Numerical Methods in Rock Engineering
- Introduction to numerical methods
- Week1, 8 Mar 2021

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Numerical Approach in Rock Engineering
Methodology in Rock Engineering

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- Empirical Method
  - RMR, Q, empirical system
- Analytical Method
  - Mathematical exact solution
- Experimental Method
  - Conduct experiment in the lab and insitu
- **Numerical Method or Numerical Analysis**
  - *Solve equations (often PDE) numerically using computer to obtain solution (either with commercially available or bespoken codes)*
  - *Apply the numerical method for rock mechanics/geomechanics problem*

Numerical Methods

- Continuum method
  - Finite Element Method
  - Finite Difference Method
  - Boundary Element Method
- Discontinuum Method
  - Discrete Element Method (explicit & Implicit)
- Hybrid Continuum/Discontinuum Method

Numerical Approach in Rock Engineering
Physical variables for THMC problems

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Physical problem	Conservation Principle $\nabla \cdot q = 0$	State Variable u	Flux σ	Material properties k	Source f	Constitutive equation $\sigma = ku'$
Elasticity	Conservation of linear momentum (equilibrium)	Displacement u	Stress σ	Young's modulus & Poisson's ratio	Body forces	Hooke's law
Heat conduction	Conservation of energy	Temperature T	Heat flux Q	Thermal conductivity k	Heat sources	Fourier's law
Porous media flow	Conservation of mass	Hydraulic head h	Flow rate Q	Permeability k	Fluid source	Darcy's law
Mass transport	Conservation of mass	Concentration C	Diffusive flux q	Diffusion coefficient D	Chemical source	Fick's law

Structure of state variables and fluxes are mathematically similar –
a convenient truth!

Governing Equation - Elasticity

- Strain-displacement relationship (6)
- Stress-strain relationship (6)
- Equation of motion (3)

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$$

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$$

$$\sigma_{ji,j} + \rho b_i = \rho \frac{\partial^2 u_i}{\partial t^2}$$

- Navier's equation

$$Gu_{i,jj} + (\lambda + G)u_{j,ji} + \rho b_i = 0$$

$$G\nabla^2\mathbf{u} + (\lambda + G)\nabla\nabla\cdot\mathbf{u} + \rho\mathbf{b} = 0$$

$$G\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2}\right) + (\lambda + G)\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_y}{\partial x \partial y} + \frac{\partial^2 u_z}{\partial x \partial z}\right) + \rho b_x = 0$$

$$G\left(\frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_y}{\partial z^2}\right) + (\lambda + G)\left(\frac{\partial^2 u_x}{\partial x \partial y} + \frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_z}{\partial y \partial z}\right) + \rho b_y = 0$$

$$G\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2}\right) + (\lambda + G)\left(\frac{\partial^2 u_x}{\partial x \partial z} + \frac{\partial^2 u_y}{\partial y \partial z} + \frac{\partial^2 u_z}{\partial z^2}\right) + \rho b_z = 0$$

  - Three governing equations for three displacement components

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)}$$

Governing Equation – Elasticity vs Diffusion equation - Heat conduction and Porous media fluid flow

- Diffusion equation

$$A\frac{\partial c}{\partial t}+\nabla\cdot(-D\nabla c)=R$$

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=\rho c\frac{\partial T}{\partial t}$$

  - Time-dependent
  - One parameter k is necessary for steady state behaviour

- Navier's equation

$$G\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_x}{\partial y^2}+\frac{\partial^2 u_x}{\partial z^2}\right)+(\lambda+G)\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_y}{\partial x\partial y}+\frac{\partial^2 u_z}{\partial x\partial z}\right)+\rho b_x=0$$

$$G\left(\frac{\partial^2 u_y}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}+\frac{\partial^2 u_y}{\partial z^2}\right)+(\lambda+G)\left(\frac{\partial^2 u_x}{\partial x\partial y}+\frac{\partial^2 u_y}{\partial y^2}+\frac{\partial^2 u_z}{\partial y\partial z}\right)+\rho b_y=0$$

$$G\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_x}{\partial y^2}+\frac{\partial^2 u_x}{\partial z^2}\right)+(\lambda+G)\left(\frac{\partial^2 u_x}{\partial x\partial z}+\frac{\partial^2 u_y}{\partial y\partial z}+\frac{\partial^2 u_z}{\partial z^2}\right)+\rho b_z=0$$

  - Not time-dependent
  - Three coupled equations
  - Two parameters (isotropy)

- Alternative form.

$$-\nabla\cdot(c\nabla\mathbf{u})=F$$

$$c=\begin{bmatrix}\begin{bmatrix}2G+\mu & 0\\ 0 & G\end{bmatrix} & \begin{bmatrix}0 & \mu\\ G & 0\end{bmatrix}\\ \begin{bmatrix}0 & G\\ \mu & 0\end{bmatrix} & \begin{bmatrix}G & 0\\ 0 & 2G+\mu\end{bmatrix}\end{bmatrix}$$

An example of analytical solution: Kirsch solution (1898)

$$\sigma_r = \frac{S_{H\max} + S_{h\min}}{2}\left(1 - \frac{R^2}{r^2}\right) + \frac{S_{H\max} - S_{h\min}}{2}\left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right)\cos 2\theta$$

$$\sigma_\theta = \frac{S_{H\max} + S_{h\min}}{2}\left(1 + \frac{R^2}{r^2}\right) - \frac{S_{H\max} - S_{h\min}}{2}\left(1 + \frac{3R^4}{r^4}\right)\cos 2\theta$$

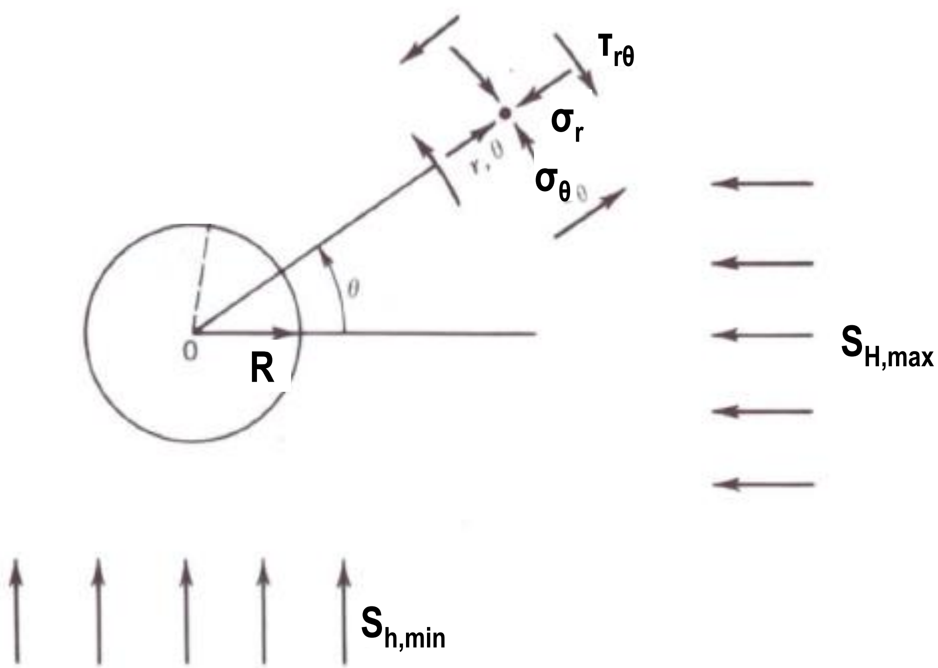
$$\tau_{r\theta} = \frac{S_{H\max} - S_{h\min}}{2}\left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right)\sin 2\theta$$

R: radius of well

r: radial distance from the center of the well

θ: measured from $S_{H,max}$

$S_{H,max}$ and $S_{H,max}$: maximum and minimum horizontal insitu stress



Numerical Approach in Rock Engineering
Advantage/Usefulness – analytical approach

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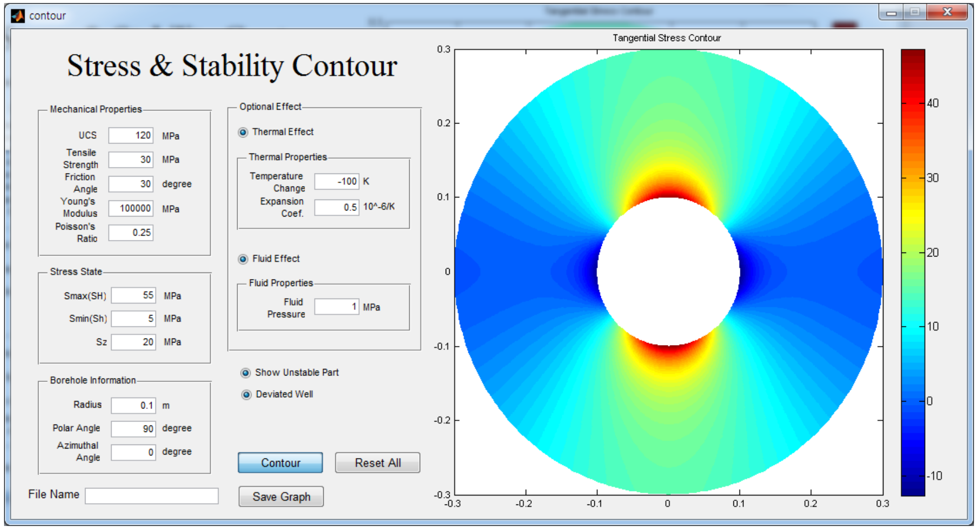
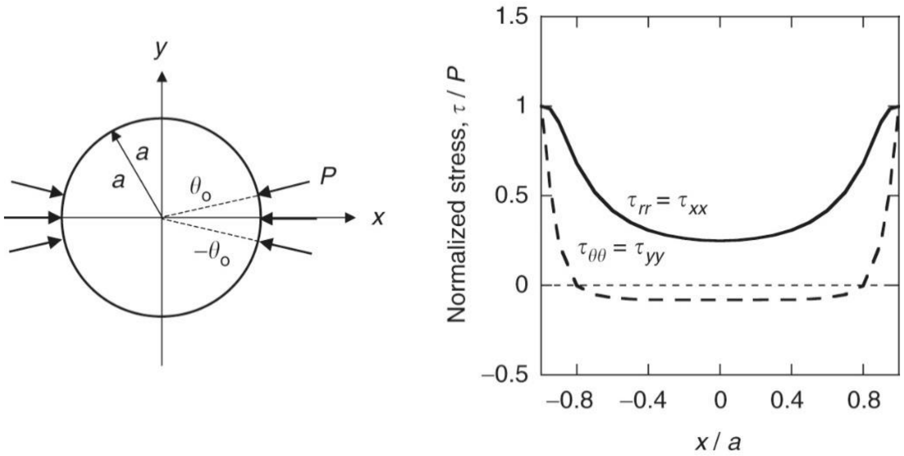
Kirsch solution



Diametral compression



- Numerous analytical solutions exist – fast evaluation & still powerful
- However, 1) complex geometry, 2) multiple formation, 3) complex boundary condition, 4) complex process cannot be handled accurately.

Courtesy of Kwon S

Numerical Approach in Rock Engineering
Advantage/Usefulness – analytical approach

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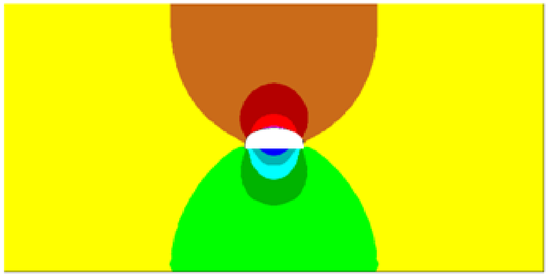
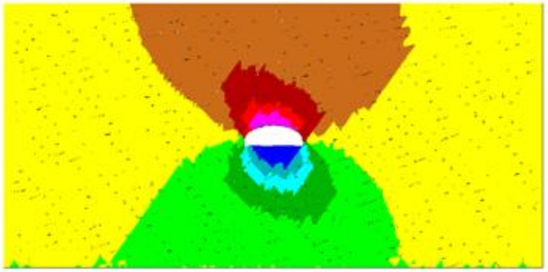
- Analytical solution is of limited value when,
  - When geometry is not simply circular,
  - Domains are divided into regions of distinct properties
  - When fractures around rock is considered especially when fractures are not regular
  - Boundary/initial conditions are not simple
  - Complex constitutive relations are associated – stress dependent permeability





Numerical Approach in Rock Engineering*

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- Reasons for popularity in numerical modeling
  - Easy-to-access powerful PC
    - Positive /negative
    - Tool is a means to a solution.(not the solution itself!)
  - Dramatic increase in ability to include geological detail in models
    - More detail imply better model?
    - The art of modeling lies in determining what aspects of the geology are essential.
  - Predictive capability in physical process
  - Success of modeling in other branches of engineering
    - Similarity & differences with aerospace eng?

*Starfield, A.M. and P.A. Cundall, 1988, *TOWARDS A METHODOLOGY FOR ROCK MECHANICS MODELING.* Int J Rock Mech Min Sci & Geomech Abstr, 25(3): p. 99-106

Numerical Approach in Rock Engineering

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- Problems in applying numerical approach
  - Misuse
    - Use in a wrong way:
    - Need to be familiar with the theory of the numerical methods
  - Abuse or overuse
    - Numerical tool is not a magic box
    - Appropriate modeling methodology needed

Verification vs. Validation

- Verification: the provision of assurance that a code correctly performs the operations it specifies (e.g., PDE)[1].
  - A common method of verification is the comparison of a code's results with solutions obtained analytically (Kirsch solution, Boussinesq…)
  - Is the program doing what it claims to be doing
  - Are we getting the answers that we think we are getting?
- Validation: the determination that the code or model indeed reflects the behavior of the real world [2]
  - Validated model is the one that provides a good representation of the actual processes occurring a real system [3].
  - Are we getting the answers that we need?

