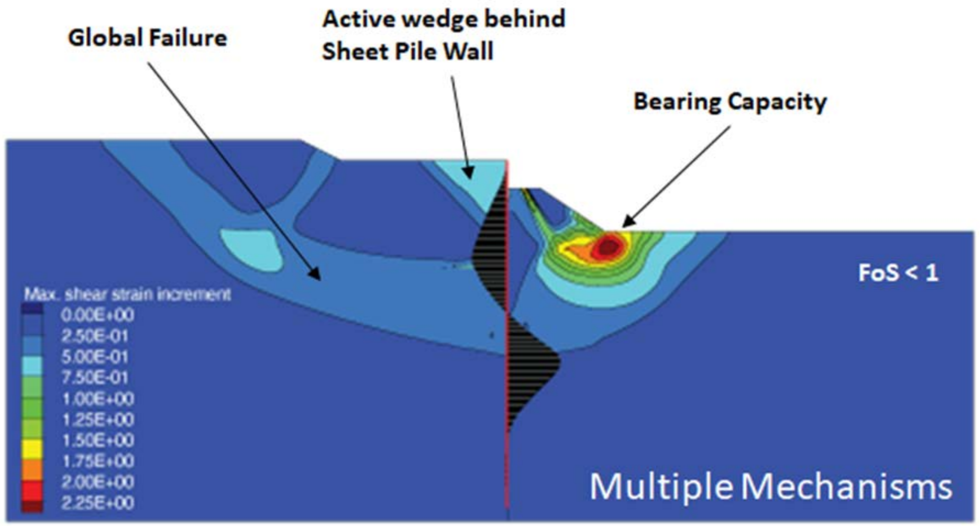
Derrick Dasenbrock, MnDOT

- Use cases for numerical analysis
  - Complex structures
  - Soil-structure interaction
  - Slope stability
  - Temporary shoring
- Four brief case histories

Varun, Itasca Consulting Group

- Getting started:
  - ❖ Need to choose the software and material behavior based on the problem
  - ❖ Use different soil models depending upon anticipated behavior, and static versus dynamic
  - ❖ Start simple and add complexity as needed
- Shear strength reduction method
- Comparison of LEM versus numerical methods
- Case histories:
  - ❖ Soil slope case history
  - ❖ Soil retention case history
- Pros and cons of computational modeling





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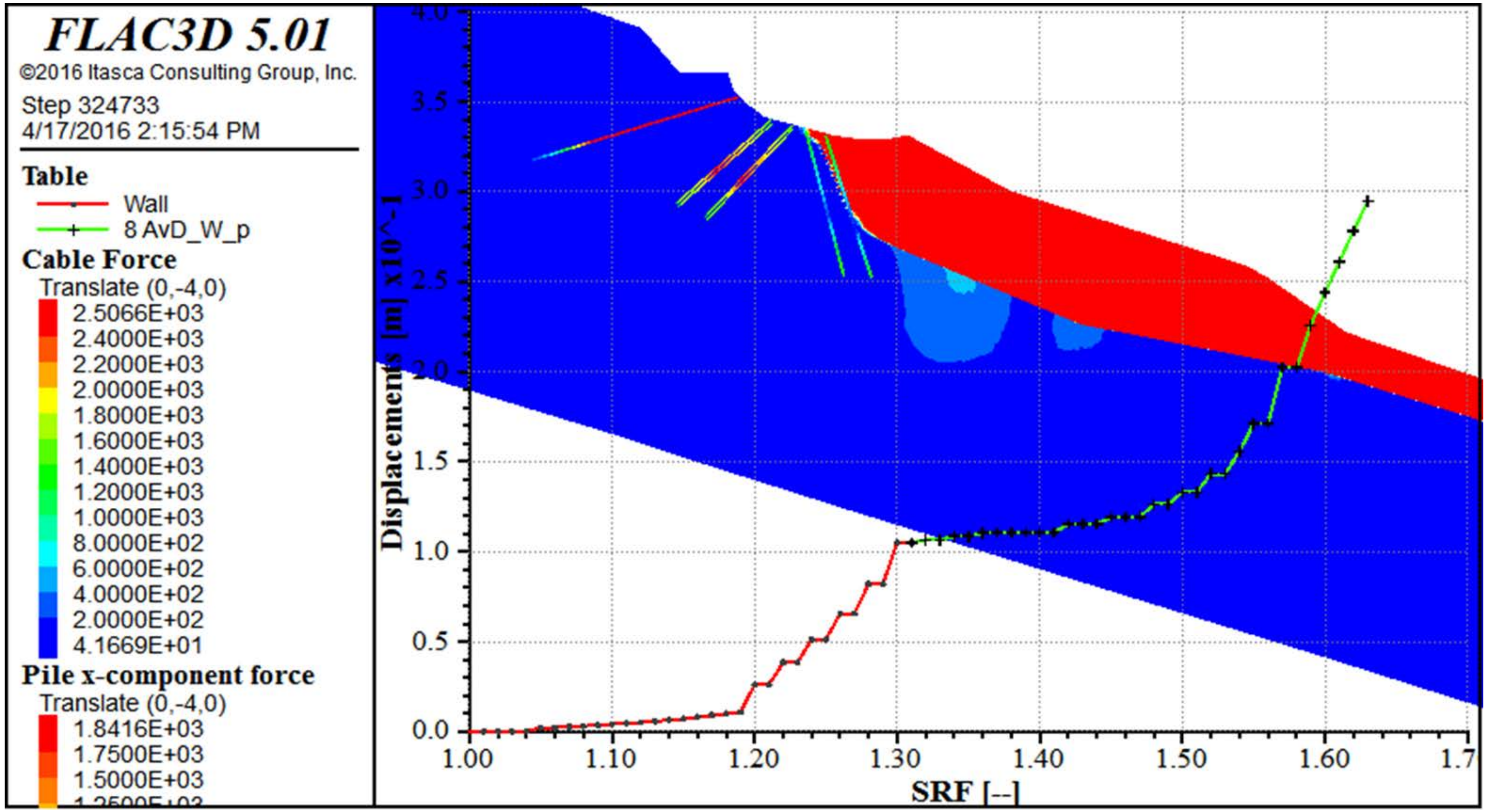
Augusto Lucarelli, Itasca Consulting Group

- Fountain Slide emergency stabilization



Speakers

Key Objective Review

- Simplification, or unintended oversimplification, can often miss key mechanisms governing the problem
  - Examples by all three speakers
  - Multiple deformation mechanisms
  - LEM can't address deformable structures
  - Complex geometries
- Benefits of numerical modeling with respect to assumptions, effort, project complexity, and risk and reliability
  - Many fewer assumptions about problem layout, material behavior, etc.
  - Additional effort may be minimal to substantial, depending upon problem complexity
    - If substantial effort is necessary, should question ability of simplified methods to address problem
  - Risk and reliability are enhanced, because more problem considerations are included

Key Objective Review

- Steps involved in formulating and implementing a computation model
  - Design criteria and design constraints
  - Project geometry
  - Subsurface materials
  - Material behavior and properties
  - Initial structures and remedial measures
  - Sequence

“Costs” of Utilizing Computational Modeling

- Computational modeling, while more capable, is more complex
- “Costs” include:
  - Software
  - Staff training
  - Learning curve, and keeping staff skills current
  - Need more information, especially deformability information

Potentially Overlooked Advantages

- Applicability for complex sites and problems
- Revealing failure mechanisms that were not originally appreciated—including multiple or complex mechanisms
- Ability to use advanced exploration data, such as CPTu
- Ability to use advanced monitoring data including rate effects
- Using the output and visualizations to help describe risk for strength, permeability, and deformation problems

Result? →

Better understanding of project risk/confidence for decision-making

Evaluation of the effectiveness of proposed designs

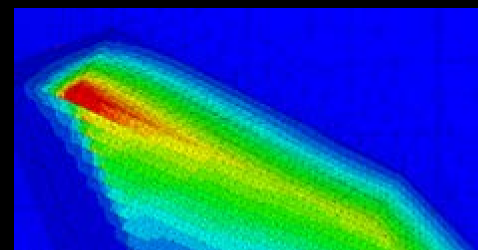
Closing Remarks

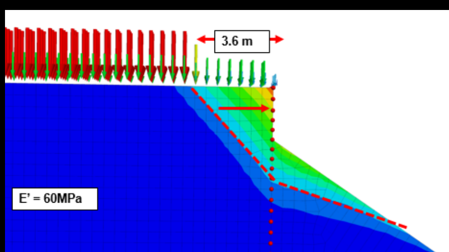
- Computational methods are a project investment
- The outcomes often lead directly to project cost and schedule impacts
- Either:
  - Finding problems and adapting design and construction accordingly
  - Finding that there are no problems
- Lead to an improved project outcome as compared to uncertainty surrounding geotechnical issues

Thank you for your attention!

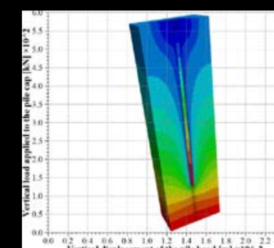
Solving problems.

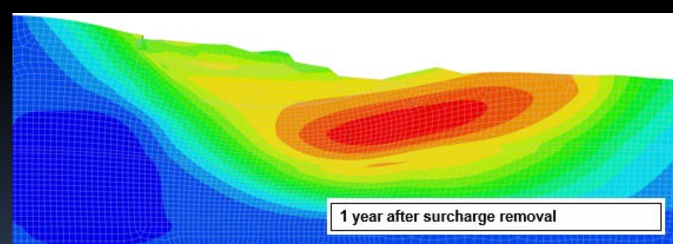
Geotechnical design problems encountered by State DOTs and how numerical modeling, analysis, and presentation enhance project value









Derrick Dasenbrock, P.E., F. ASCE
Geomechanics/LRFD Engineer
Minnesota DOT Office of Materials and Road Research

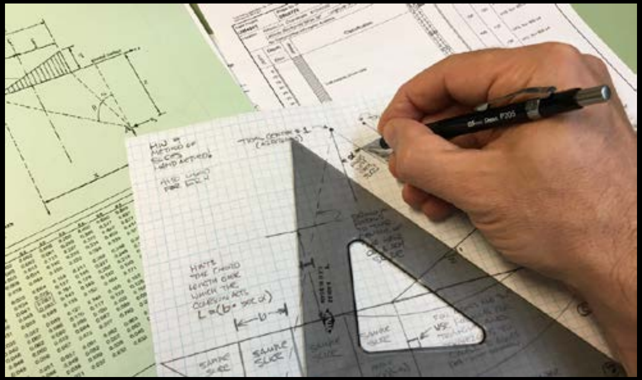
MINNESOTA

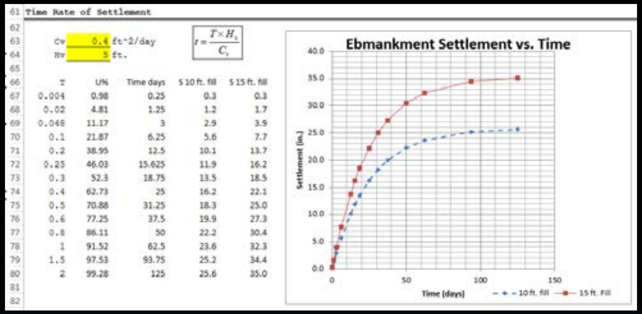
Common geotechnical design problems

- Life cycle performance
  - Strength (bearing capacity)
  - Settlement
  - Deformation and slope stability
  - Reliability and extreme events
  - Original design & reconstruction
- Typical DOT features
  - Bridges and walls
  - Culverts and channels
  - Embankments and slopes
  - Tunnels
  - Pavement and guardrail
  - Signs and towers
  - Buildings

Tools in the geotechnical toolkit

- Hand methods
  - Bearing capacity
  - Settlement
  - Slope stability
- Spreadsheets
  - Bearing capacity
  - Settlement
  - Slope stability
- Software programs
  - Bearing capacity
  - Settlement
  - Slope stability



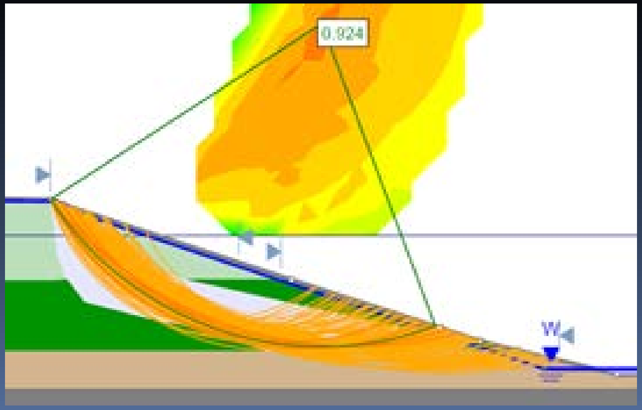


Time Rate of Settlement

Cv 0.4 ft^2/day
Hv 5 ft.

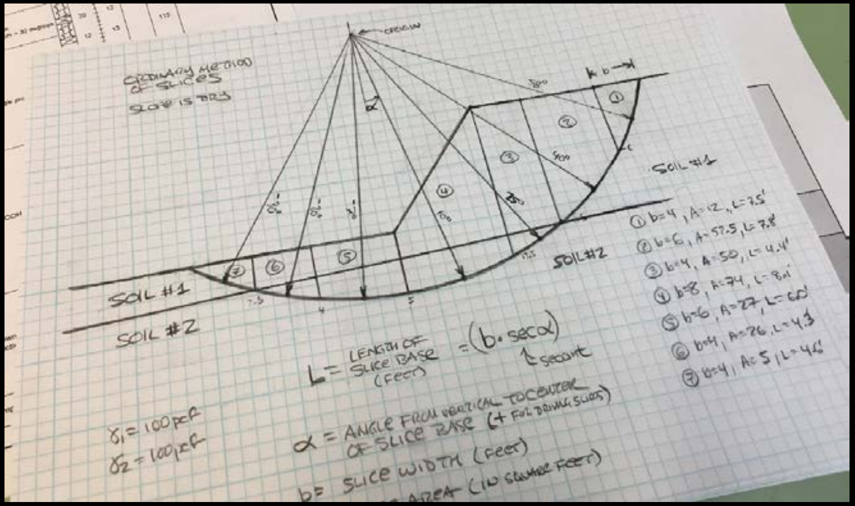
$t = \frac{T \times H_v}{C_v}$

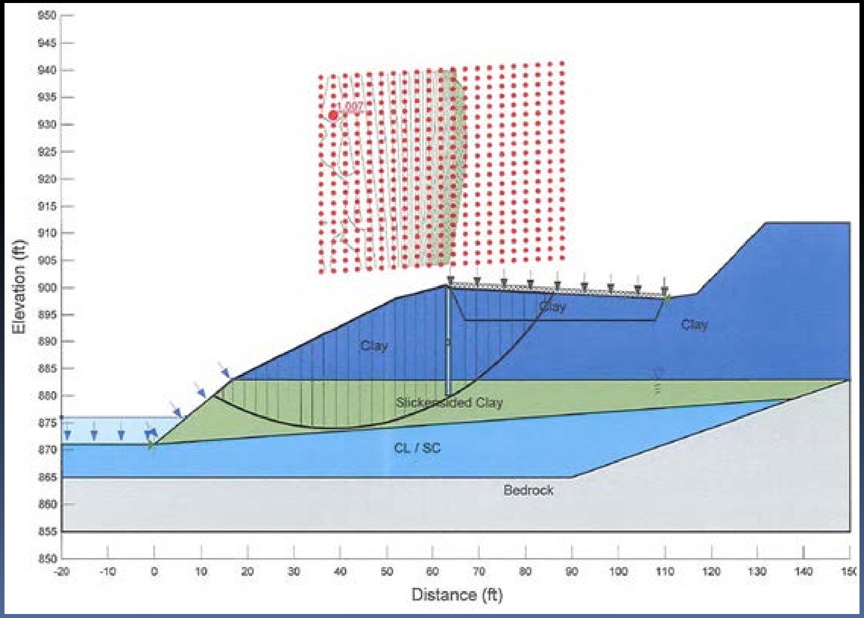
T	U%	Time days	S 10 ft. fill	S 15 ft. fill
0.004	0.98	0.25	0.3	0.3
0.02	4.81	1.25	1.2	1.7
0.048	11.17	3	2.9	3.9
0.1	21.87	6.25	5.6	7.7
0.2	38.95	12.5	10.1	13.7
0.25	46.03	15.625	11.9	16.2
0.3	52.3	18.75	13.5	18.5
0.4	62.73	25	16.2	22.1
0.5	70.88	31.25	18.3	25.0
0.6	77.25	37.5	19.9	27.3
0.8	86.11	50	22.2	30.4
1	91.52	62.5	23.6	32.3
1.5	97.53	93.75	25.2	34.4
2	99.28	125	25.6	35.0



Older (less complex) tools

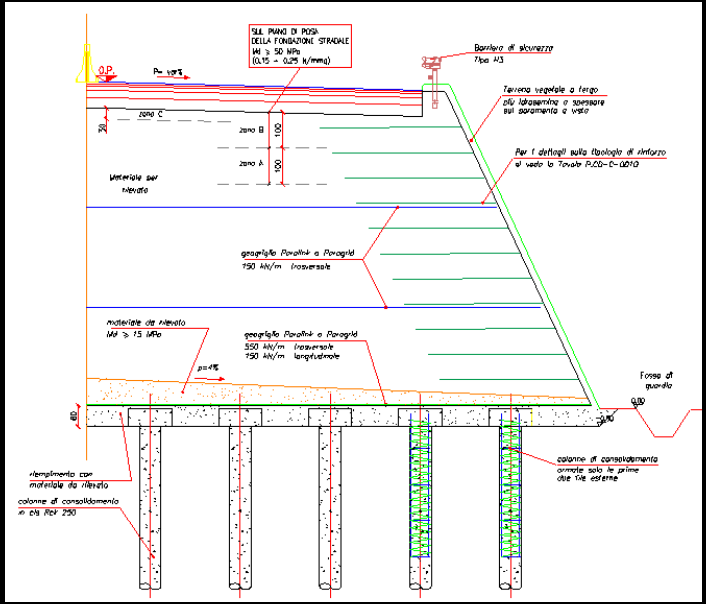
- Input
  - Stratigraphy/geometry
  - Material properties
  - Water & loading
- Methodology
  - Nature/derivation of method
  - Simplifying assumptions
  - Geometric/function constraints
- Operational
  - Time & availability
  - Talent/expertise
  - Cost/expense

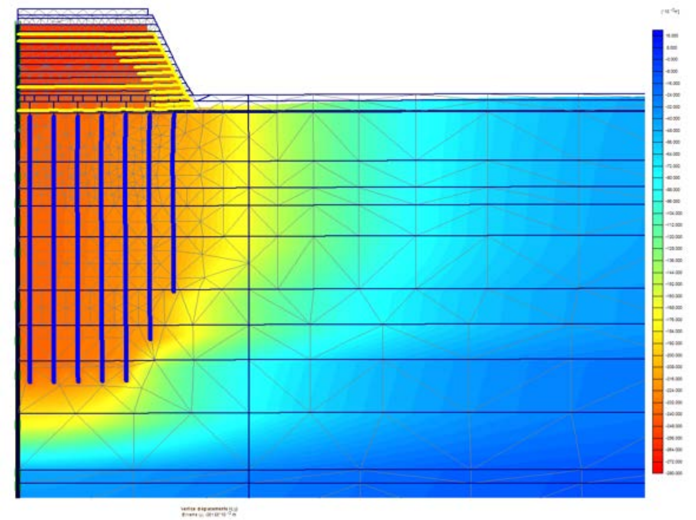




Newer numerical analysis tools

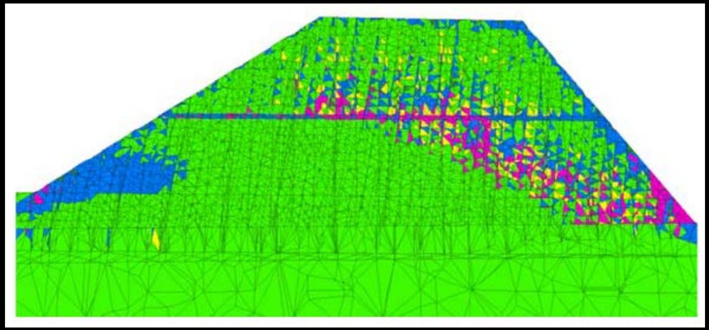
- Benefit from new field methods
  - Improved spatial stratigraphy, water & properties from newer in-situ methods
- Provide more robust results
  - Remove many constraints associated with simplified solutions
  - Handle complexity + interaction better
- Include analysis of
  - Strength, deformation, rate effects, permeability, reinforcement, structures
- Depict variation in results
  - Graphics and visualizations improve comprehension of local/regional effects

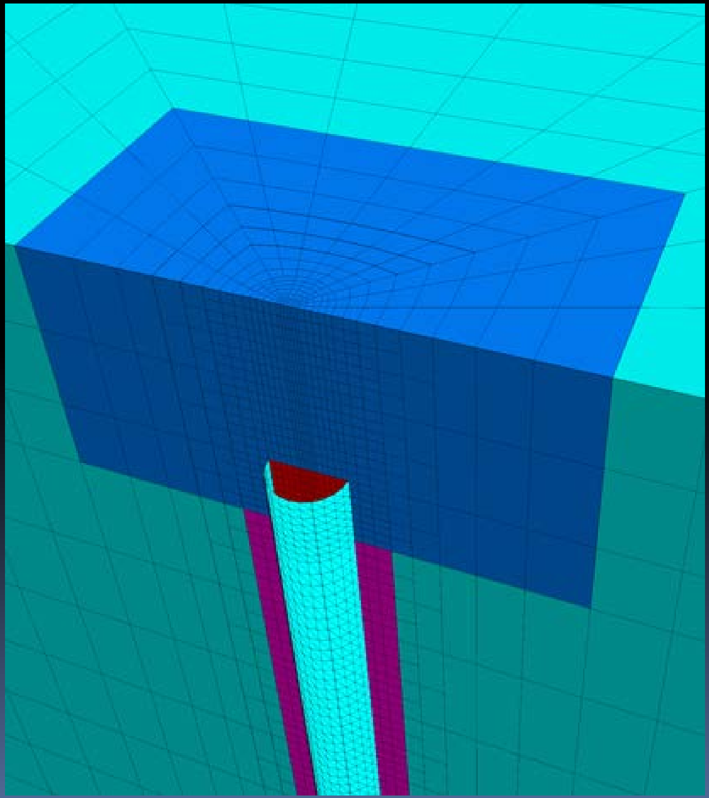




Use cases for numerical analysis tools

- Complex structures
  - Multiple related support systems, staged construction or unusual geometry or discontinuities
- Soil-structure interaction
  - Parametric studies based on field exploration and monitoring
- Slope stability
  - Complex site character or the potential for multiple failure methods
- Temporary shoring
  - Deformation resulting from complex or non-standard geometry and/or staged construction





Complex structures:

