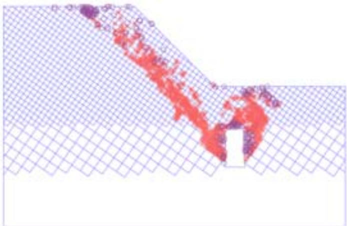
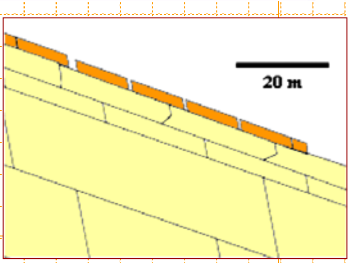


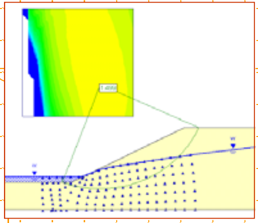
EOSC433:

Geotechnical Engineering
Practice & Design

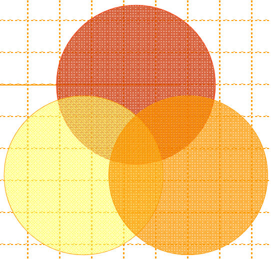
Lecture 11:
Discontinuum Analysis & the Distinct-Element Method

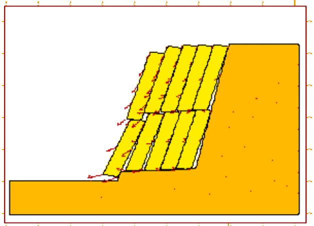


Analysis in Geotechnical Engineering

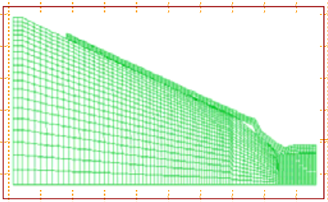


LIMIT EQUILIBRIUM
(infinite slope,
method of slices, etc.)

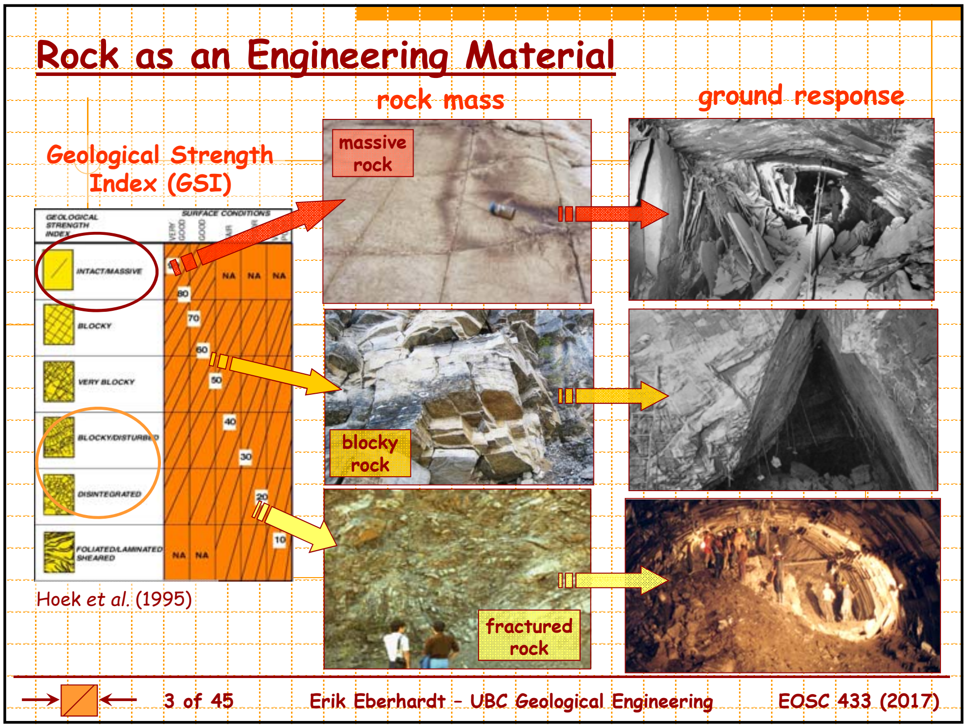




DISCONTINUUM
(distinct element, etc.)



CONTINUUM
(finite element,
finite difference, etc.)