1. **US Nuclear Regulatory Commission (NRC, NUREG-0865, 1990)**
2. **US Department of Energy (DOE/RE-0073, 1986)**
3. **IAEA, Radioactive waste management glossary (IAEA-TECDOC-264, 1982)**

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Verification vs. Validation

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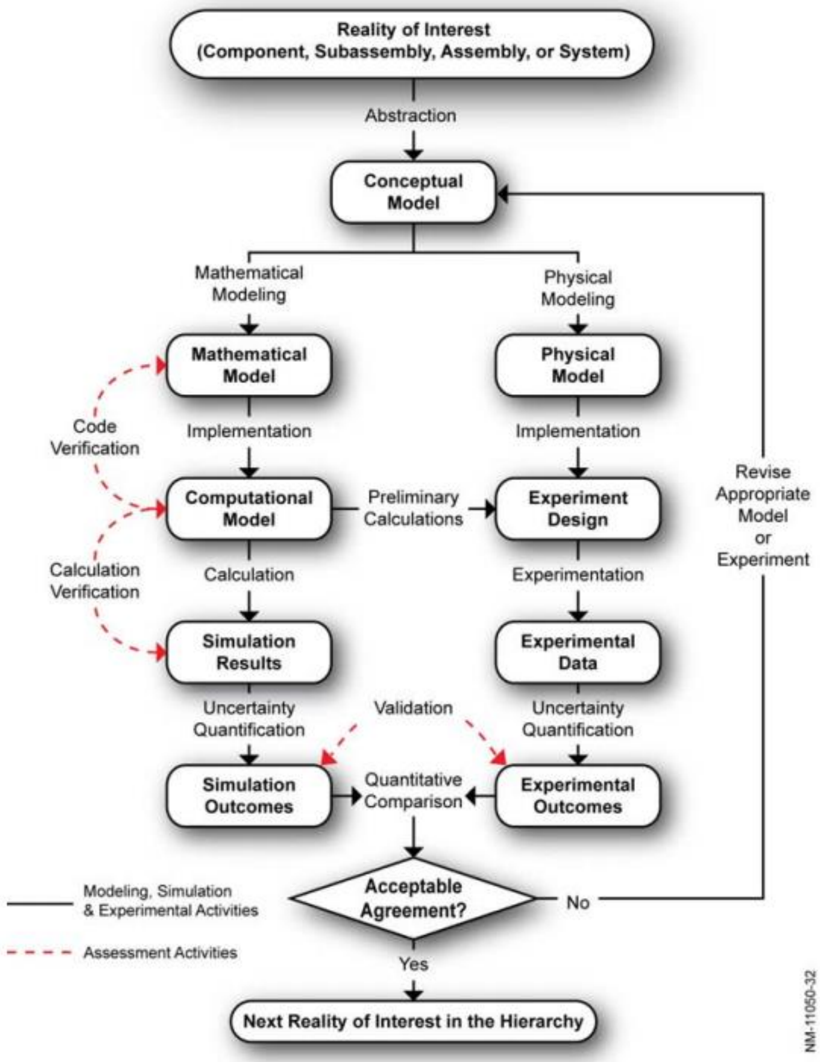
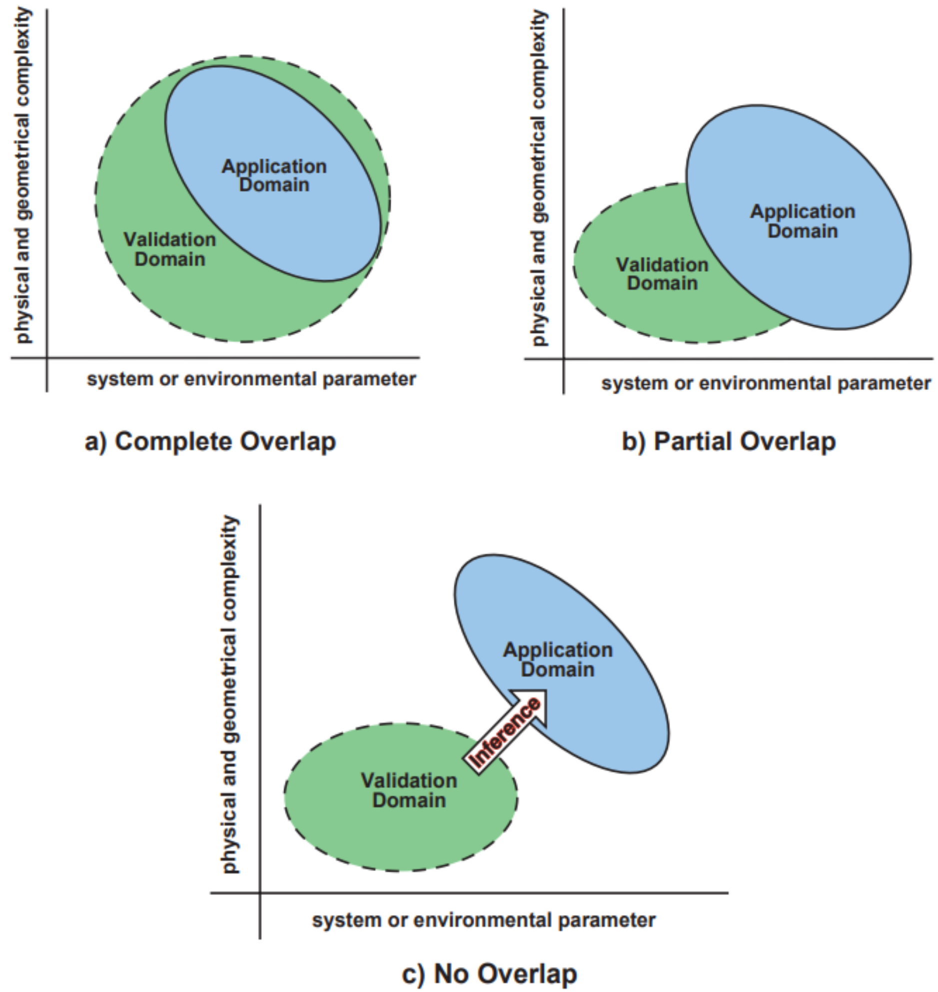


Schwer, L.E. (2006): An overview of the ASME guide for verification and validation in computational solid mechanics, Prod. 5. LS-DYNA Anwenderforum, A-II: 111-122

Numerical Approach in Rock Engineering
Validation vs. Prediction

- Validation domain
  - Relevant physics are understood in this region
- Application domain
  - Region where predictive capability is needed



Oberkampf, W.L. et al. (2003): Verification, validation and predictive capability in computational engineering and physics, SANDIA report SAND2003-3769

Error vs. Uncertainties

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- Error
  - A recognizable deficiency in any phase or activity of modeling and simulations that is *not* due to lack of knowledge
  - Acknowledged error
    - Characterized by knowledge of divergence from an approach or ideal condition that is considered tobe a baseline for accuracy.
    - Ex) finite precision arithmetic in a computer, conversion of PDEs into discrete equations
  - Unacknowledged error
    - Blunders or mistakes
    - Programming errors, input data erors, and compiler errors
    - Code verification mainly deals with unacknowledged errors

Oberkampf, W.L. et al. (2003): Verification, validation and predictive capability in computational engineering and physics, SANDIA report SAND2003-3769

Error vs. Uncertainties

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- Uncertainties
  - First meaning (often called, aleatory uncertainty)
    - estimated amount may differ from its true value
    - Inherent variation associated with physical system
    - Often handled by probability distribution
    - Ex) data experiments
  - Second meaning (often called, epistemic uncertainty)
    - Related to the lack of knowledge about physical systems
    - Ex) Failure criterion

Oberkampf, W.L. et al. (2003): Verification, validation and predictive capability in computational engineering and physics, SANDIA report SAND2003-3769

Numerical Approach in Rock Engineering
Issues in Geomechanics

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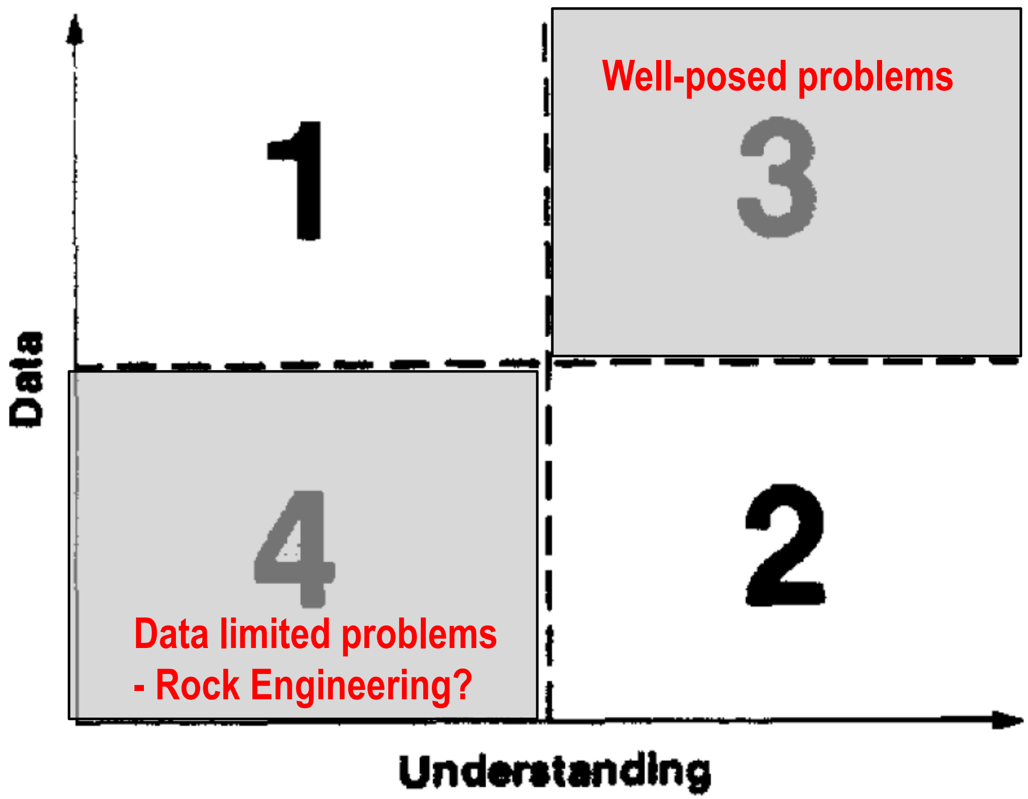
- Uncertainty in Geological Feature
- Uncertainty in Boundary Condition
  - In situ stress not easy to characterize
- Hard to obtain data in Rock/Fracture properties
  - Costly, unavailable
- Up-scaling issue
  - measure in the lab may not represent the values in large scale

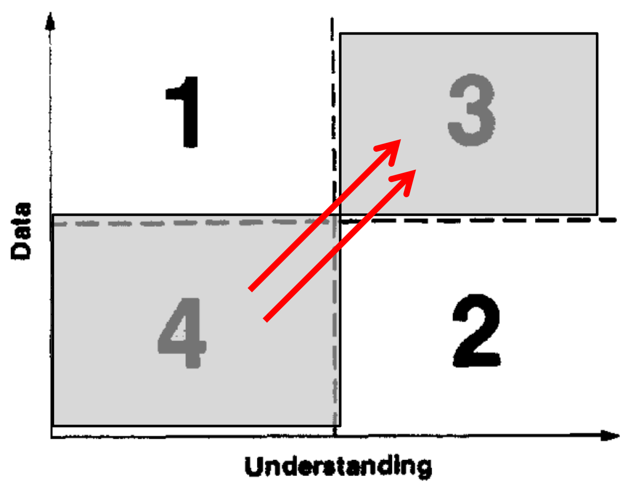
Numerical Approach in Rock Engineering
Data limited problems



Recited from Starfield and Cundall (1988)

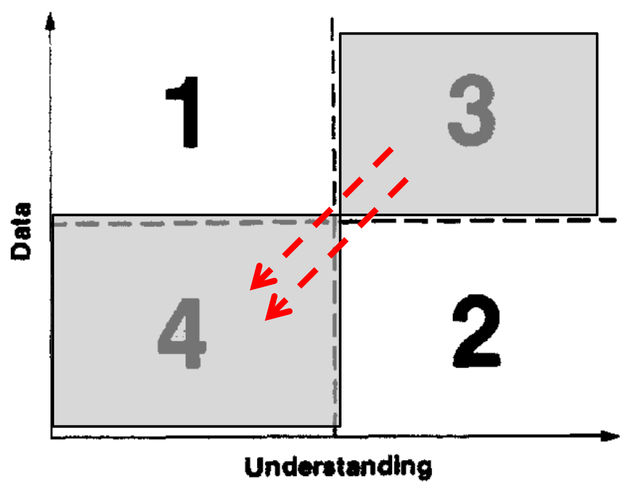
Data limited problems

- Fitting rock engineering problem into region 3 (lots of data plus good understanding)
  - Impossible to have sufficient data
  - We loses control of intellectual control of the model



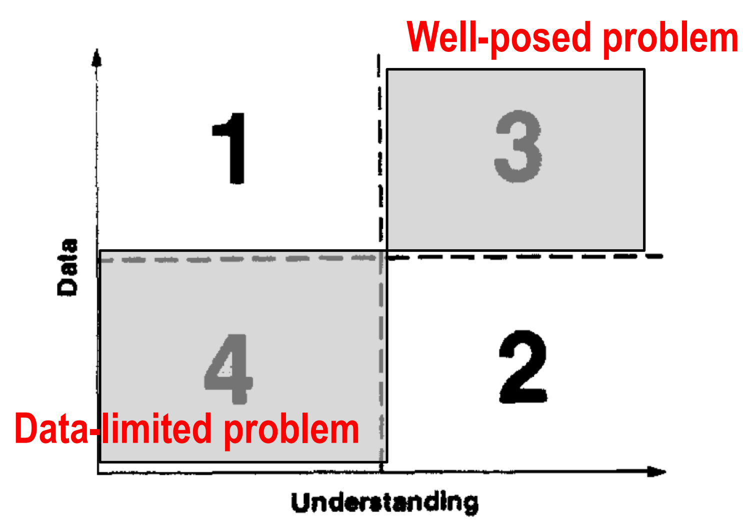
Data limited problems

- Apply the tools developed for region 3 to rock engineering problem
  - Numerical tool is a means to a solution!



Modeling guidelines

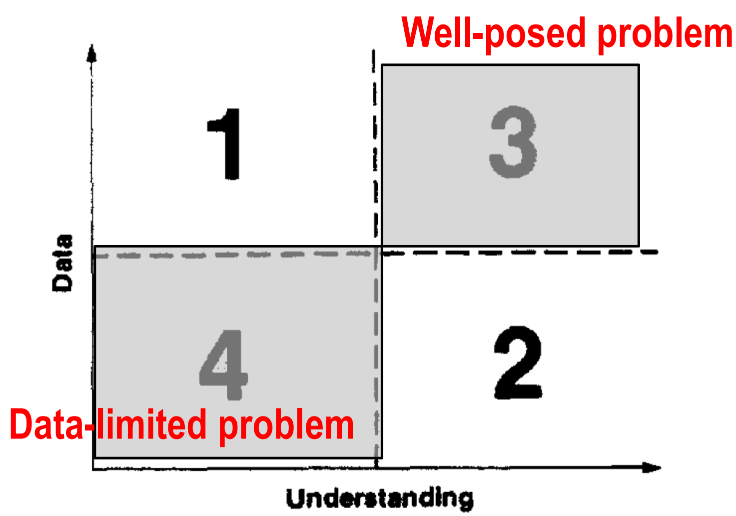
- Differences between well-posed and data-limited problems
  - Resolution
  - Validation
  - Once validated, can it be used routinely?