Nine Mile Creek Causeway

Controlled Modulus Column and MSE Wall Concept with 3 Platform Levels

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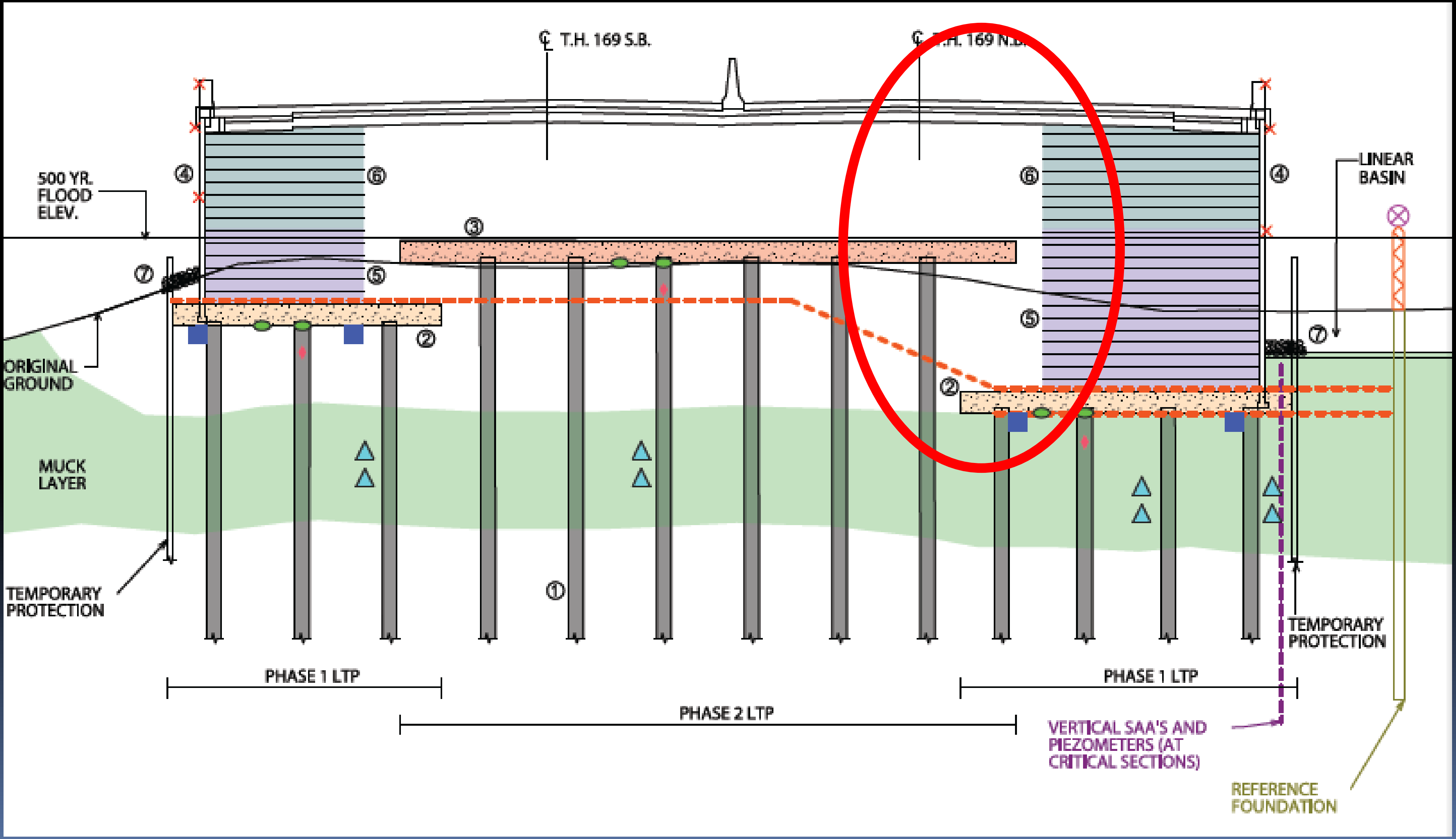
Nine Mile Creek Causeway

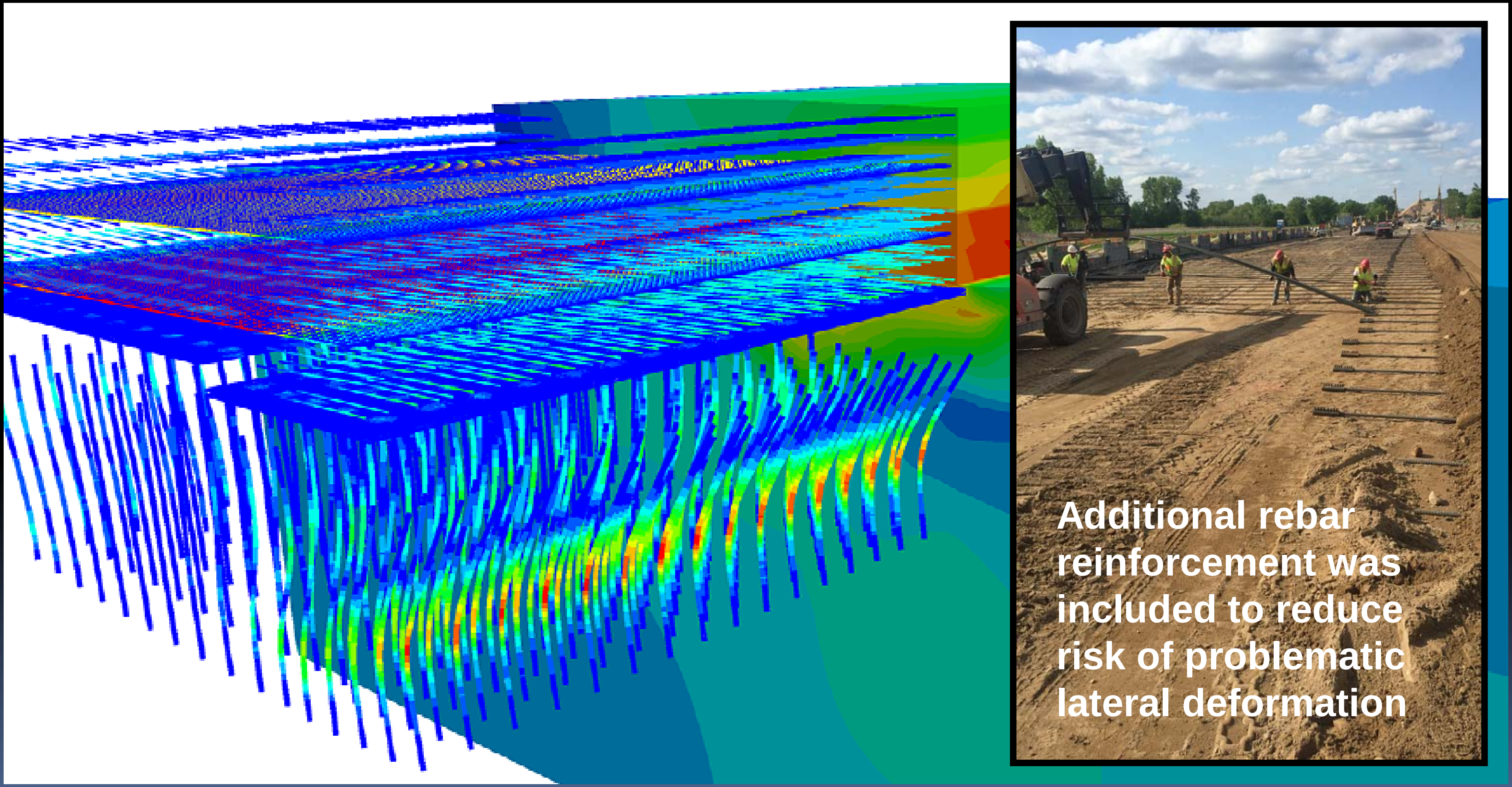
Controlled Modulus Column and MSE Wall Concept with 3 Platform Levels



Complex structures:

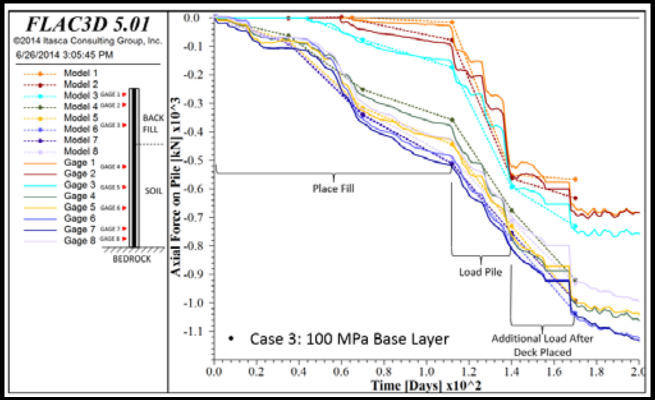
Nine Mile Creek Causeway

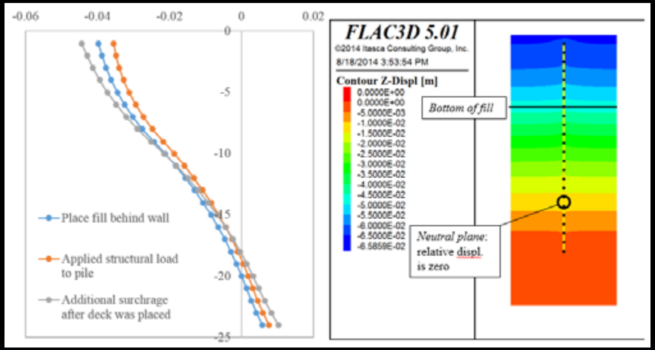
The 3-D computational model includes columns, load transfer platforms, MSE reinforcement, and additional internal reinforcement

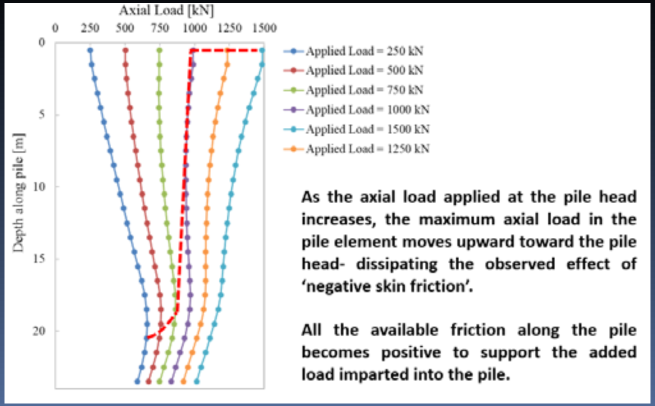


Soil structure interaction:

Evaluation of downdrag force on H-piles to rock

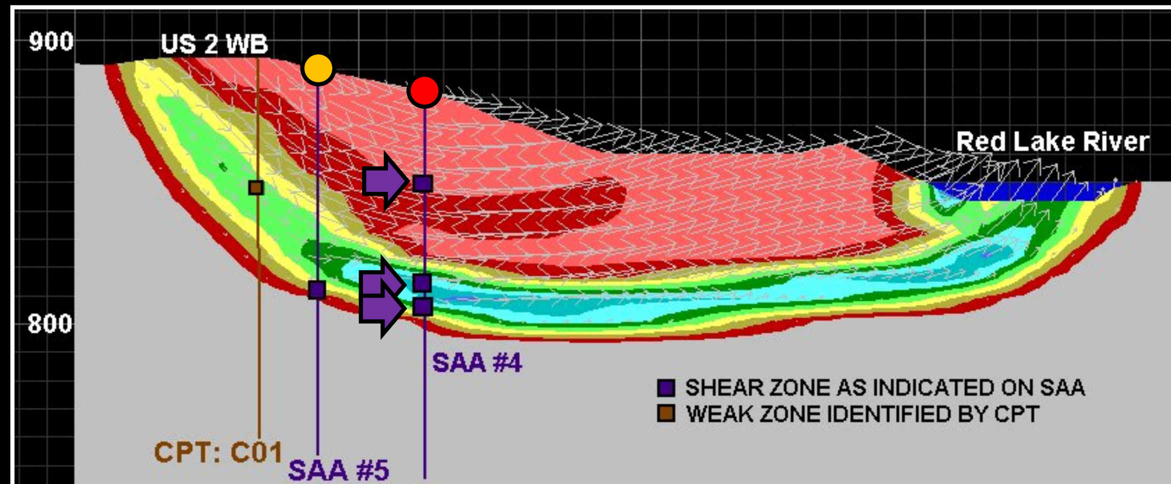


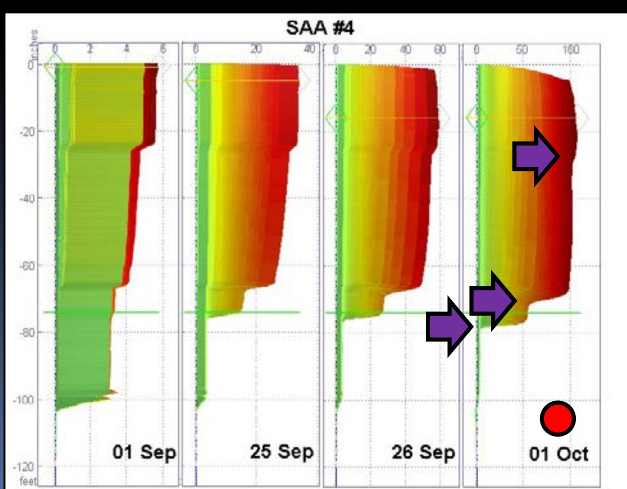




Slope stability:

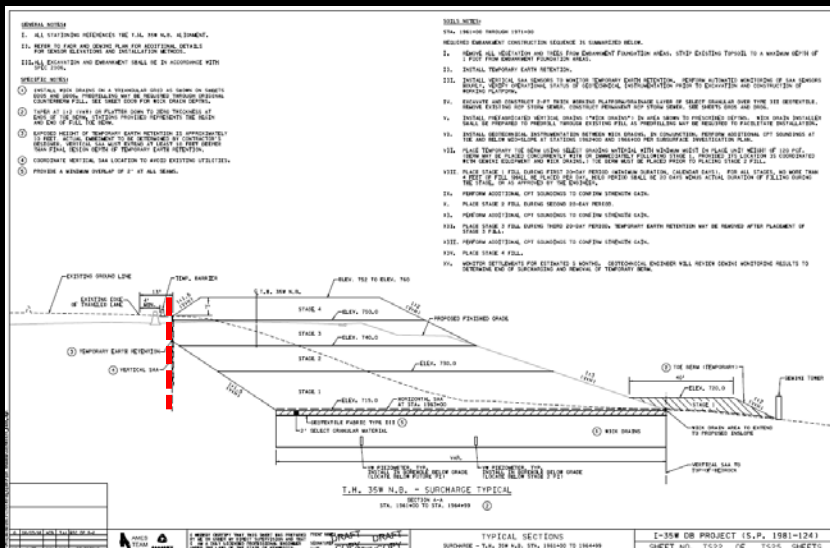
US 2 roadway failure in Crookston, MN

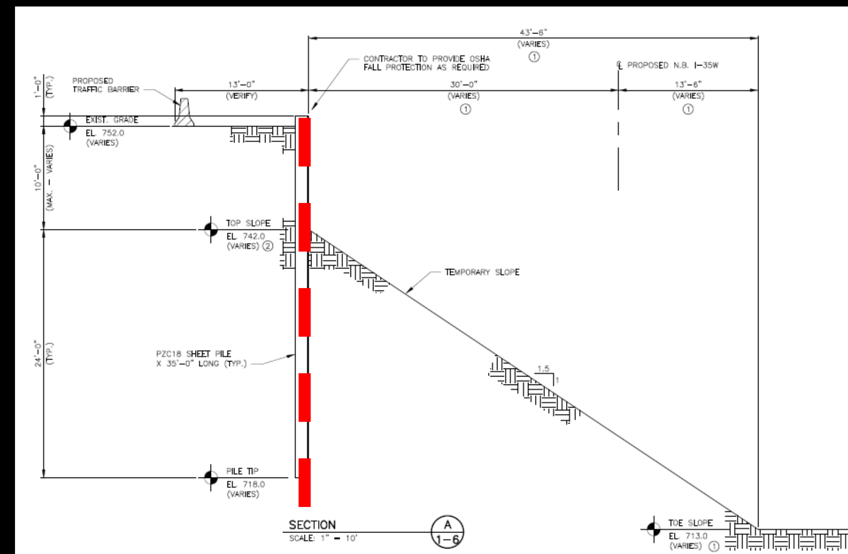


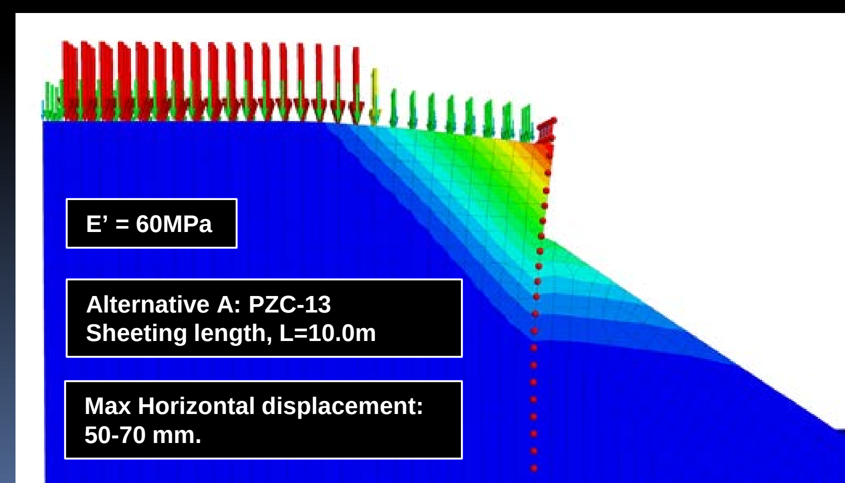


Temporary support and shoring:

I-35W embankment widening for new bridge construction

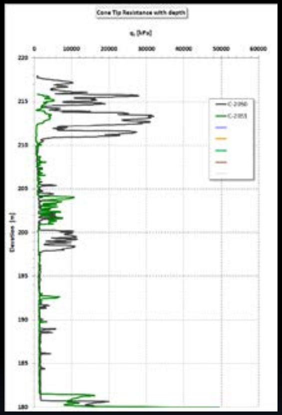


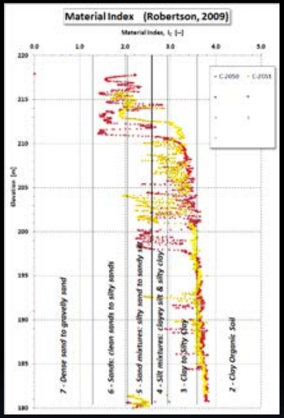


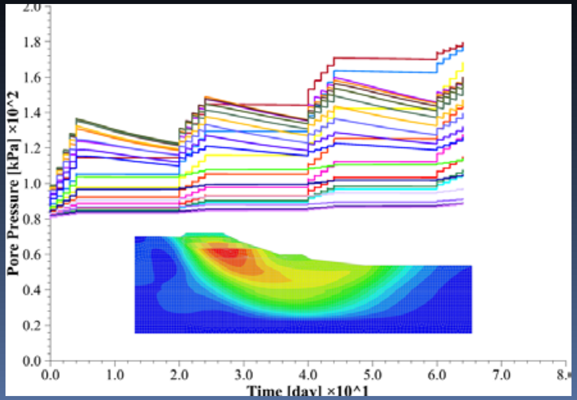


Costs/benefits: Numerical analysis tools

- Costs
  - As with all geotechnical computations and modeling: these tools require experience and familiarity to be correct, efficient and productive
  - Software or consulting services may be comparatively expensive
- Benefits
  - Handles complexity better than other methods; results are often insightful/meaningful
  - Able to relate strength, deformation, permeability, and time dependent behavior
  - Excellent visualization, often showing a continuum of behavior
  - Increases value of exploration + field monitoring
  - Quality of the methods aid in decision making

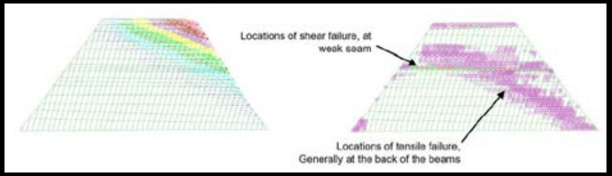


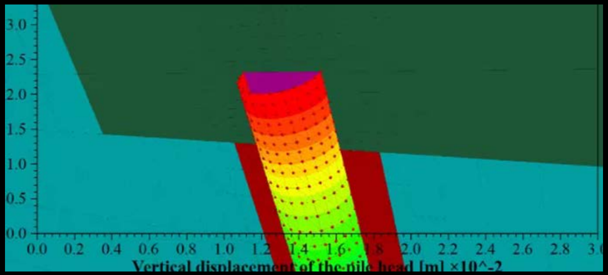


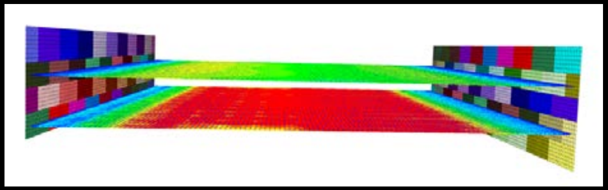


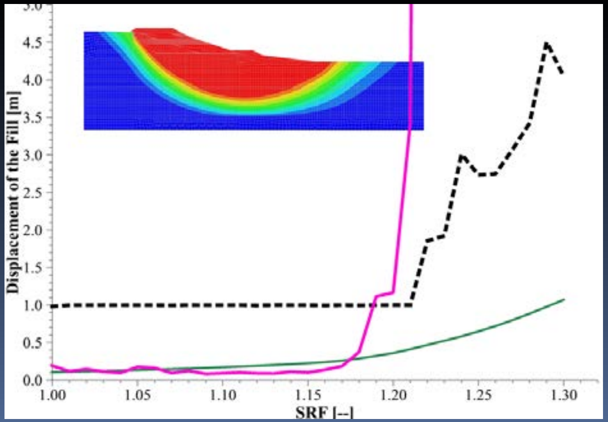
Applications: Numerical analysis

- Initial design
  - Use with modern in-situ methods to provide design recommendations with high confidence (reduced risk)
- Independent verification
  - Provides an important check for ‘reasonableness’ or ‘appropriateness’ of answers from simpler methods
  - Internal or as part of independent design oversight (QC, QA, IQA)
- Forensic analysis*
  - Provides the advantages of the method in critical situations





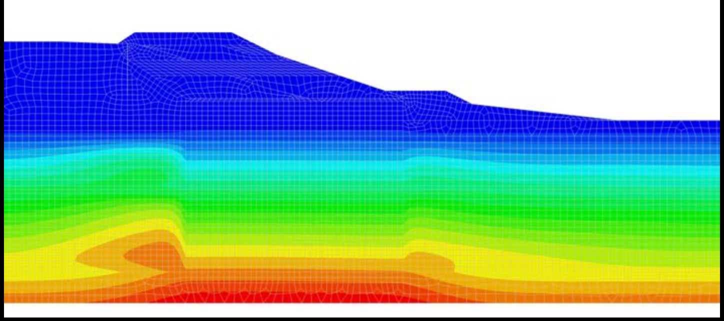


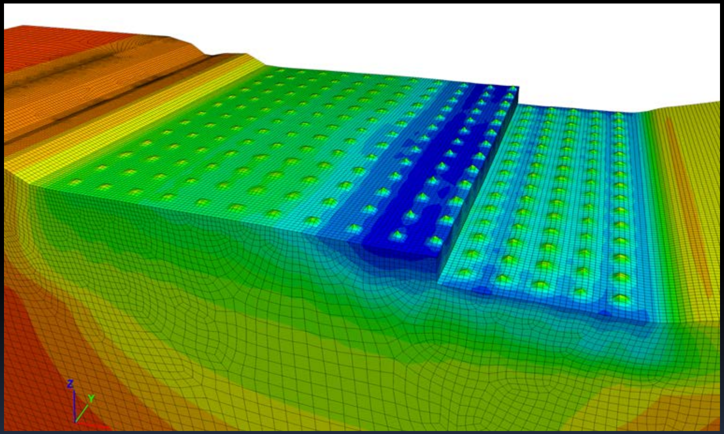


*often the current limited use case

Adding project value

- Implementation strategies
  - Develop in-house expertise
  - Use prequalification or other selection processes for contract modelling work (ongoing or on a project-specific basis)
  - Apply in conjunction with risk registries for added confidence in selecting alternatives or use in construction as design validation
  - Use case histories documenting results and project impact (cost, time, or other outcomes, such as averted problems, as a result of modeling findings) as a basis to adopt modern analysis methods





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Benefits of Computational Modeling for Geotechnical Engineers

Presented by Varun (Senior Geomechanics Engineer), varun@itascacg.com

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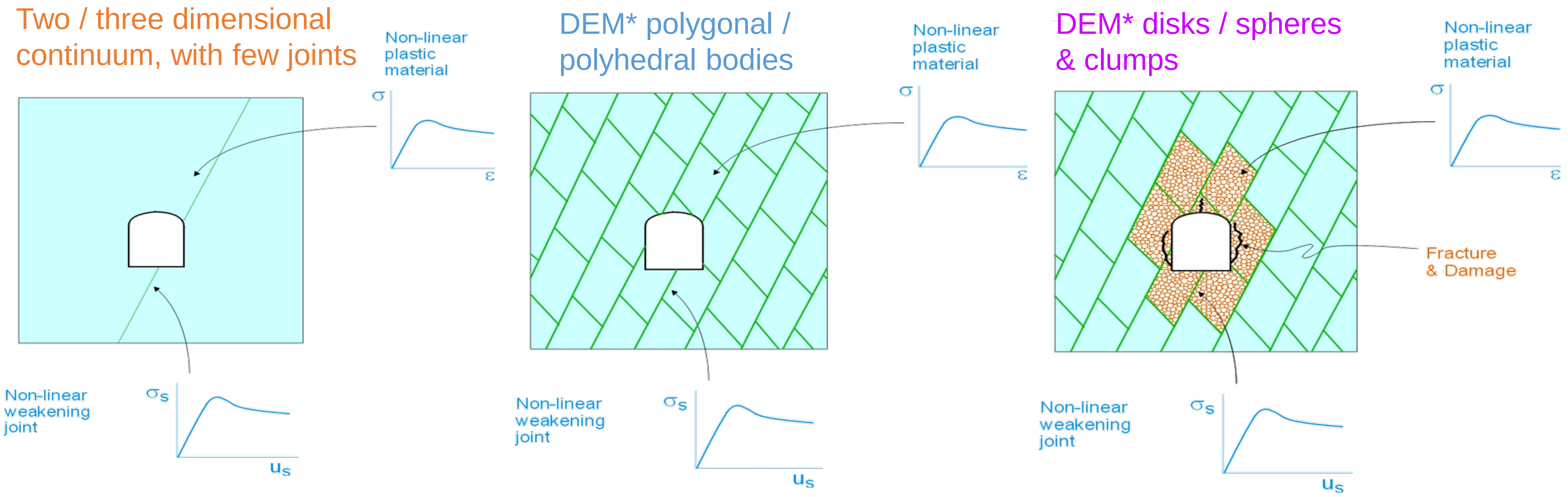
SELECTING THE NUMERICAL TOOL

- What type of material are we trying to model? Different options available for different types of problems
  - Continuum (Finite Element Method, Finite Volume Method, Finite Difference, etc.)
  - Blocky (Distinct Element Method)
  - Fracture growth (Discrete Element Method, Extended FEM, etc.)