Rock as an Engineering Material

rock mass

ground response

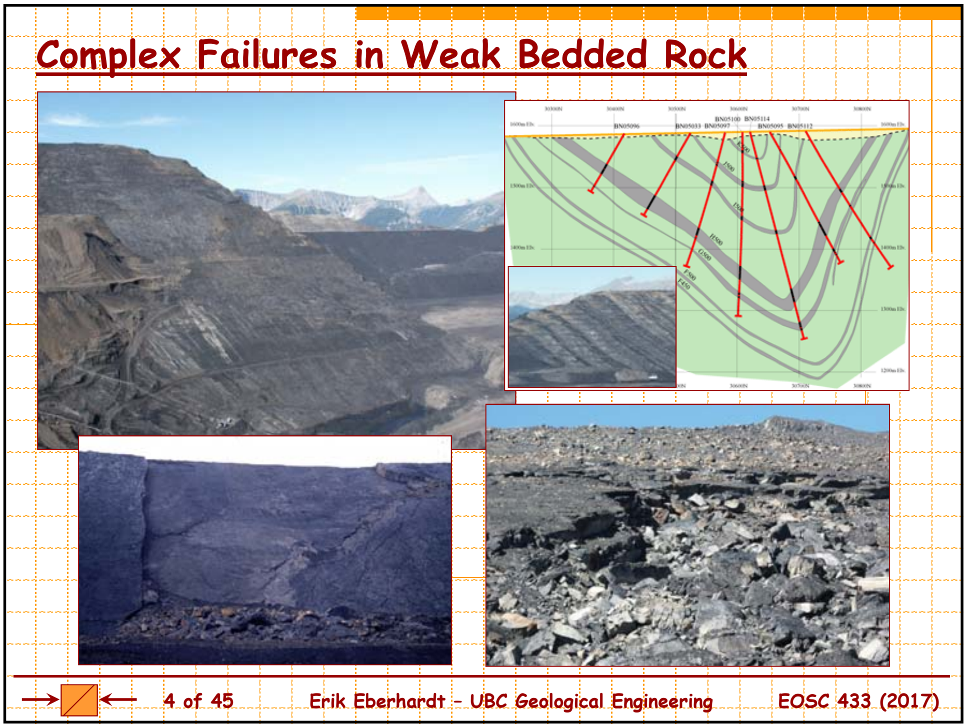
Geological Strength Index (GSI)

Hoek *et al.* (1995)

massive rock

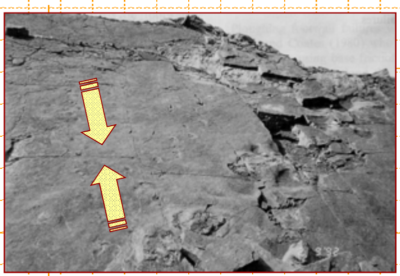
blocky rock

fractured rock

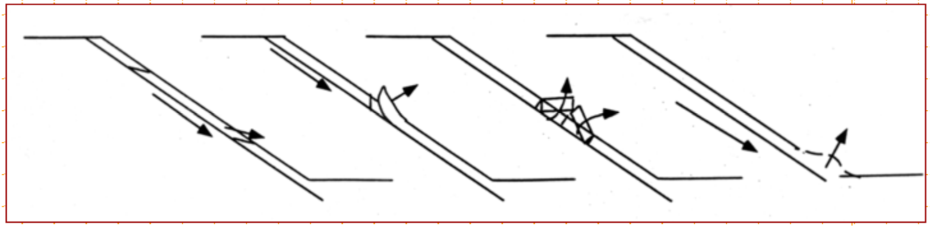


Complex Failures in Weak Bedded Rock

Complex Failures in Weak Bedded Rock



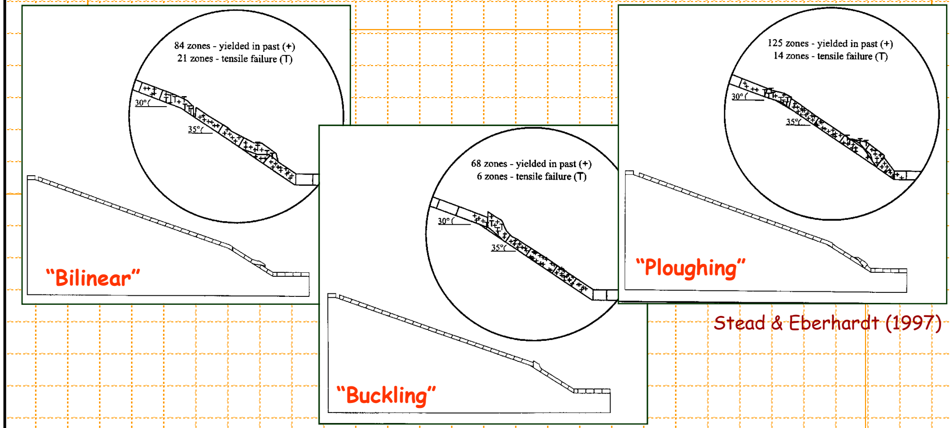
… cross joints can be extremely tight and go undetected due to the large driving forces acting across the joint surfaces; yet at the same time, they have a significant control on the failure mechanism of bedded dip slopes.



Stead & Eberhardt (1997)

Complex Failures in Weak Bedded Rock

Discontinuum analysis!



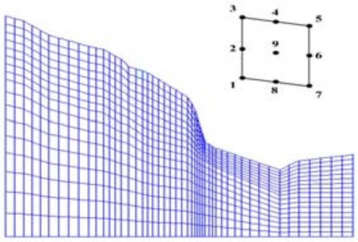
Stead & Eberhardt (1997)

Distinct-element "discontinuum" modelling of the influence of cross-bedding on failure mode. Note that the complexity of these different failure modes involves both slip along the controlling discontinuities and yielding of the intact rock material.