- **Data-limited problems**
  - ***"A model is a simplification of reality rather than an imitation of reality. A model is an intellectual tool."***
  - The design of the model should be driven by the questions that the model is supposed to answer rather than the details of the system. → helps in simplifying and controlling the model
  - More appropriate to build a few very simple models than one complex model.
  - Try to gain confidence in the model and modify it as one uses it. Approach to the model is that of a detective (not mathematician)
  - Purpose is to gain understanding and to explore potential trade-offs and alternatives. (not absolute predictions)

Modeling guidelines

- Data-limited problems
  - One progresses slowly from region 4 to region 3 ← from simple to complex model, suggest new data or new models. ← Adaptive modeling



Modeling guidelines

- Clear about why you are building a model and what questions you are trying to answer
- Use a model at the earliest possible stage in a project to generate both data and understanding.
  - Do not delay while waiting for field data. You need a conceptual model in place as soon as possible.
- Look at the mechanics of the problem.
  - Identify important mechanisms
- Try to visualize qualitatively what the answer of your modeling would be

Numerical Approach in Rock Engineering
Modeling guidelines

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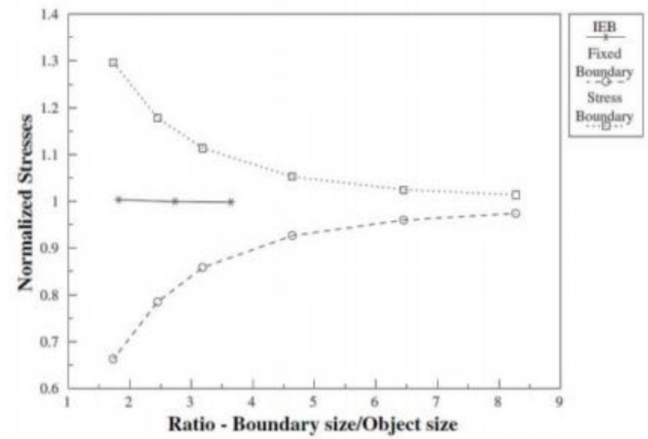
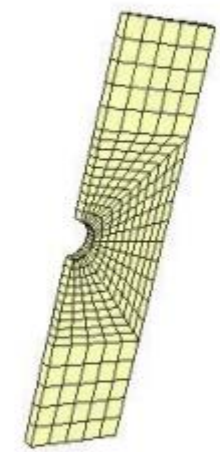
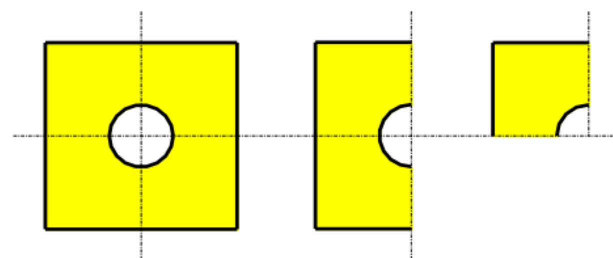
- Design the simplest model that will allow the important mechanisms to occur ← serve as a laboratory for the thoughts experiments
- Implement your simplest modeling – run it – and improve it.
  - Proceed to more complex modeling
  - Or, identify the weakness and remedy them before continuing
  - If your model has weakness that you cannot remedy → make a series of simulations that will bracket the true case.
- Numerical modeling is very similar to laboratory work
- Visualizing and anticipating solutions *before* running a model is an important discipline.
- Modeling in a cautious way actually generate new knowledge

Modeling guidelines

- Considerations
- Appropriate numerical modeling technique
- Initial and boundary conditions
- Appropriate model size
- Choice of constitutive models
- Meshing and mesh-dependency
- 2D vs. 3D
- Coupled process
- Modeling sequence
- Continuum vs Discontinuum
- Calculation efficiency vs. Accuracy
- Static vs. Dynamic



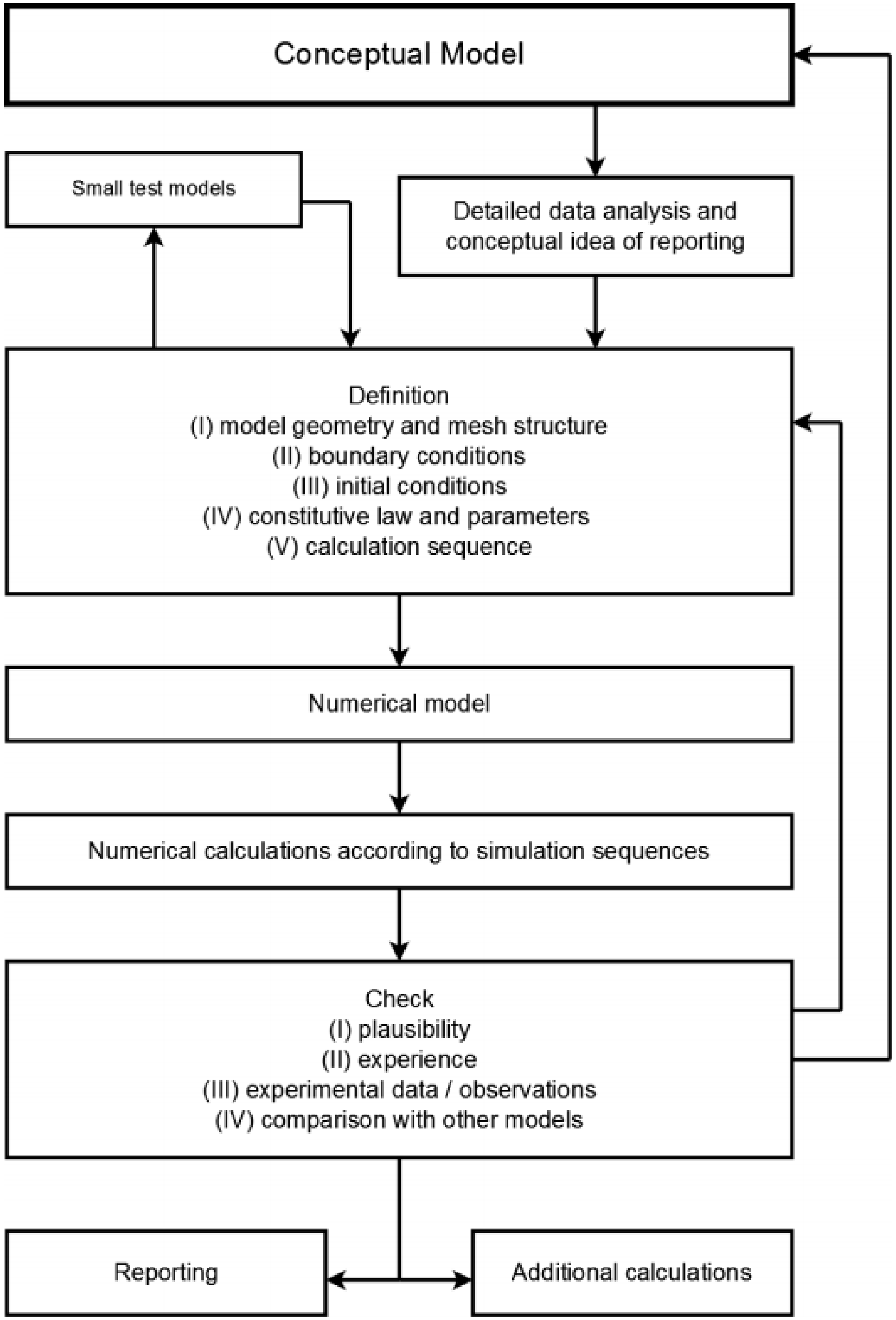




Konietzky, 2021, Ch.9 Practical hints for using numerical methods in rock mechanics, Introduction into geomechanics

Numerical Approach in Rock
Modeling guidelines

- Numerical model workflow



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Modeling Report

- General description
  - Name of used numerical code including version (and sub-version) number
  - Numerical method (e.g. FEM, DEM, ..) and calculation scheme (explicit vs. implicit)
- Specific model description:
  - Model size, meshing, calculation time (run time)
  - Constitutive models and parameters
  - Initial and boundary conditions
  - Calculation sequence (construction stages etc.)
  - Usage of small or large strain calculation scheme
- Graphical presentation of simulation results:
  - Any plot should contain a coordinate system
  - For each presented physical quantity the corresponding units m be given
  - Sign (+ vs. -) for physical quantities like stresses, inflow

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Numerical Approach in Rock Engineering
Modeling Report

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- Graphical presentation of simulation results:
  - Specific physical quantities may be plotted in form of vectors or magnitudes (filled colour plots or isoline plots)
  - Documentation of initial state (e.g. virgin stress state, initial pore water pressure distribution etc.) as well as all relevant subsequent modelling stages
- Evaluation / Interpretation of simulation results:
  - Simulation results have to be interpreted according to the modelling task (description + figures + diagrams + tables).
  - Results have to be checked using different other available techniques, like comparison with practical experience, in-situ measurements, analytical solutions, calculations with other methods etc.
  - May include sensitivity, uncertainty and robustness analysis.
  - The potential problem of mesh-dependency should be discussed.
  - Choice and calibration of parameters has to be discussed.
  - Model simplifications and their potential impact on modelling results should be discussed.
  - Chosen initial and boundary conditions should be justified.

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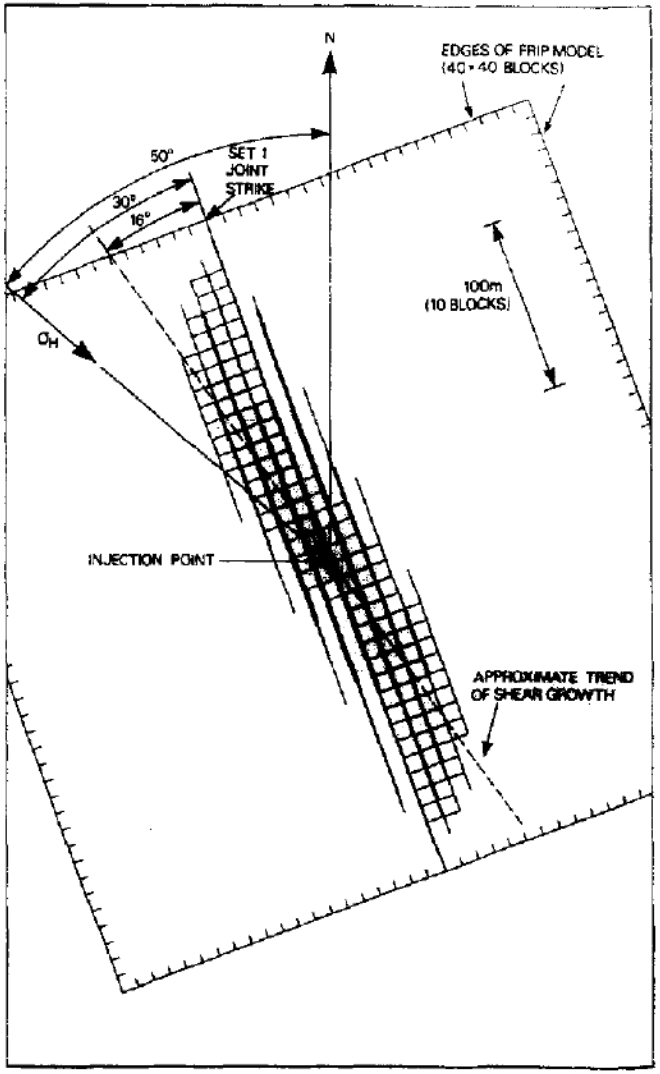
- Fluid flow enhancement due to hydraulic stimulation in a EGS project in Cornwall (Pine, 1985)



Recited from Starfield and Cundall (1988)

Case Studies (Rock Slope Stability)

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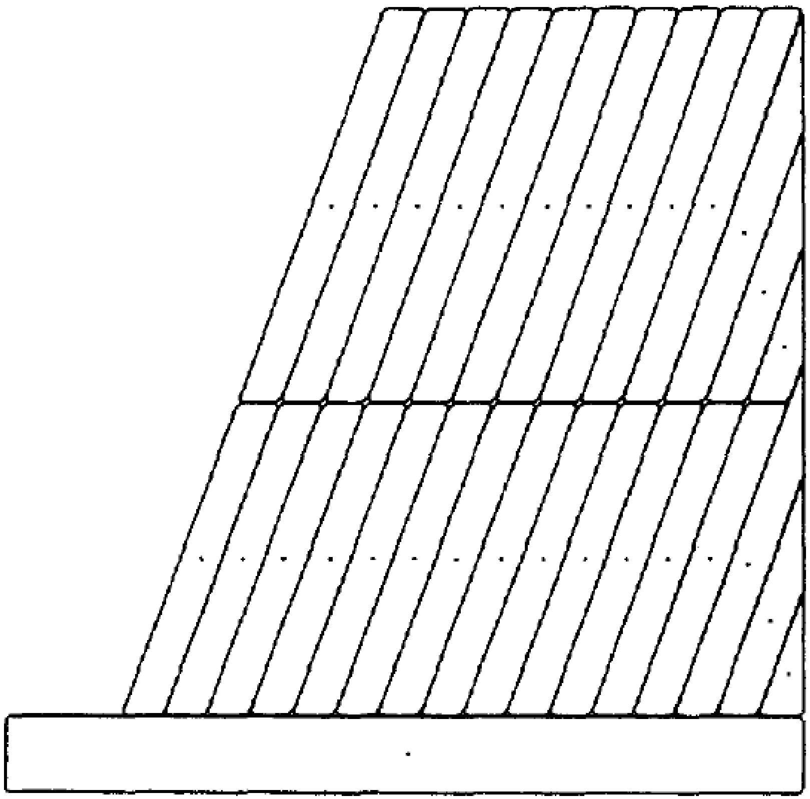
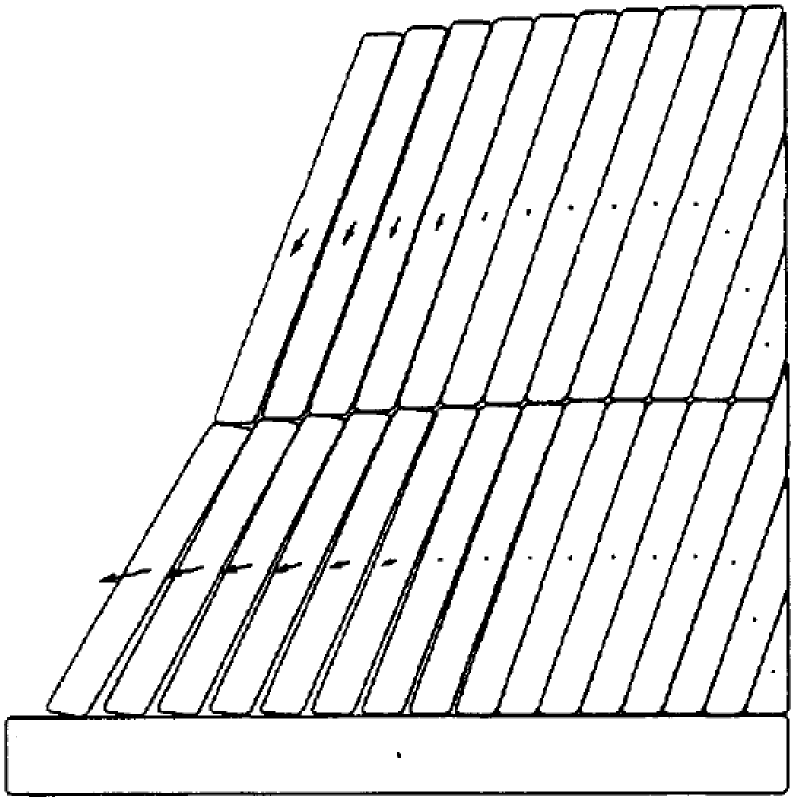




- So obvious? Easy to say…detective novel…

Recited from Starfield and Cundall (1988)

