Introduction to Machine Learning in Geomechanics

A Comparison of Classical Numerical Modeling to the New Paradigm of Machine Learning

Schedule	
1:00 – 1:40 pm	Introduction to Numerical Modeling
1:40 – 2:20 pm	Introduction to Machine Learning & Surrogate Modeling
2:20 – 2:40 pm	Coffee Break & Networking
2:40 – 3:20 pm	Estimating Intact Rock Strength from Core Logging Data using Machine Learning
3:20 – 4:00 pm	Building a Surrogate Model for Rock Blasting Application

Introduction to Numerical Modeling

Wei Fu
wei@itascacg.com

Why Discuss Numerical Modeling

- Representation of systems or phenomena using mathematical models (governing equations vs algorithms)
- Predict and approximate reality; Convergence (unbalanced force, loss function)
- “*Black Box*” ?
- Surrogate Model (nonsense input data produces nonsense output)

What is Numerical Modeling

Numerical modeling

- Numerical modeling is a simulation of real-world systems using numerical methods.
- Always remember that a numerical model is an approximation – not reality. There are always limitations requiring simplifications.
- Numerical models provide us with a means to rapidly investigate various scenarios and conditions that can't be otherwise easily evaluated.
- Critical thinking and conceptual understanding are important.
- An appropriate constitutive- or contact- model is required.

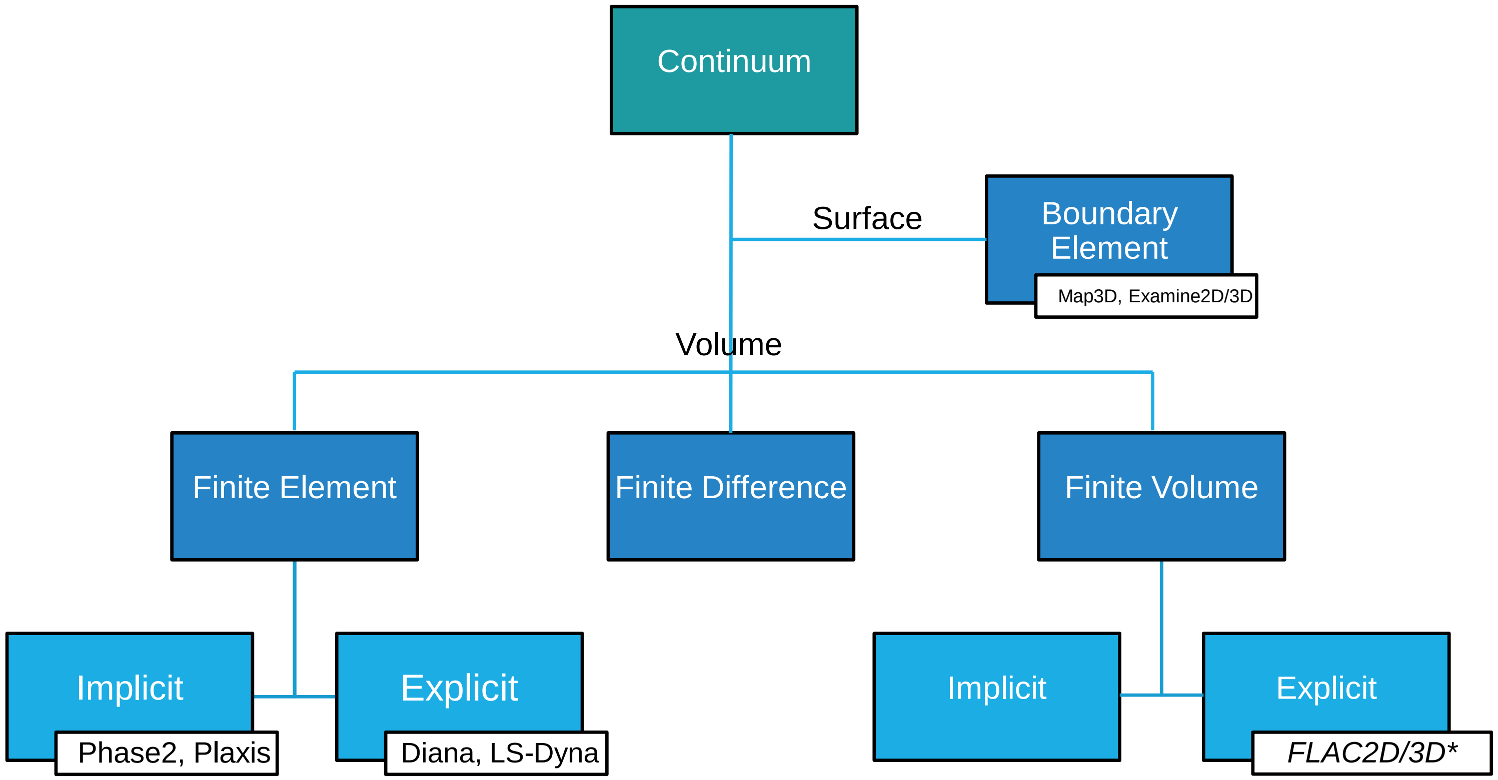
"… all models are wrong, but some are useful."

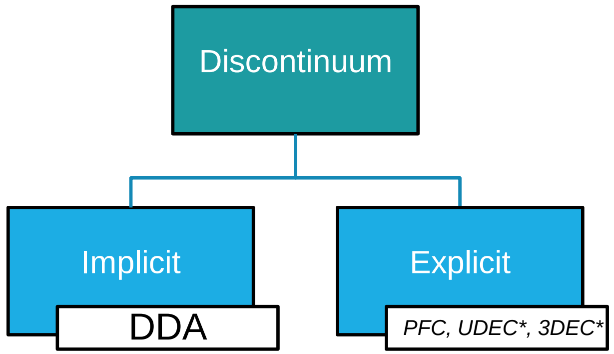
(Box, 1976)

"Numerical modeling should be an aid to thought, not a substitute for thought."

(Starfield and Cundall, 1988)

Numerical Modeling Methods

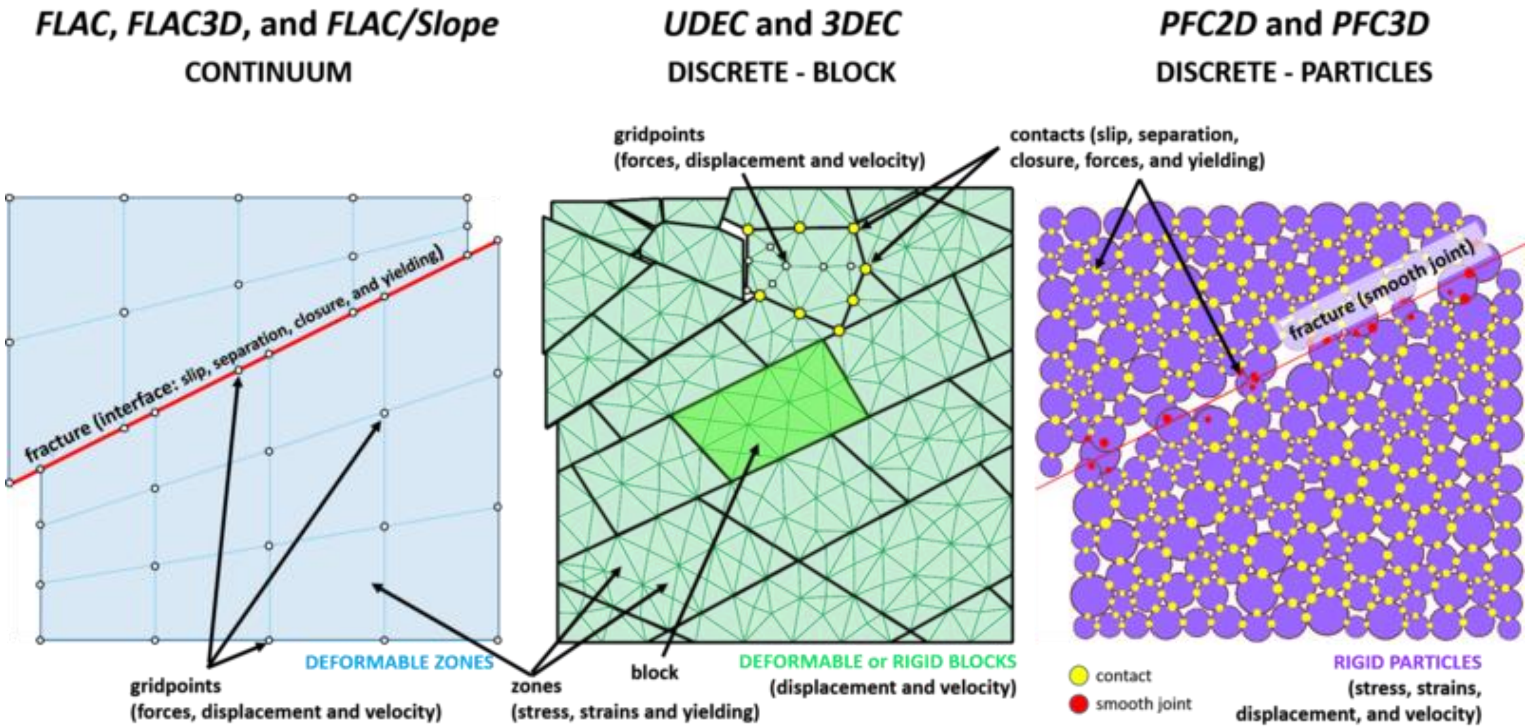




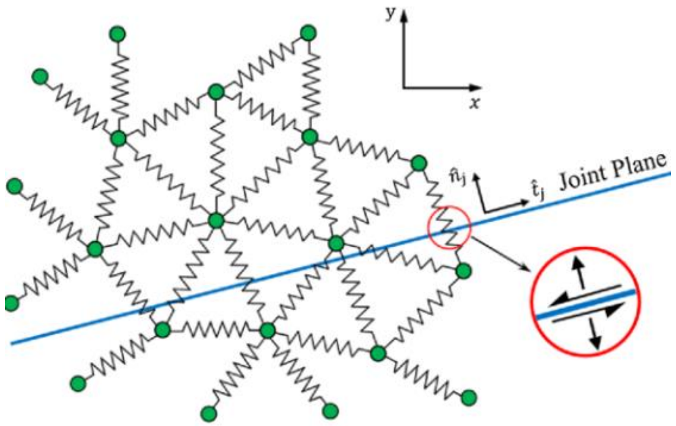
**UDEC* and *3DEC* are actually hybrid methods