Numerical Analysis – Differential Methods

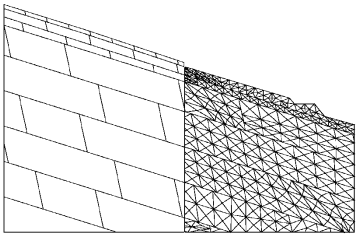
Continuum Methods

- ✓ Rock/soil mass behaviour represented as a continuum.
- ✓ Procedure exploits approximations to the connectivity of elements, and continuity of displacements and stresses between elements.

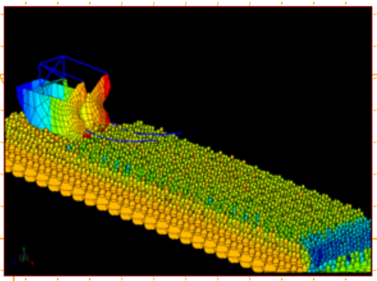


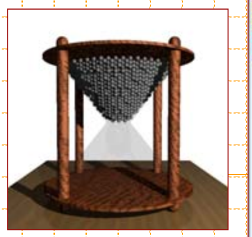
Discontinuum Methods

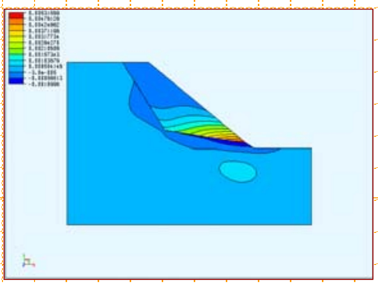
- ✓ Rock mass represented as a assemblage of distinct interacting blocks or bodies.
- ✓ Blocks are subdivided into a deformable finite-difference mesh which follows linear or non-linear stress-strain laws.

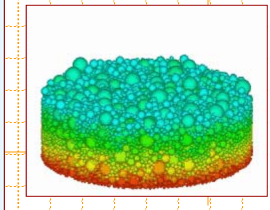


Discontinuum Methods









Numerical Analysis – Differential Methods

Analysis Method	Critical Parameters	Advantages	Limitations
Continuum Modelling (e.g. finite-element, finite-difference)	Representative slope geometry; constitutive criteria (e.g. elastic, elasto-plastic, creep, etc.); groundwater characteristics; shear strength of surfaces; *in situ* stress state.	Allows for material deformation and failure (factor of safety concepts incorporated); can model complex behaviour and mechanisms; 3-D capabilities; can model effects of pore pressures, creep deformation and/or dynamic loading; able to assess effects of parameter variations; computer hardware advances allow complex models to be solved with reasonable run times.	Users must be well trained, experienced and observe good modelling practice; need to be aware of model and software limitations (e.g. boundary effects, meshing errors, hardware memory and time restrictions); availability of input data generally poor; required input parameters not routinely measured; inability to model effects of highly jointed rock; can be difficult to perform sensitivity analysis due to run time constraints.
Discontinuum Modelling (e.g. distinct-element, discrete-element)	Representative slope and discontinuity geometry; intact constitutive criteria; discontinuity stiffness and shear strength; groundwater characteristics; in situ stress state.	Allows for block deformation and movement of blocks relative to each other; can model complex behaviour and mechanisms (combined material and discontinuity behaviour coupled with hydro-mechanical and dynamic analysis); able to assess effects of parameter variations on instability.	As above, user required to observe good modelling practice; general limitations similar to those listed above; need to be aware of scale effects; need to simulate representative discontinuity geometry (spacing, persistence, etc.); limited data on joint properties available (e.g. jk_n, jk_s).

Coggan *et al.* (1998)

Discontinuum Methods

A class of numerical techniques collectively described as <u>discrete element</u> codes provides the capability to represent the motion of multiple, intersecting bodies. This requires an efficient algorithm for detecting and classifying contacts:

Distinct-Element – uses an explicit time-marching scheme to solve the equations of motion directly for a system of rigid or deformable bodies; contacts are deformable.

Discontinuous-Deformation – assumes contacts between deformable bodies are themselves smaller rigid bodies.

Momentum-Exchange – assumes both contacts and bodies are rigid, with momentum being exchanged between two contacting bodies during an instantaneous collision.

UDEC – <u>U</u>niversal <u>D</u>istinct <u>E</u>lement <u>C</u>ode (by Itasca)

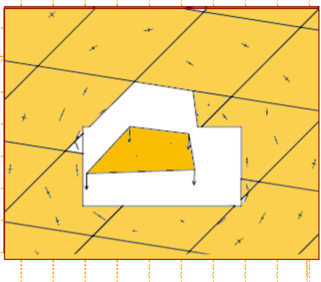
distinct-element

Distinct-Element Method

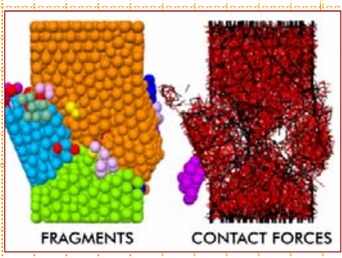
Discontinuum methods treat the problem domain as an assemblage of distinct, interacting blocks that are subjected to external loads and are expected to undergo significant motion with time.