Numerical Approach in Rock Engineering
Good and bad examples

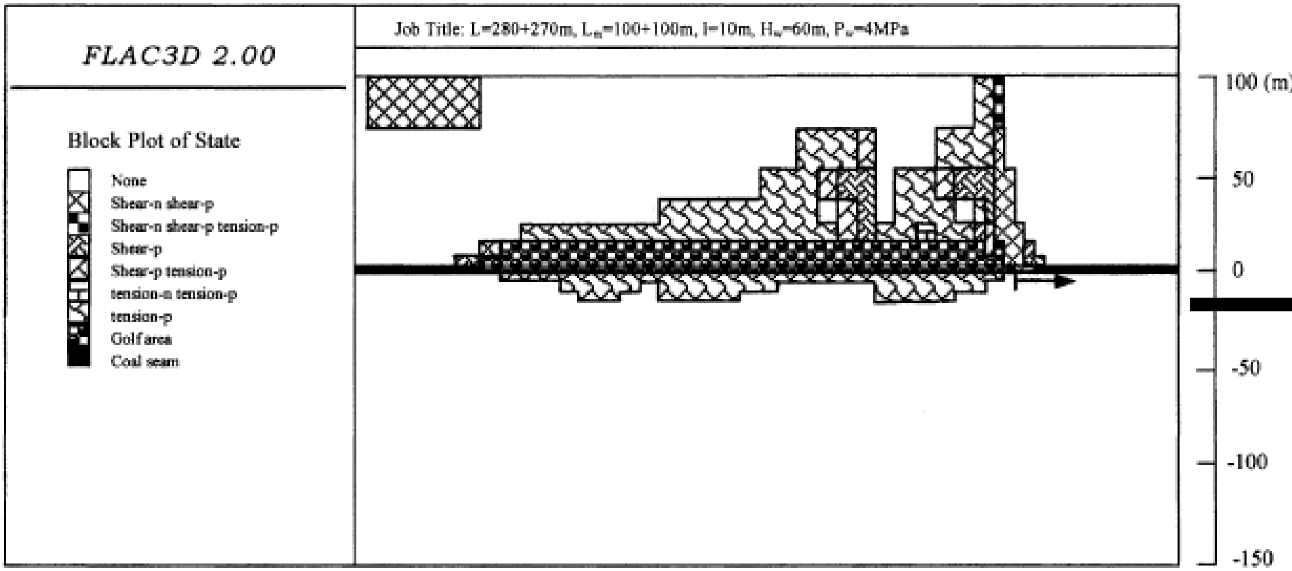


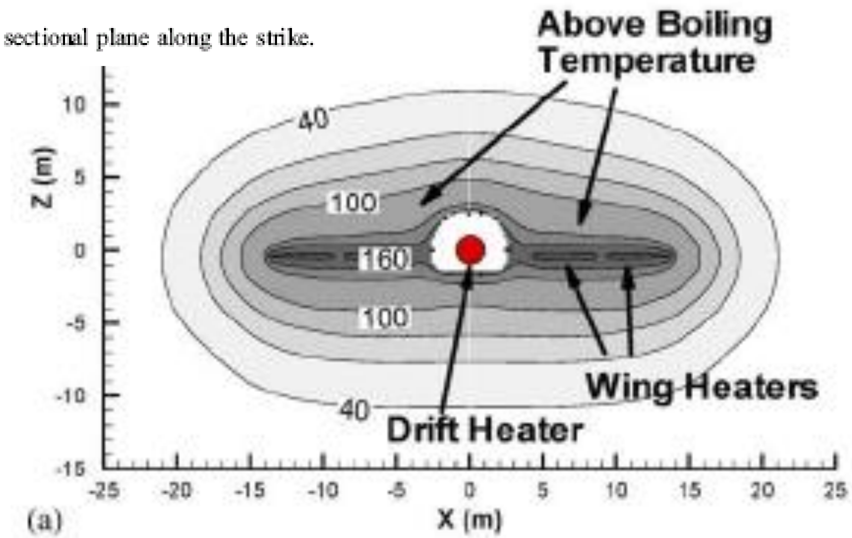
Fig. 7. Indication of the fracture zones in the floor and roof strata on a sectional plane along the strike.

unclear legend

unclear plot

Not easy to read

(xxx,2002)



Clear legend

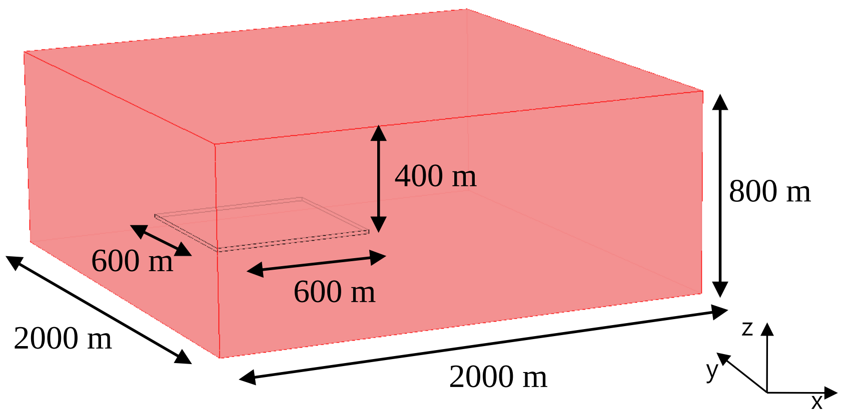
Clear plot

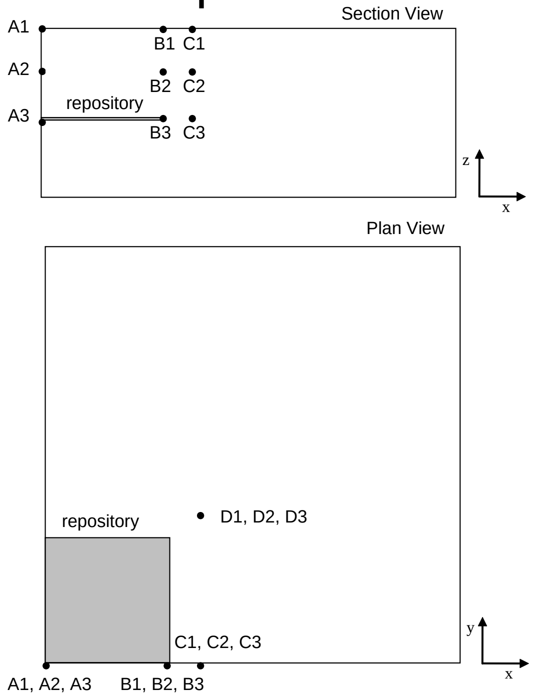
Easy to read

(Rutqvist et al., 2005)

Numerical Approach in Rock Engineering
Continuum – TM analysis

- High level nuclear waste repository in Sweden
  - What would be the stress, displacement and temperature around repository when ~6000 canisters are placed in the deposition holes





Locations of monitoring points

Min KB, Lee JW, Stephansson O, Implications of Thermally-Induced Fracture Slip and Permeability Change on the Long-term Performance of a Deep Geological Repository, Int J Rock Mech Min Sci, 2013;61:175-288.

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Continuum – TM analysis

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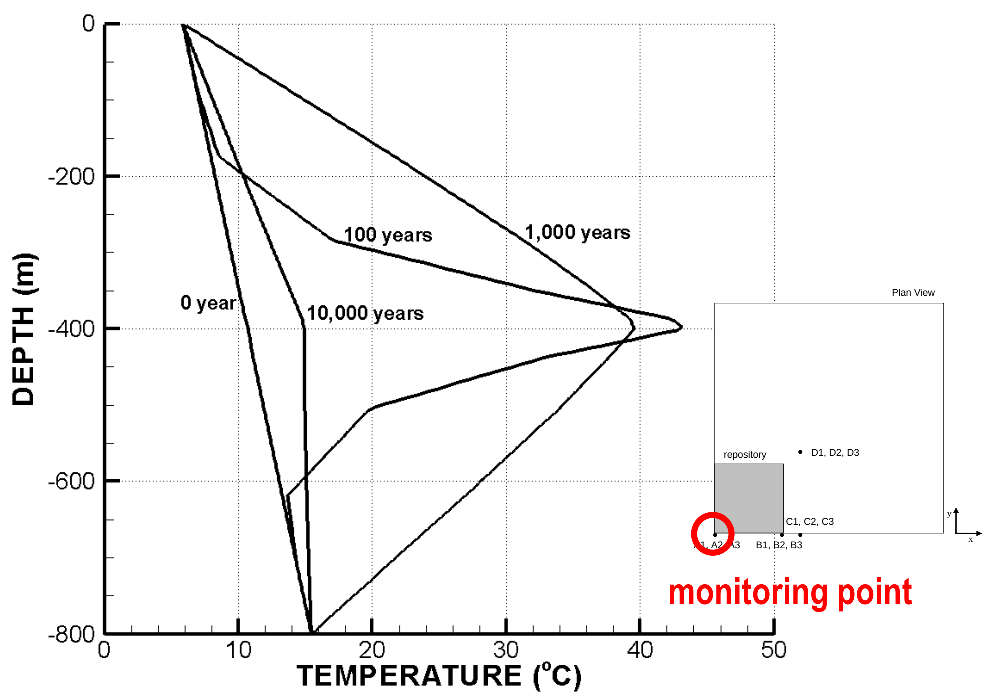
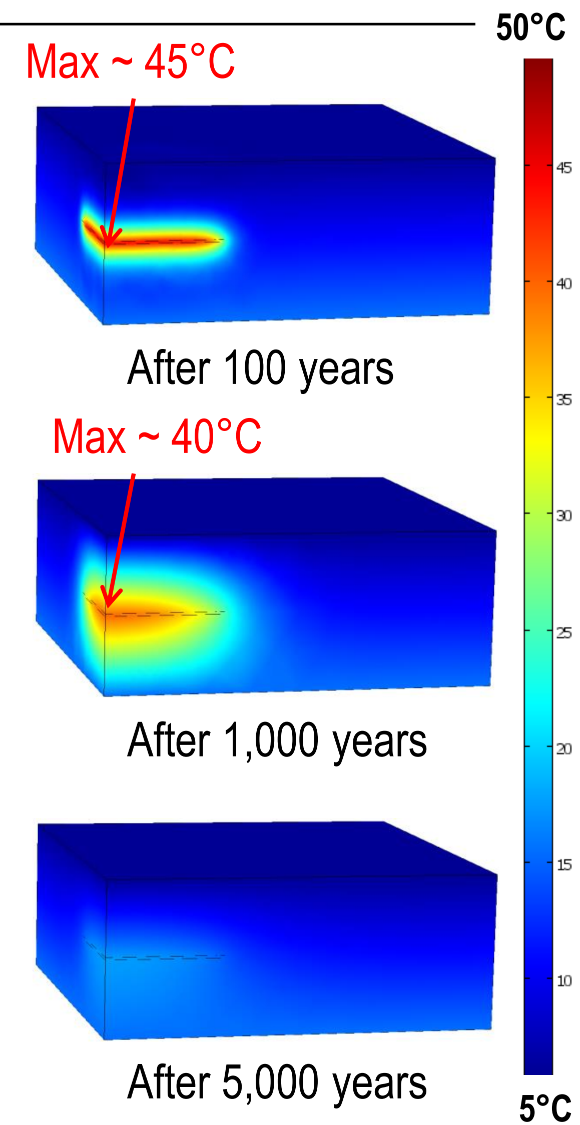
Maximum temperature around 45 °C.



Temperature profile along the center of the repository



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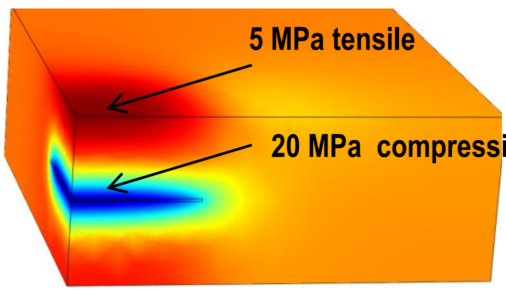
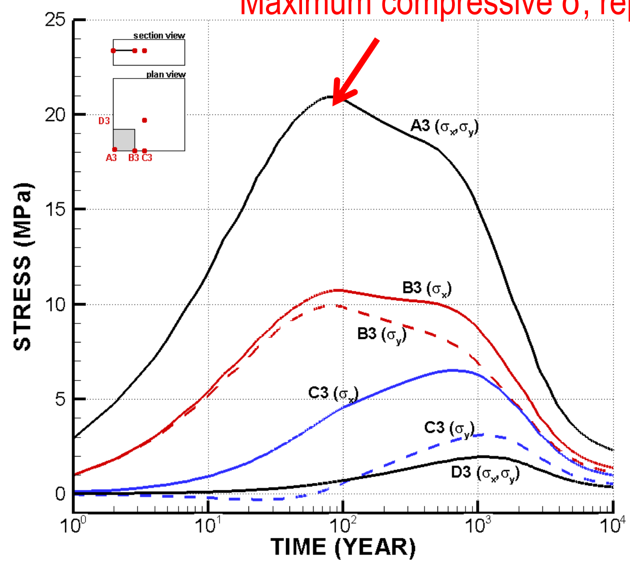
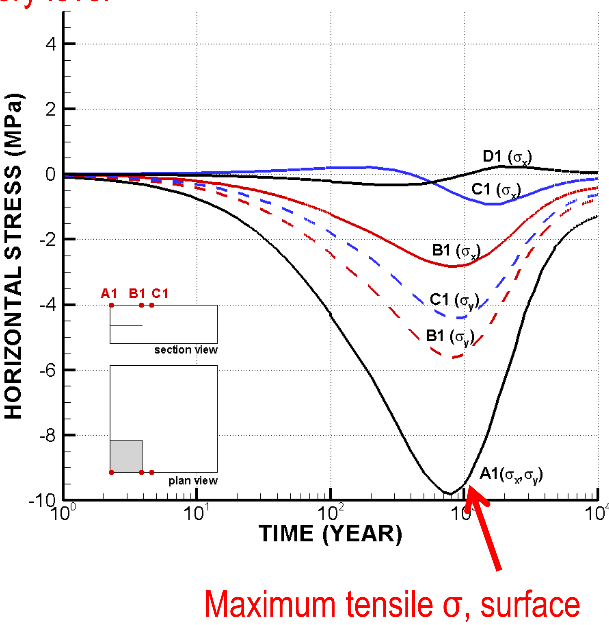
Numerical Approach in Rock Engineering
Continuum – TM analysis



Horizontal stress at 100 years





- Maximum compressive stress ~ 20 MPa near repository at ~ 100 years
- Maximum tensile stress ~10 MPa at surface at ~ 1,000 years

Min KB, Lee JW, Stephansson O, Implications of Thermally-Induced Fracture Slip and Permeability Change on the Long-term Performance of a Deep Geological Repository, Int J Rock Mech Min Sci, 2013;61:175-288.

Numerical Approach in Rock Engineering
Continuum – Code coupling THM analysis

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TOUGH-FLAC simulator

- TOUGH2 (Lawrence Berkeley National Laboratory, LBNL) + FLAC3D (ITASCA™)

Thermal & hydraulic result

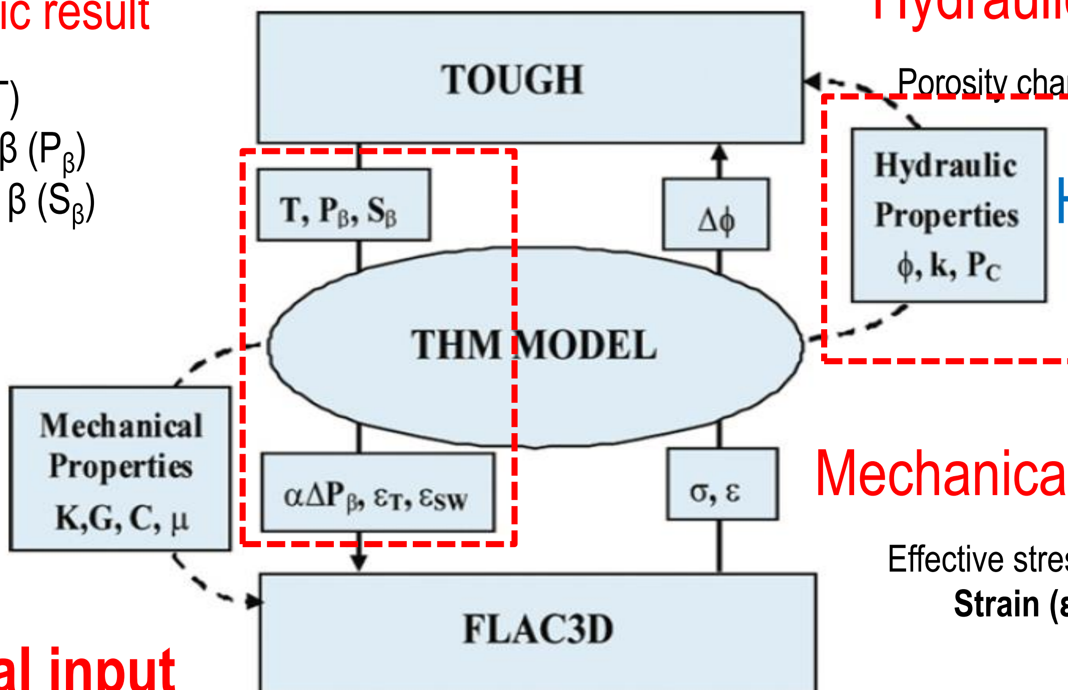
Temperature (T)
Pressure of phase β (P_β)
Saturation of phase β (S_β)

Hydraulic input

Porosity change (**ΔΦ**)

Hydraulic property

Porosity (Φ)
Permeability (k)
Capillary pressure (P_c)