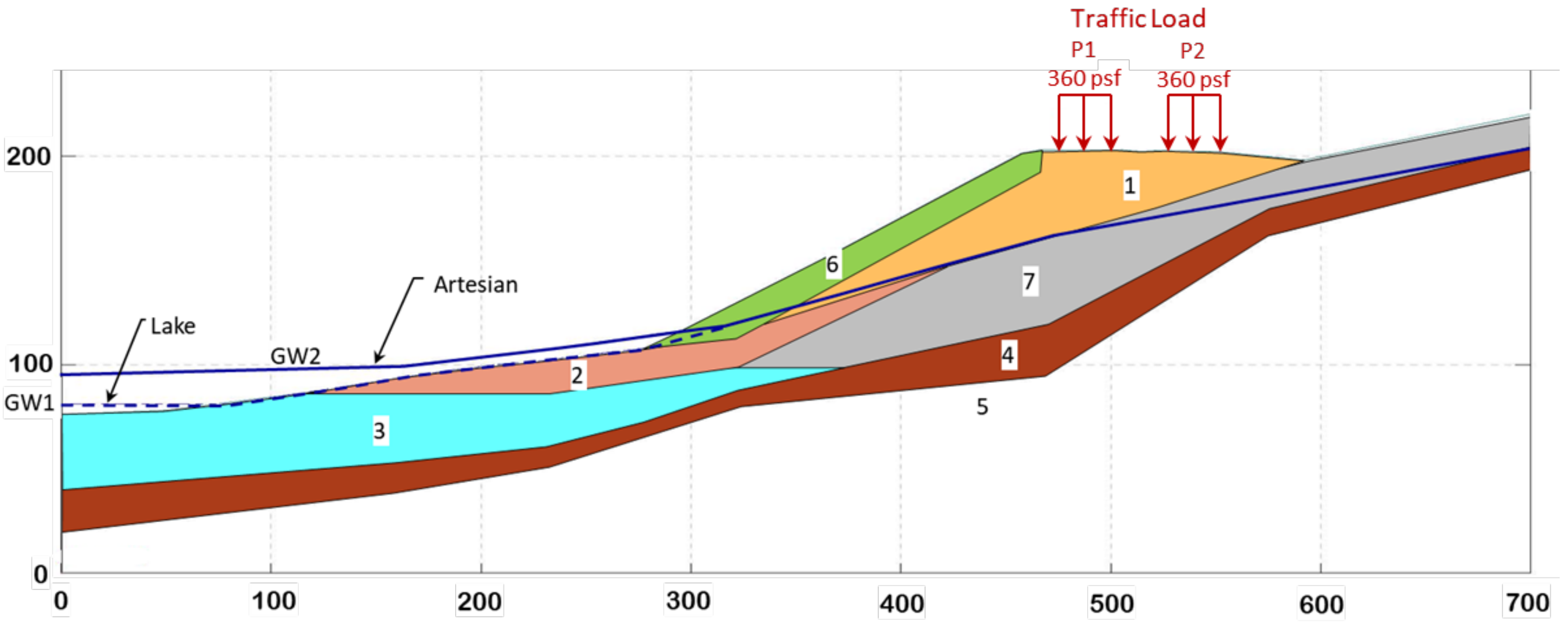


SELECTING THE CONSTITUTIVE MODEL

- What type of material behavior are we trying to capture? Increasing level of complexity can be included
  - Elasto-plastic with failure in shear or tension (Mohr Coulomb with tensile cut-off)
  - Elasto-plastic and a plane of weakness (Mohr Coulomb with ubiquitous joint)
  - Shear softening or hardening after failure (Mohr Coulomb with shear softening / hardening)
  - Modulus change as a function of shear strain (Plastic Hardening / Small strain modulus)
  - Permanent volume change as a function of increasing confining pressure (compaction) resulting in change of modulus and shear strength (Cam Clay)
  - Dynamic Loading (UBCSAND, PM4SAND, SANISAND)
    - Hysteretic damping and modulus reduction during loading, unloading and reloading
    - Pore pressure buildup due to volumetric compaction caused by cyclic loading
- Start simple and add complexity as needed. Simple models are easier to calibrate and often give a lot of insight. But do not oversimplify!

SLOPE STABILITY PROBLEM

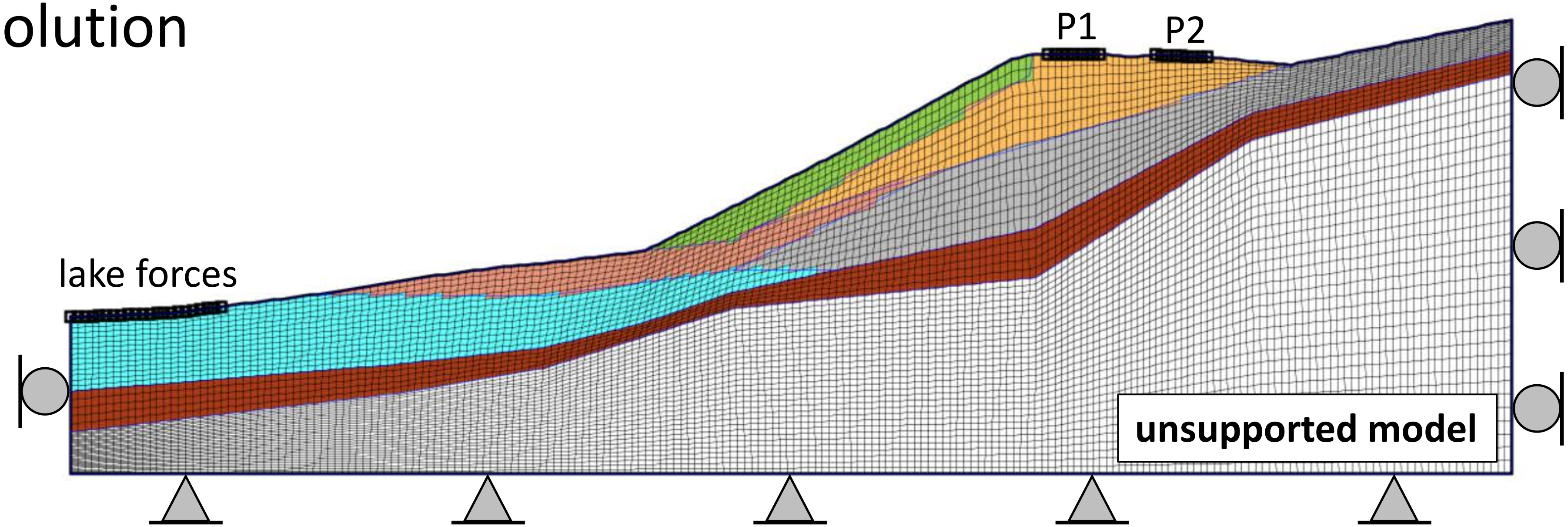
- Goal: To support the roadway embankment
- Roadway loads are at P1 and P2
- Geometry, soil properties, water tables, and loads as provided
- Constraints:
  - Cannot violate the lake
  - Long-term Factor of Safety (FoS) of 1.5
- Assumptions:
  - Slope as is
  - 2D plane strain
  - Long-term strength is associated with drained conditions



Soil Layer	Soil Type	g_m (pcf)	g_{sat} (pcf)	s_u (psf)	Drained c' (psf)	Drained f' (°)	Phreatic Surface
1	Embankment Fill	120	125	-	0	32	Lake (GW1)
2	Colluvial1	120	125	-	0	30	Lake (GW1)
3	Silt & Clay	117	120	500	0	25	Lake (GW1)
4	Sand & Gravel	125	130	-	0	36	Artesian (GW2)
5	Glacial Till	130	135	-	0	38	Lake (GW1)
6	Rockfill	130	135	-	0	45	Lake (GW1)
7	Colluvial2	120	125	-	0	34	Lake (GW1)

SOLUTION APPROACH

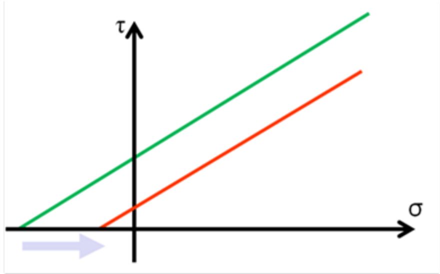
- Two-dimensional finite difference continuum software
- Mohr-Coulomb material model
- Effective stress/pore pressure
- Factor of Safety analysis using the Shear Strength Reduction (SSR) method
- Structural elements for ground reinforcement
- Practicable support solution
  - Cost
  - Installable
- Step-wise, iterative



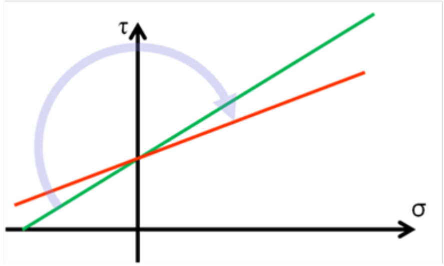
SHEAR STRENGTH REDUCTION

- Progressively reduce shear strength (τ) of materials to bring model to a metastable state
- Series of simulations done using trial values (F^{trial}) to reduce the cohesion (c) and friction angle (ϕ) until failure occurs
- May also reduce tensile strength and ground support strength properties
- For efficiency, a bracketing approach is used (stable and unstable states), and then this range is progressively reduced until the difference between the solutions falls below a tolerance

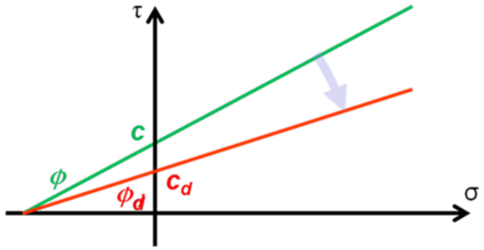
$$\tau = c + \sigma \cdot \tan(\phi)$$



- variable cohesion
- constant friction



- constant cohesion
- variable friction



- variable cohesion
- variable friction

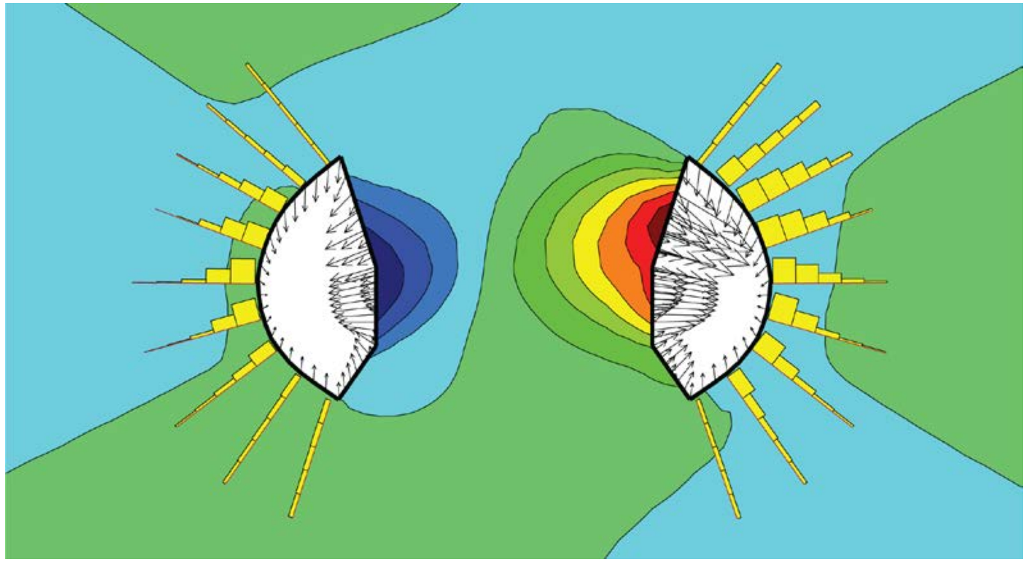
$$c^{trial} = \frac{1}{F^{trial}} c \qquad \phi^{trial} = \tan^{-1}\left(\frac{\tan(\phi)}{F^{trial}}\right)$$

BENEFITS OF NUMERICAL MODELING

	Finite Element / Finite Volume / Finite Difference	Limit Equilibrium Method (LEM)
Equilibrium	Satisfied everywhere	Satisfied only for specific objects (slices)
Stresses	Computed everywhere using field equations	Computed approximately on certain surfaces
Deformation	Part of the solution	Not considered
Failure	Yield condition satisfied everywhere; failure surfaces develop “automatically” as conditions dictate	Failure allowed only on certain pre-defined surfaces; no check on yield condition elsewhere
Kinematics	The “mechanisms” that develop satisfy kinematic constraints	Kinematics are not considered – mechanisms may not be feasible

STRUCTURAL ELEMENTS

- Structural elements of arbitrary geometry and properties, and their interaction with a soil or rock, may be modeled to simulate ground support
- 3D effects of regularly spaced elements is accommodated by scaling their material properties in the out-of-plane direction
- Available structural elements:
  - Surface Support Elements (beams, liners, and support)
  - Shear Support Elements (cables and strips)
  - Shear and Normal Support (piles and rockbolts)
- Can accommodate large displacements
- Can fail, redistributing forces in the model
- Can be linked (tied) together
- Can be utilized in dynamic (seismic) simulations



STRUCTURAL ELEMENTS USED

CABLES

- Supports for which tensile capacity is important
- Can also fail in tension and compression, no flexural resistance
- Can be point-anchored or grouted so that the cable element develops forces along its length, resisting relative motion between cable and grid
- May be pre-tensioned, if desired
- Applications include:
  - rockbolts
  - cable bolts
  - tie-backs
  - anchors

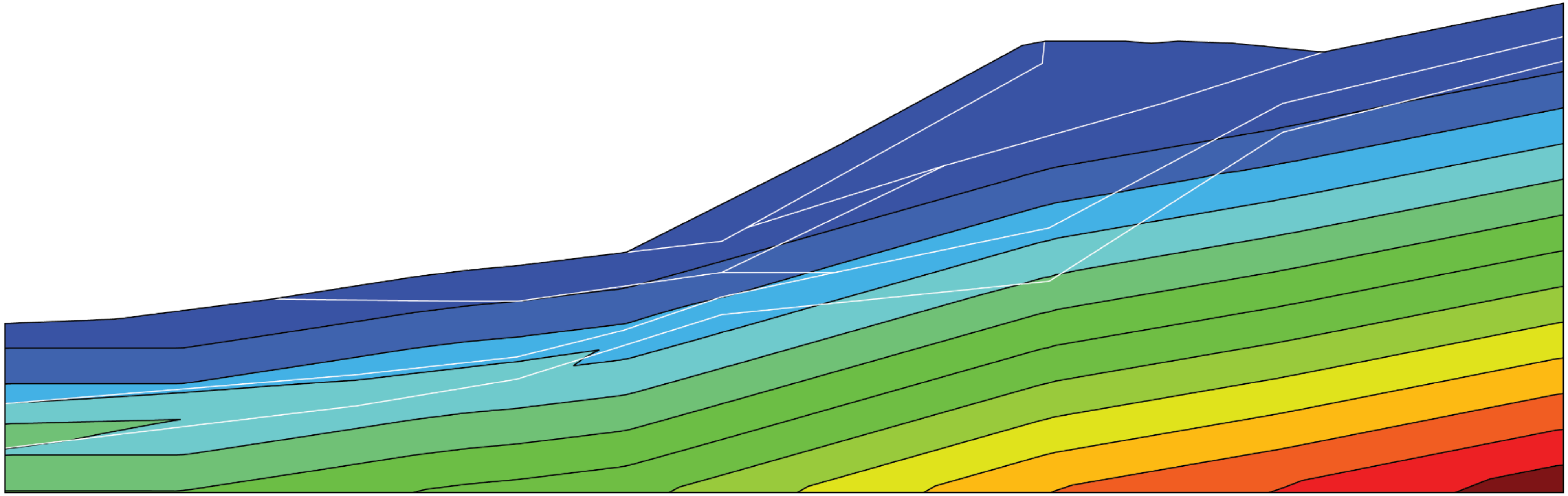
BEAMS

- Modeling of structural support in which bending resistance is important
- Linear axial displacement (cubic deflection)
- Axial peak and residual strengths
- Nodal behavior may also include plastic hinges
- Applications include:
  - sheet piles
  - support struts

PILES

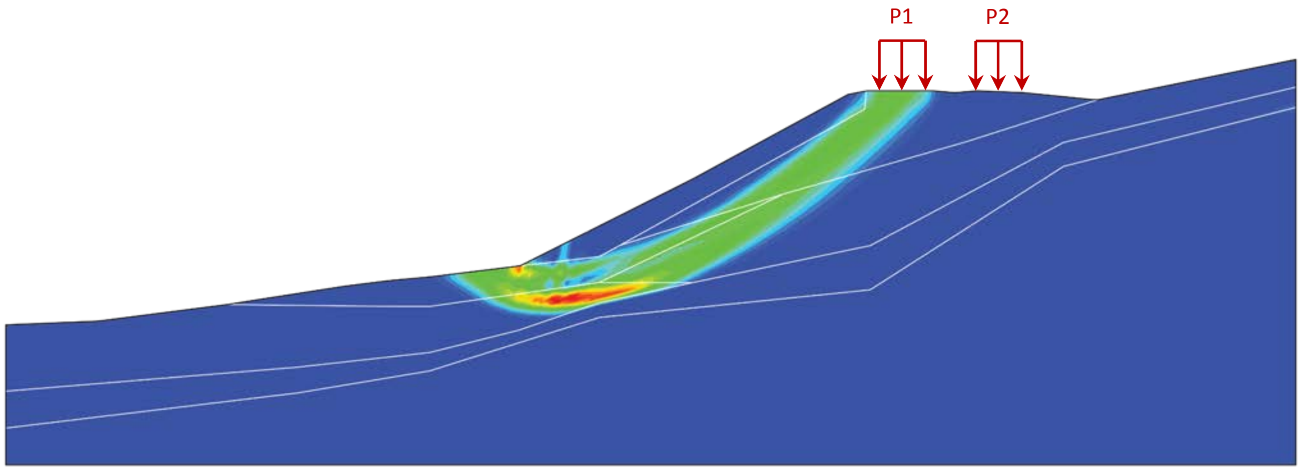
- Combines structural behavior of beams and medium/structure interaction of cables
- Can also develop frictional forces along its length, resisting relative normal motion between pile and grid
- Applications include:
  - Foundation piles
  - Stabilizing piles

PORE PRESSURE DISTRIBUTION



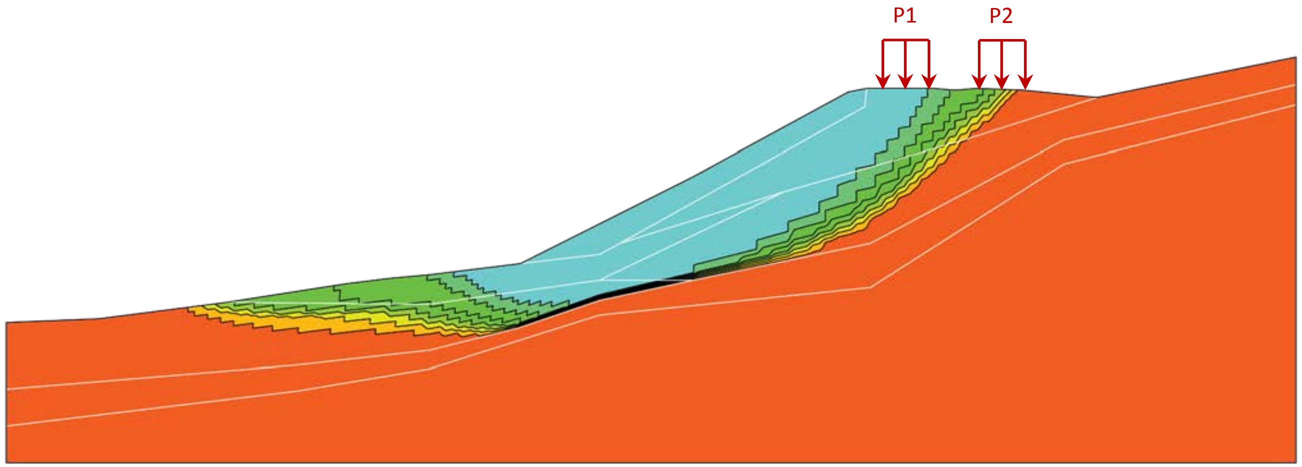
- The pore pressure distribution can be represented accurately including artesian conditions.
- Seepage problem can also be solved to determine phreatic surface if needed.