The distinct-element method utilizes a calculation procedure that solves the equations of motion and contact force for an assemblage of deformable blocks or rigid particles. In the case of the latter, these are known as "particle flow codes".

Deformable Block Codes (e.g. UDEC)



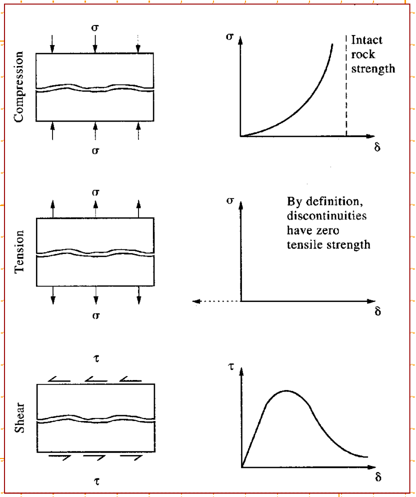
Particle Flow Codes (e.g. PFC)



Mechanical Properties of Discontinuities

The mechanical behaviour of discontinuities is generally plotted in the form of stress-displacement curves, with the result that we can measure discontinuity stiffness (typically expressed in units of MPa/m) and strength.

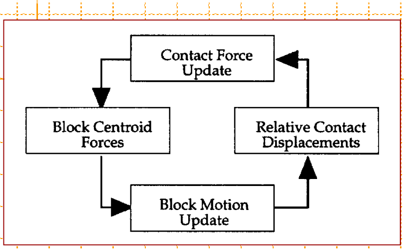
In compression, the rock surfaces are gradually pushed together, with an obvious limit when the two surfaces are closed. In tension, by definition, discontinuities can sustain no load. In shear, the stress-displacement curve looks like that for compression of intact rock, except of course failure is localized along the discontinuity.

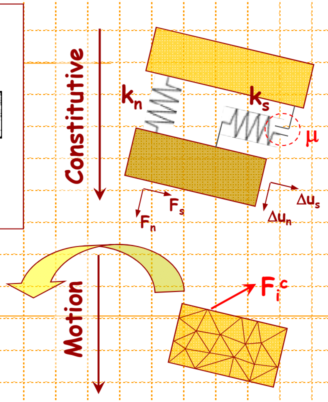


Hudson & Harrison (1997)

Distinct-Element Method

The underlying basis of the distinct-element method is that the dynamic equation of equilibrium for each block in the system is formulated and repeatedly solved until the boundary conditions and laws of contact and motion are satisfied. The method thus accounts for complex non-linear interaction phenomena between blocks.





All Contacts:

$F_n = F_n - k_n \Delta u_n$

$F_s = F_s - k_s \Delta u_s$

$F_s = \min\{\mu F_n, |F_s|\}$

Deformable Elements

Elements (Zones):

$\Delta\varepsilon_{ij} = \frac{1}{2}(d\mathring{u}_i/dx_j + d\mathring{u}_j/dx_i)\Delta t$

$\sigma_{ij} = C(\sigma_{ij}, \Delta\varepsilon_{ij}, \ldots)$

Gridpoints:

$F_i^e = \int_z \sigma_{in} n_j \, ds$

$F_i = F_i^e + F_i^c$

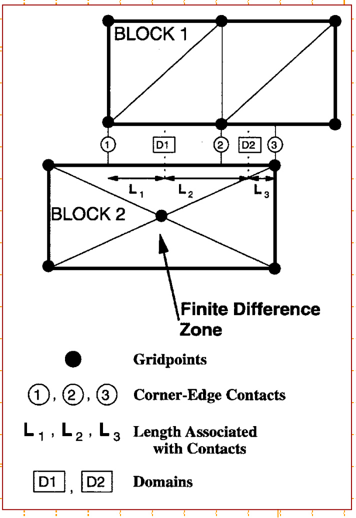
$\ddot{u}_i = F_i/m$

etc…

Distinct-Element Method

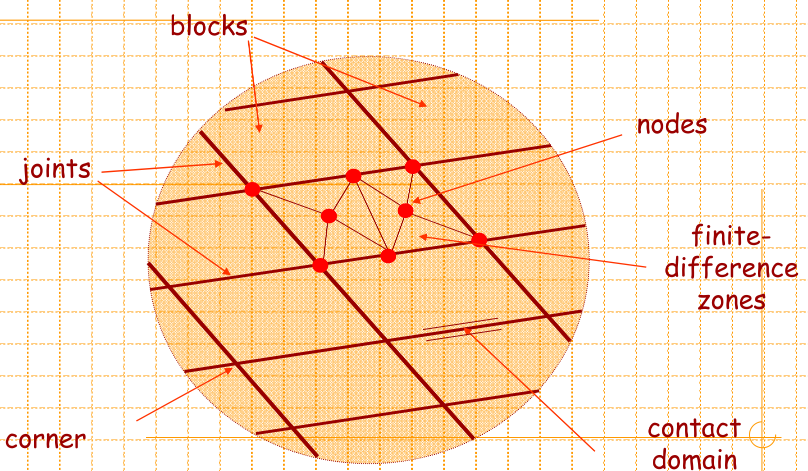
Joints are viewed as interfaces between the blocks and are treated as a boundary condition rather than a special element in the model. Block deformability is introduced through the discretization of the blocks into internal finite difference constant-strain elements.