Mechanical property

Bulk modulus (K)
Shear modulus (G)
Cohesion (C)
Friction coefficient (μ)

Mechanical result

Effective stress (σ')
Strain (ε)

Mechanical input

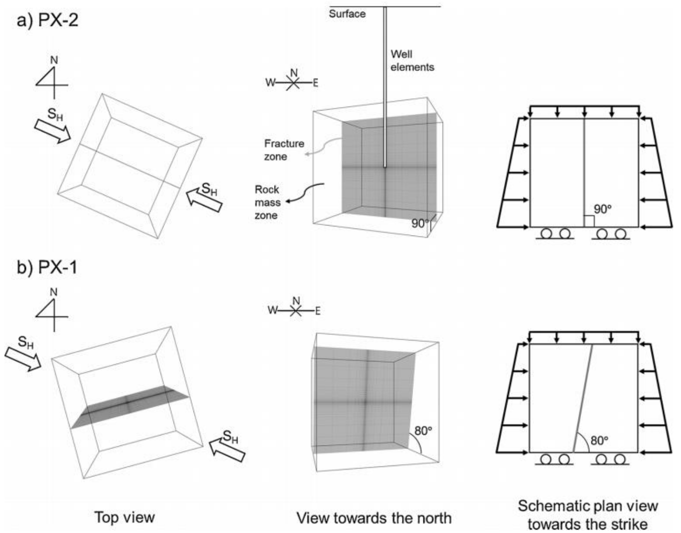
Biot coefficient (α)
Pressure of phase β (P_β)
Thermal strain (ε_T)
Swelling strain (ε_{SW})

Simulation logic (Rutqvist, 2011)

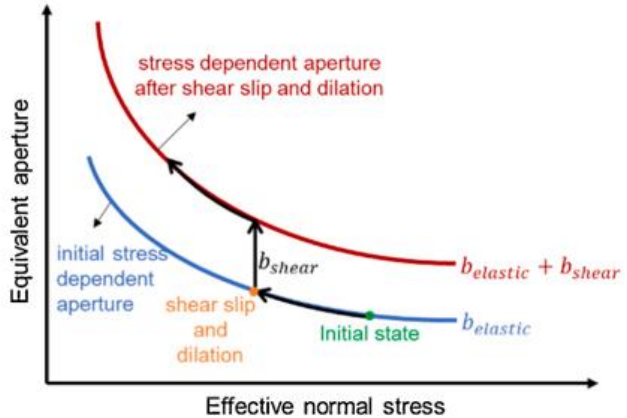
Rutqvist, J. (2011). "Status of the TOUGH-FLAC simulator and recent applications related to coupled fluid flow and crustal deformations." Computers & Geosciences 37(6): 739-750.

Numerical Approach in Rock Engineering
Continuum – Code coupling THM analysis

- Models
  - Rock mass zone: constant permeability
  - Fracture zone: permeability changes by effective normal stress
    - PX-1: shearing + jacking
    - PX-2: jacking

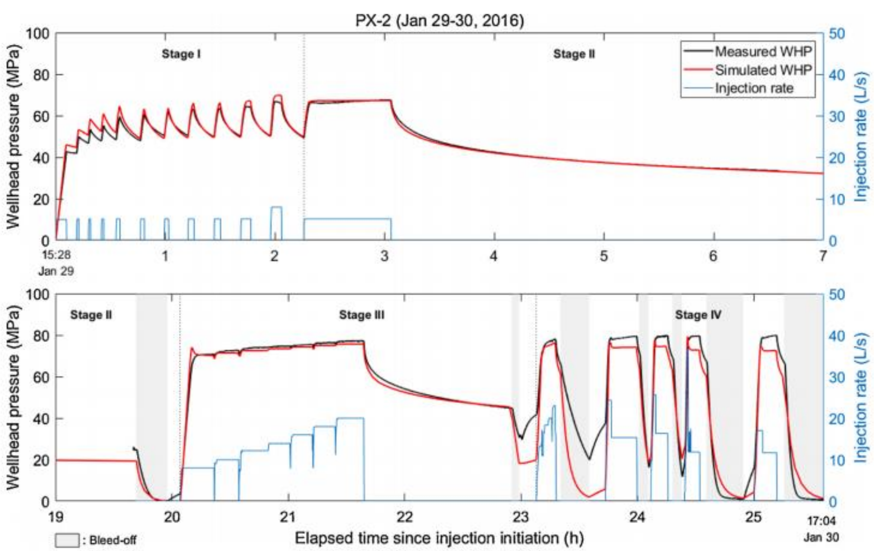


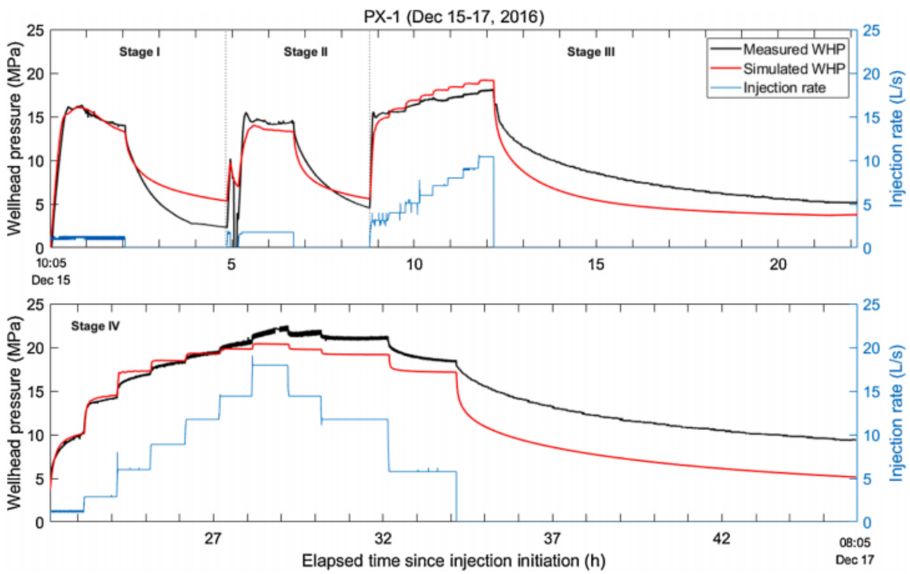
Initial and boundary condition and model geometry



Yoo, H., Park, S., Xie, L., Kim, K.-I., Min*, K.-B., Rutqvist, J., Rinaldi, A. P. Hydro-mechanical Modeling of the First and Second Hydraulic Stimulations in a Fractured Geothermal Reservoir in Pohang, South Korea. Geothermics, 2021, 89:101982

- Coupled hydromechanical modeling of hydraulic stimulation
  - Numerical modeling in general matches the pressure response



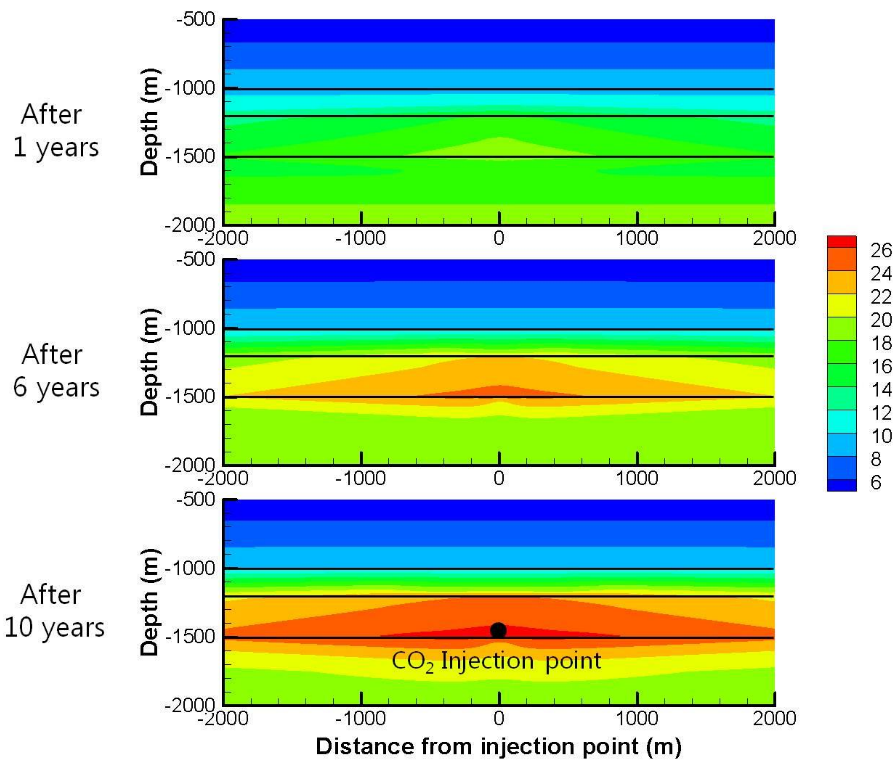


Yoo, H., Park, S., Xie, L., Kim, K.-I., Min*, K.-B., Rutqvist, J., Rinaldi, A. P. Hydro-mechanical Modeling of the First and Second Hydraulic Stimulations in a Fractured Geothermal Reservoir in Pohang, South Korea. Geothermics, 2021, 89:101982

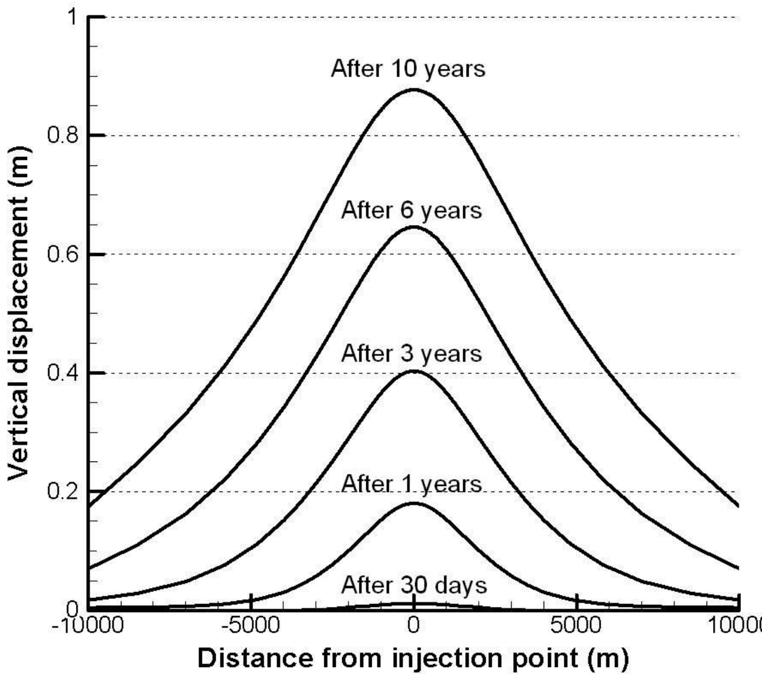
Numerical Approach in Rock Engineering
Continuum – (T)HM analysis

- How much heaving is expected after injecting xxx tons of CO2 at a given geological formation?

TOUGH-FLAC 해석 결과



주입공 주변에서의 간극 수압 변화 (단위: MPa)

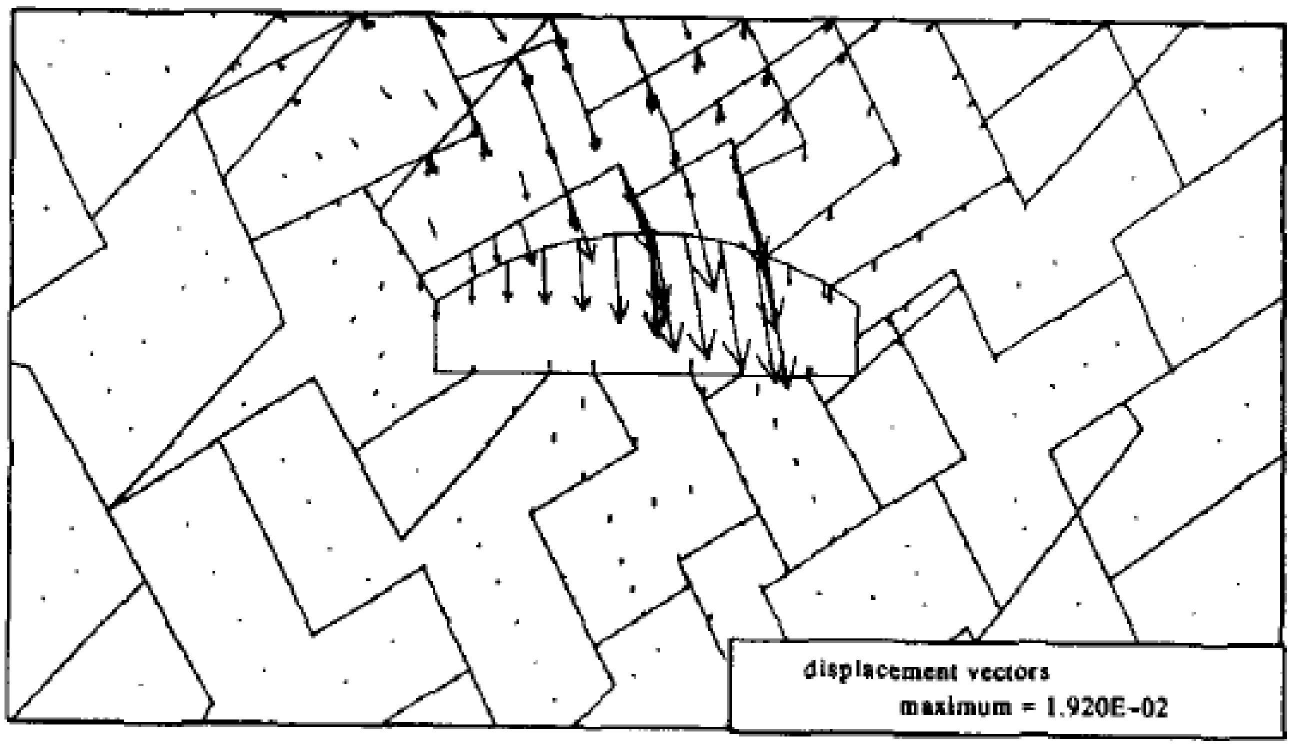


수직 변위 그래프

- **10년 후**
  - 간극 수압 : 약 **12 MPa**
  - 수직 변위 : 약 **0.87 m**

Lee JW, Min KB, Rutqvist J, Probabilistic Analysis of Fracture Reactivation Associated with Deep Underground CO_2 injection, Rock Mechanics and Rock engineering, 2013, 46(8):801-820.

- Underground ice hockey stadium in Norway – discontinuum method was used for design



Barton, N., et al. (1994). "Predicted and measured performance of the 62 m span Norwegian olympic ice Hockey Cavern at Gjøvik." International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 31(6): 617-641.