**Both FLAC2D and FLAC3D can perform implicit fluid and thermal calculations.*

Software for Continuum and Discontinuum Modeling



XSITE (Hydraulic Fracturing Simulator)
DISCRETE - LATTICE



quasi-randomly distributed lattice nodes
connected by springs

Continuum models, with non-linear stress/strain laws & structures

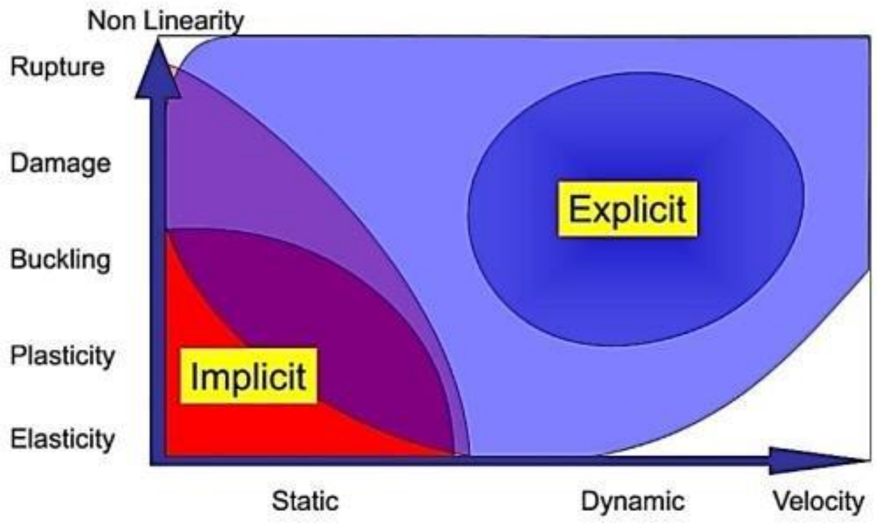
Simulations of systems of angular blocks – e.g., jointed rock

Assemblies of disks or spheres, with or without bonding

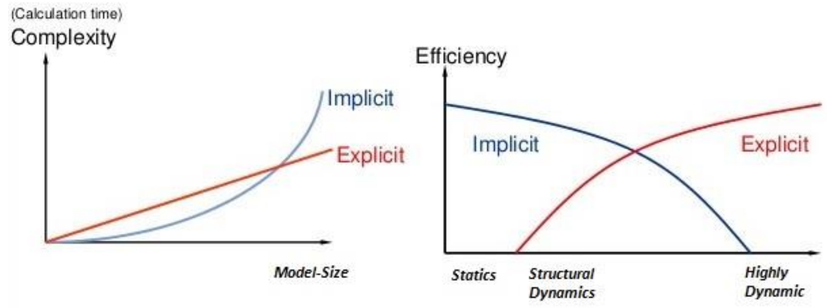
Lattice of springs and masses with fluid interaction; spring break -> microcracks

Explicit and implicit methods

- Explicit and implicit methods are used in numerical analysis to approximate the solution of time-dependent differential equations.
- ***Explicit methods*** calculate the state of a system at a later time based on the state of the system at the current time. Solve local equations for each point based only on nearest neighbors.
- ***Implicit methods*** find a solution by solving governing equations that involve both the current state and the later state of the system. Solve complete set of equations for each calculation step.
- For nonlinear and/or dynamic analyses, explicit approach is typically preferred.



https://yasincapar.com/implicit-vs-explicit-approach-in-fem/



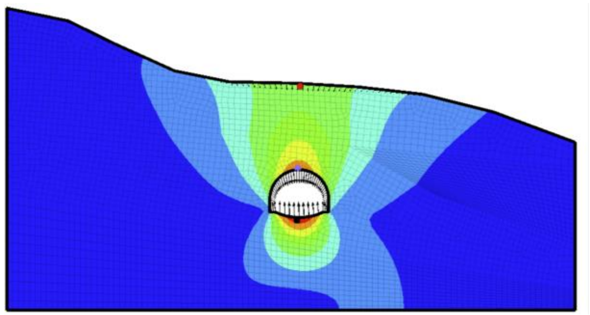
Continuum Modeling

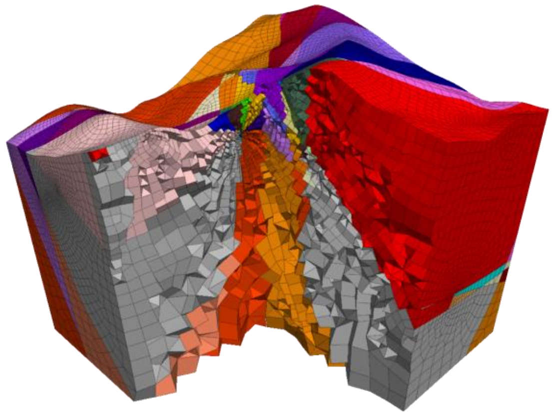
Advantages

- Fast (> 5 million elements on regular PC)
- Mature (fluid, thermal, structural elements, etc.)
- Can directly specify constitutive behavior
- Easy interpretation (stress, displacement)

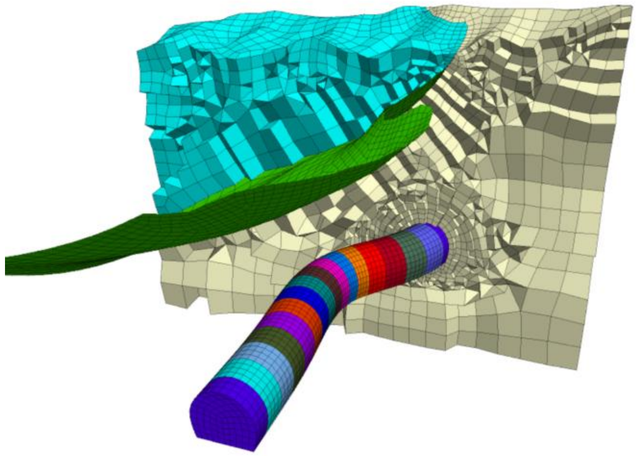
Limitations

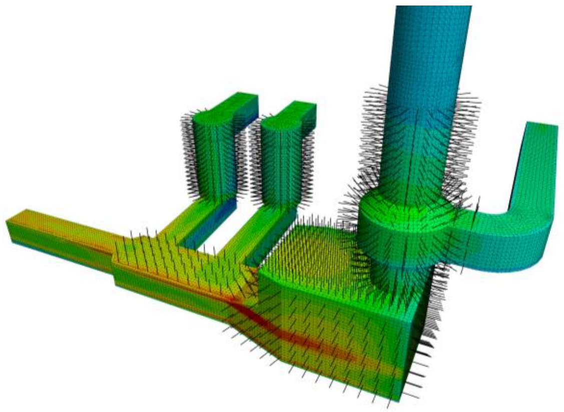
- Applicability of continuum assumption
- Models can only handle limited number of discontinuities
- Simplifications in constitutive models





FLAC2D / FLAC3D models

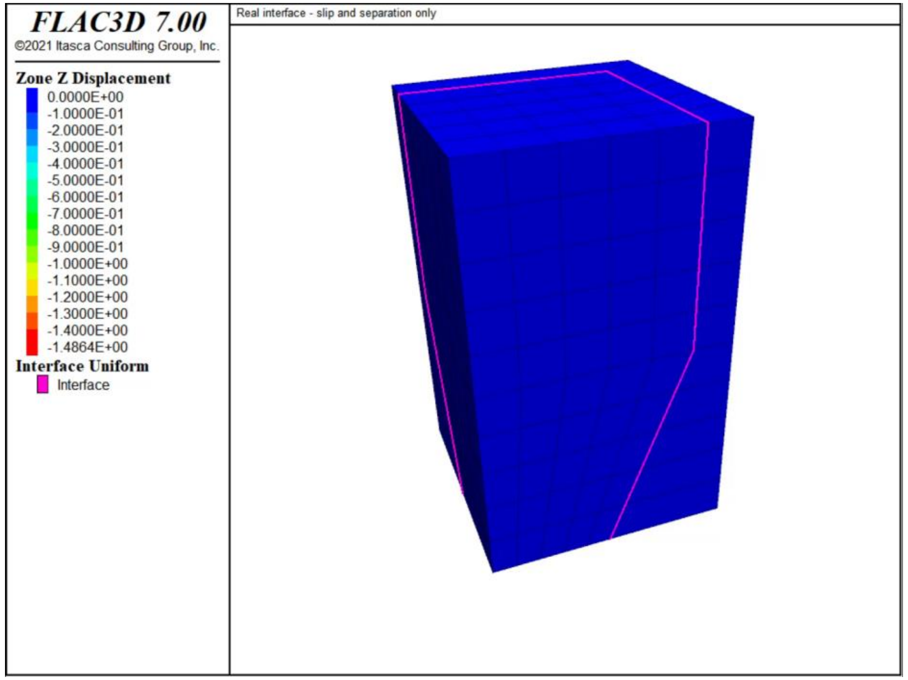




Solutions to the Limitations

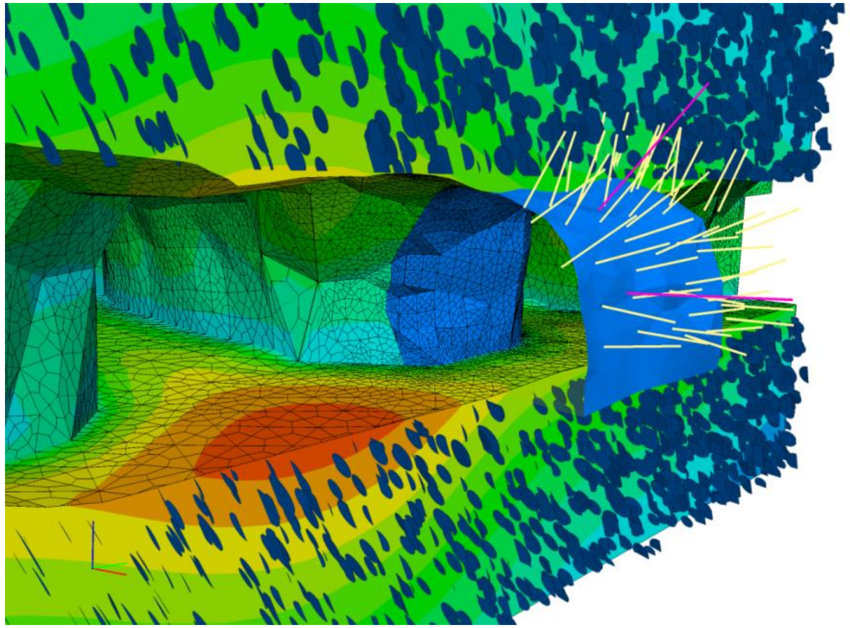
Fewer joints – model explicitly

- True discontinuities (slip, separation and formation of new contacts)