The dual nature of the distinct-element method makes it particularly well suited to problems that involve jointed rock masses; it can simulate large displacements due to slip, or opening, along discontinuities, while at the same time model the deformation and material yielding of the joint-bounded intact rock blocks.

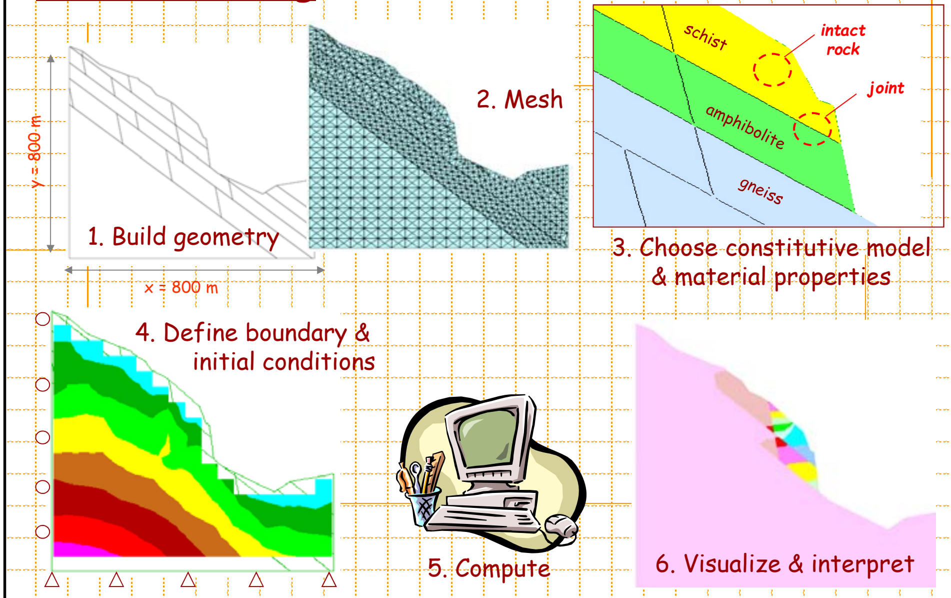


Hart (1993)

DEM Terminology



Problem Solving



1. Build geometry
2. Mesh
3. Choose constitutive model & material properties
4. Define boundary & initial conditions
5. Compute
6. Visualize & interpret

Problem Solving – Model Development

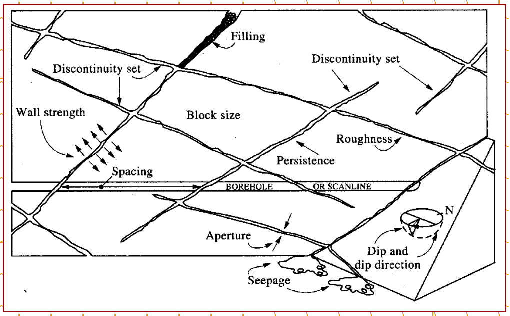
The level of detail included in a model often depends on the purpose of the analysis. Complicating features should be omitted if they are irrelevant or likely to have little influence on the model's response. It is therefore important to have a conceptual picture of the problem to provide an initial estimate of the expected behaviour under the imposed conditions.

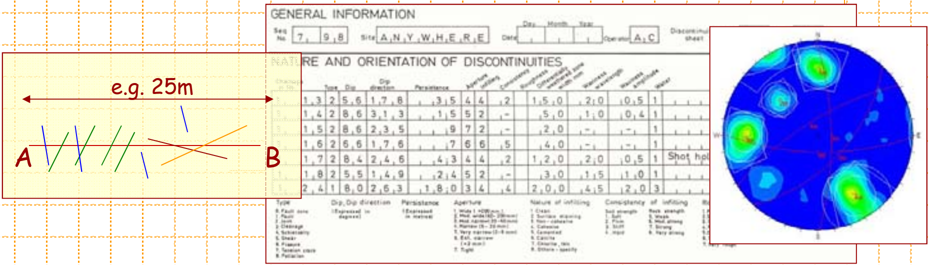
In constructing a distinct-element model, the advantages inherent in the methodology should be utilized. These include the consideration of:

- Geology (rock/soil/mixed)
- Discontinuities (spacing/persistence)
- Constitutive Criteria
- Material Properties (intact/discontinuity)
- Groundwater Pressures/Seismic Loading
- In Situ Stress and External Loads
- Deterministic/Probabilistic Analysis

Rock Mass Structure

The main features of rock mass geometry include spacing and frequency, orientation (dip direction/dip angle), persistence (size and shape), roughness, aperture, clustering and block size.