Numerical Approach in Rock Engineering
Discontinuum – Blocky DEM (M analysis)

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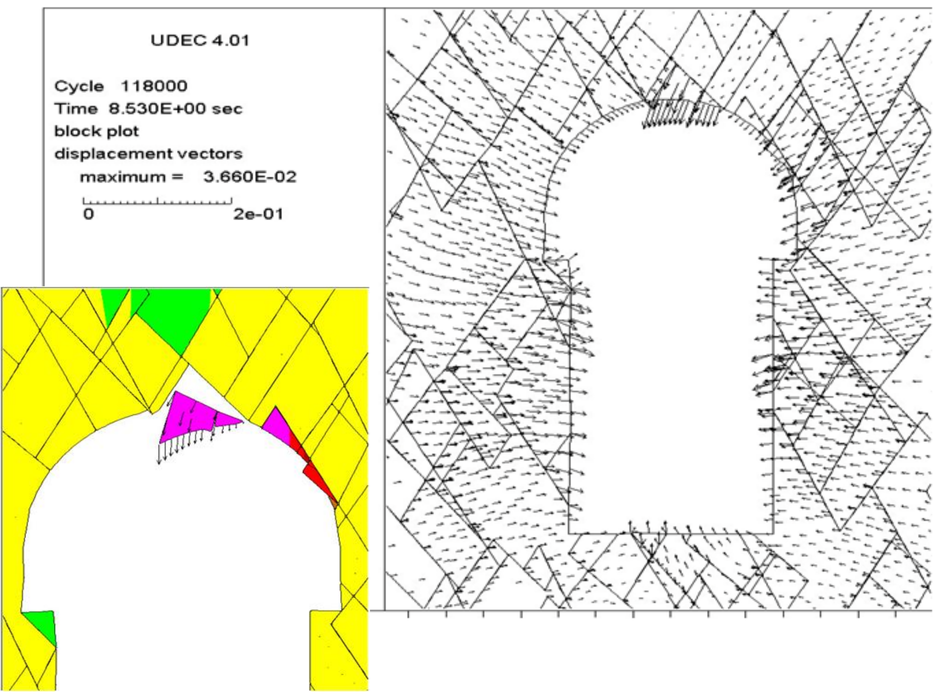
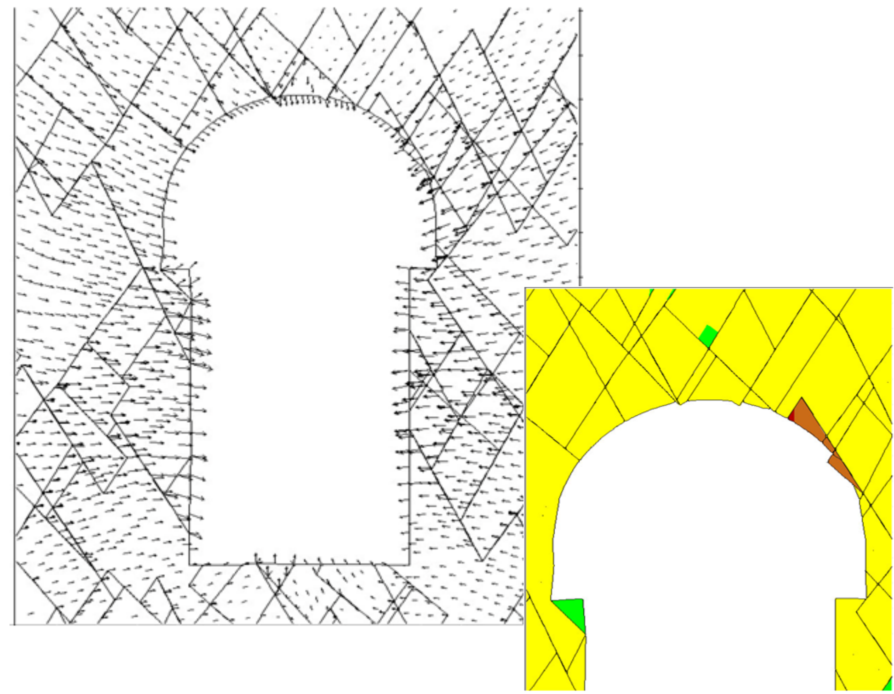


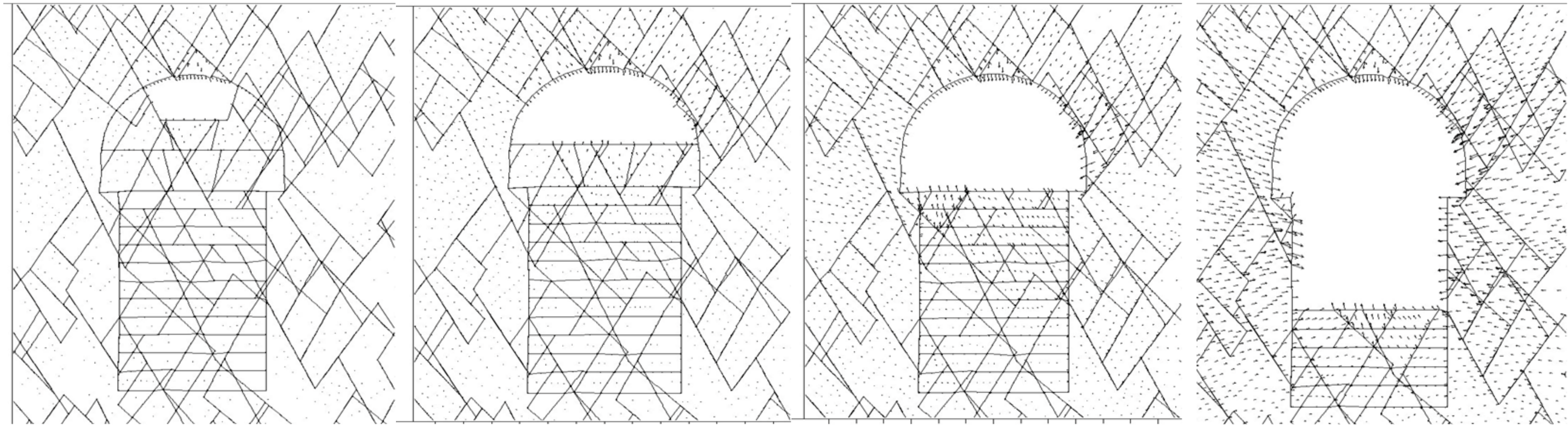
절리면 마찰각 25도

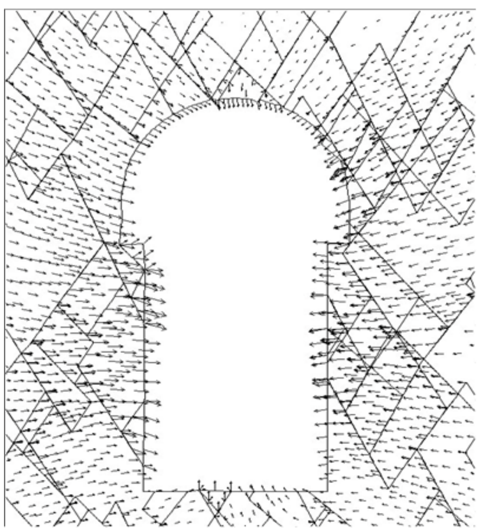


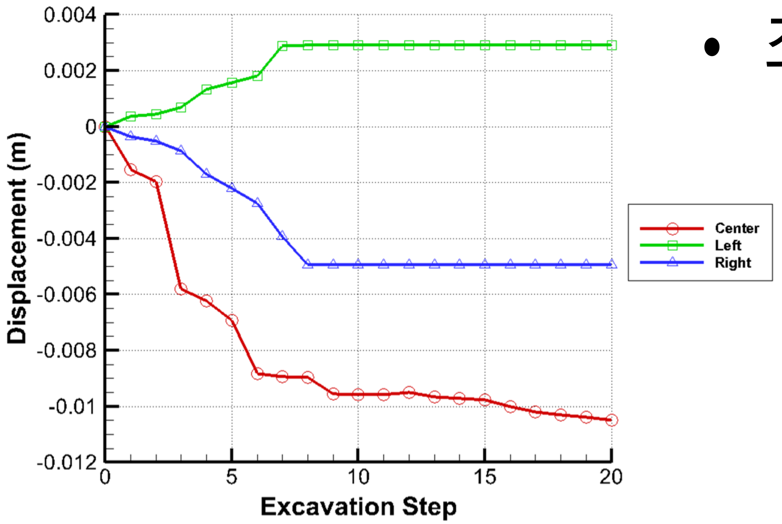
절리면 마찰각 35도

Min KB, Lee JW et al., 2011, Unpublished report

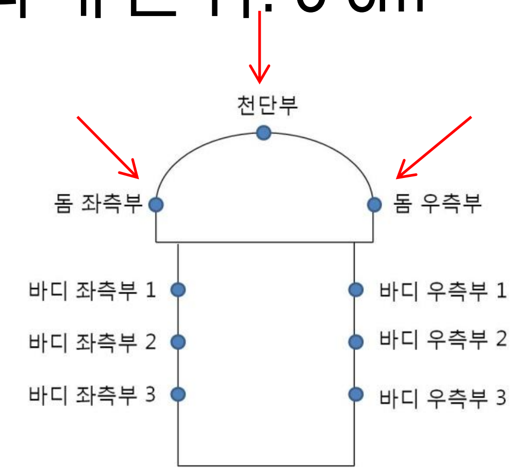
Numerical Approach in Rock Engineering
Discontinuum – Blocky DEM (M analysis)







- 최대변위: 3 cm



Min KB, Lee JW et al., 2011, Unpublished report

Numerical Approach in Rock Engineering
Discontinuum – Blocky DEM (TM analysis)

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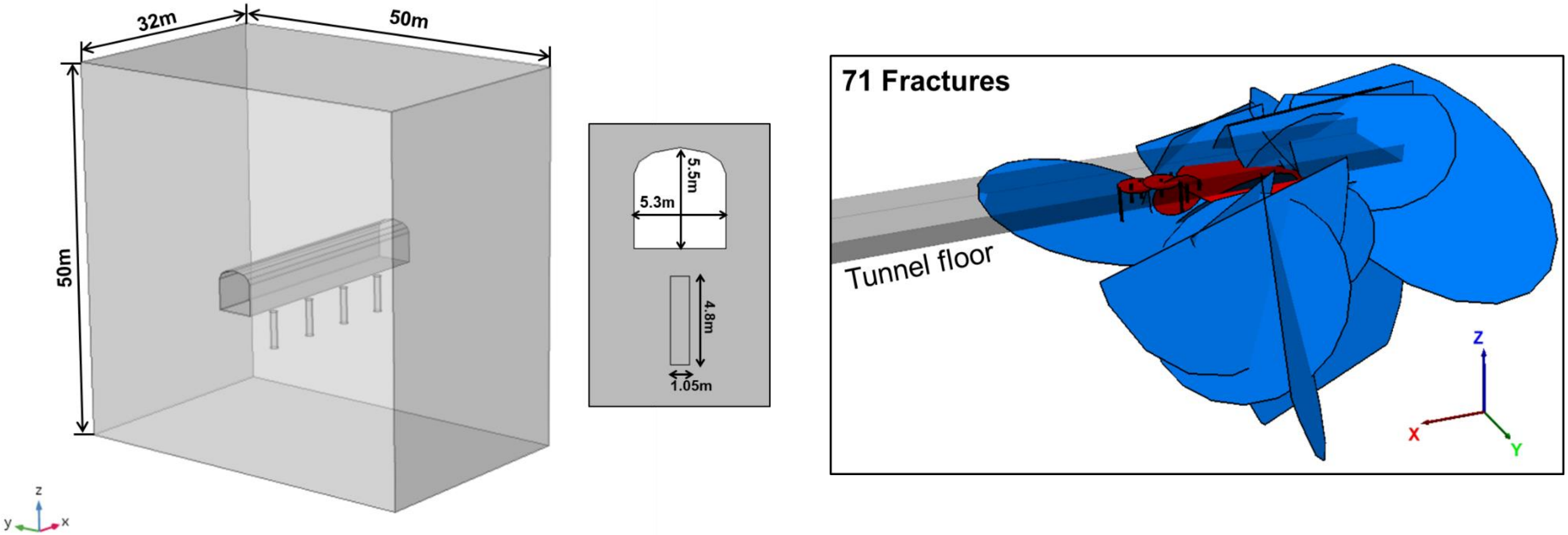
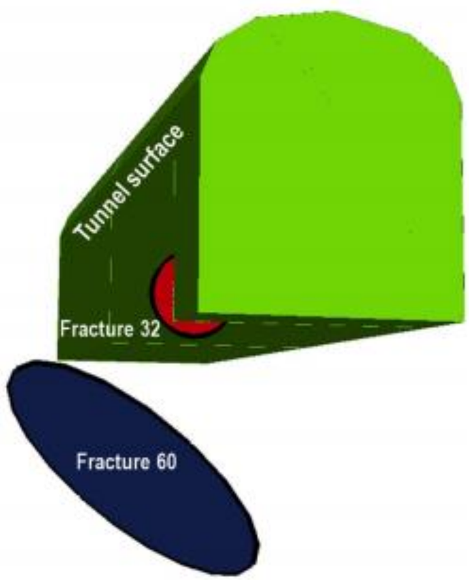
- Geometry and fractures (Kwon and Min, 2020)

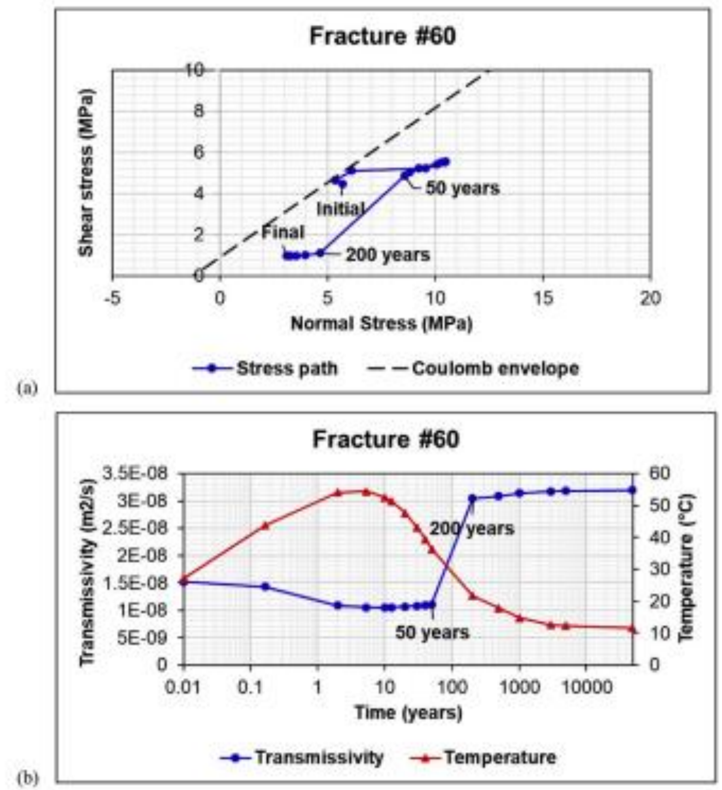


Kwon S, Min KB*, Fracture Transmissivity Evolution around the Geological Repository of nuclear waste caused by Excavation Damage Zone, Thermoshearing and Glaciation, Int J Rock Mech Min Sci 2020, 137:104554

Numerical Approach in Rock Engineering
Discontinuum – Blocky DEM (TM analysis)

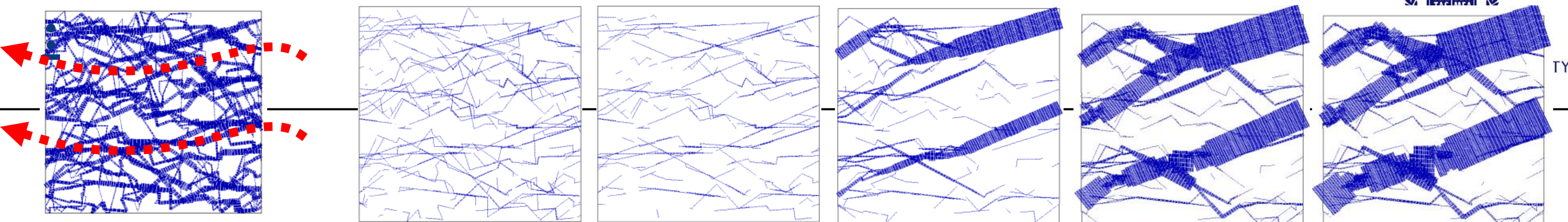
- Stress path during thermal loading (Shear dilation)
  - <u>Irreversible change </u>by shear dilation
  - Effects of shear dilation could be more significant after the dissipation of heat (normal closure)