Lots of joints – equivalent continuum

- Hoek-Brown constitutive model considers joint density quality
- Ubiquitous joint model behaves *as if* there were many closely spaced, parallel joints



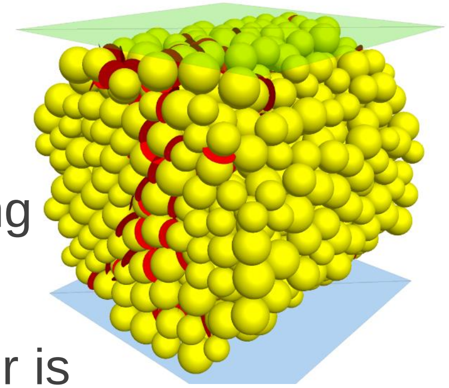
Constitutive model Development

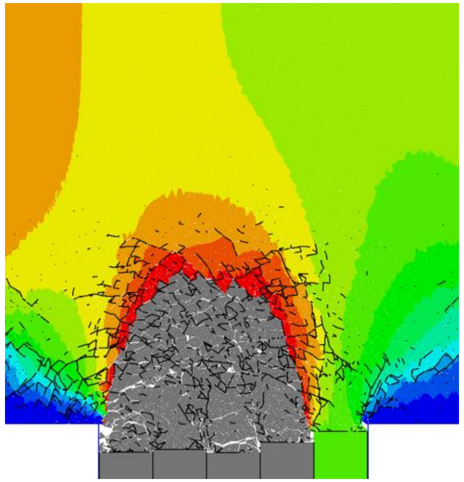
- e.g., IMASS model, which accounts for the progressive failure and disintegration of the rock mass from an intact/jointed condition to a bulked material

Discontinuum Model

Advantages of Discontinuum Model

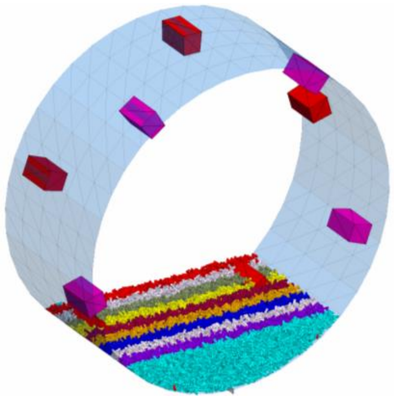
- Specifically designed to model discontinuities
- Rotation and movement of pieces yields realistic bulking and spalling behavior
- No need for complicated constitutive models – behavior is emergent (DEM)