GENERAL INFORMATION

Seq No 7, 9,8 Site A,N,Y,W,H,E,R,E Date Day Month Year Operator A,C Discontinuity sheet

NATURE AND ORIENTATION OF DISCONTINUITIES

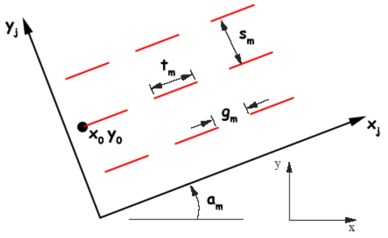
	Type	Dip	Dip direction	Persistence	Aperture	Infilling	Consistency	Roughness	Differentially weathered zone width mm	Waviness wavelength	Waviness amplitude	Water	
1,3	2	5,6	1,7,8	,3,5	4	4	,2		1,5,0	,2,0	,0,5	1	
1,4	2	8,6	3,1,3	,1,5	5	2	,-		,5,0	,1,0	,0,4	1	
1,5	2	8,6	2,3,5	,9	7	2	,-		,2,0	,-,	,-,	1	
1,6	2	6,6	1,7,6	,7	6	6	,5		,4,0	,-,	,-,	1	
1,7	2	8,4	2,4,6	,4,3	4	4	,2		1,2,0	,2,0	,0,5	1	Shot hol
1,8	2	5,5	1,4,9	,2,4	5	2	,-		,3,0	,1,5	,1,0	1	
2,4	1	8,0	2,6,3	,1,8,0	3	4	,4		2,0,0	,4,5	,2,0	3	

Type Dip, Dip direction Persistence Aperture Nature of infilling Consistency of infilling

UDEC – Problem Geometry

Joint geometry:

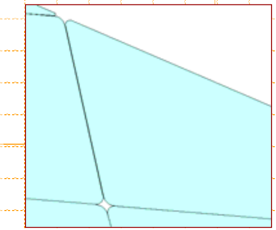
In UDEC, the problem geometry starts off as a block that encompasses the physical region being analyzed, which is then cut into smaller blocks whose boundaries represent joints and other types of discontinuities. The joint set generator in UDEC can be used to create a joint pattern, which is defined by different geometric properties (with a mean and standard deviation).



JSET a_m, a_d t_m, t_d g_m, g_d s_m, s_d x_0, y_0

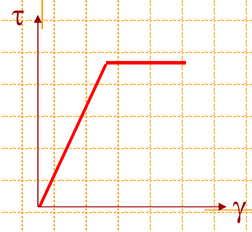
Rounding:

In a real rock mass, small sharp corners formed by intersecting joints will fracture due to high stress concentrations or be crushed during block movement. Since the modelled blocks in UDEC cannot fracture, they start off initially rounded to avoid the development of artificially high stresses.

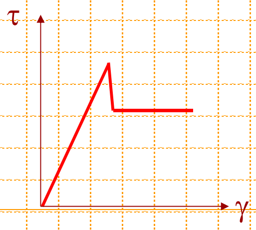


Joint Constitutive Models

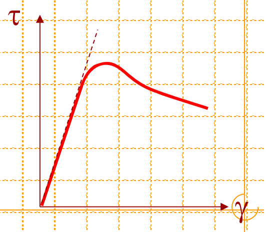
The joint area contact model is intended for closely-packed blocks and provides a linear representation of joint stiffness and yield limit (based upon elastic stiffness, friction, cohesion, tensile strength and dilation). The residual-strength version of this model simulates displacement-weakening of the joint by loss of frictional, cohesive and/or tensile strength at the onset of shear or tensile failure. The continuously yielding joint model simulates continuous weakening behavior as a function of accumulated plastic-shear displacement.