DRAINED CASE (UNSUPPORTED)



Maximum Shear Strain Increment

- Strains are derived from displacements
- Approximate slip plane
- **FoS = 0.95**

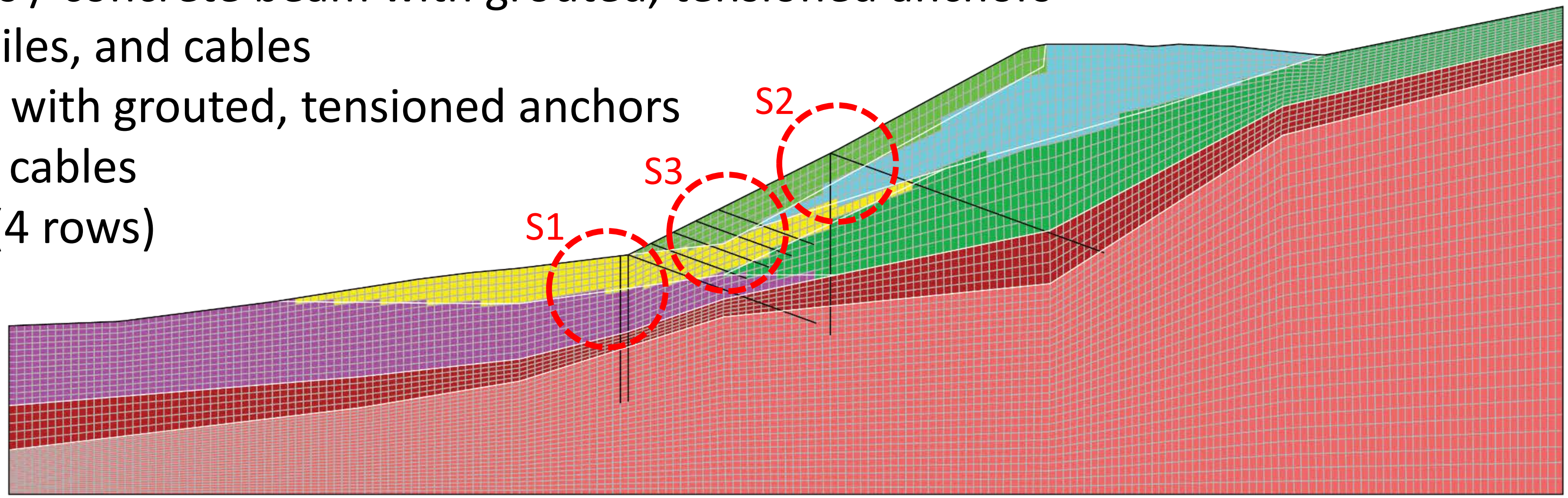


Factor of Safety Contours (Safety Map)

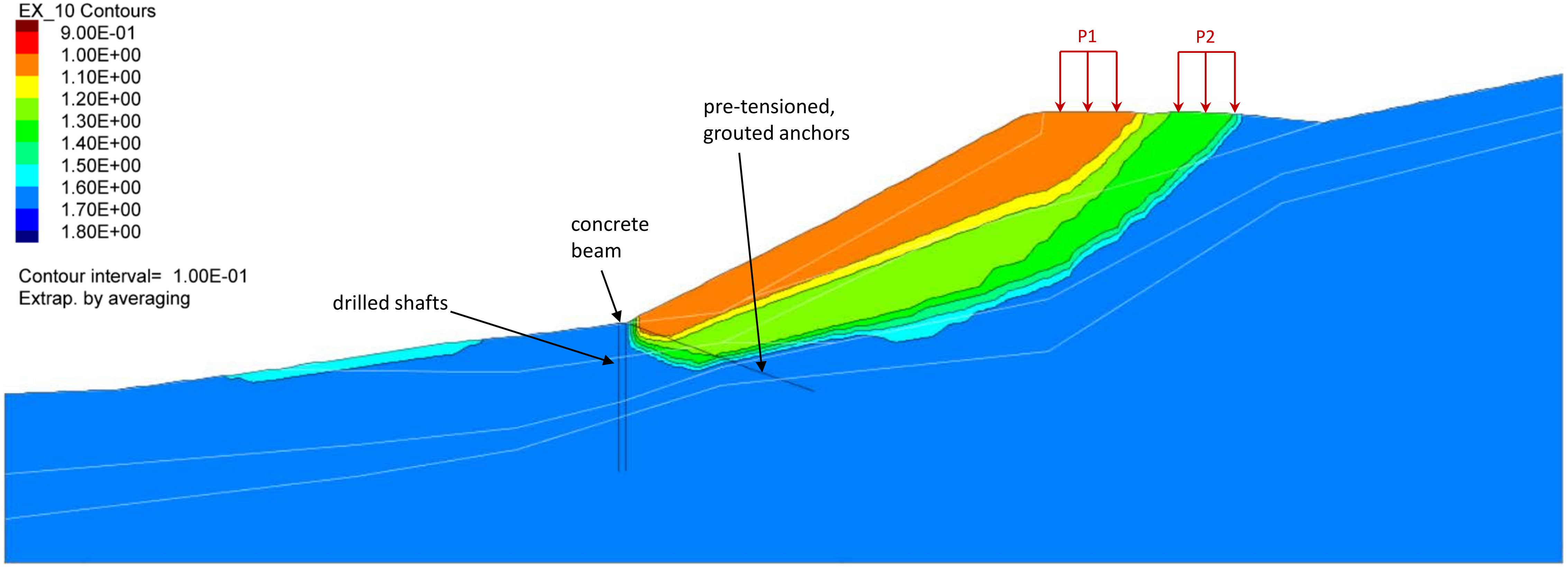
- Material property sensitivities
- Localization

STABILIZATION SOLUTION

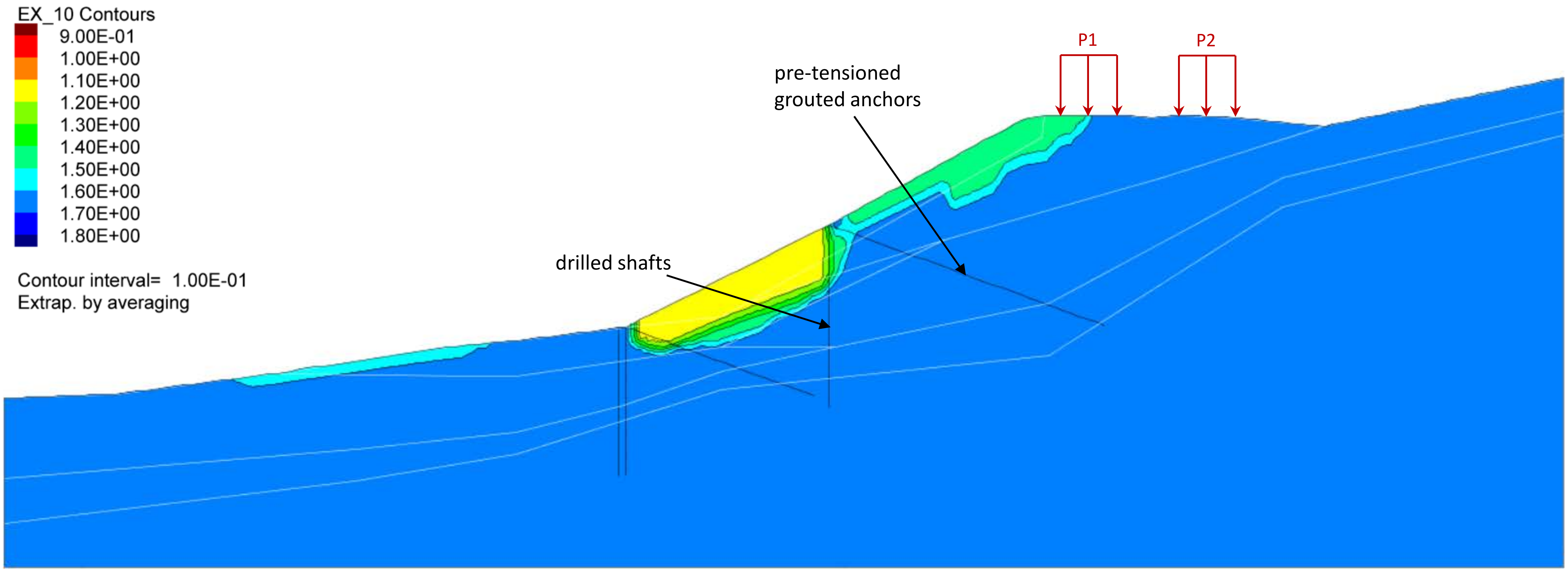
- Challenging problem
  - High FoS target
  - Slope and roadways exists (i.e., limits support options, installation more difficult)
  - Relatively weak soils
  - Global failure is relatively deep seated
- Lowering the water table was not considered for long-term solution (continuous pumping required)
- Ground support incrementally added
  - S1: Vertical drilled shafts / concrete beam with grouted, tensioned anchors
  - Modeled with beams, piles, and cables
  - S2: Vertical drilled shaft with grouted, tensioned anchors
  - Modeled with piles and cables
  - S3: Fiberglass soil nails (4 rows)
  - Modeled with cables



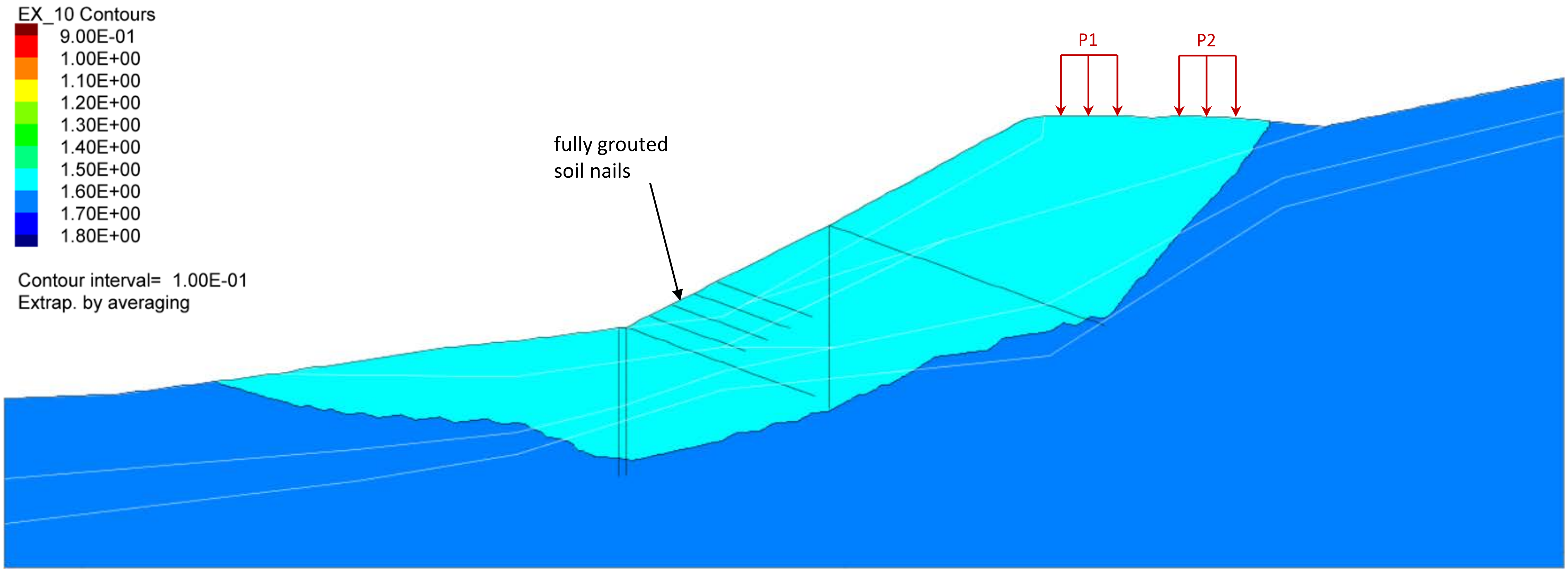
S1: DRILLED SHAFTS/ANCHORS



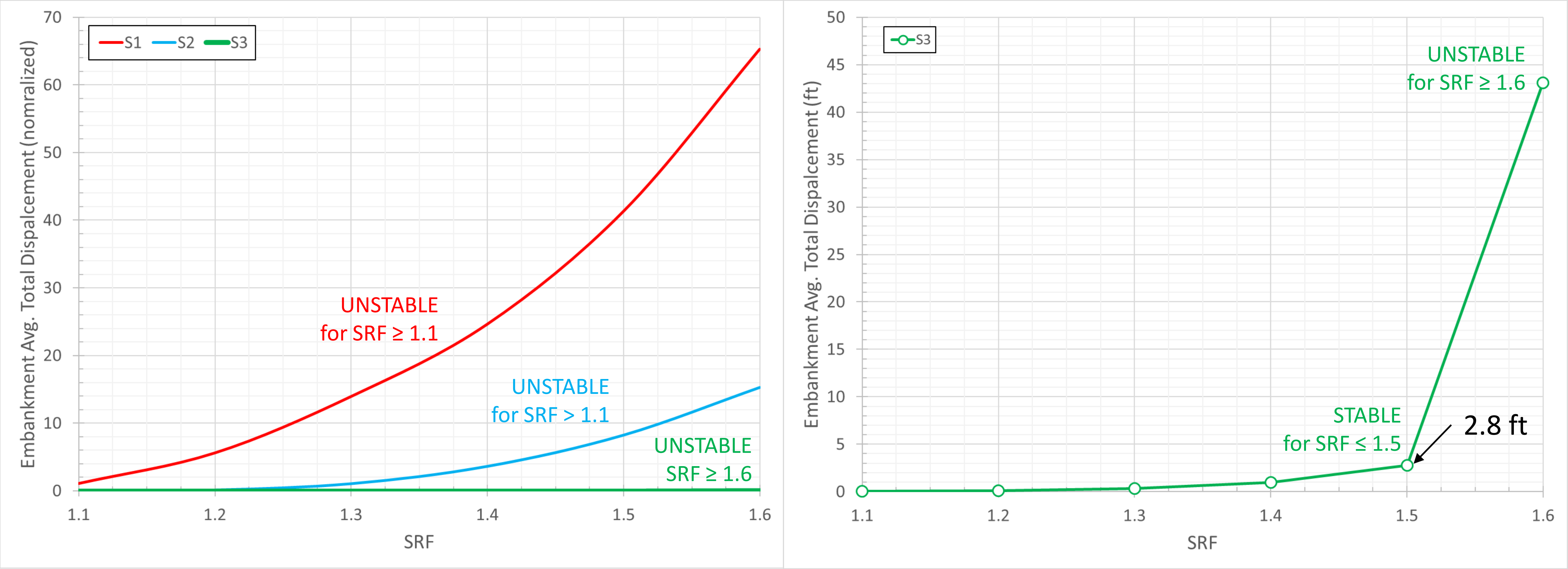
S2: DRILLED SHAFT/ANCHORS



S3: FIBERGLASS SOIL NAILS



GROUND SUPPORT EFFECTIVENESS

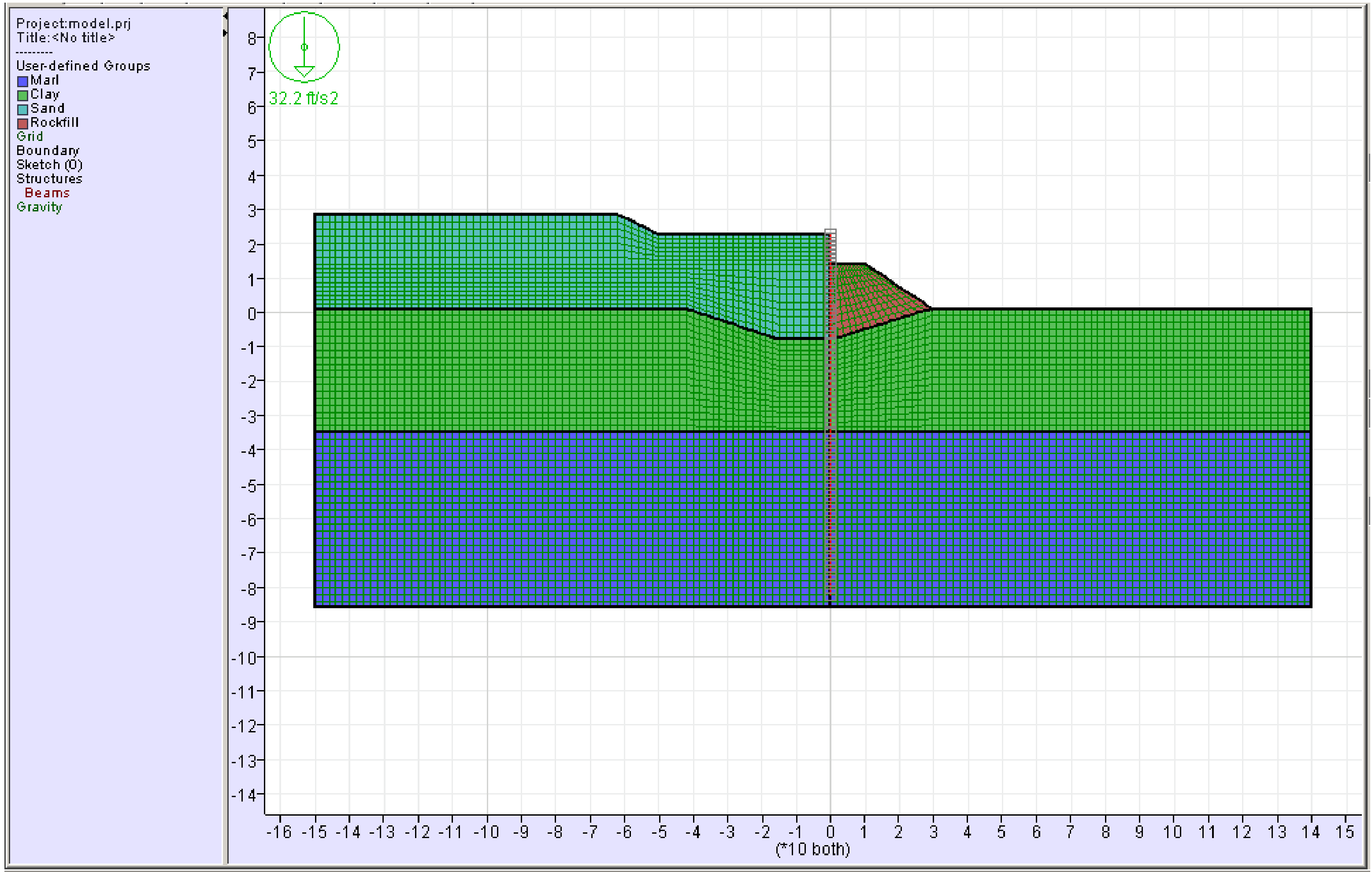


Monitoring displacements as strength is progressively reduced remains a useful indicator of stability because sometimes, Service Limit State may be more critical than the Ultimate Limit State.

EARTH RETAINING STRUCTURE

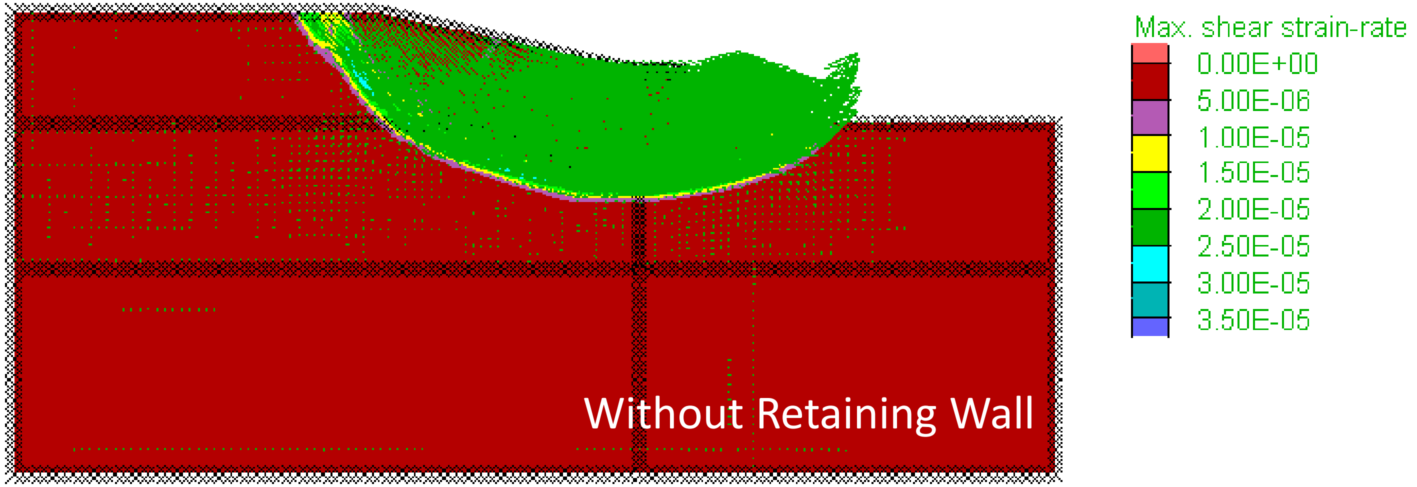
- Goal: To support the soil on the left using a sheetpile retaining wall (center)

- Evaluate different options including soil improvement or stronger / stiffer wall

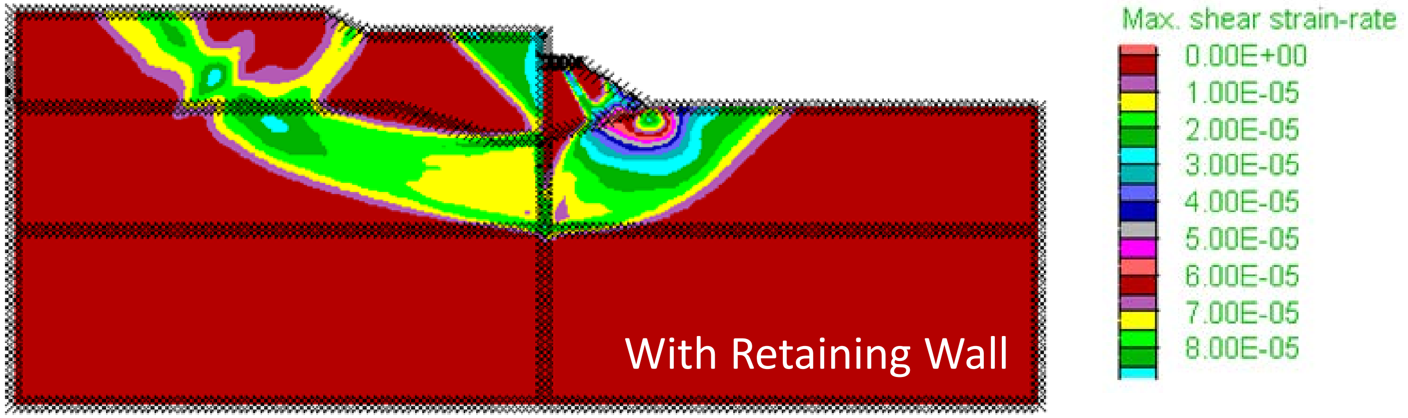


FACTOR OF SAFETY

- FoS without the sheet pile wall using shear strength reduction method = 0.40
  - Same as obtained using limit equilibrium method

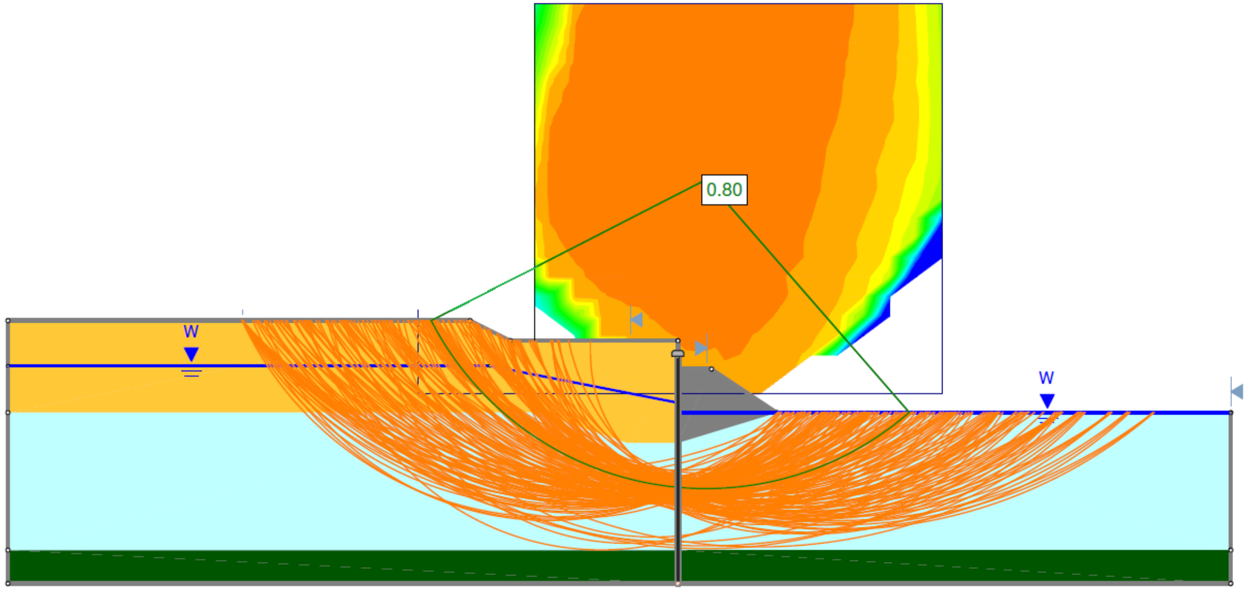


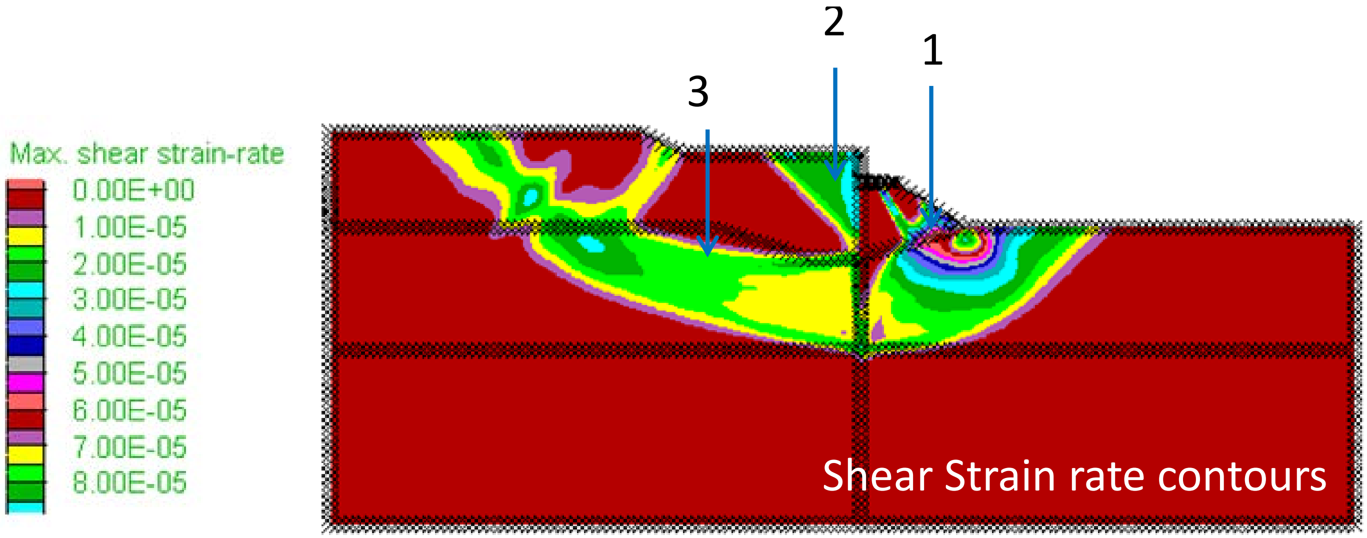
- FoS with the sheet pile wall using SSR = 0.45
  - LEM predicted 0.80