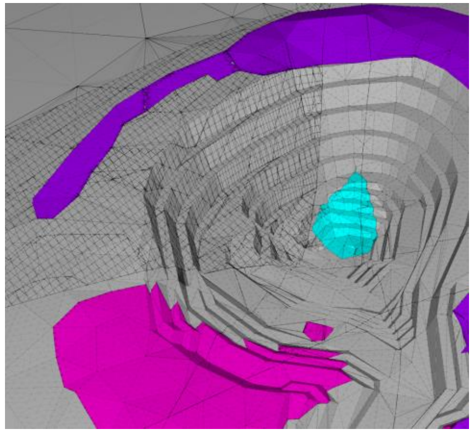




PFC models

3DEC models

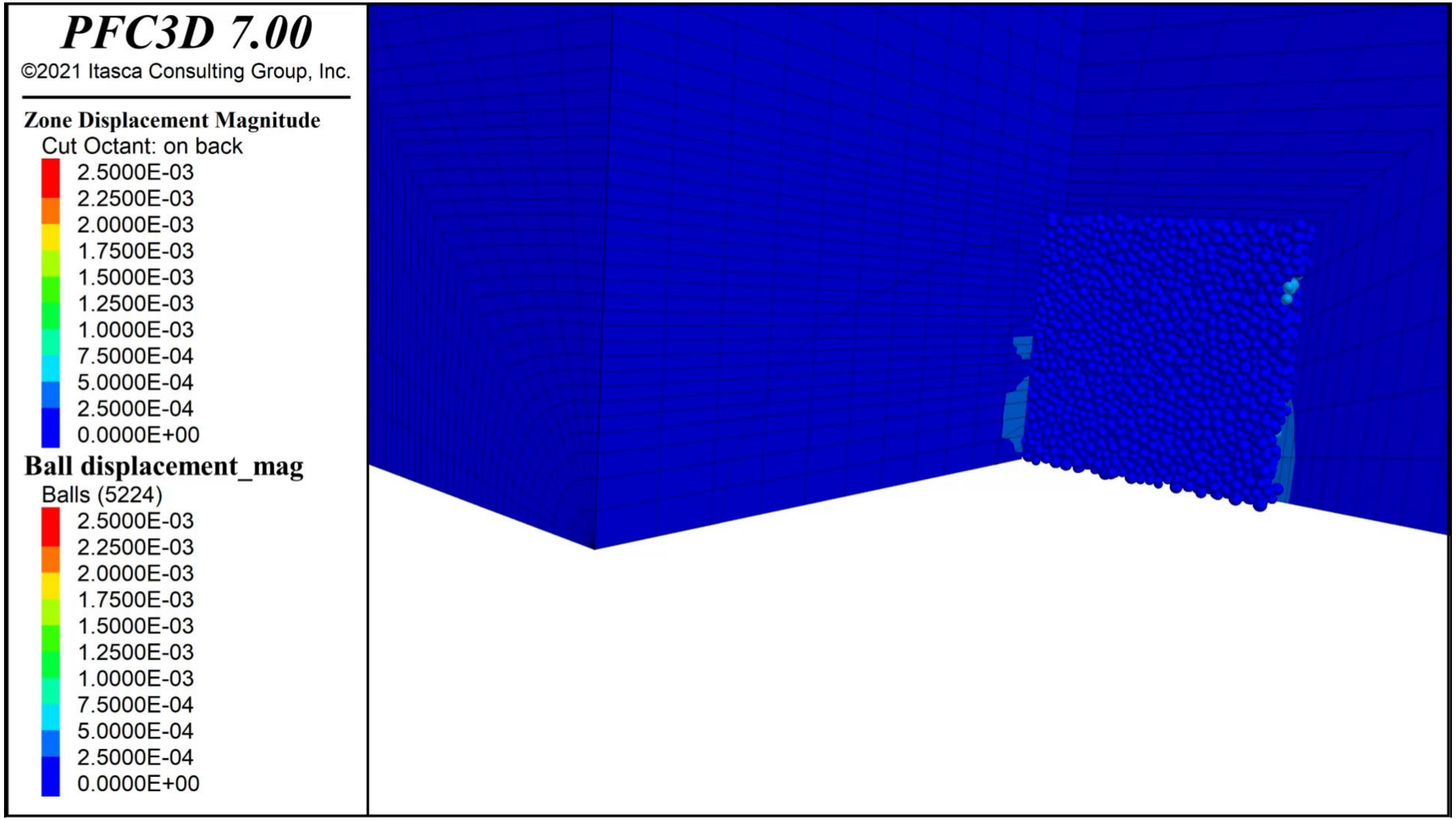




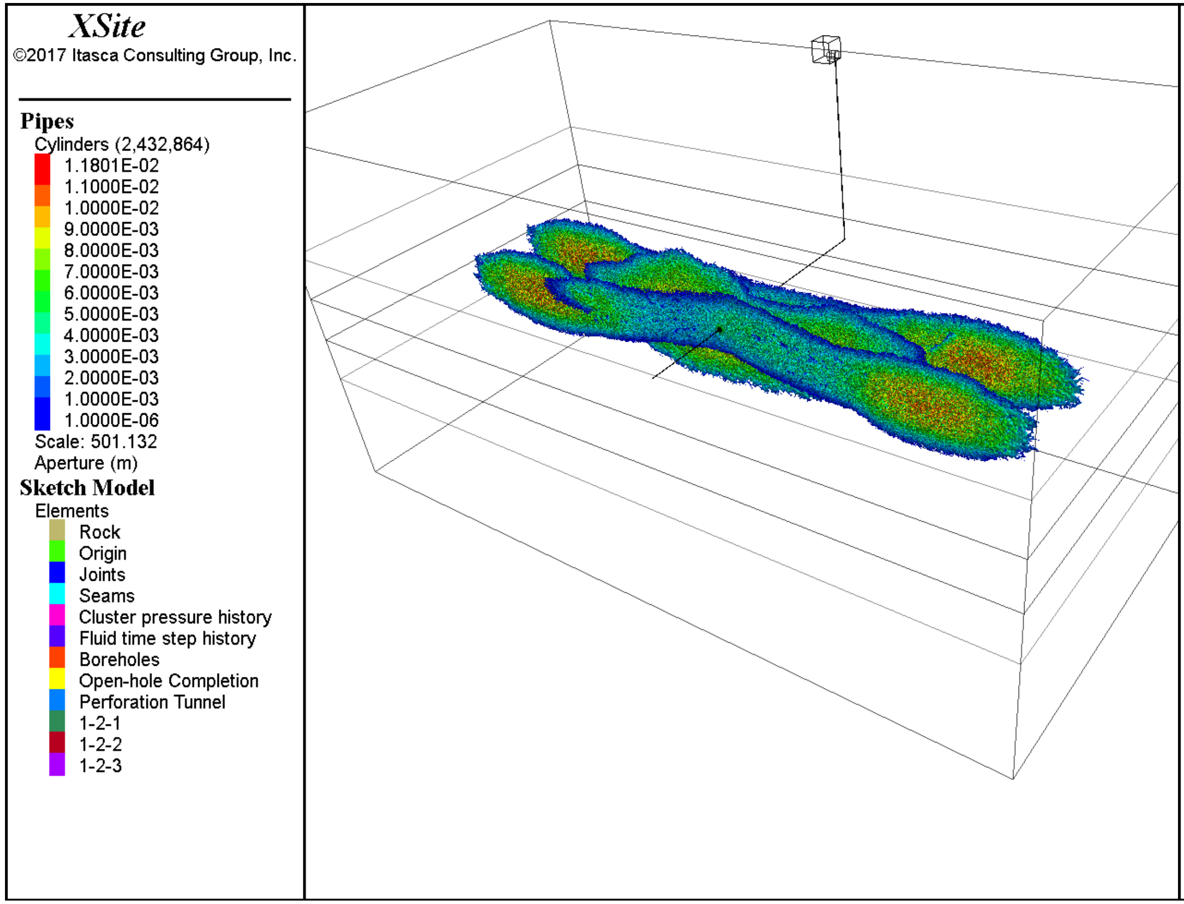
Limitations

- Requires calibration to match macro parameters (DEM)
- Still too slow to do field-scale problems!! (DEM)
- Solutions
  - ❖ Simplified DEM (lattice)
  - ❖ Coupled to continuum

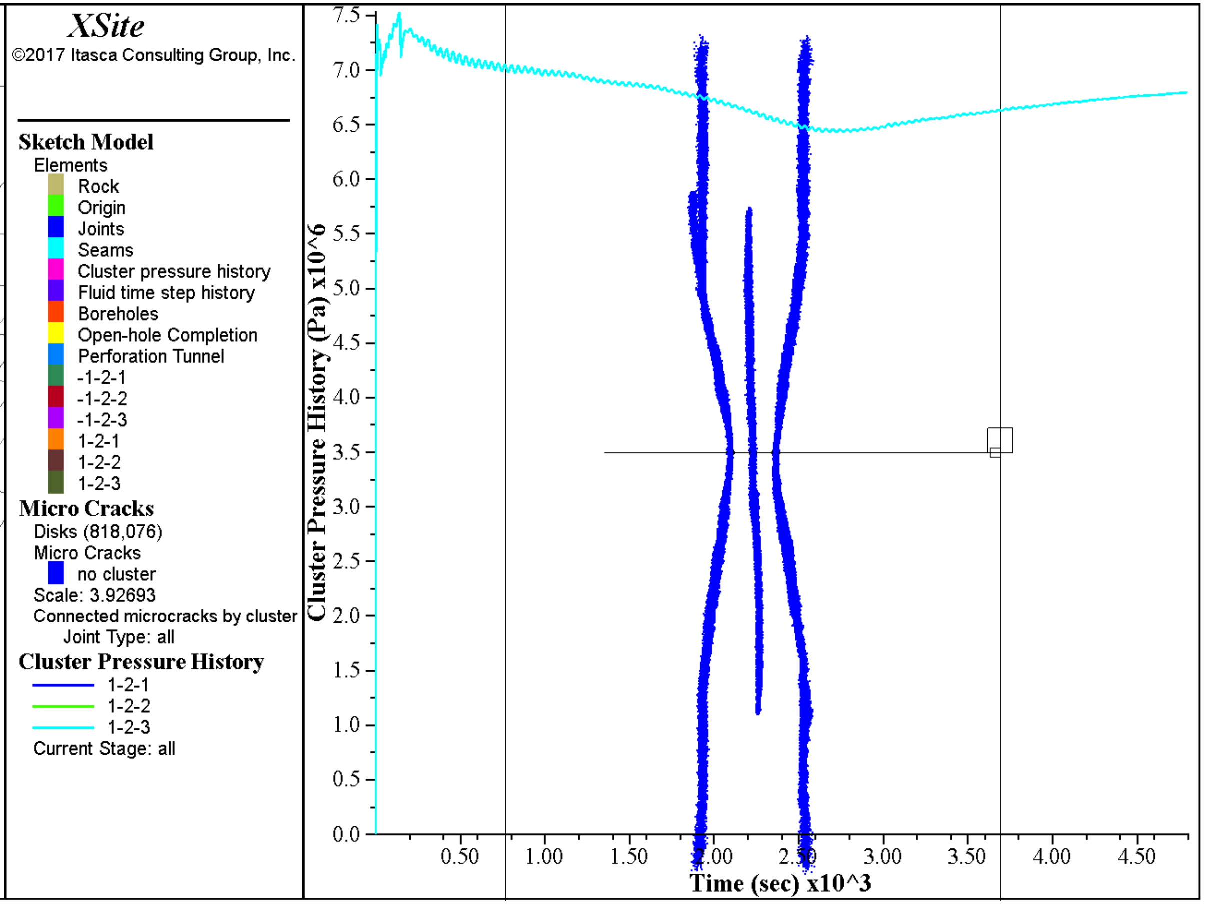
Solutions: Coupling Discontinuum to Continuum



Solutions: Lattice Model – Hydraulic Fracturing in XSite



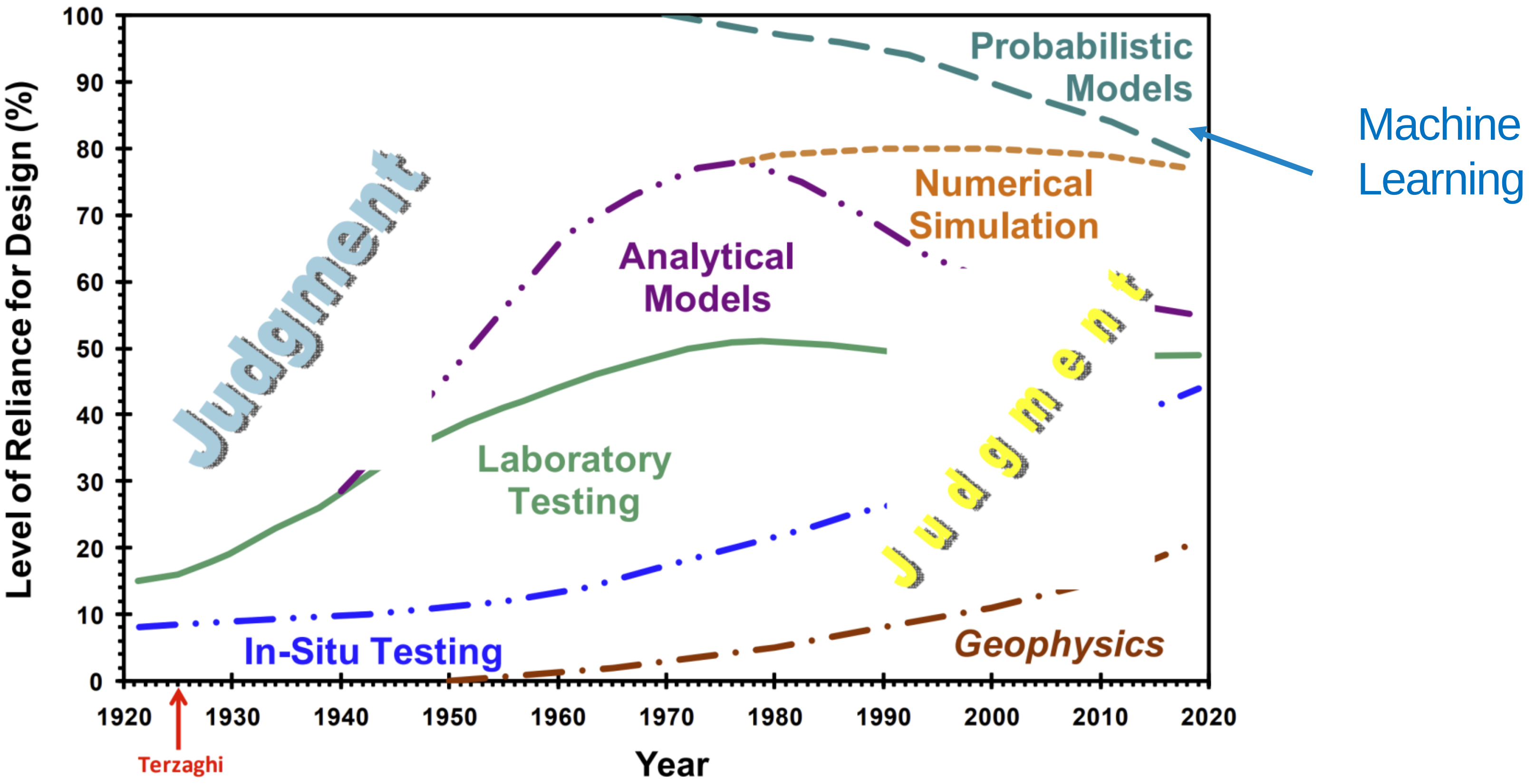
isometric view



plan view

When to use Numerical Models

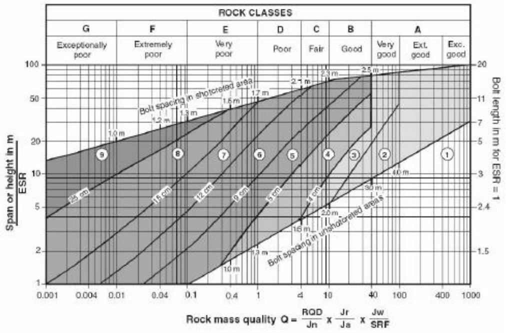
Evolution of design-based processes for geotechnics



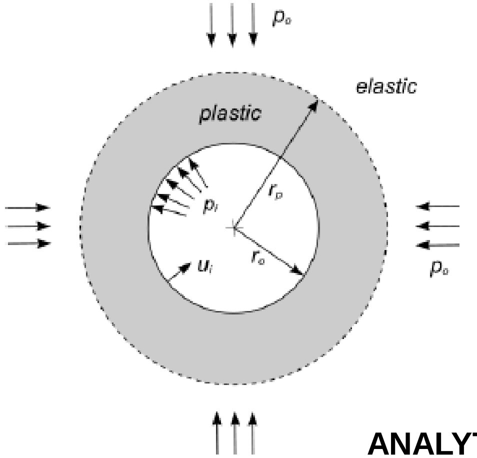
Mayne, P. W. (2012). Geotechnical site characterization in the year 2012 and beyond. In *Geotechnical Engineering State of the Art and Practice: Keynote Lectures from GeoCongress 2012* (pp. 157-186).