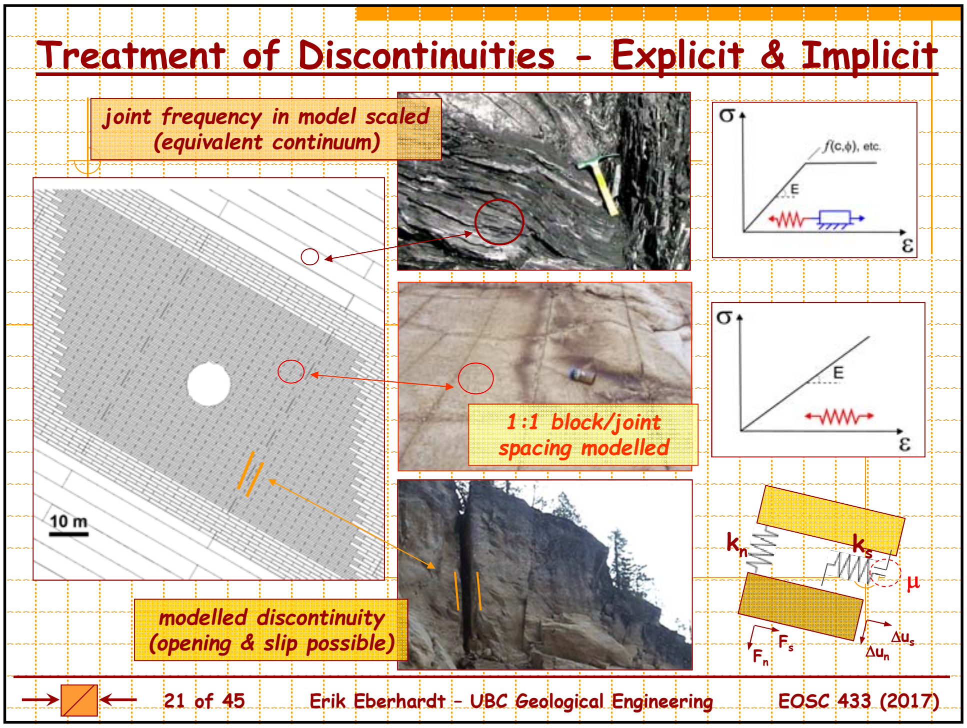
Coulomb slip



Coulomb slip with displacement weakening



Continuous yielding

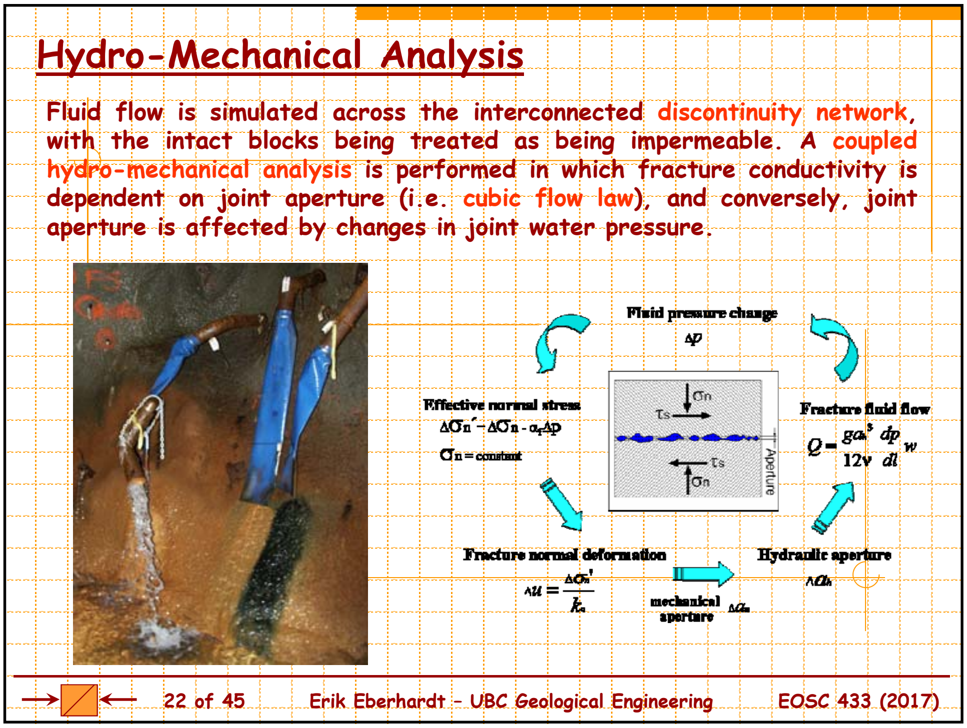


Treatment of Discontinuities - Explicit & Implicit

joint frequency in model scaled (equivalent continuum)

1:1 block/joint spacing modelled

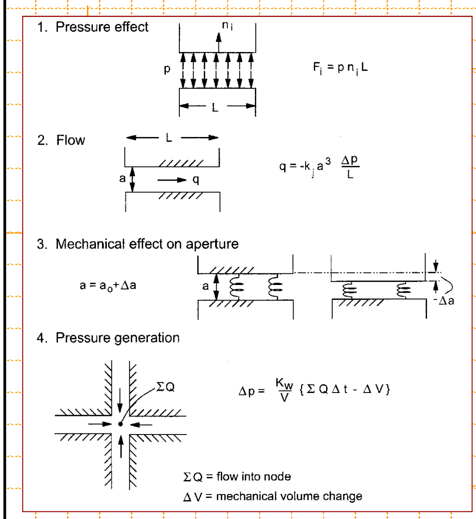
modelled discontinuity (opening & slip possible)



Hydro-Mechanical Analysis

Fluid flow is simulated across the interconnected discontinuity network, with the intact blocks being treated as being impermeable. A coupled hydro-mechanical analysis is performed in which fracture conductivity is dependent on joint aperture (i.e. cubic flow law), and conversely, joint aperture is affected by changes in joint water pressure.

Analysis of Joint Fluid Pressures

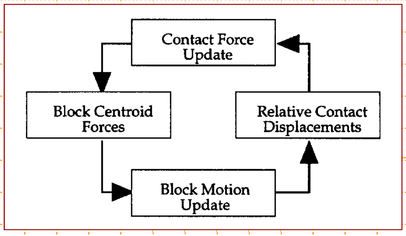


Fluid flow is simulated through a series of interconnected discontinuities, whereby the intact blocks are assumed to be impermeable. A coupled hydro-mechanical analysis is performed in which fracture conductivity is dependent on mechanical deformation and, conversely, joint water pressures affect the mechanical behaviour. Flow is then idealized along planar contacts where the rate of flow is assumed to be dependent upon the cubic power of the joint aperture (i.e. cubic flow law).