INTERACTING MECHANISMS

- Sheet pile wall was modeled explicitly in the SSR approach whereas LEM used a shear force distribution obtained using a subgrade reaction program
- LEM failed to capture the multiple failure mechanisms developing
  - Mode 1: Local slope failure through rockfill and clay
  - Mode 2: Active wedge failure behind sheetpile
  - Mode 3: Lower FoS for global deep seated failure due to reduced resistance caused by 1 and 2





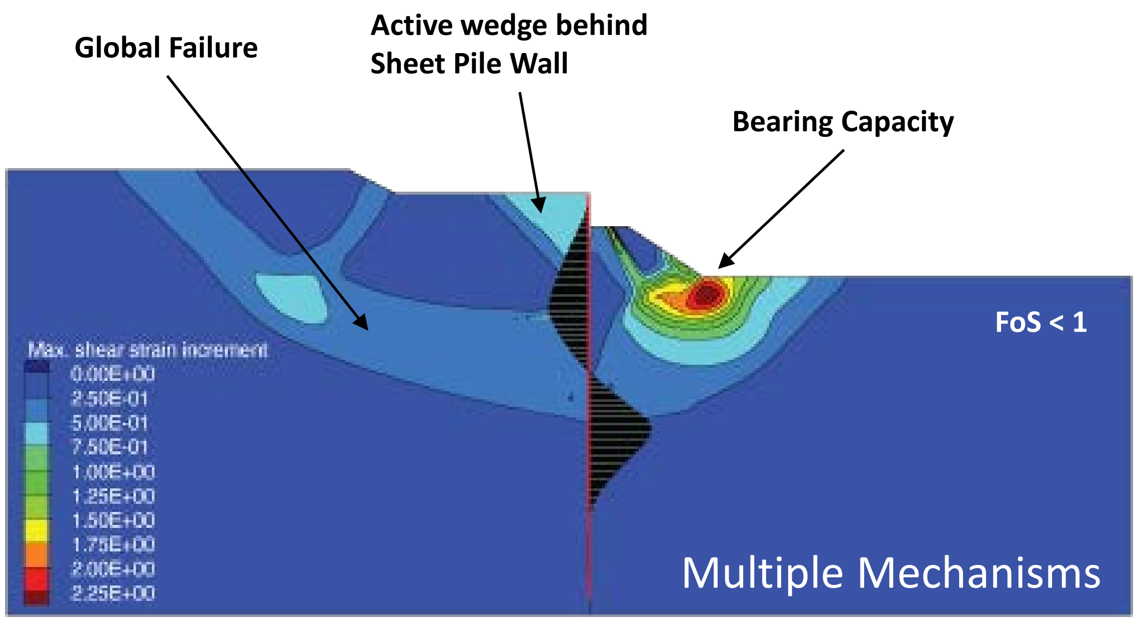
SHEAR STRENGTH REDUCTION

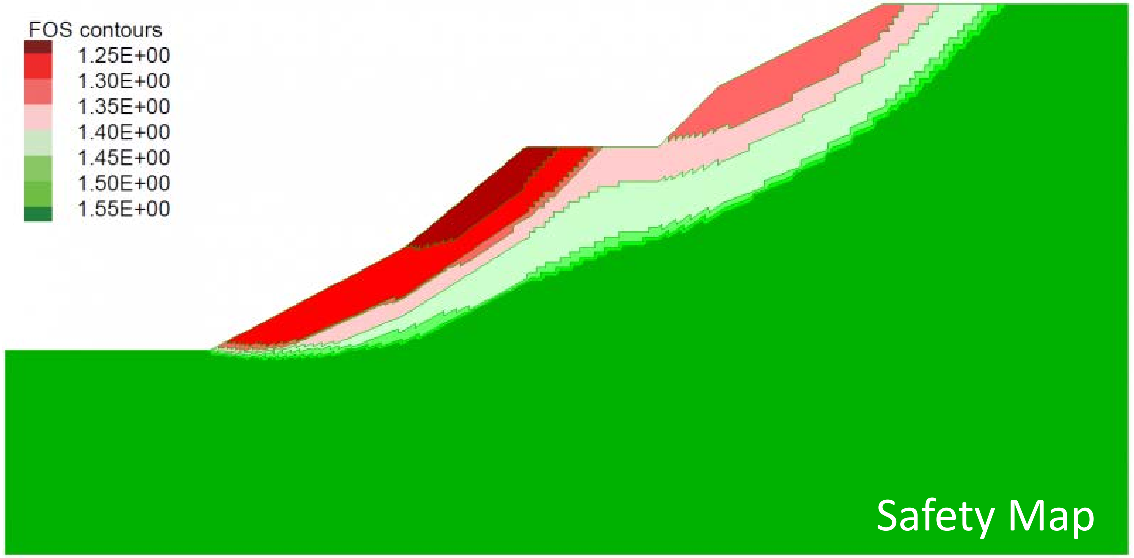
PROS

- 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:
    - Full soil-structure interaction (beams, sheet pile walls, piles, liners, anchors, etc.)
    - Structural reactions are not "wished-in-place"
    - Create a Safety Map (FoS contours)

CONS

- Solution time can take minutes to hours or more, increasing with grid refinement and 3D





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Jet Grouting Applications for Earth Retaining Structures

31 August 2018

"De Lelli" underground park – Verona (Italy)
"Repubblica" underground park – Verona (Italy)
"GA Merlata" cut & cover tunnel – Highway A4 – Milan-Venice
Keller Fondazioni (Italian branch of Keller Group)

Presented by Augusto Lucarelli, Principal Engineer at ITASCA

General Outline

Underground park in Verona (Italy).

Excavation depth around 13 m. About 3000 m^2.

Soil is a mixture of gravel and sand with cobbles.

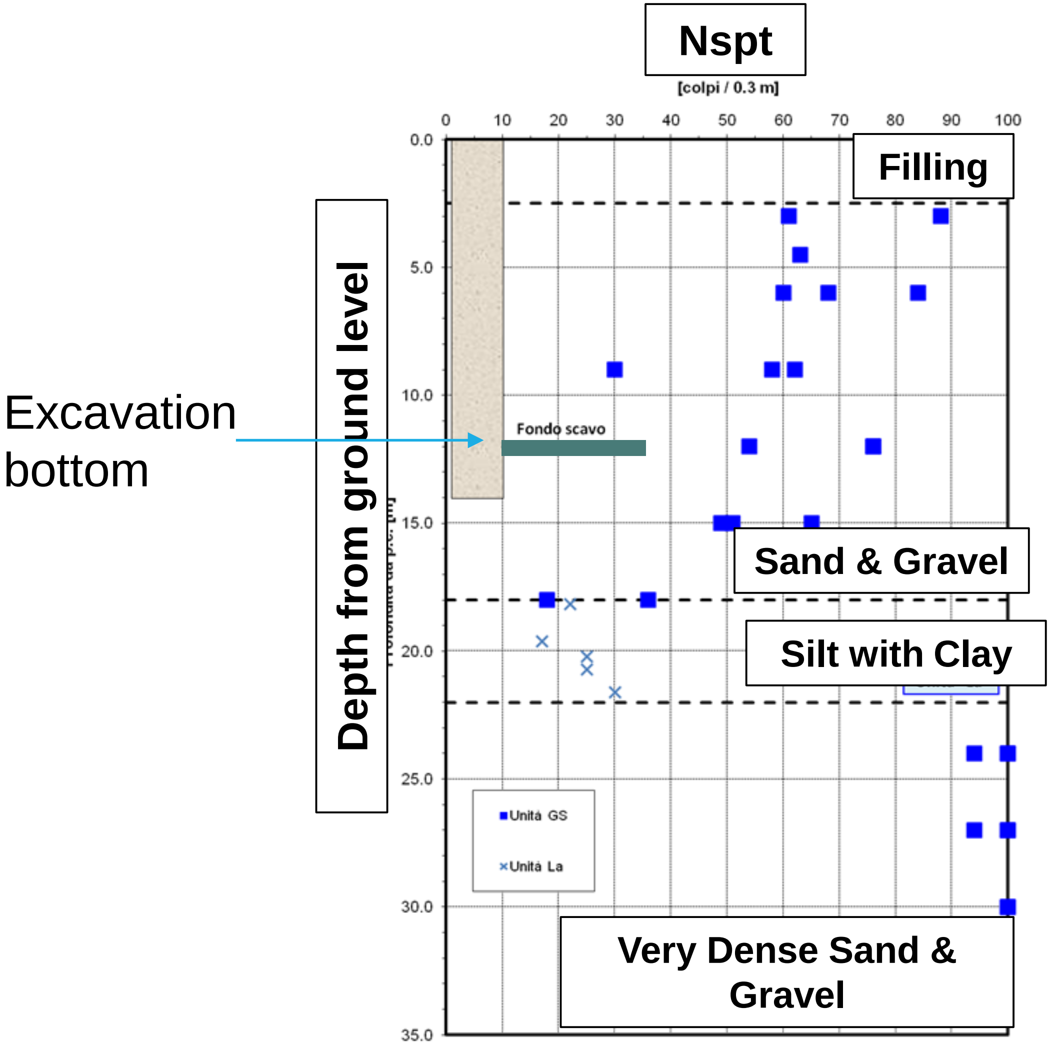
After many trials, the only practical solution was to realize a jet-grouting wall with anchors.

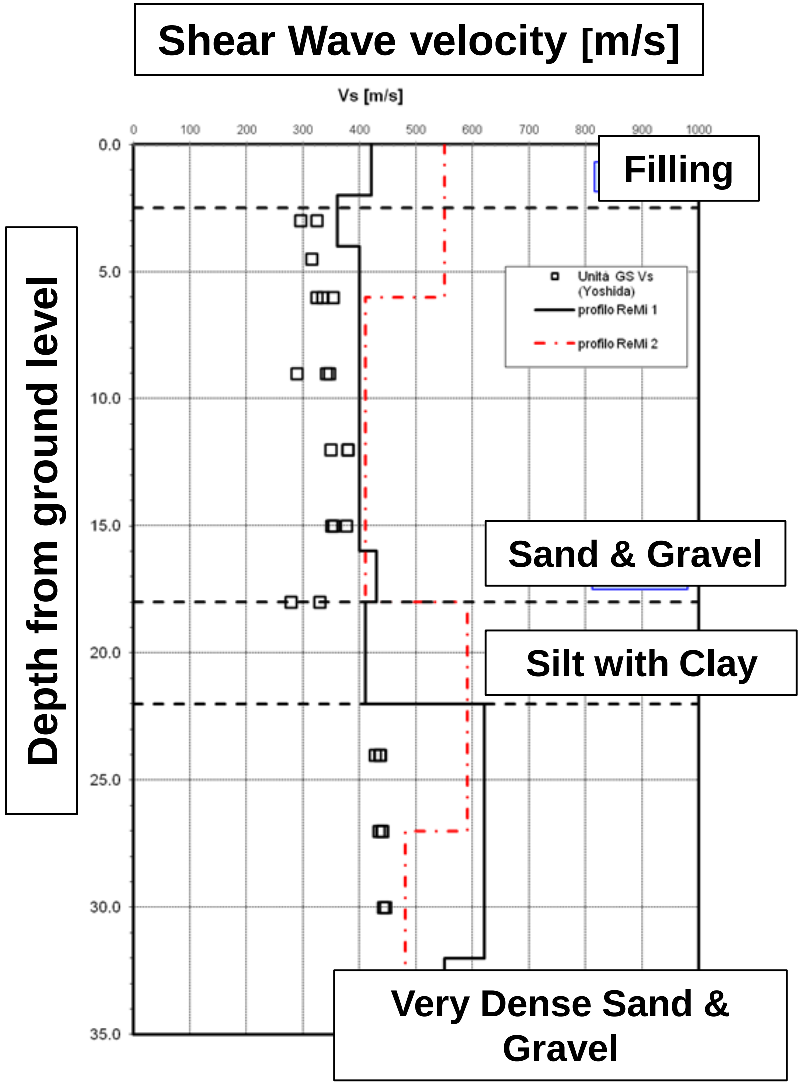
Overview of the Job Site During Construction

The quality of the Jet Grouting obtained was very good.

UCS was about 15 MPa.

Overview of Soil Conditions





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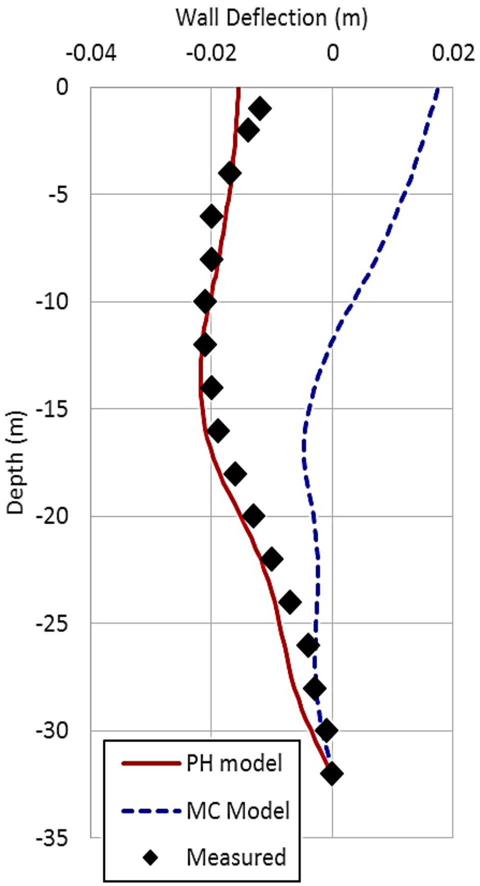
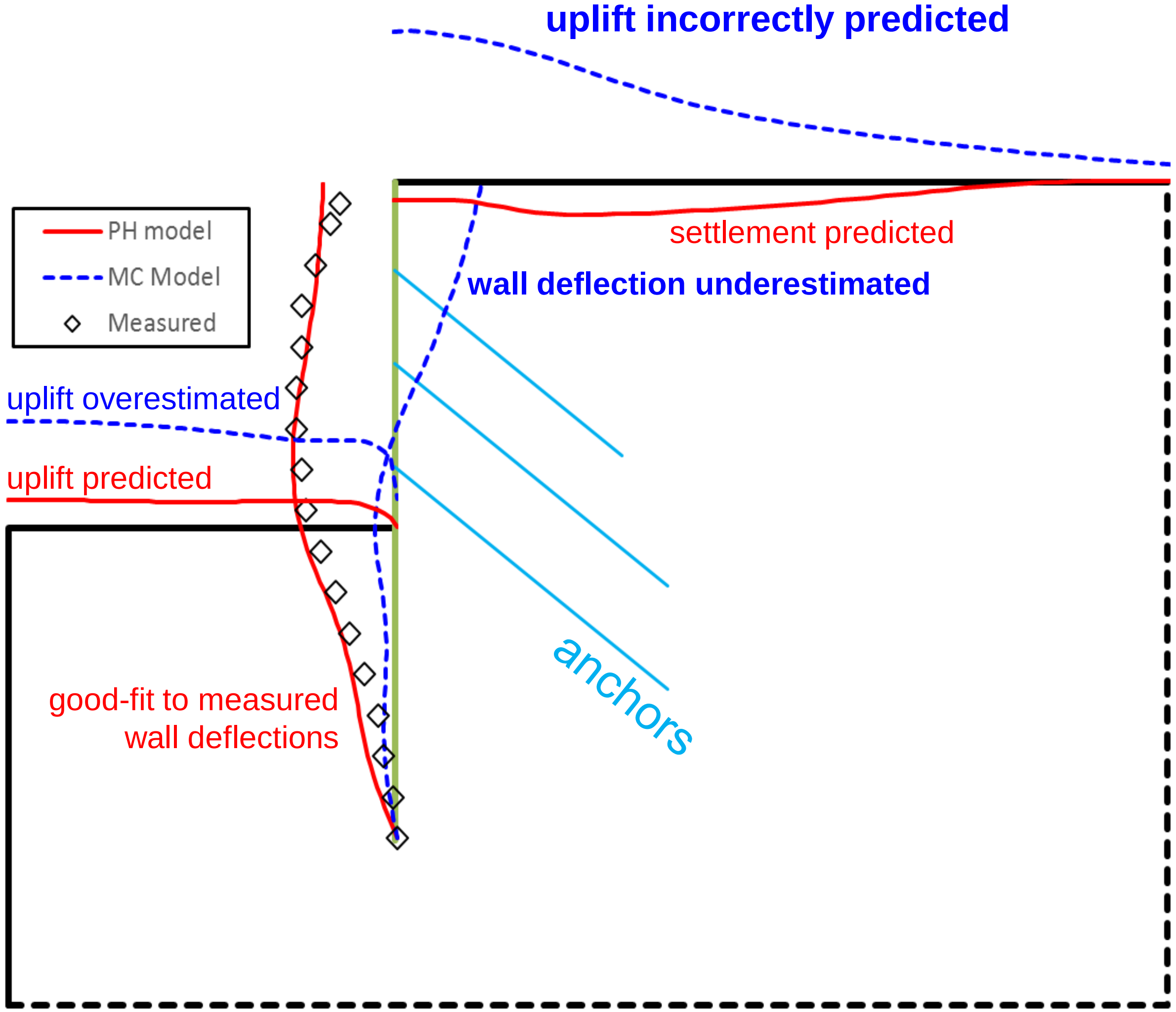
Plastic Hardening (PH) Constitutive Model: Why?





Unloading:

Generally, the MC model is not acceptable. The stress path is much more complex than in loading. The displacement field is generally non-realistic. The stress resultants in the support is underestimated most of the time.

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PH Constitutive Model: Background

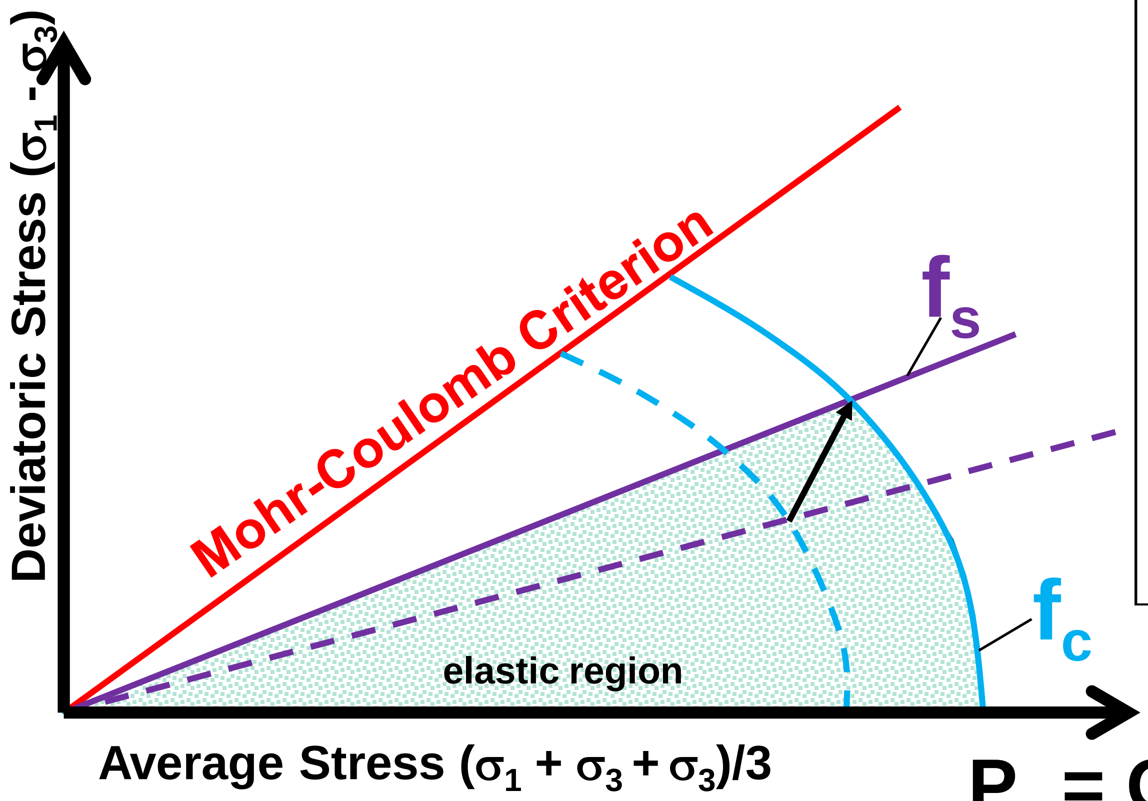
- It is used worldwide and well known inside the civil geotechnical community.
- It has become a "standard" model for civil engineering design in many areas such excavations, foundations, tunneling, and soil-structure interaction in general.
- Several regulatory agencies, especially in Europe, require (or at least strongly endorse) this type of model for civil applications.
- It easy to calibrate and uses names and conventions of familiar properties.
- It is available in every software package under different names (such as FLAC3D/FLAC, PLAXIS, MIDAS, ZSOIL, PHASE2 etc.). Easy to compare results with other codes.