When to use Numerical Models

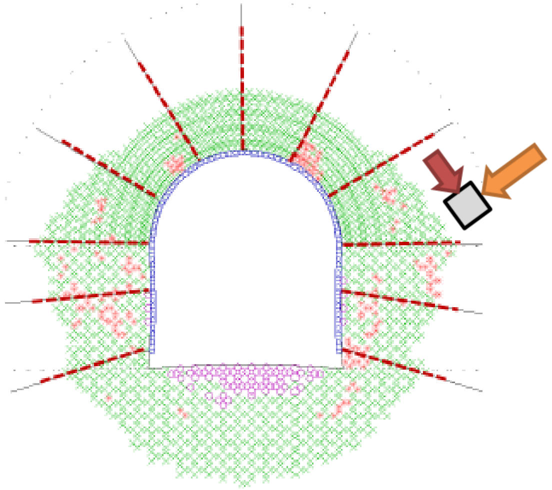
- Empirical methods cannot be extended to new situations
- No other methods (for example analytical or limit equilibrium) are available, or the available methods are too simplistic (or lead to underestimation of the actual solution)
- They can be used to understand and explain complex physical behaviors (e.g., collapse)
- Multiple options can be analyzed (e.g., different design hypothesis)



EMPIRICAL



ANALYTICAL

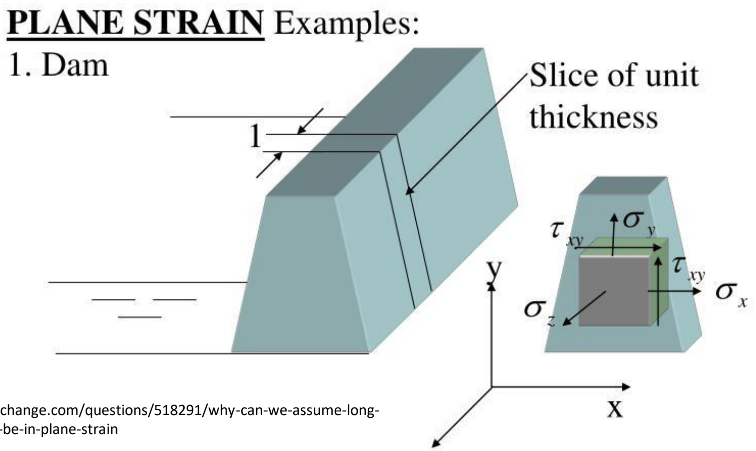


NUMERICAL

General Modeling Considerations

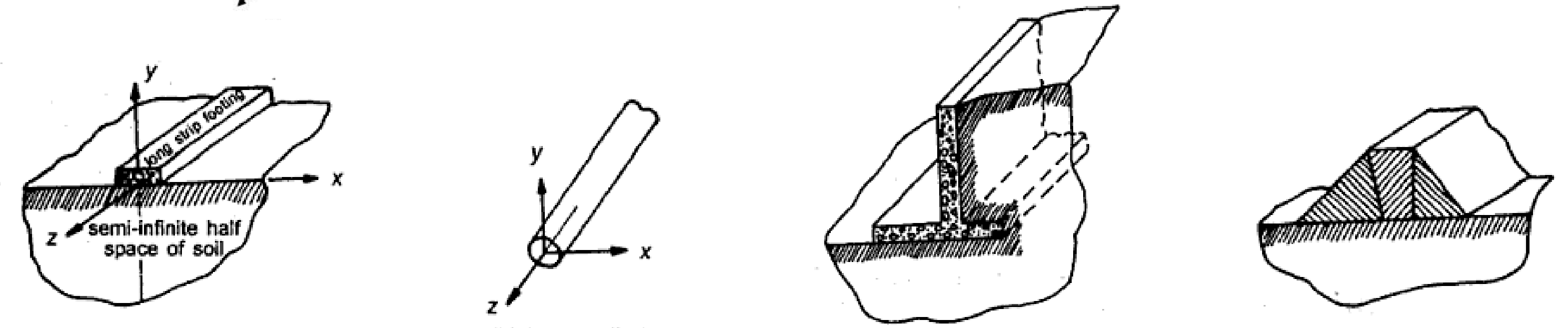
Model Dimensions

- *FLAC2D* modeling assumes plane strain condition (i.e., strain perpendicular to the model plane is assumed to be zero)



https://physics.stackexchange.com/questions/518291/why-can-we-assume-long-structural-members-to-be-in-plane-strain

$$\underline{\underline{\boldsymbol{\varepsilon}}} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & 0 \\ \varepsilon_{21} & \varepsilon_{22} & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad \underline{\underline{\boldsymbol{\sigma}}} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & 0 \\ \sigma_{21} & \sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{bmatrix}$$

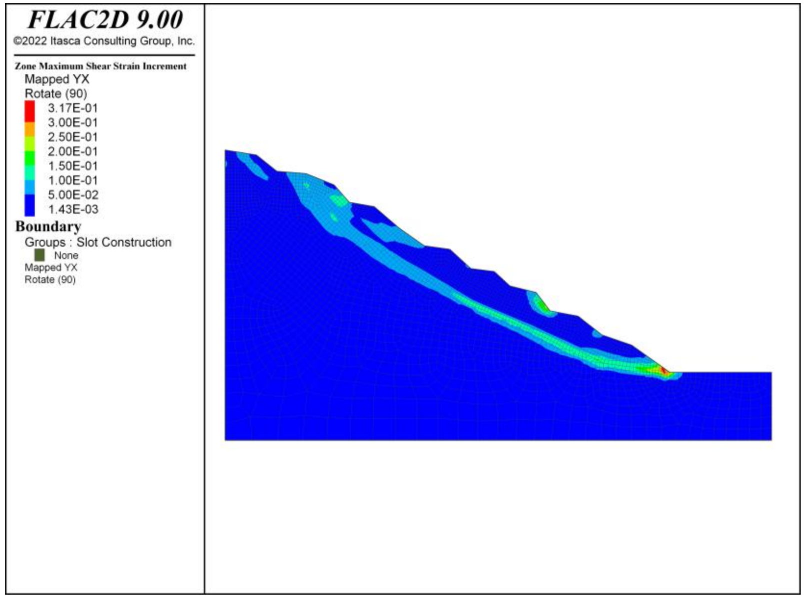


(a) Strip footing (b) Long cylinder (c) Retaining wall (d) Earth dam

Ramamurthy (2010)

Model Dimensions

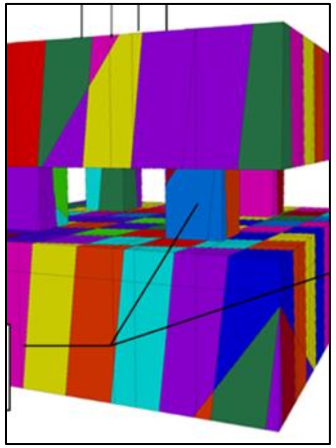
- *2D* analysis is faster than equivalent *3D* analysis
- It is usually simpler to work with 2D geometry/models
- It is usually cheaper to run 2D models

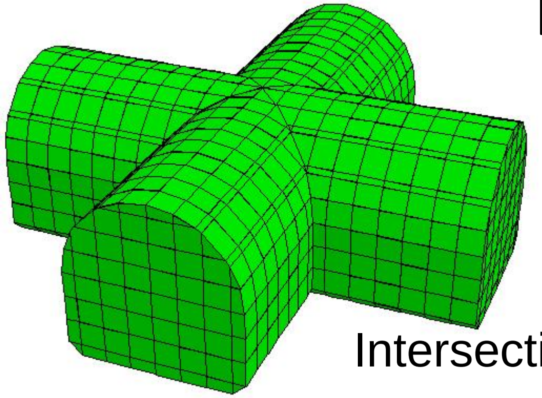


Always think first: is 2D analysis suitable for the problem?

Is this a circular shaft or trench?