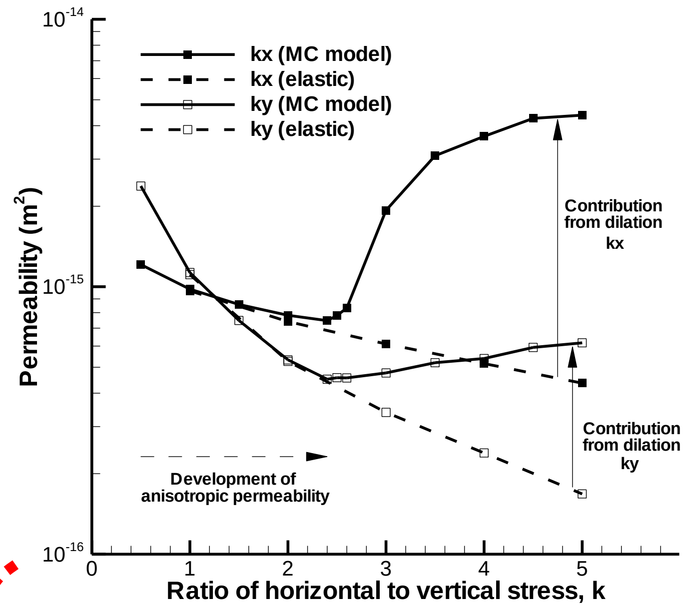


Kwon S, Min KB*, Fracture Transmissivity Evolution around the Geological Repository of nuclear waste caused by Excavation Damage Zone, Thermoshearing and Glaciation, Int J Rock Mech Min Sci 2020, 137:104554

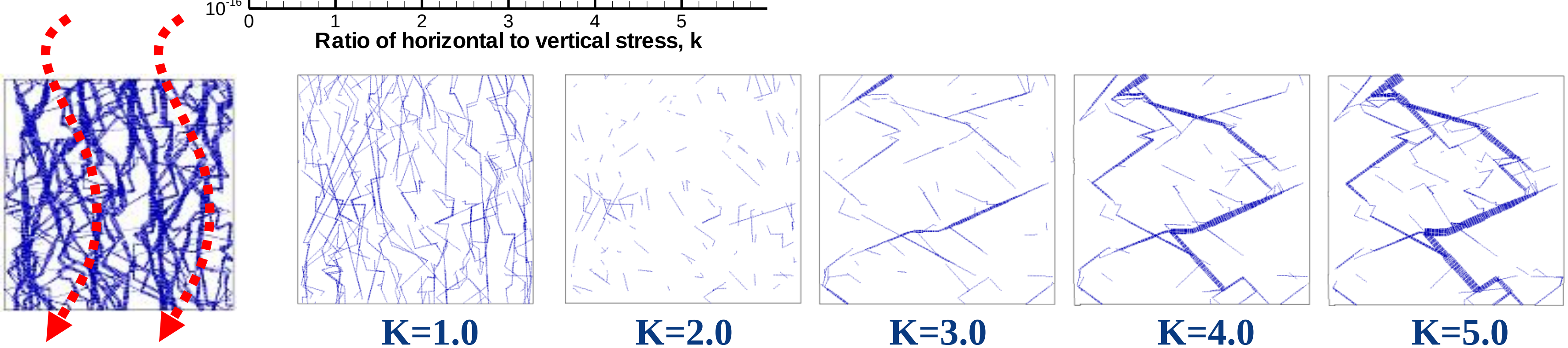
Flowrates



Zero stress | K=1.0 | K=2.0 | K=3.0 | K=4.0 | K=5.0



- Shear induced permeability increase
- This partly explains why fluid flow in a few fractures are dominating the fluid behaviour



K=1.0 | K=2.0 | K=3.0 | K=4.0 | K=5.0

Min, Rutqvist, Tsang, & Jing (2004). "Stress-dependent permeability of fractured rock masses: a numerical study." International Journal of Rock Mechanics and Mining Sciences 41(7): 1191-1210.

Numerical Approach in Rock Engineering
Discontinuum – Bonded Particle DEM (M analysis)

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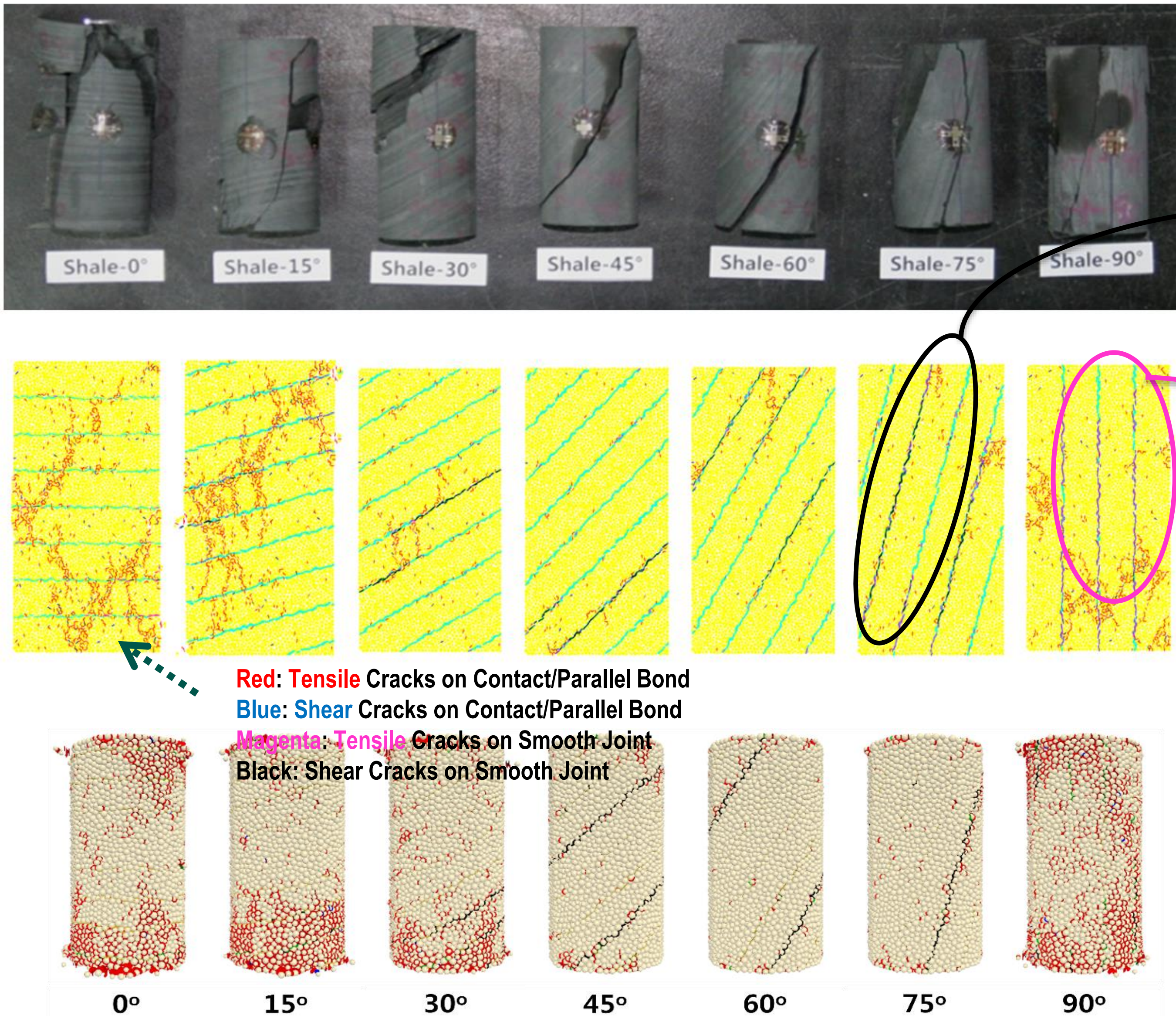

Shear Failure along the Weak Planes

Tensile Failure along the Weak Planes

Park, B. and Min, K.B., 2015, Bonded-Particle Discrete Element Modeling of Mechanical Behavior of Transversely Isotropic Rock, IJRMMS, Int J Rock Mech Min Sci 76: 243-255
Park B, Min KB*, Thompson N, Horsrud P, Three-dimensional bonded-particle discrete element modeling of mechanical behavior of transversely isotropic rock, Int J Rock Mech Min Sci, 2018, 110:120-132

Numerical Approach in Rock Engineering
Discontinuum – Bonded Particle DEM (M analysis)

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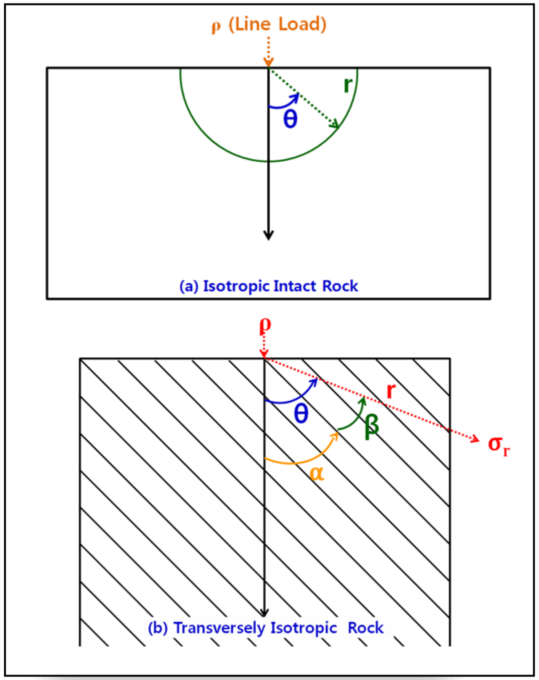
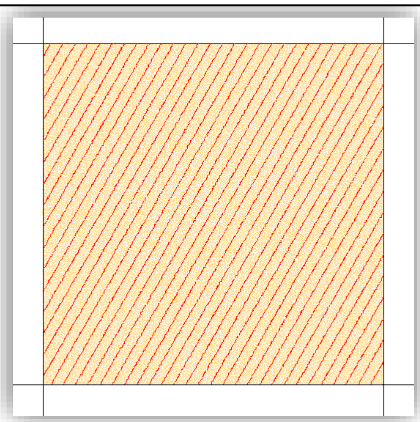
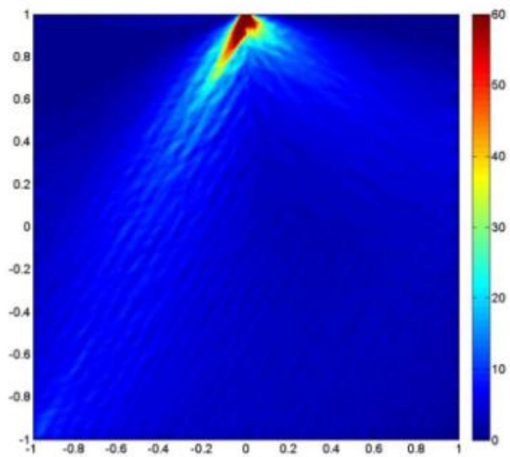
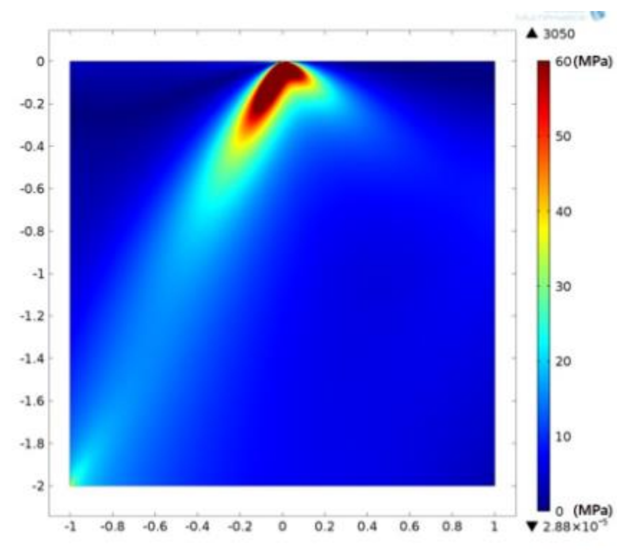






Discontinuum



Continuum

Park, B. and Min, K.B., 2015, Bonded-Particle Discrete Element Modeling of Mechanical Behavior of Transversely Isotropic Rock, IJRMMS, International Journal of Rock Mechanics and Mining Sciences 76: 243-255.

Numerical Approach in Rock Engineering
Discontinuum – Bonded Particle DEM (M analysis)