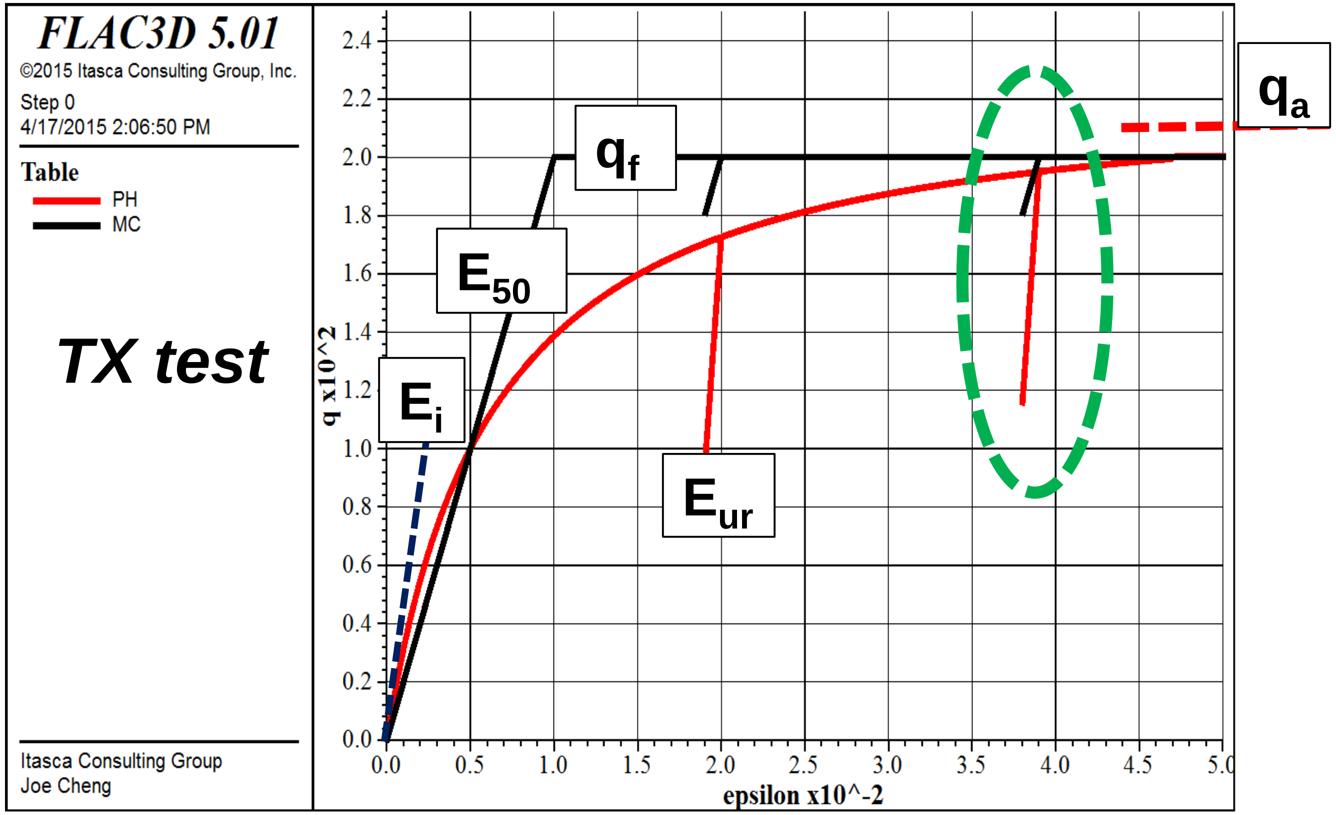
- More info at: http://www.itascacg.com/software/flac3d/flac3d-plastic-hardening-model
  Theory, calibration examples (from lab and in-situ tests), design examples.

PH Constitutive Model: Background

f_s shear hardening yield function

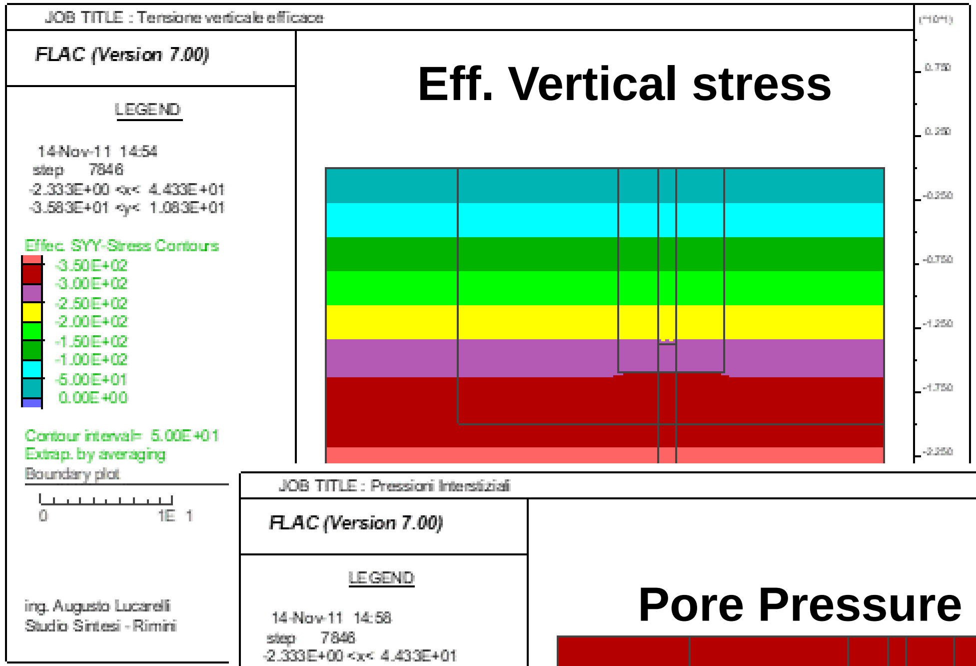
f_c volumetric hardening (cap) yield function

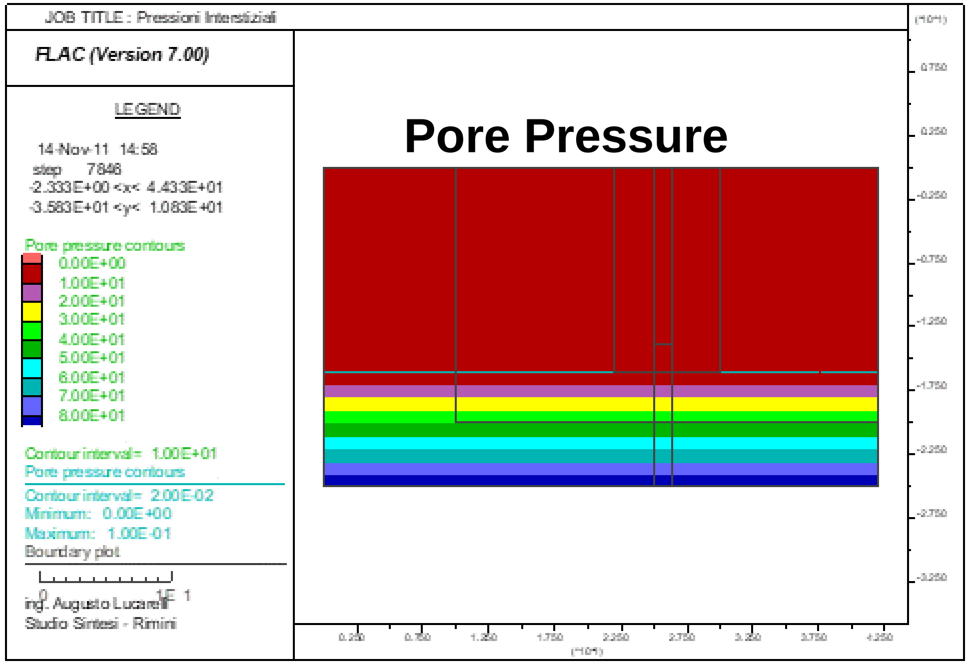


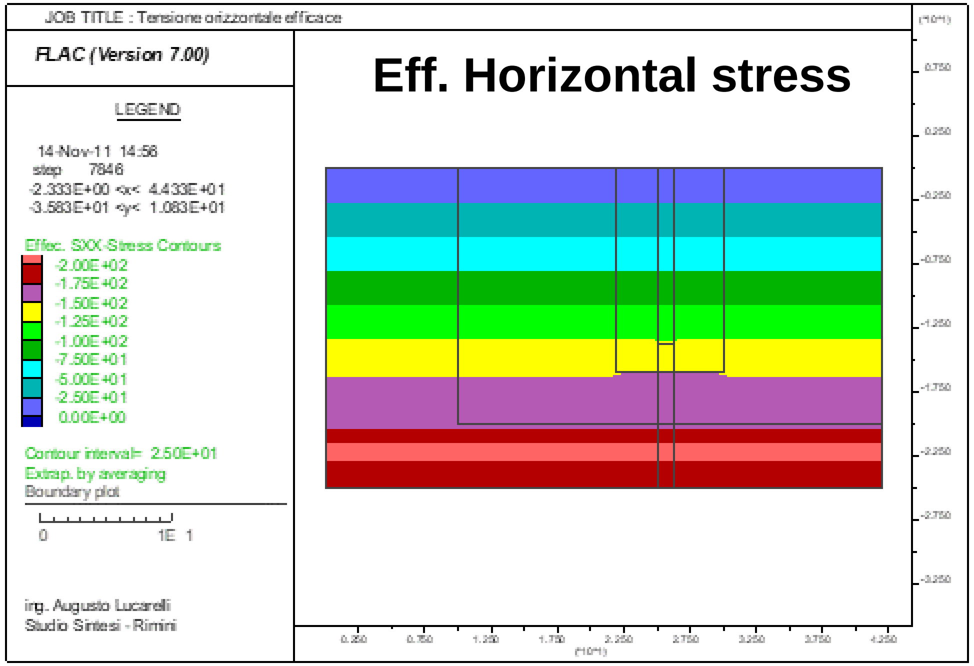


$$P_p = OCR\ P_{nc}$$

Construction Stage Modeling: Stress Initialization







After the initial stress is in equilibrium, the PH model is activated. Properties can be given to each zones using tables.

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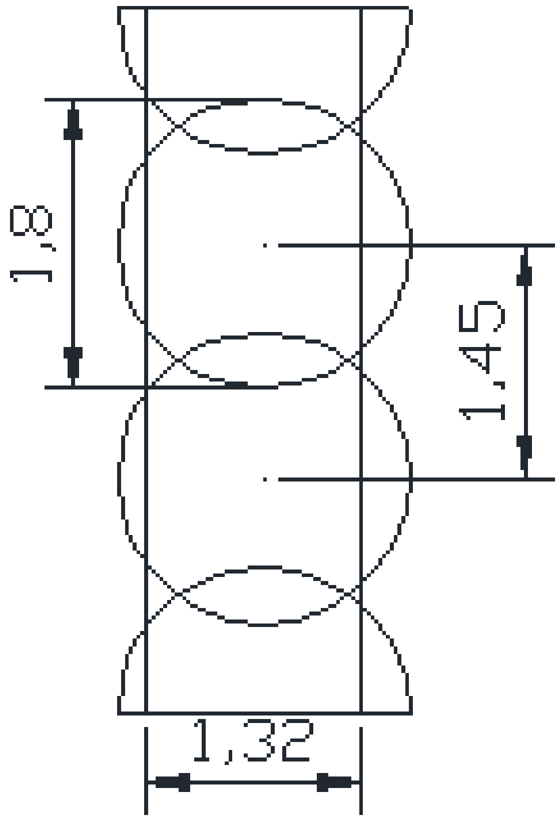
Execution Phases: Jet Grouting Wall Activation



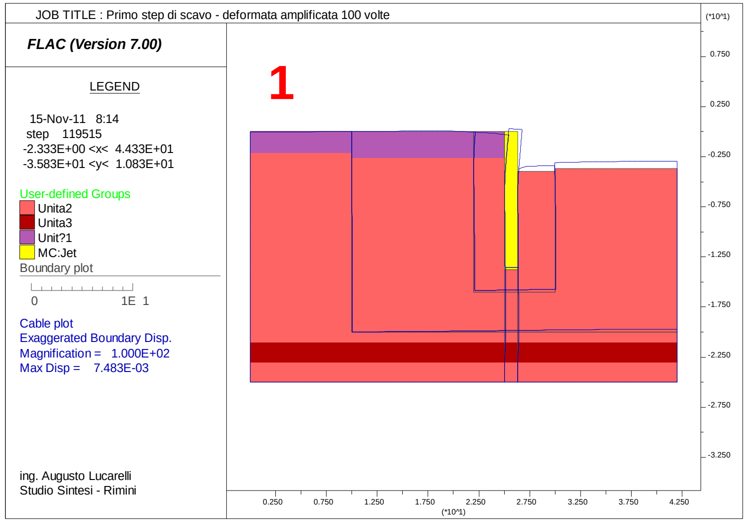
The jet wall has been modeled as a Mohr Coulomb material with the following parameters:

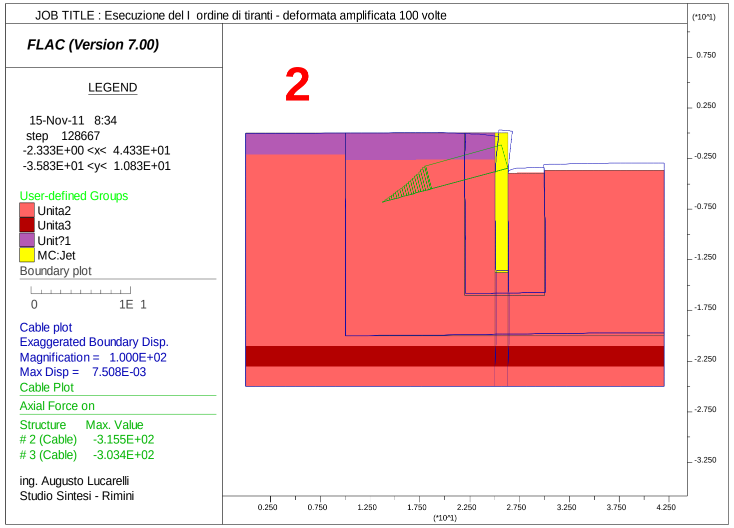
γ = 15	**kN/m3**	**unit weight**
c' = 250	**kPa**	**cohesion**
φ' = 38	**°**	**friction angle**
E' = 1.0	**GPa**	**elastic modulus**
UCS = 4	**Mpa**	**Unconfined Compressive strength**

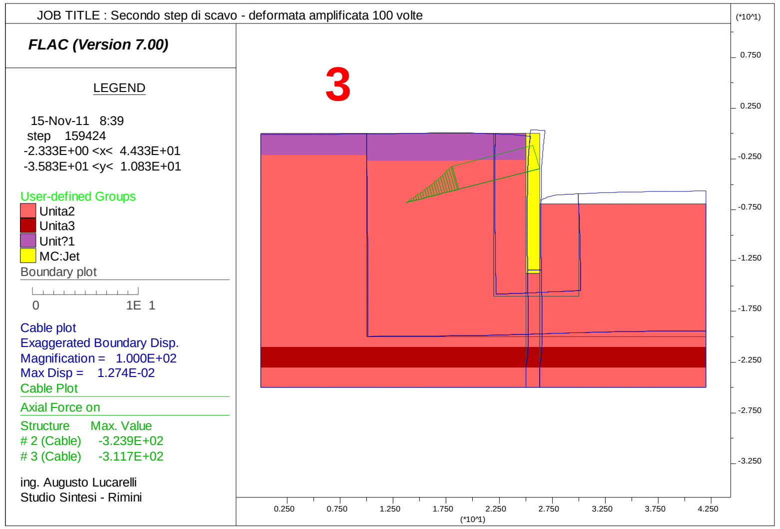
tensile strength = 0

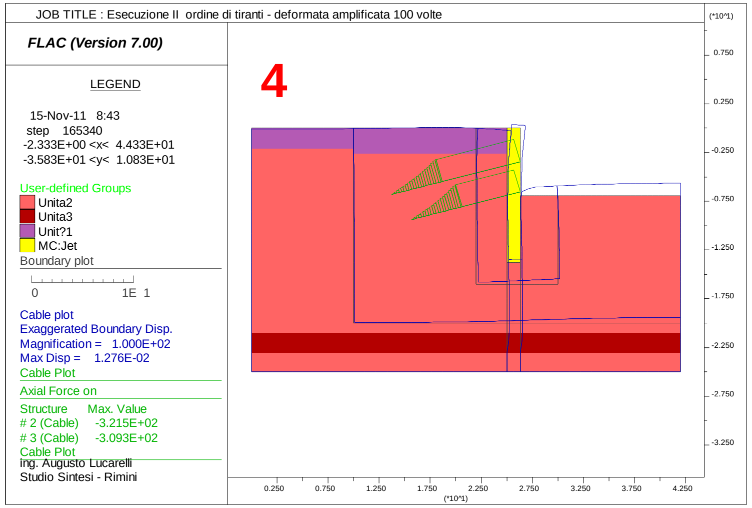
These are quite conservative parameters. In reality, the UCS obtained was about 15 MPa.

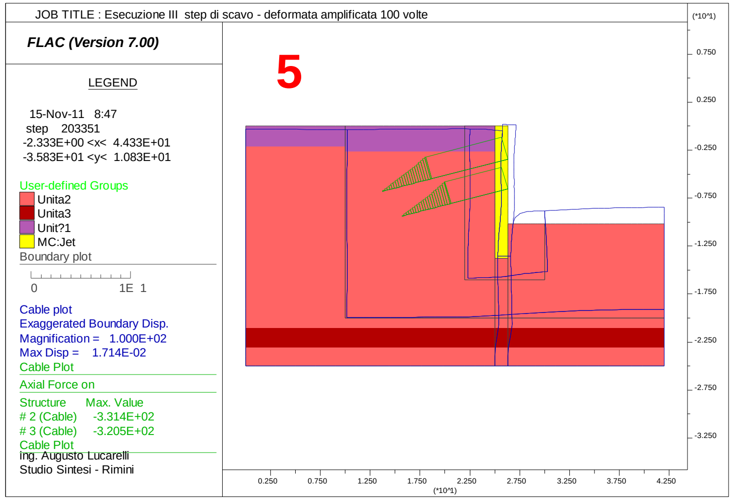
Execution Phases: Excavation and Anchors Activation

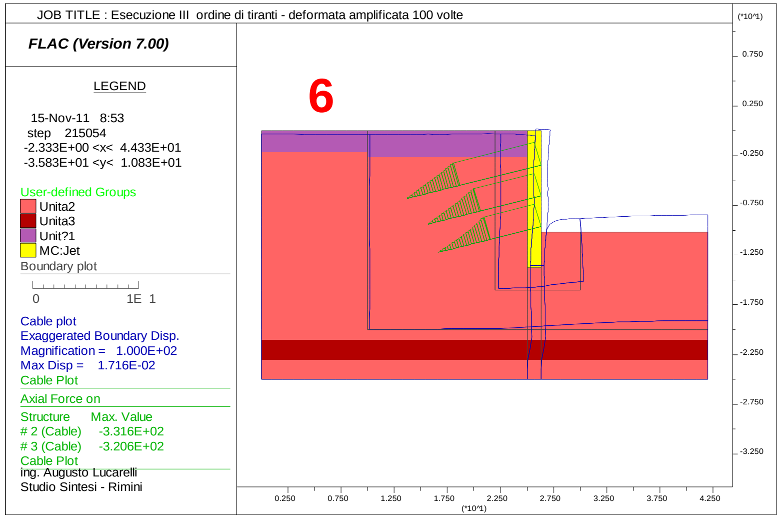












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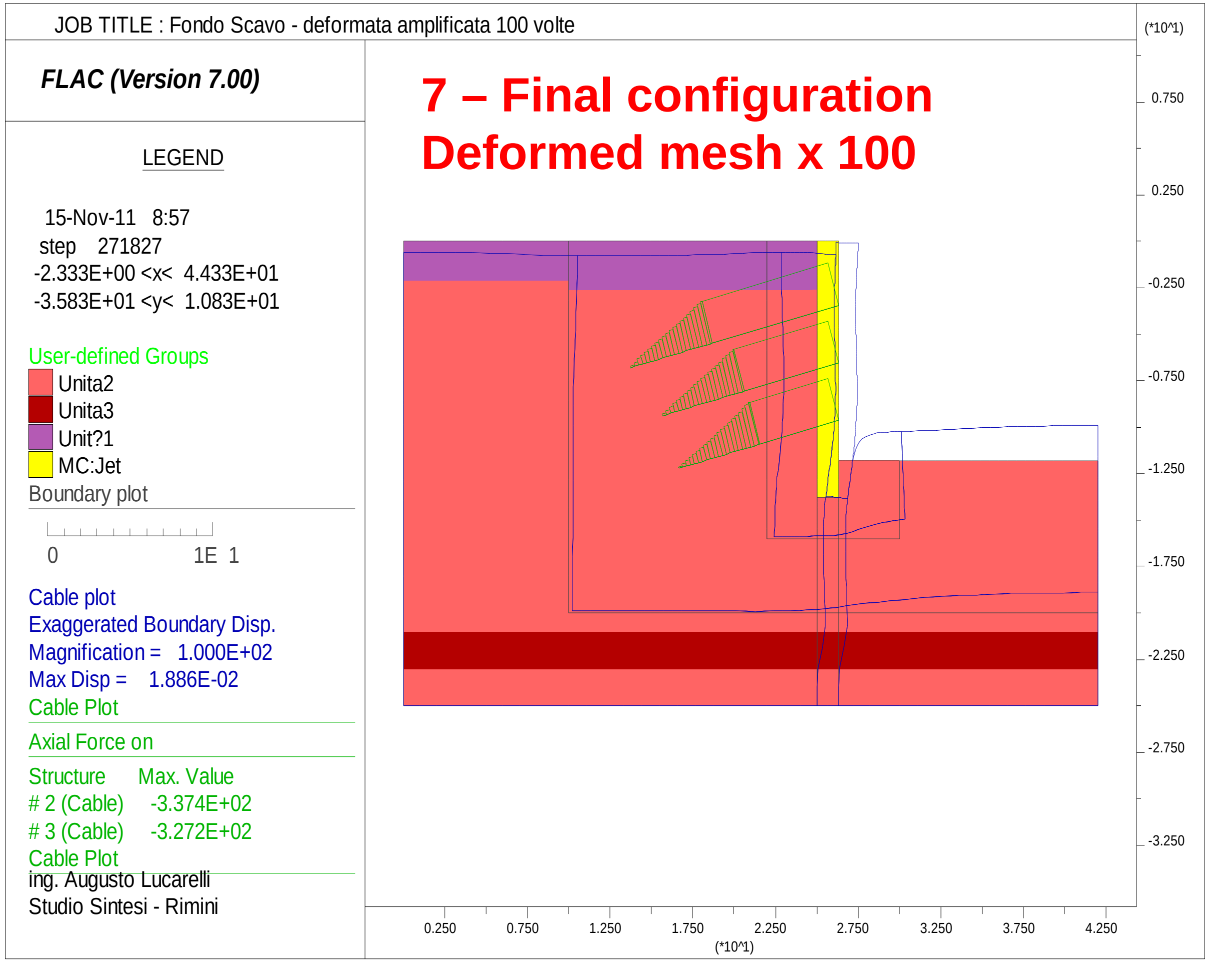
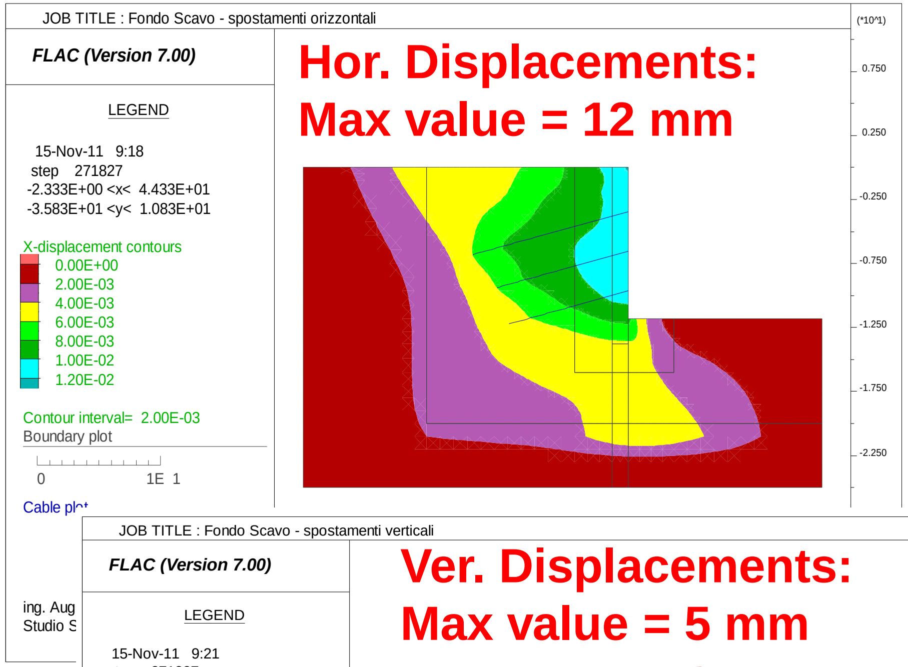
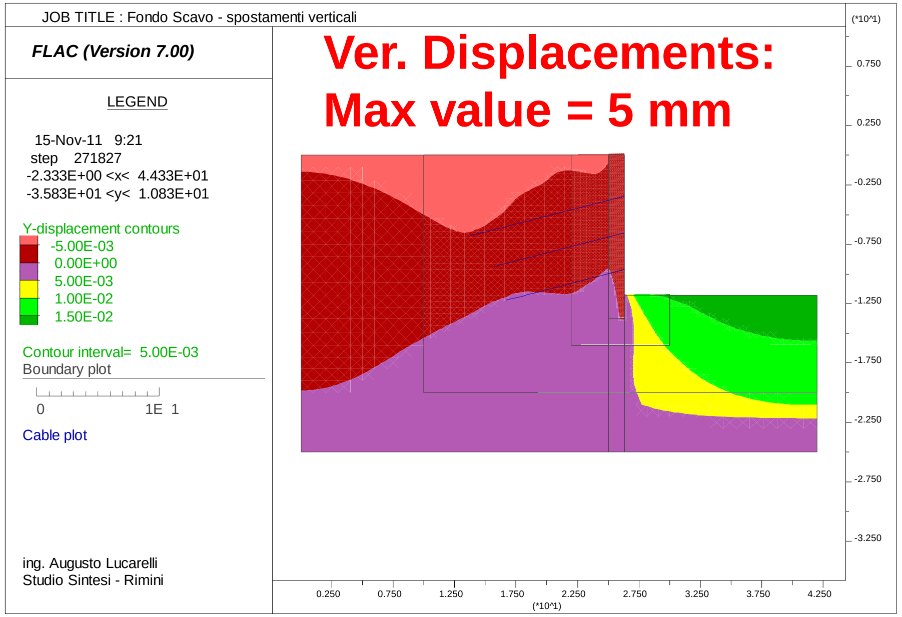
Final Configuration and Main Results