3D jointing





Intersections are 3D

Model Dimensions and discontinuities

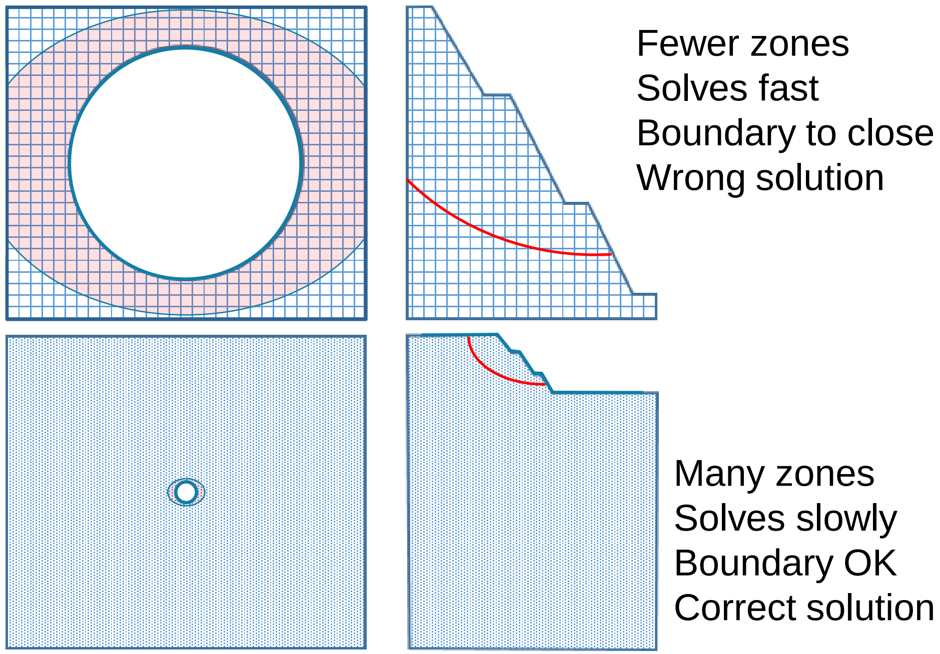
3D modeling should be used if:

- joint orientations change in out-of-plane direction
- material has anisotropy in out-of-plane direction
- in-situ principal stresses are not perpendicular/parallel to the axis of interest (e.g., excavation direction)
- several excavations intersect such that interaction occurs in 3D
- displacements (strains) and acting forces have components in all three directions

Model Size

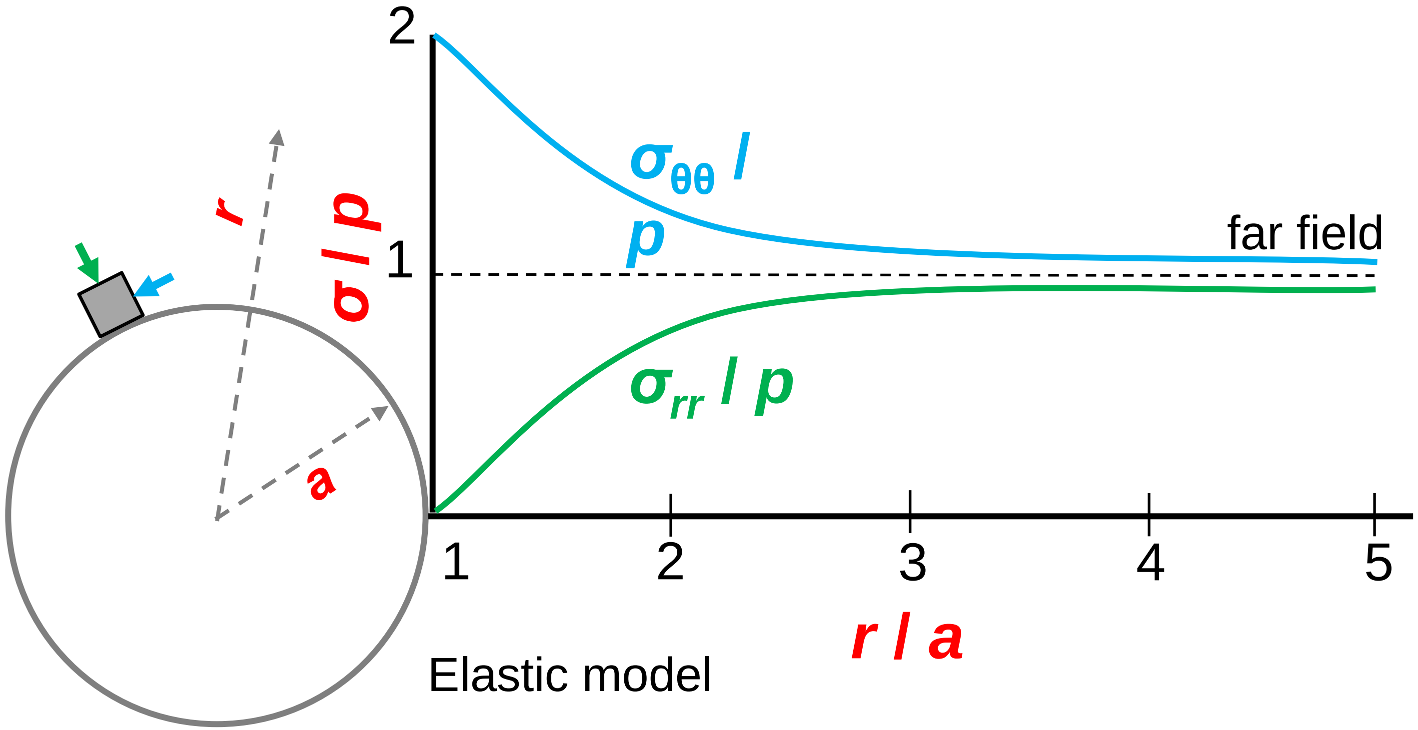
How Large should the Model Be?

- The artificial boundary may be placed slightly further away without serious error.
- Any artificial boundary must not be too close that it attracts plastic flow or prevents joint displacement, thereby invalidating the solution.
- When plastic behavior is present, there is a natural cutoff distance within which most of the “action” occurs.



Excavation Region of Influence

- Stress distribution around a circular hole
- As a rough guide, use a boundary-to-object size ratio of at least 5 (ideally, 6 - 8).



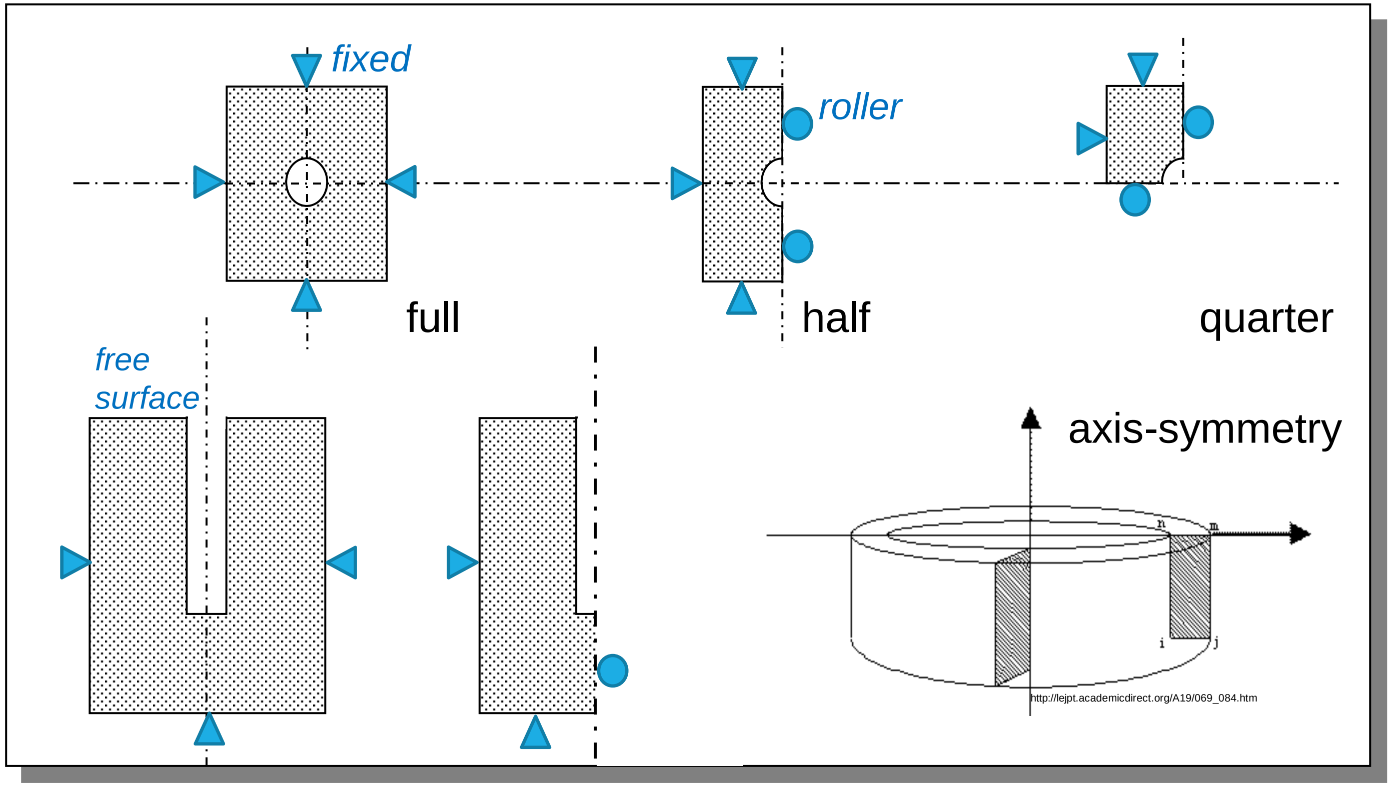
Kirsch solution (describes the elastic stresses around the hole in an infinite plate)

$$\sigma_{rr} = \frac{\sigma}{2}\left(1 - \frac{a^2}{r^2}\right) + \frac{\sigma}{2}\left(1 + 3\frac{a^4}{r^4} - 4\frac{a^2}{r^2}\right)\cos 2\theta$$

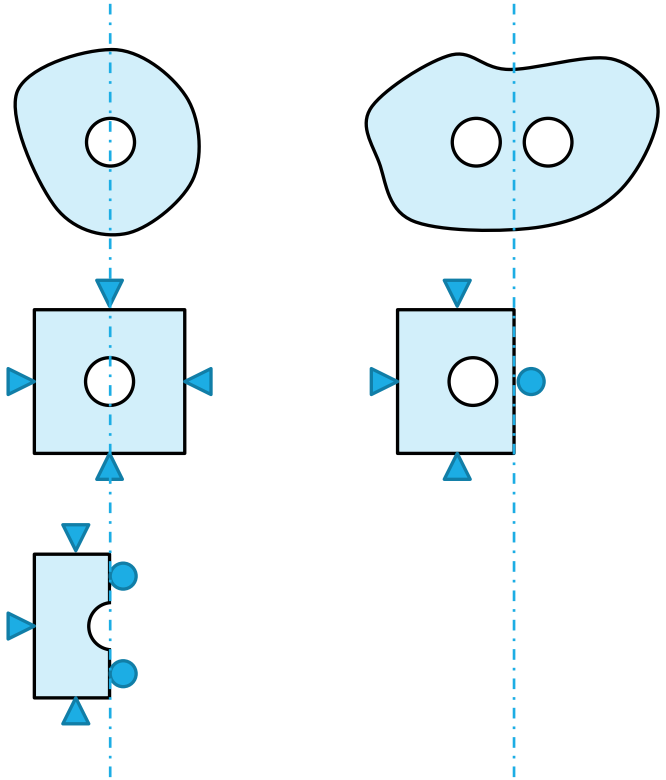
$$\sigma_{\theta\theta} = \frac{\sigma}{2}\left(1 + \frac{a^2}{r^2}\right) - \frac{\sigma}{2}\left(1 + 3\frac{a^4}{r^4}\right)\cos 2\theta$$

$$\sigma_{r\theta} = -\frac{\sigma}{2}\left(1 - 3\frac{a^4}{r^4} + 2\frac{a^2}{r^2}\right)\sin 2\theta$$