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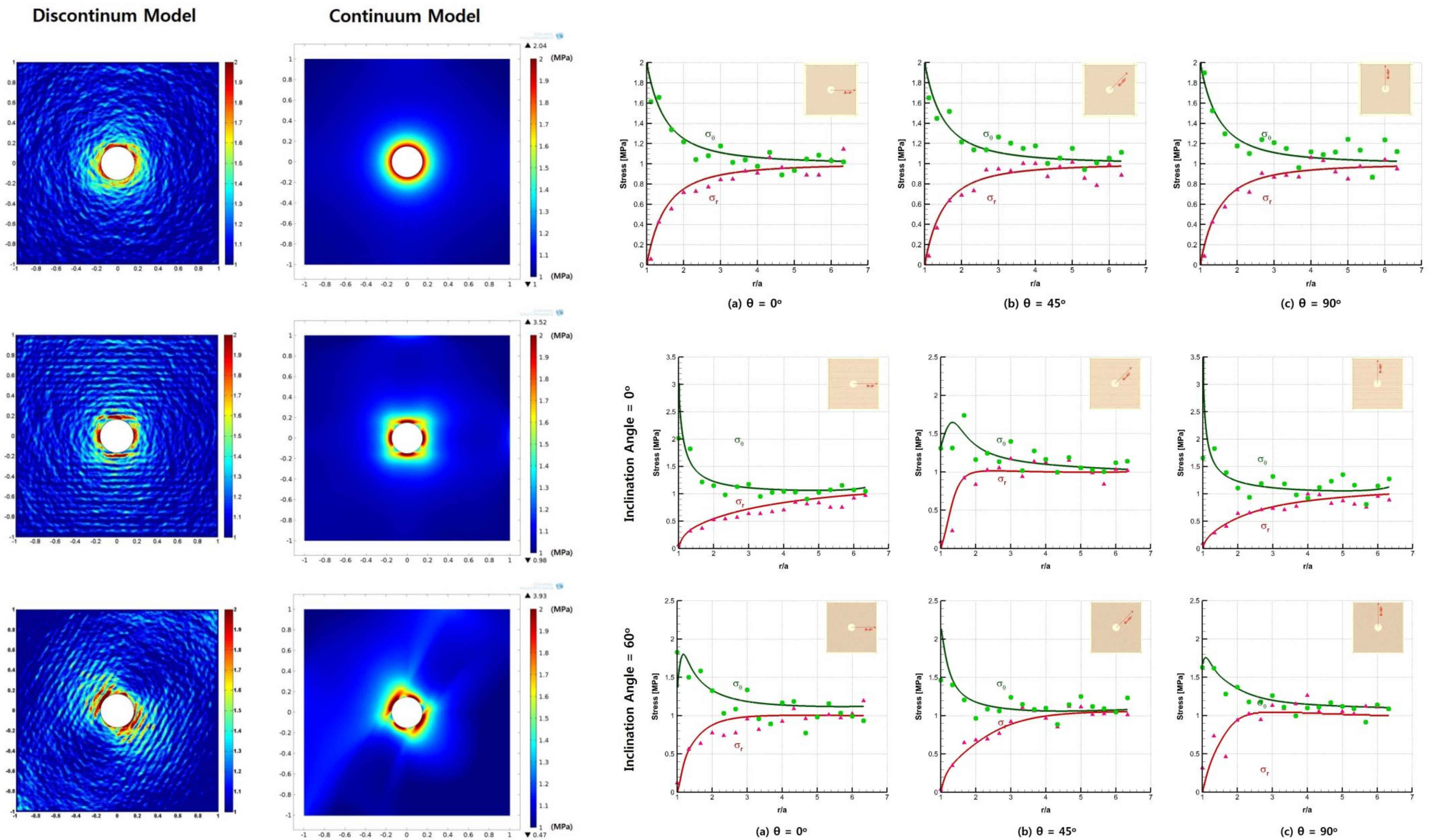
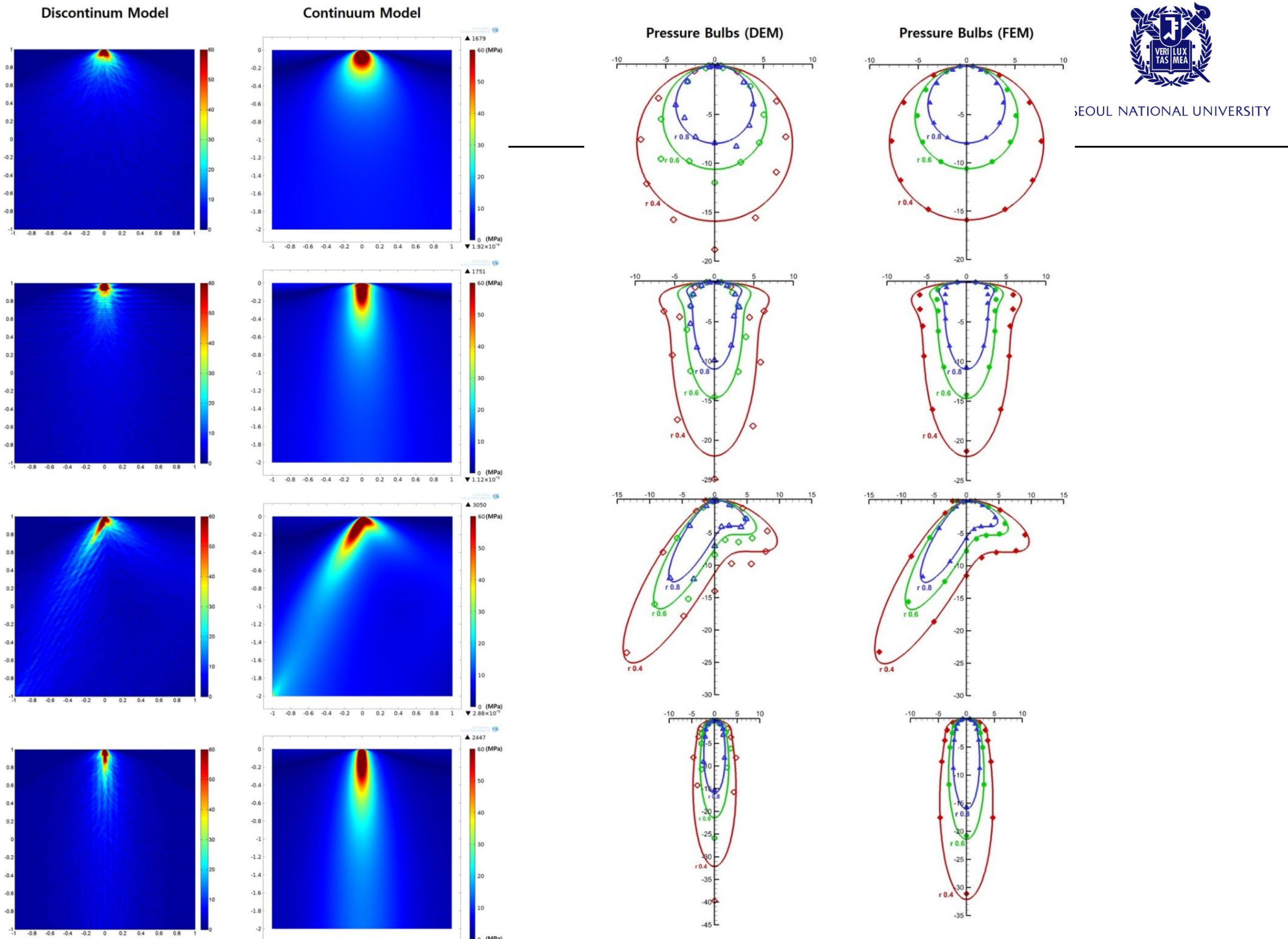


Park, B. and Min, K.B., 2015, Discrete element modeling of transversely isotropic rock applied to foundation and borehole problems, 13rd ISRM Congress, Vancouver, Canada, Paper No.843



Park, B. and Min, K.B., 2015, Bonded-Particle Discrete Element Modeling of Mechanical Behavior of Transversely Isotropic Rock, IJRMMS, International Journal of Rock Mechanics and Mining Sciences 76: 243-255.

Numerical Approach in Rock Engineering
Discontinuum – Code coupling THM analysis

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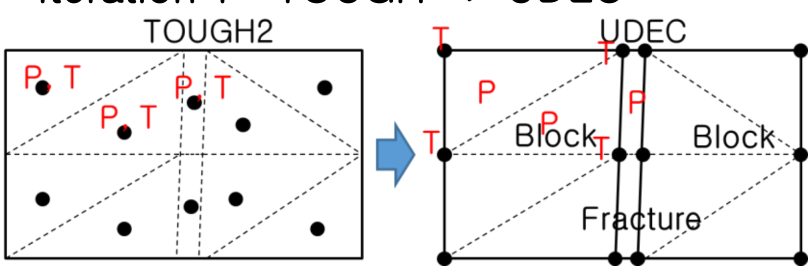
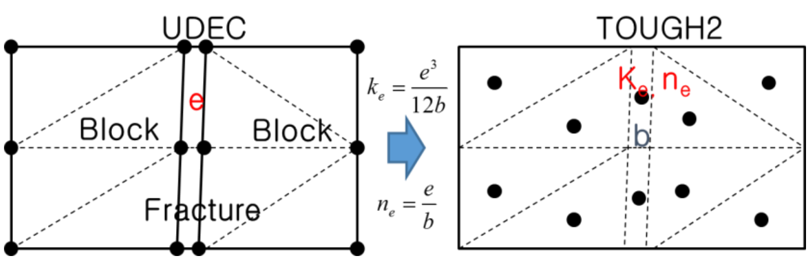
- TOUGH-UDEC Simulator

TOUGH analysis	Iteration 1 → / ← Iteration 2	UDEC analysis
- IFDM method - Heat transfer and multiphase, multicomponent fluid flow - No mechanical processes		- DEM - Mechanical and thermal behavior of solid medium - Fluid only through fractures

- Iteration 1 : TOUGH -> UDEC

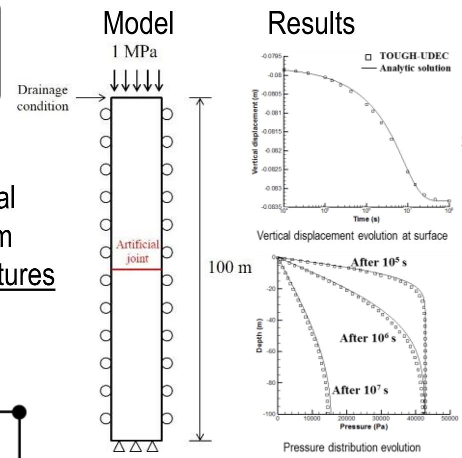


- Iteration 2 : UDEC -> TOUGH

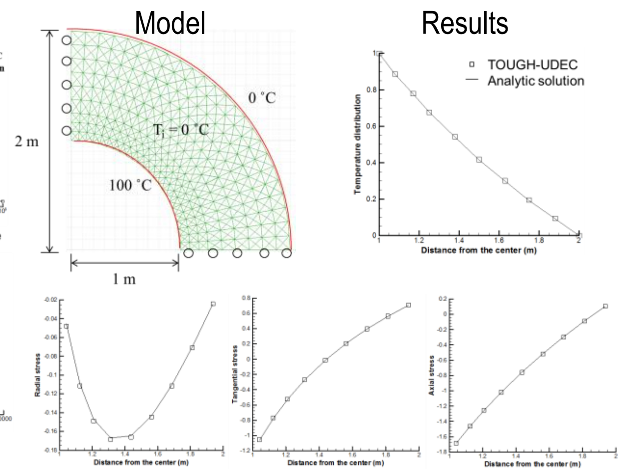


- Verifcation (Lee et al., 2018)

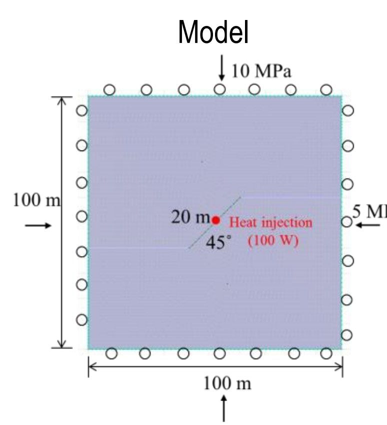
1) 1D consolidation

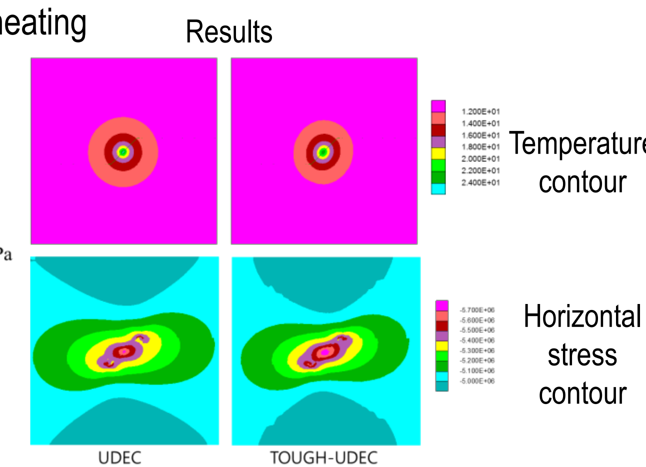


2) Heating of a hollow cylinder



3) Stress change due to heating





Lee J, Kim KI, Min KB*, Rutqvist J, 2019, TOUGH-UDEC Simulator for Coupled Multiphase Fluid Flows, Heat Transfers and Discontinuous Deformations in Fractured Porous Media, Computers and Geosciences, 126:120-130

Numerical Approach in Rock Engineering
Discontinuum – Code coupling THM analysis

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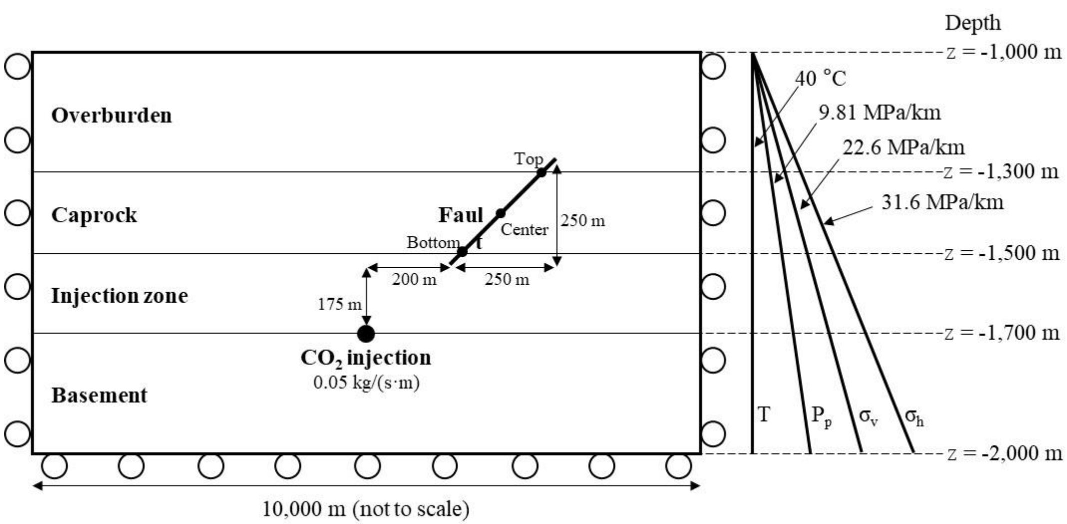
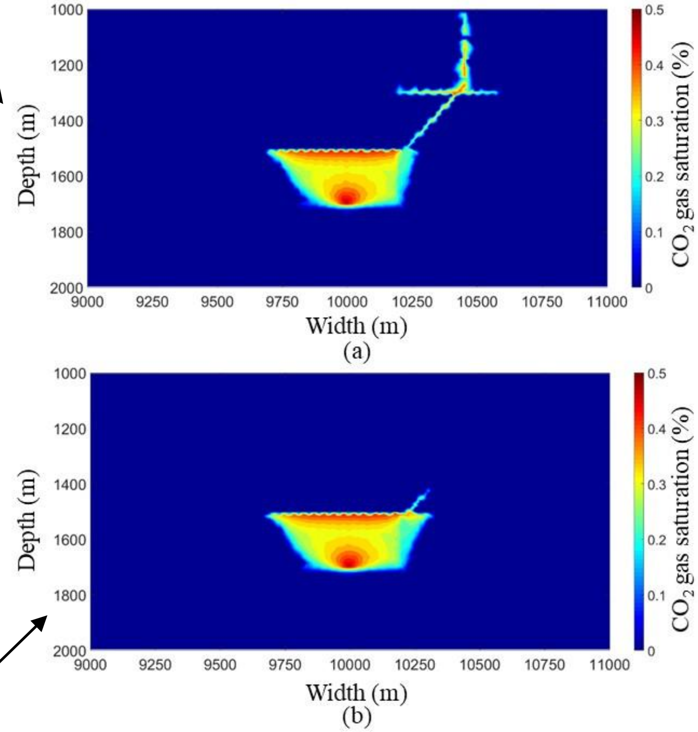
- Geometry and slip modeling



Case 1
(lower friction angle)



Case 2
(higher joint friction angle)

Lee J, Kim KI, Min KB*, Rutqvist J, 2019, TOUGH-UDEC Simulator for Coupled Multiphase Fluid Flows, Heat Transfers and Discontinuous Deformations in Fractured Porous Media, Computers and Geosciences, 126:120-130

Numerical Approach in Rock Engineering
Concluding remark

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- Numerical method is a indispensable part of engineering analysis – needs a thorough understanding
- Numerical method has a unique role that other analytical or experimental methods cannot play.
- Thorough understanding on the principle of numerical method is prerequisite in the analysis using them
- However, we must bear in mind that numerical methods is only a means not the answer itself.
  - Garbage in, garbage out - The results is only as good as the data
  - A model is an aid to thought, rather than a substitute for thinking
  - Plan the modeling exercise in the same way as you would plan a laboratory experiment

References

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- Starfield, A.M. and P.A. Cundall, 1988, *TOWARDS A METHODOLOGY FOR ROCK MECHANICS MODELING.* Int J Rock Mech Min Sci & Geomech Abstr, **25**(3): p. 99-106 – highly recommended.
- Cundall PA, 2000, A Discontinuous Future for Numerical Modelling in Geomechanics?, *Geotech Eng*, 149(1):41-47 – importance of DEM modeling
- Fairhurst, C., 1994, *Analysis and design in rock mechanics - The general context*. Comprehensive Rock Engineering, ed. J.A. Hudson. Vol. 2., Pergamon: Oxford. 1-29.
- Konietzky, 2021, Ch.9 Practical hints for using numerical methods in rock mechanics, Introduction into geomechanics, https://tu-freiberg.de/sites/default/files/media/professur-felsmechanik-32204/E-book/09_practical_hints_for_using_numerical_methods_in_rock_mechanics_1.pdf
- Oreskes, N., K. Shrader-Frechette and K. Belitz., 1994, Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences, *Science*, ***263***, 641-646 – highly critical in predictive ability of numerical modeling