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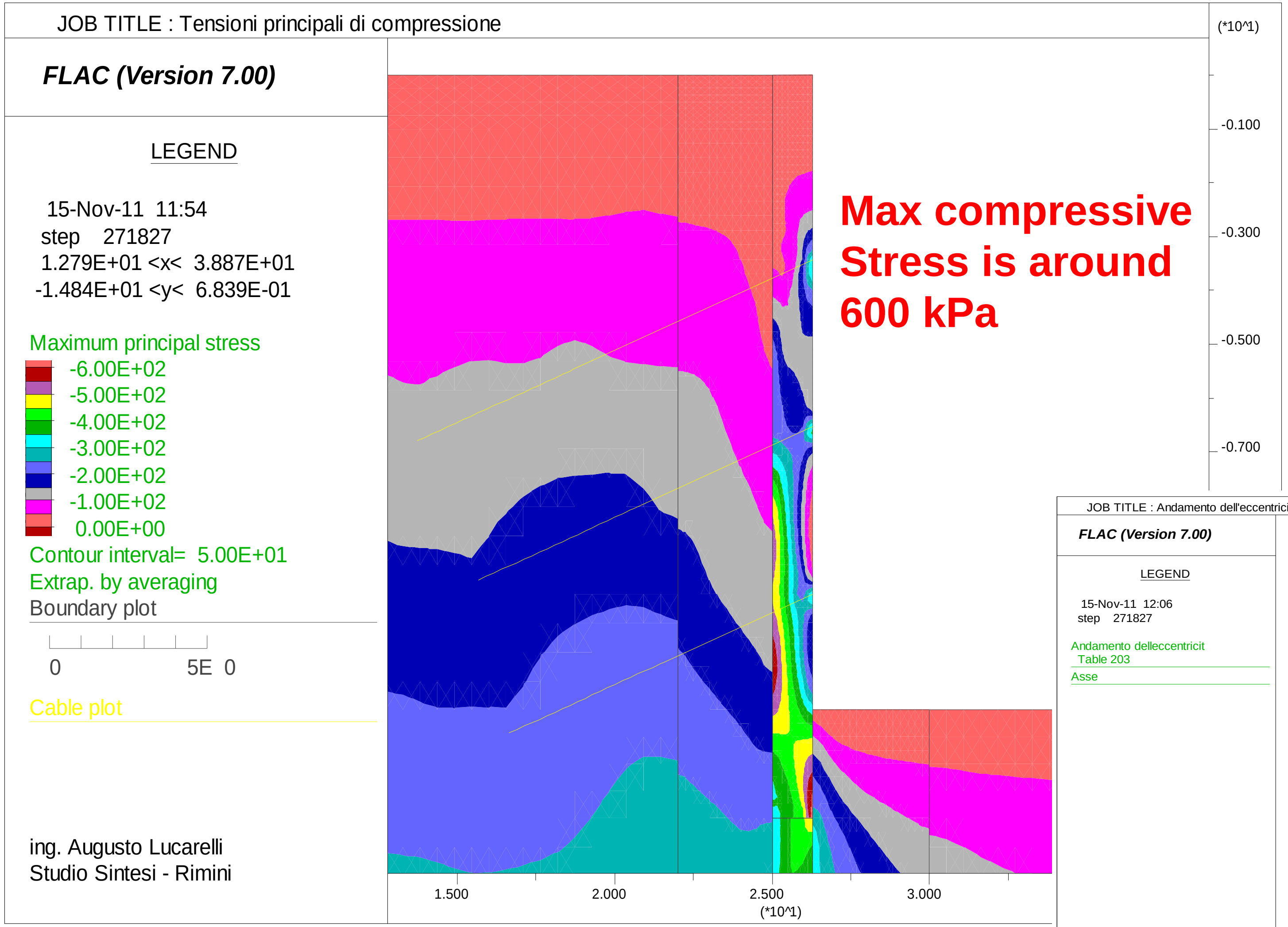
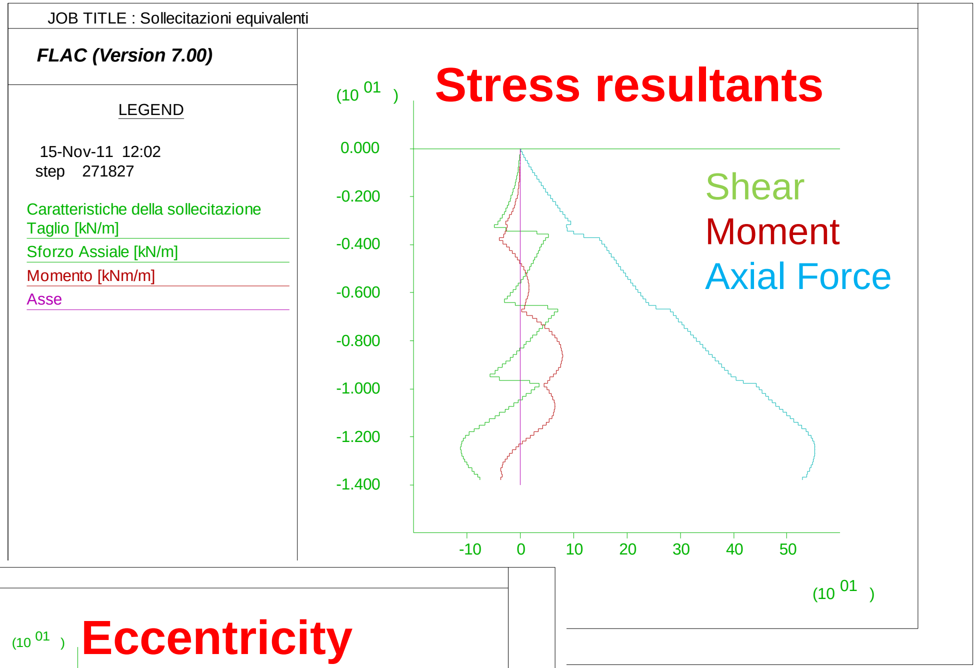
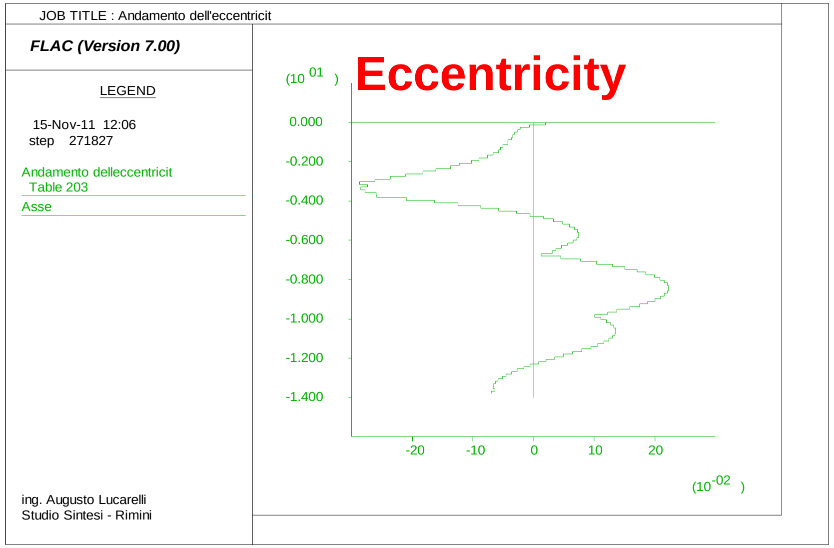
Stress Distribution in the Jet Wall







Location of neutral axis

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Global Stability Analysis: is a Safety Factor Number Satisfactory?

Strength Reduction Method (SRM) allows:

- Ability to monitor the structural behavior while strength properties are reduced.
- Tracking of structural elements stress resultant (force in anchors, bending moment, etc.).
- Hierarchical failure: do the structural elements have enough capacity? How does the structural elements capacity (stiffness and strength) influence the prevailing potential global mechanism?
- Observation of displacements developments; Service Limit State might be more critical than the Ultimate Limit State.
- Tracking of multiple failure mechanisms.
- LEM does not allow for a comprehensive understanding of the mechanical behavior; it requires assumptions on the forces that structural elements are exchanging with the soil mass.
- Possibility to conduct a local strength reduction for the structural element itself, or for a limited portion of the model, in order to analyze critical soil-structure interaction mechanisms (for example, bearing capacity, shear capacity, etc.).

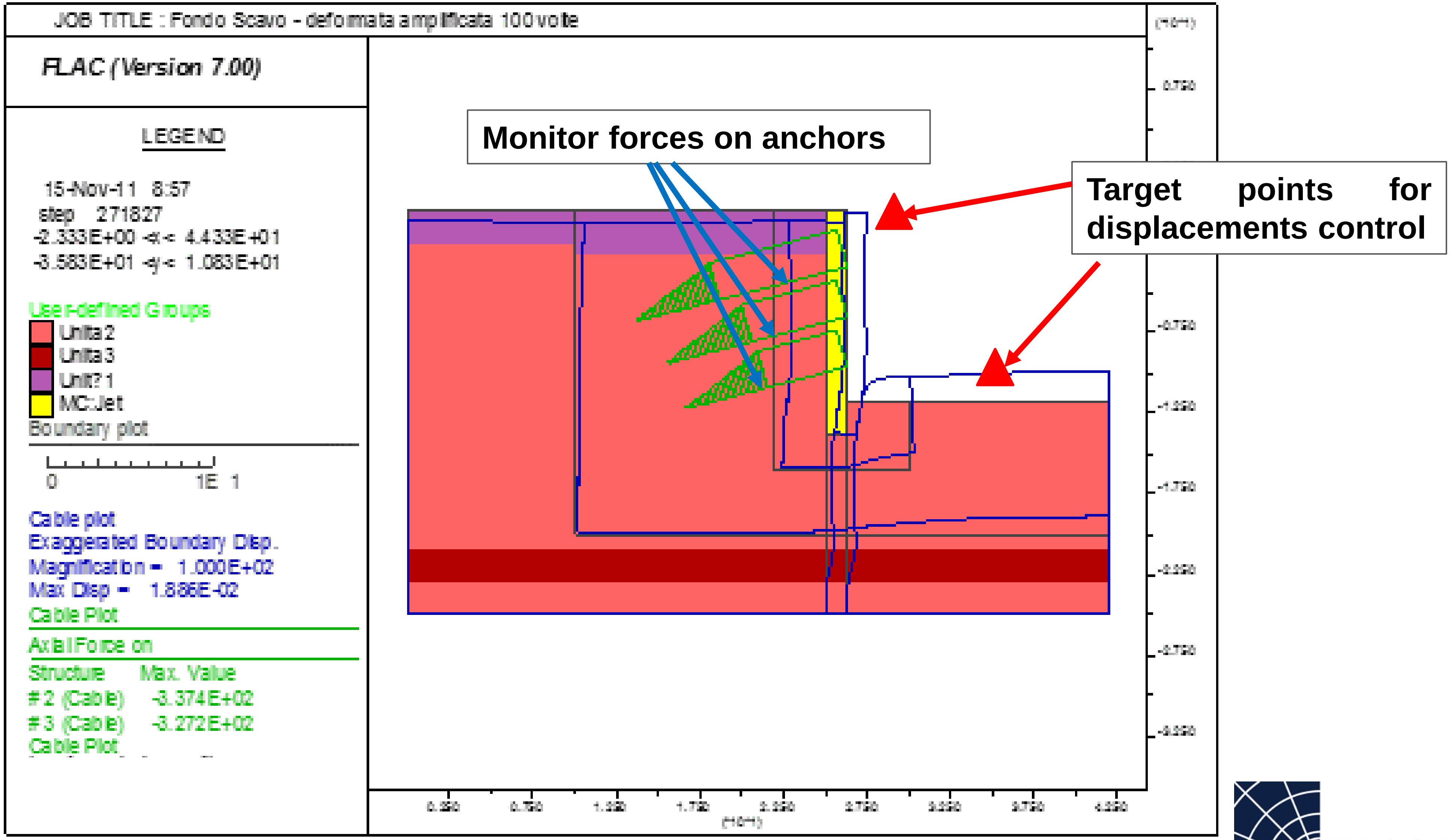
Example

Model configuration at the end of the excavation:

a) Realistic stress is in place.

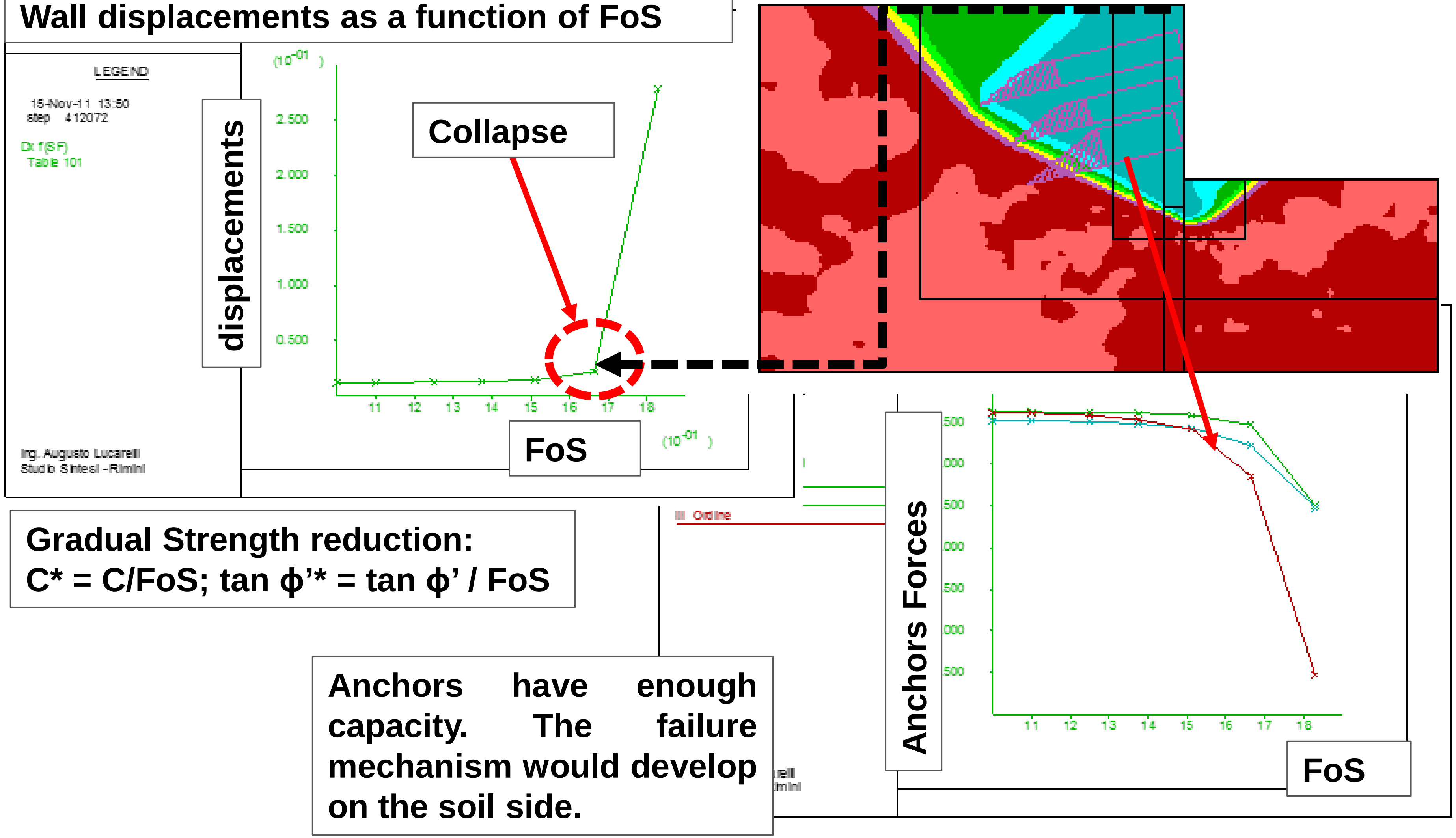
b) No assumptions about structural element forces.

c) Monitor the behavior of the structural elements and the soil mass while the properties are reduced until collapse is detected.



Example

Wall displacements as a function of FoS



Gradual Strength reduction:
C* = C/FoS; tan ϕ'* = tan ϕ' / FoS

Anchors have enough capacity. The failure mechanism would develop on the soil side.

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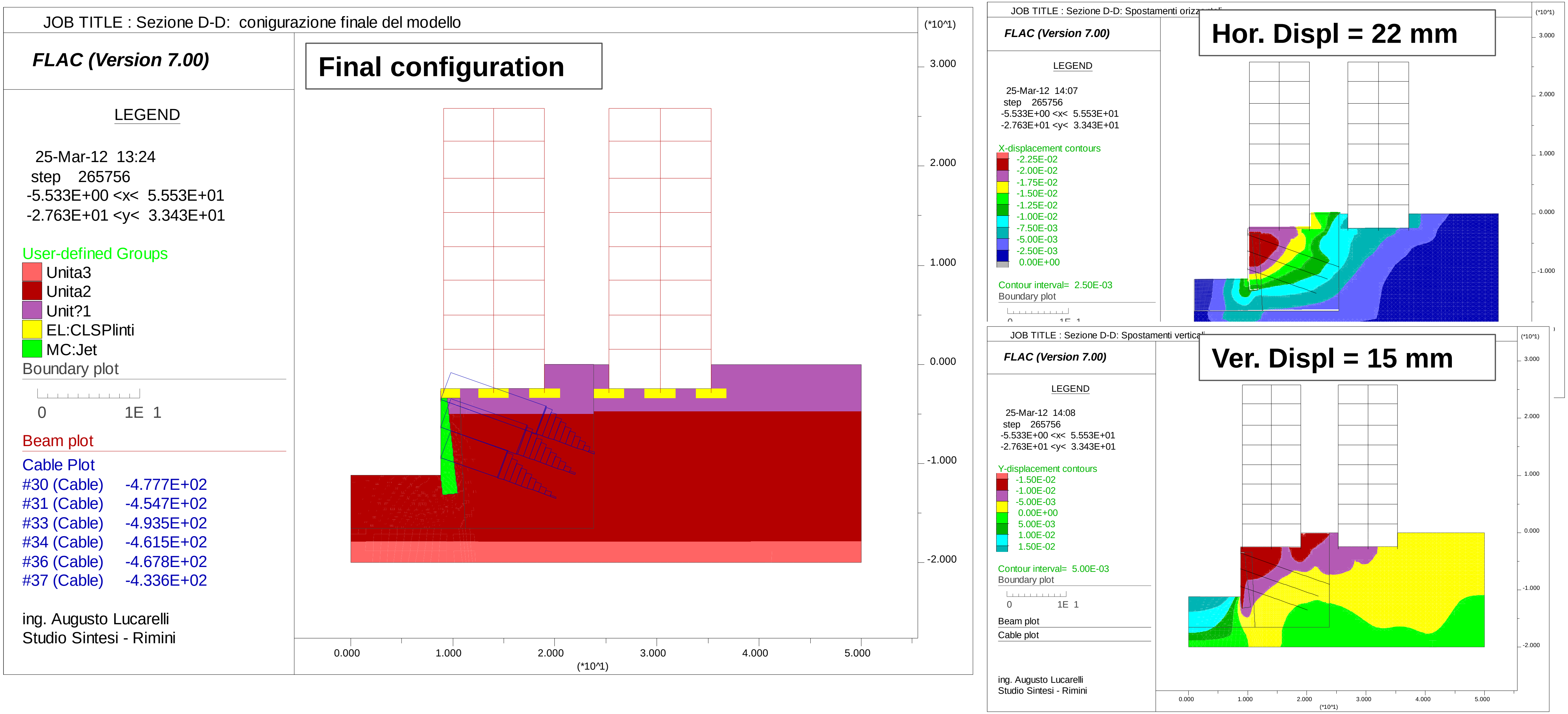
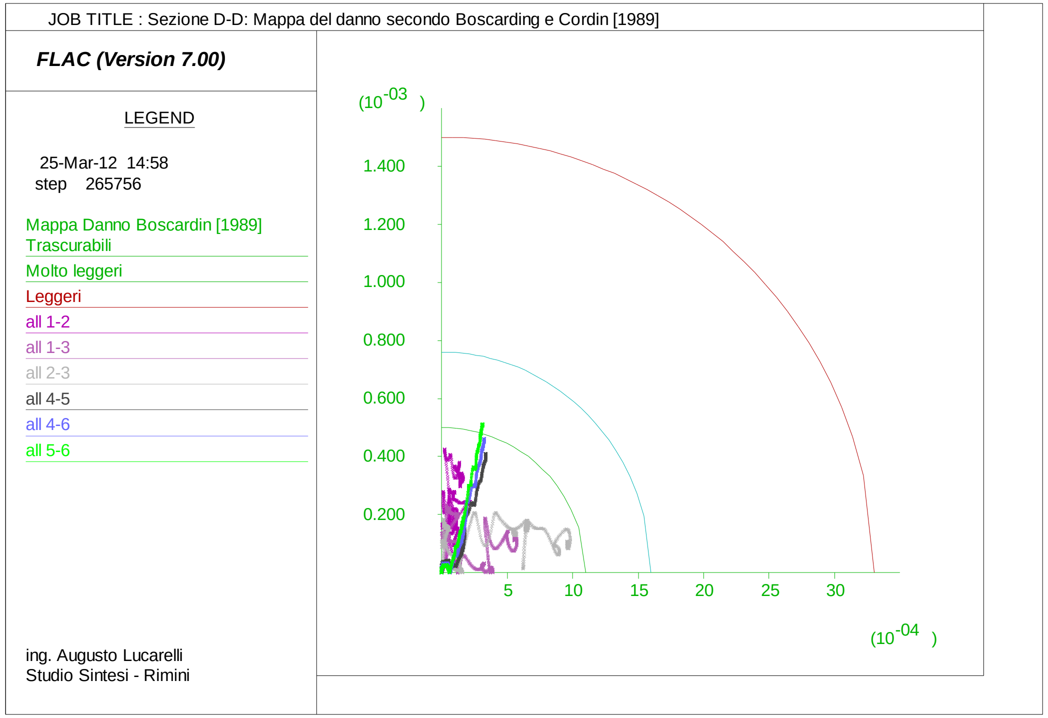
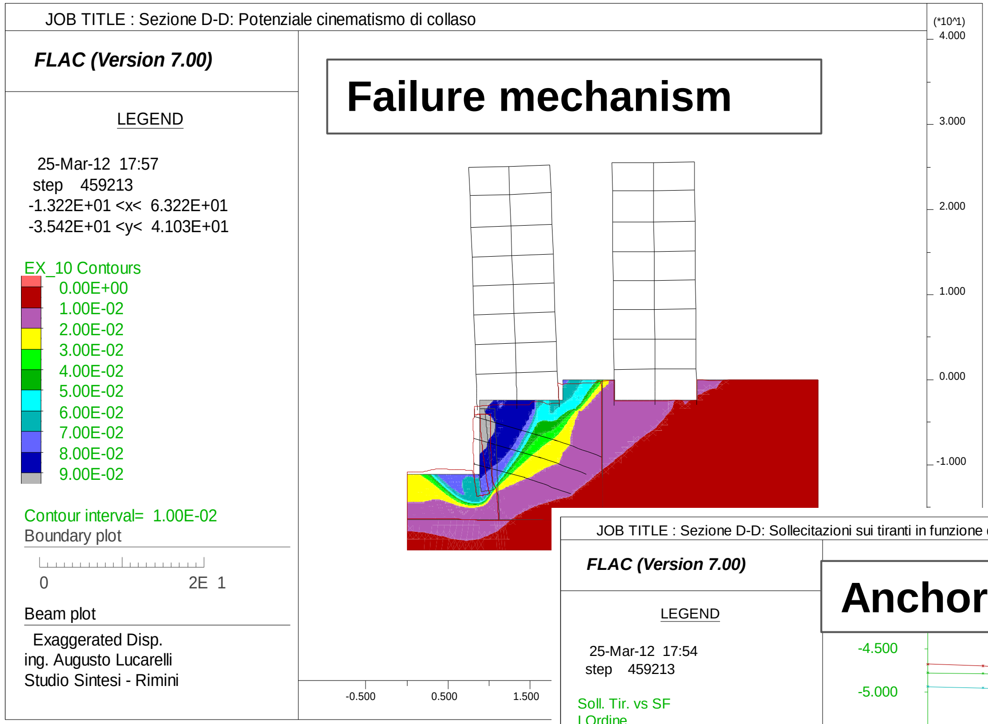
Repubblica Underground Park