Boundary Conditions & Model Symmetry

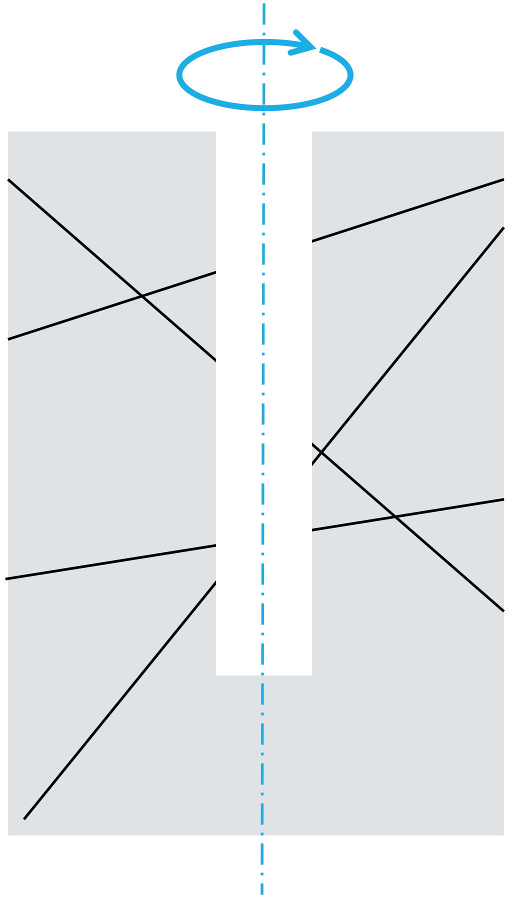


Utilize Symmetry



Axisymmetric configuration

- Configure model for axisymmetry



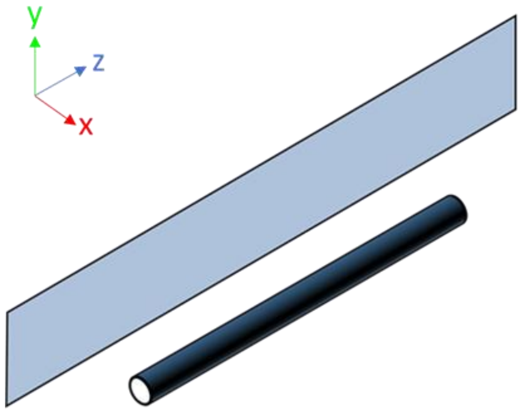
- The presence of discontinuities makes the application of symmetry lines more difficult.
- The modeler should always be careful to consider the effect of joint orientation.

Model complexity

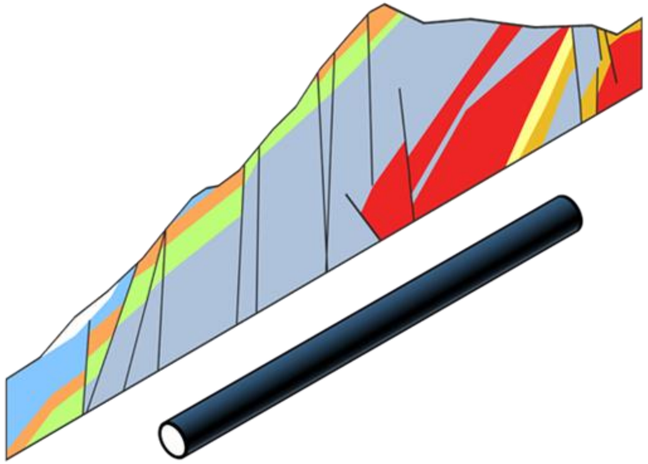
- constant stress
- one material

- varying stress
- varying materials

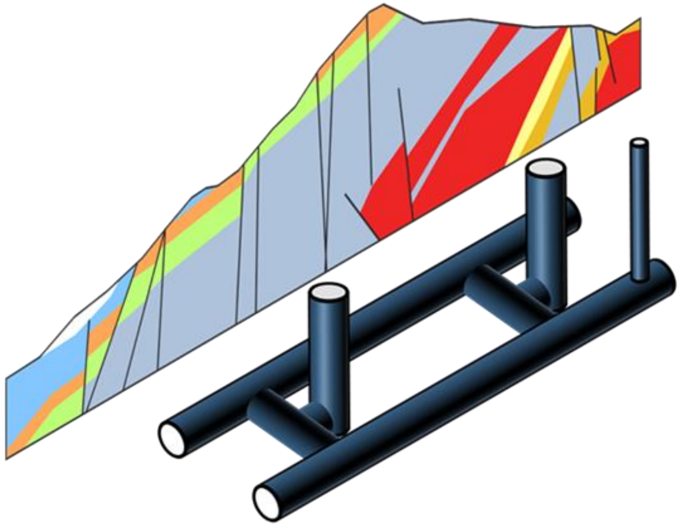
- varying stress
- varying materials
- complex geometry



2D, one model



2D, several models



3D, one model

General Modeling Strategy

Workflow for Numerical Analysis in Geomechanics

1. Define the objectives for the model analysis
2. Create a conceptual picture of the physical system
3. Construct and run simple idealized models
4. Assemble problem-specific data
5. Prepare a series of detailed model runs
6. Perform the model calculations
7. Interpretation results

STEP 1: Objective

- Ask yourself:
  - “Why am I building this model?”
  - “What are the answers I am looking to get from the models?”
  - Propose numerical experiments predicting in advance the expected results

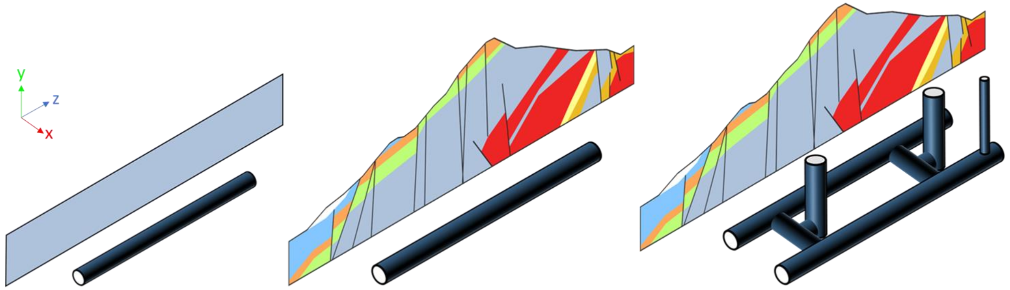
Typical situation	Complicated geology; inaccessible; no testing budget	◄ - - - - - - - - - - - - - - ►	Simple geology; $$$ spent on site investigation
Data	NONE	◄ - - - - - - - - - - - - - - ►	COMPLETE
Approach	Investigation of mechanisms	◄ - Bracket field behavior by parameter studies - ►	Predictive (direct use in design)

virtual (numerical) laboratory

ITASCA™

STEP 2: Conceptual Picture

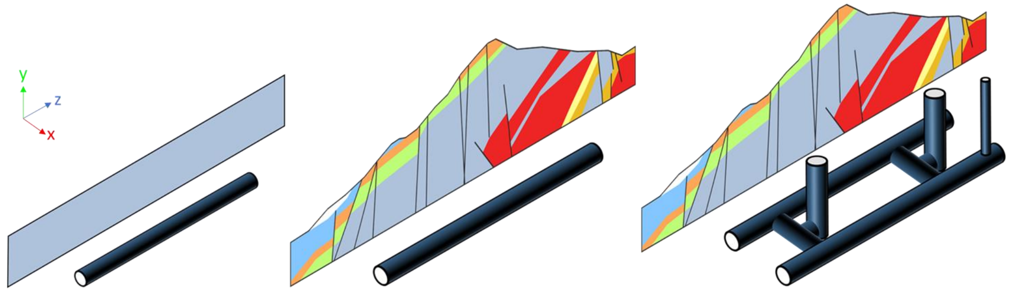
- 2D versus 3D?
- Can you take advantage of geometry symmetry to make model smaller?
- What are the model boundaries?
- Are groundwater, creep, dynamics, thermal effects important?
- What are the major geological structures?
- Set up a model as early as you can:
  - ❖ even before the input data is available
  - ❖ to understand how the system behaves.
  - ❖ can help guide field/lab investigation, initiate recollection of data and define required numerical tests.



2D, one model | 2D, several models | 3D, one model

STEP 3: Simple models

- Set up first a very simple model (that includes the essential mechanisms only), correct the problems, etc.
- Simple models solve faster
- Can suggest data gaps sooner
- Try to understand these results before moving on.
- If the results do not correspond to what you expect, try to understand the reason, do not move on (i.e., by further confusing results with complexity). Can help identify conceptual errors, typos incorrect input data, etc.
- Add complexity to the models only as it becomes necessary (according to Step 1)



2D, one model　　2D, several models　　3D, one model

STEP 4: Assemble Data

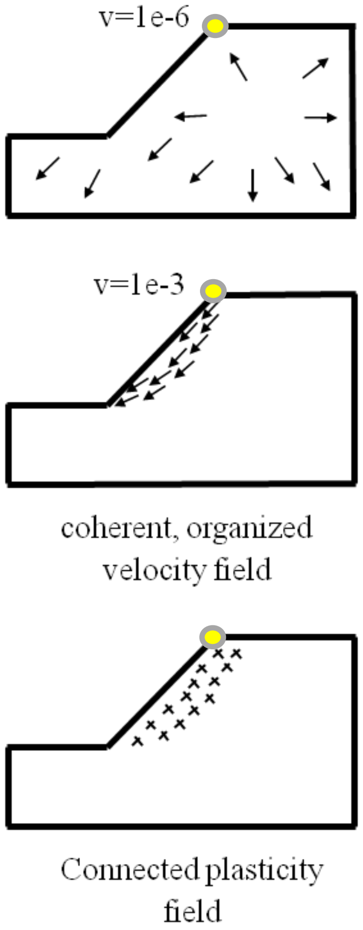
- Details of the geometry
  - profile of underground openings, surface topography, dam profile, rock/soil structures
- Locations of geologic structures
  - faults, bedding planes, joint sets
- Material behavior
  - elastic/plastic properties, post-failure behavior
- Initial conditions
  - in-situ state of stress, pore pressures, saturation, etc.
- External loading
  - seismic loading, pressurized cavern, mining induced stressed, traffic loads, buildings, etc.

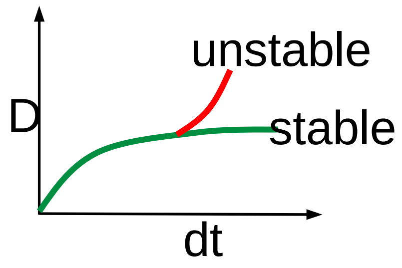
STEPS 5 and 6: Model Runs

- Ensure enough monitoring points (histories) throughout the model – including velocity and/or displacement at points of most interest.
- Always include a convergence history at the start of the model
- Observe model behavior during runs to better understand final state
- SAVE REGULARLY (model state) in the event you need to restart the model run (power failure, computer crash, etc.)
- Numerical models rarely can be used directly in the design of engineering structures, because of the lack of field data
- Normally, numerical models are used to determine mechanisms. The design is often based on simpler methods
- If the design will be based on the results from the numerical models, it should be convenient that:
    - The data is complete and reasonably exact (or representative)
    - Run the model for different conditions so as to study the influence of the uncertainty in the response

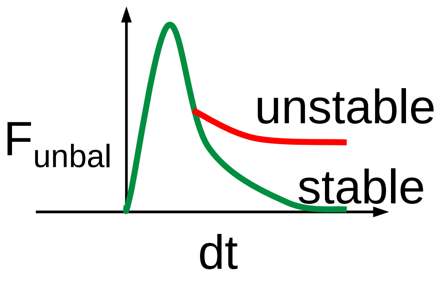
Step 7: Interpreting Results

- Monitor change in:
  - displacement
  - velocity
  - failure/plasticity and
  - force changes
- Examine everything together ...





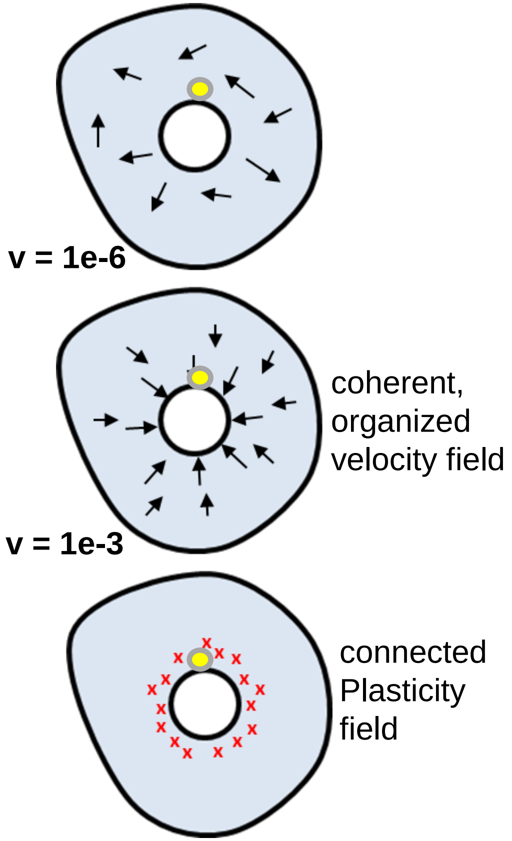
displacement rate decreasing

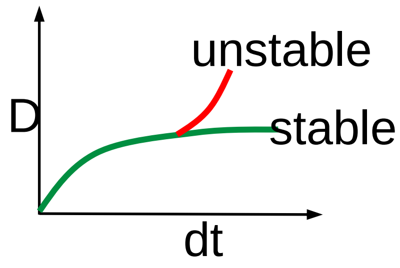


finite F_{unbal} that approaches zero

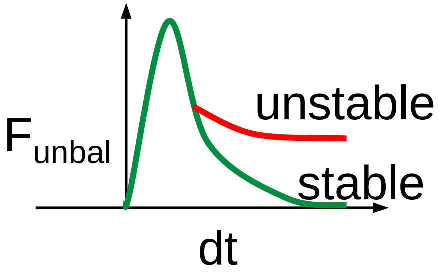
Step 7: Interpreting Results

- Monitor change in:
  - ❖ displacement
  - ❖ velocity
  - ❖ failure/plasticity and
  - ❖ force changes
- Examine everything together ...





displacement rate decreasing



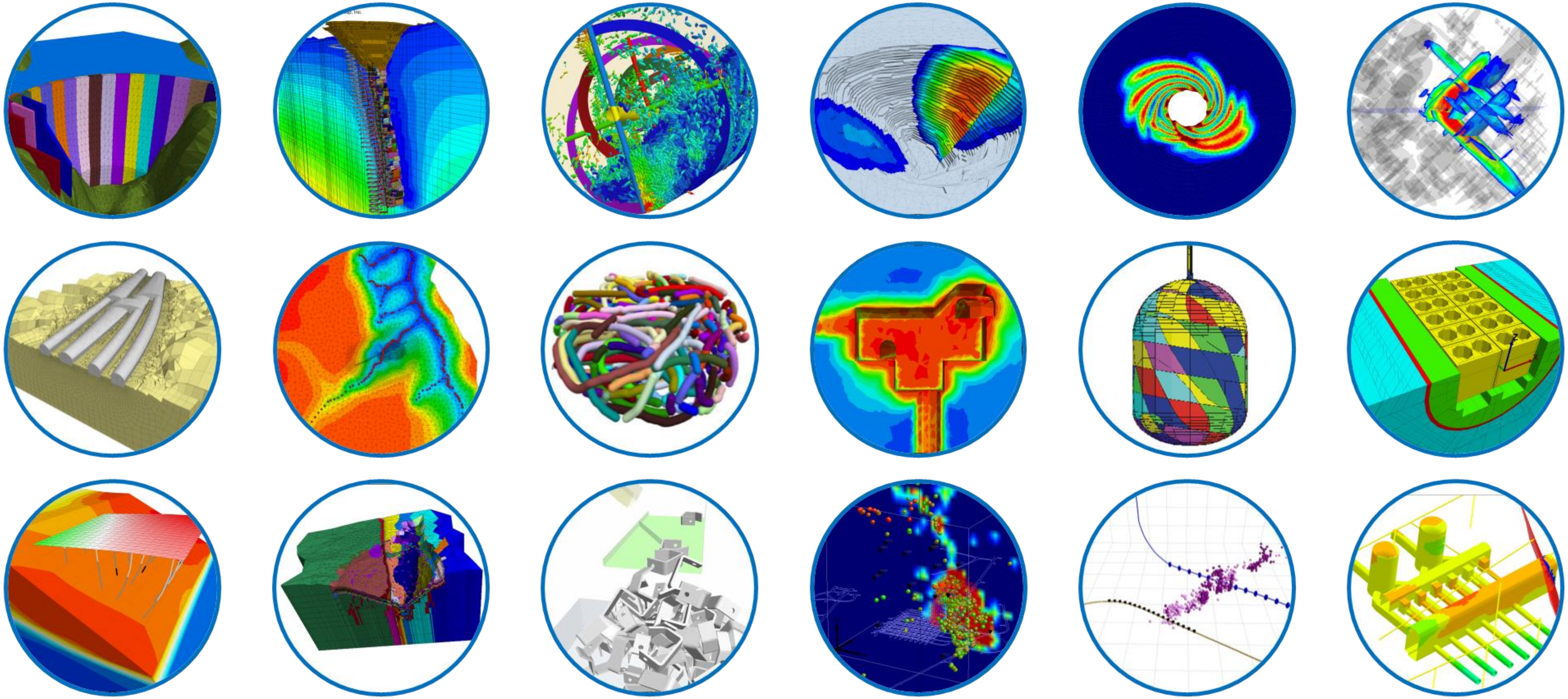
finite F_{unbal} that approaches zero

ITASCA™

Additional remarks

ITASCA'S Numerical Modeling

CIVIL | ENVIRONMENTAL | MANUFACTURING & MATERIALS | MINING | OIL & GAS | POWER GENERATION



GEOMECHANICS • HYDROGEOLOGY • MINING • CIVIL • ENERGY

ITASCA'S SOFTWARE

FLAC2D™ VERSION 9.0
Continuum Modeling for Geomechanics in 2D

UDEC™ VERSION 7.0
Distinct-Element Modeling of Jointed and Blocky Material in 2D

Griddle™ VERSION 2.0
Advanced Grid Generation Software for Engineers

FLAC3D™ VERSION 9.0
Continuum Modeling for Geomechanics in 3D

3DEC™ VERSION 7.0
Distinct-Element Modeling of Jointed and Blocky Material in 3D

MassFlow™ VERSION 9.0
Analysis of Material Flow to Drawpoints

FLAC/Slope™ VERSION 8.1
Explicit Continuum Factor-of-Safety Analysis of Slope Stability in 2D

PFC™ VERSION 7.0
General Purpose Distinct-Element Modeling Framework

KATS™
Kinematic Analysis Tool for Slopes
Probabilistic and Deterministic Slope Analysis

MINEDW™
Groundwater Flow Code for Mining Applications in 3D

XSite™ VERSION 3.0
Hydraulic Fracture Simulation of 3D Fracture Networks