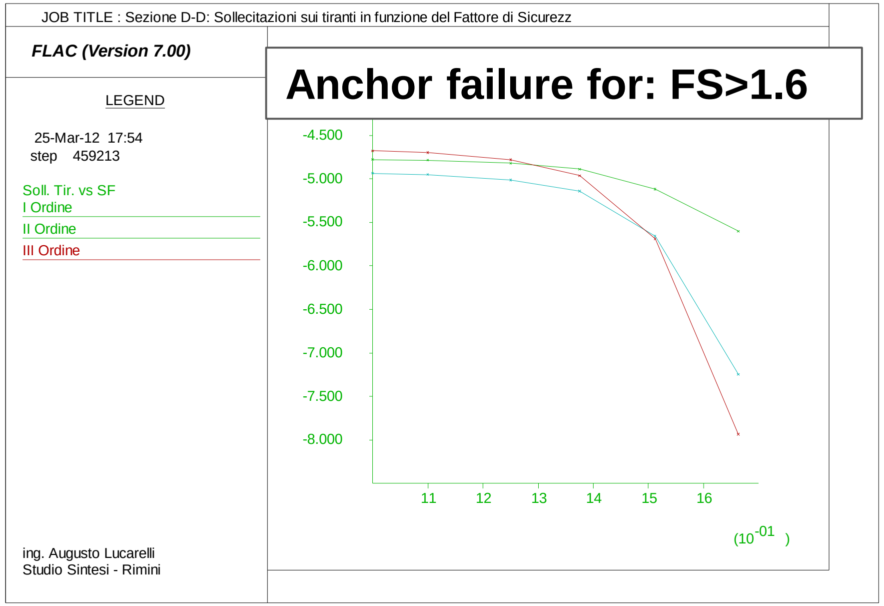


Repubblica Underground Park

Potential damage chart







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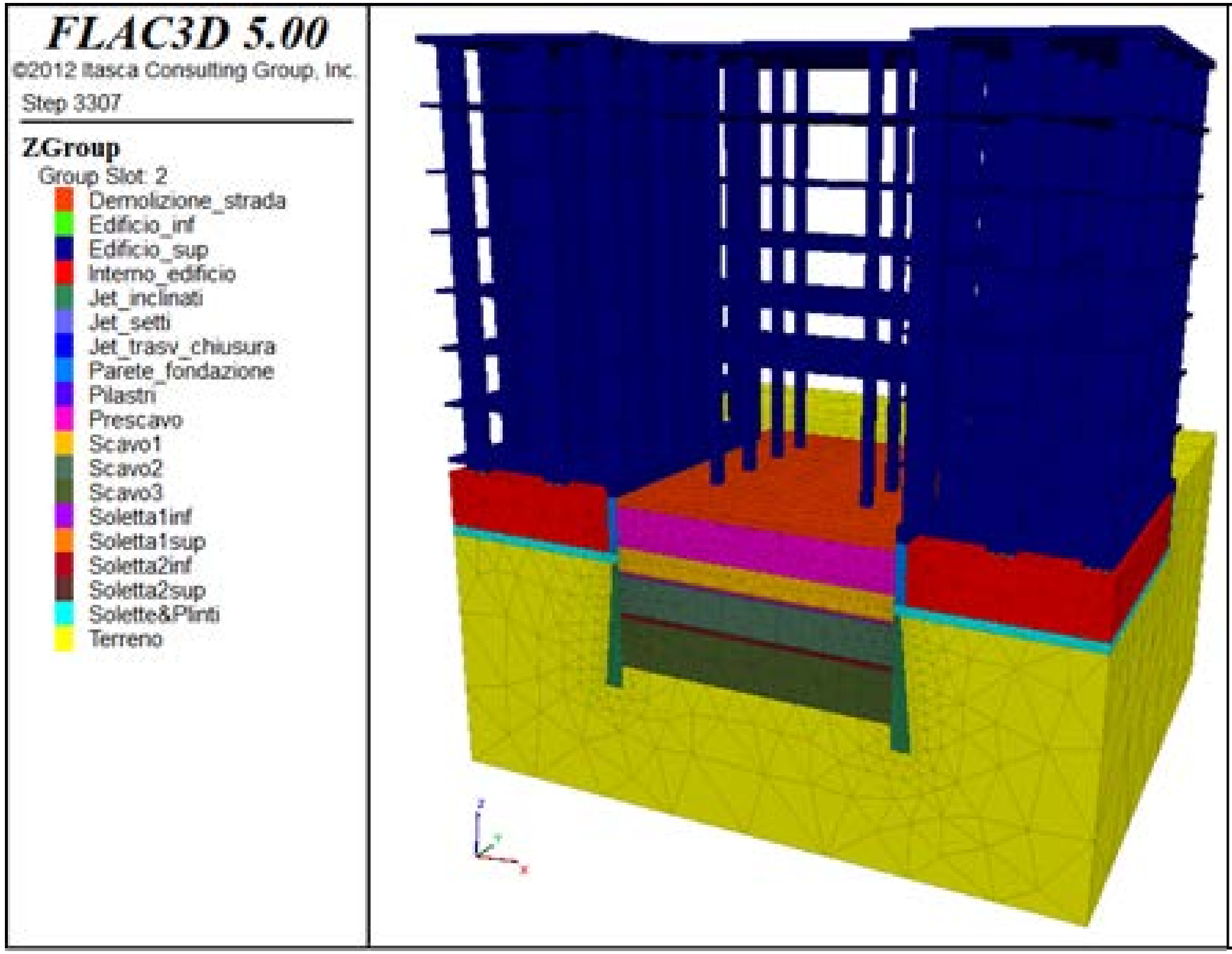
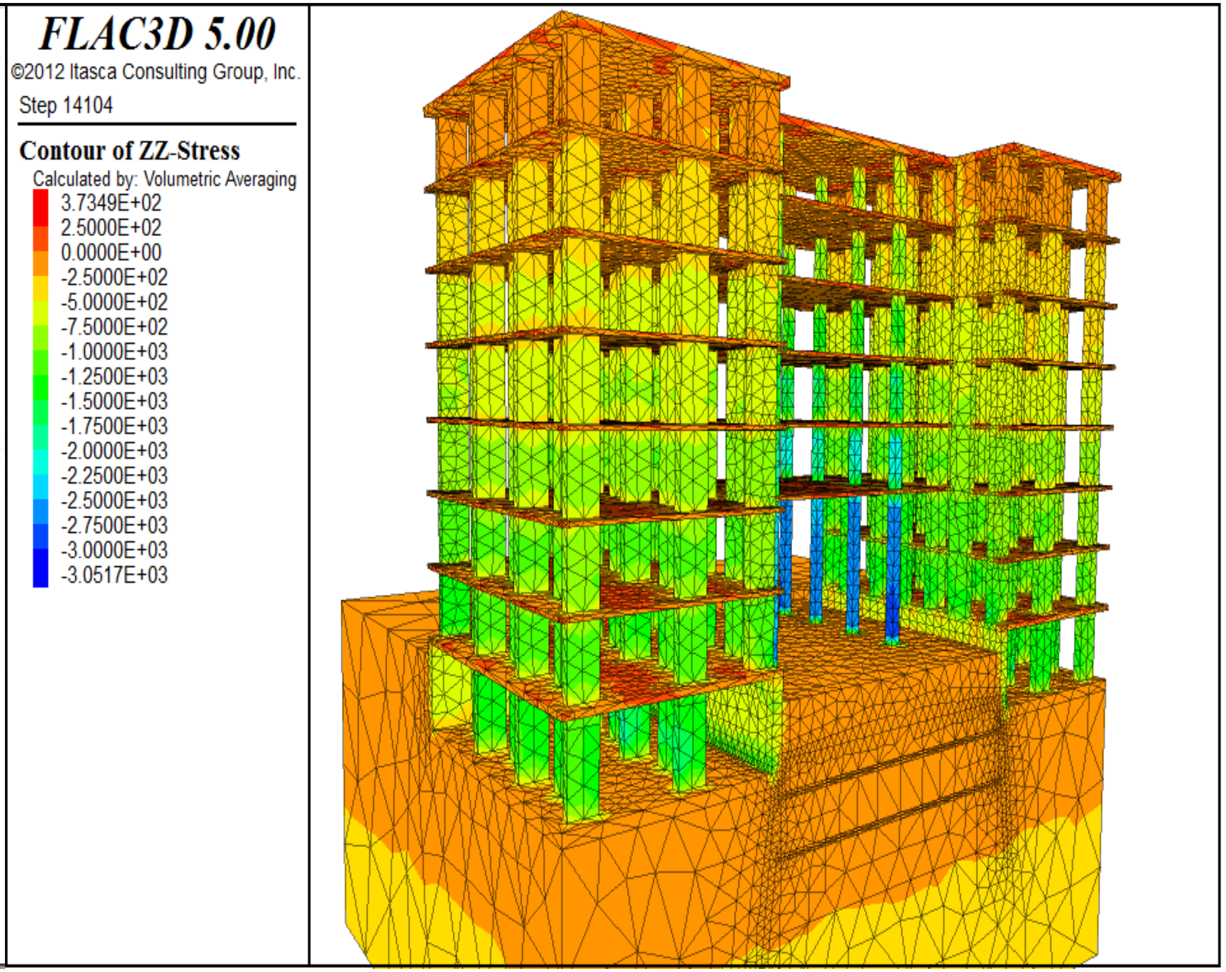
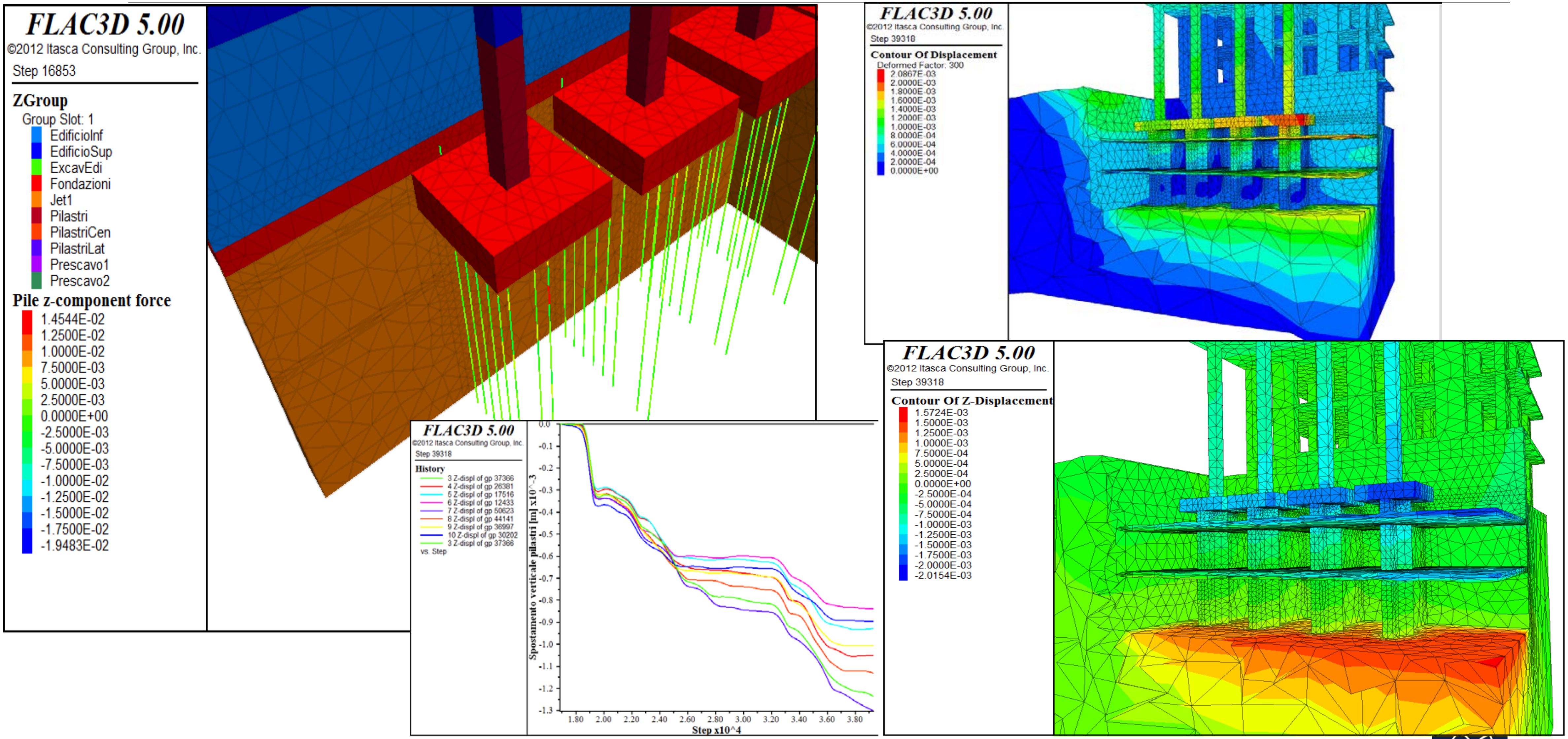
Repubblica Underground Park

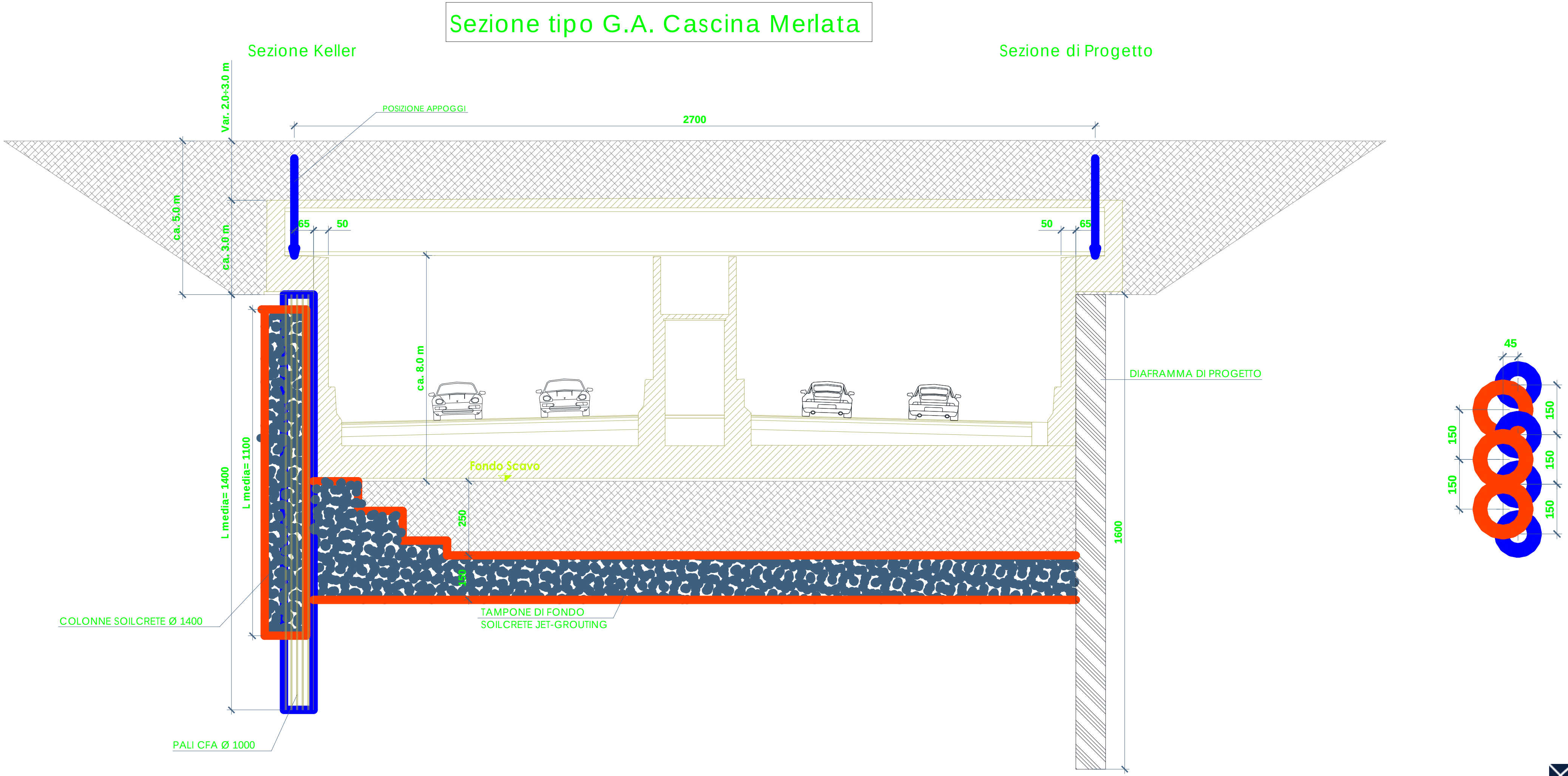




Repubblica Underground Park



Cut & Cover Tunnel, GA Merlata



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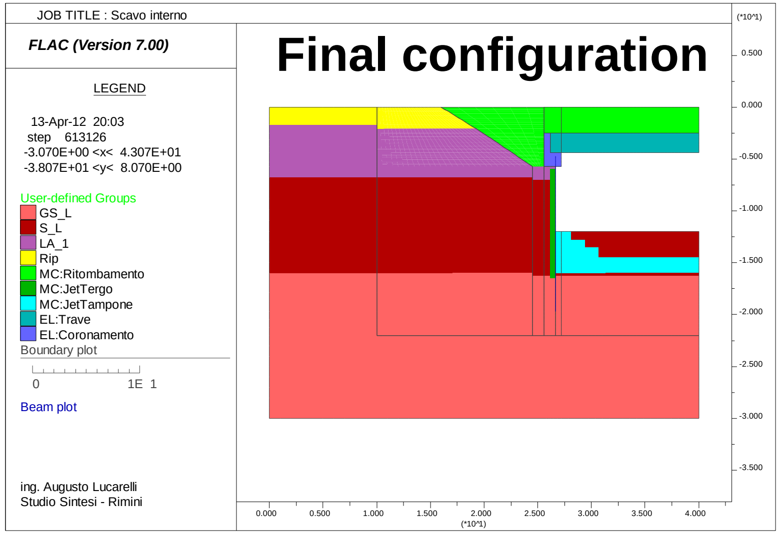
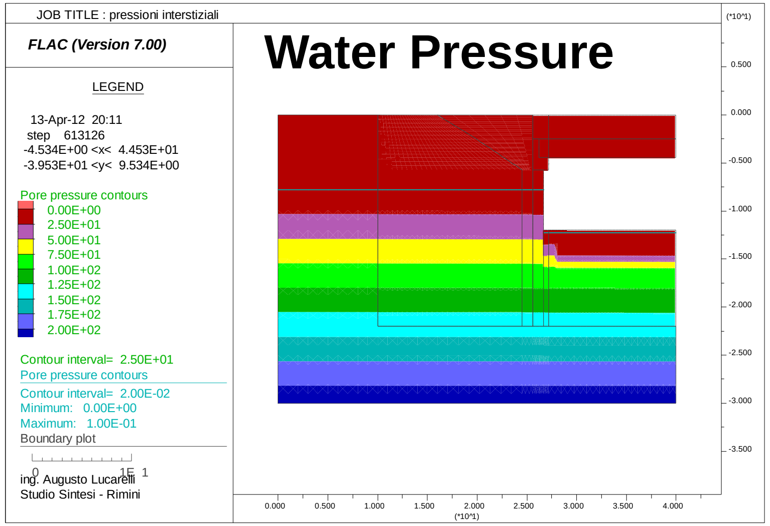
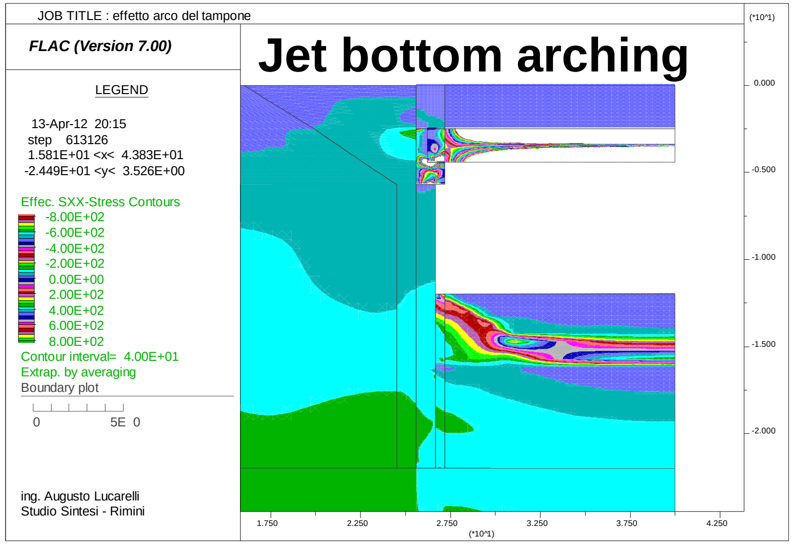
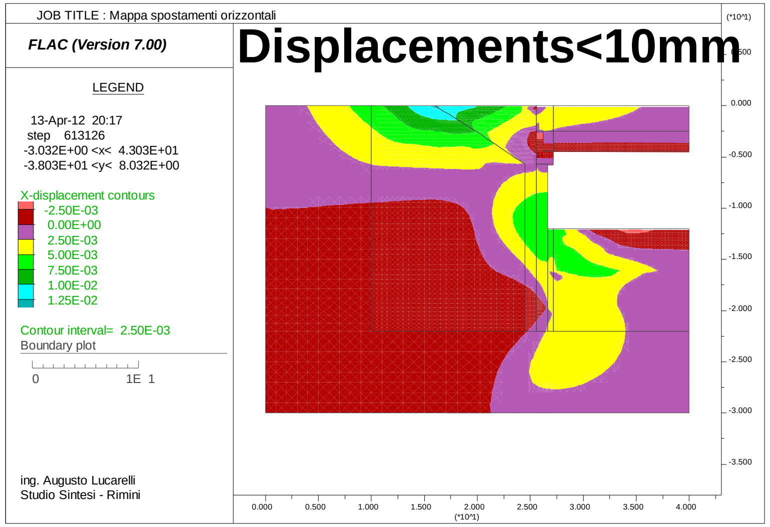
Results: Cut & Cover Tunnel, GA Merlata









Conclusions

- **Jet grouting is a valuable and competitive alternative to traditional support systems.**
- **It is quite flexible and adaptable to many circumstances and soil conditions.**
- **Can be executed using relatively little equipment.**
- **It requires a highly skilled, experienced, and specialized contractor to guarantee high-quality results.**
- **It is always recommended to execute a field trial test to calibrate the execution parameters and verify performances.**
- **Advanced numerical method has allowed for full Soil-Structure-Interaction including the evaluation of performance and Safety Factors.**
- **The Strength Reduction Method is highly recommended to better understand/evaluate the potential failure mechanism and the behavior of each component.**

Thank you for your attention.

Questions?