UDEC - Solving

Unbalanced Force:

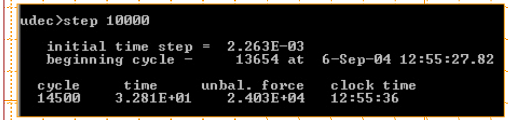
During timestepping, the *unbalanced force* is determined for the model; this indicates whether blocks in the model are moving or not, and is continuously updated on the screen. The unbalanced force is important in assessing the state of the model for static analysis. If the unbalanced forces decrease by 3-4 orders of magnitude, then the model is indicating that the problem is moving towards a stable equilibrium (i.e. any moving blocks are coming to rest). If the unbalanced force increases or remains the same, then the model is suggesting that blocks are moving or failing (i.e. yield).


Contact Force Update

Block Centroid Forces

Relative Contact Displacements

Block Motion Update

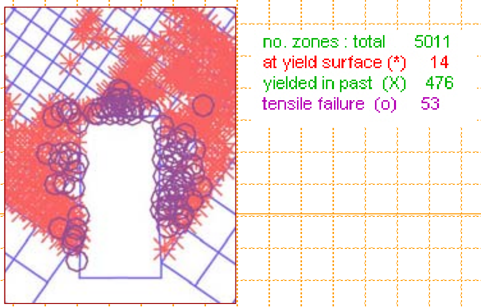


```
udec>step 10000

   initial time step =  2.263E-03
   beginning cycle -     13654 at  6-Sep-04 12:55:27.82

  cycle      time      unbal. force   clock time
  14500    3.281E+01    2.403E+04   12:55:36
```

Interpretation of Results

Plasticity Indicators:

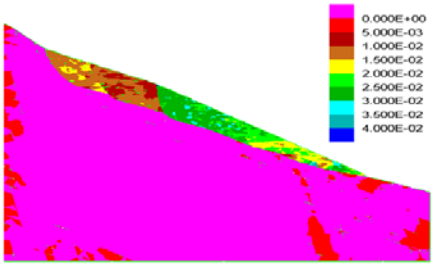
Plasticity indicators reveal those zones in which the stresses satisfy the yield criterion. A failure mechanism is indicated if there is a contiguous line of active plastic zones that join two surfaces. Note that initial plastic flow often occurs at the beginning of a simulation, but subsequent stress redistribution unloads the yielding elements so that their stresses no longer satisfy the yield criterion ("*yielded in past*"). Only the actively yielding elements ("*at yield surface*" and "*tensile failure*") are important to the detection of a failure mechanism.



Interpretation of Results

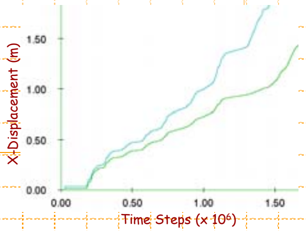
Block/Gridpoint Velocities:

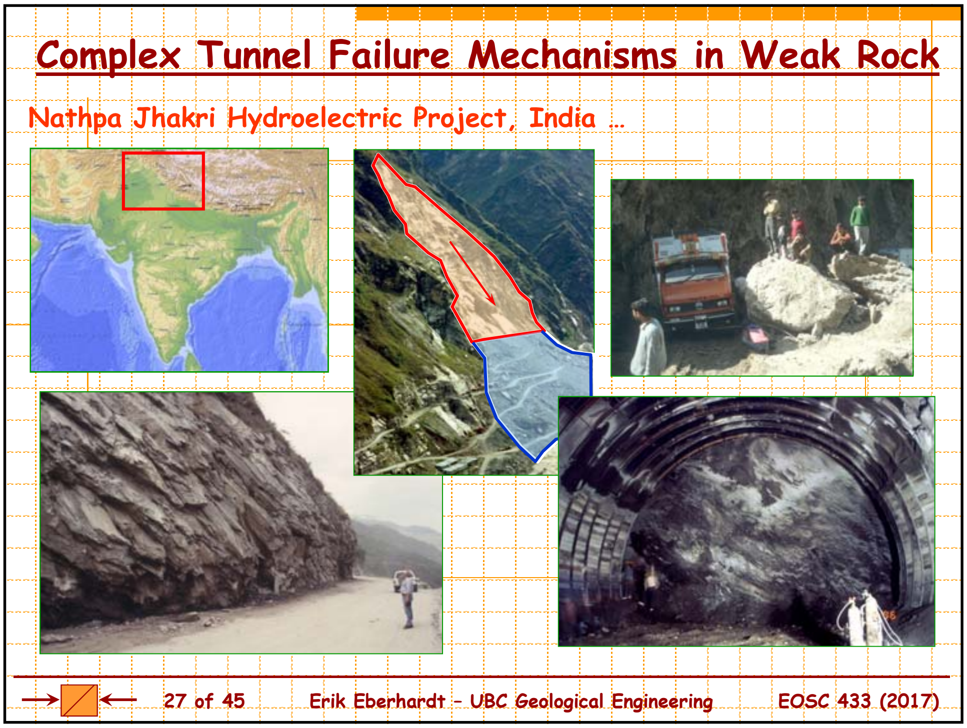
The velocities of deformable blocks may be assessed by plotting the whole field of velocities. Steady-state conditions are indicated if the velocities show near-zero values. If the velocities show high non-zero values, then either the block is falling, or steady plastic flow is occurring within the block.



Histories:

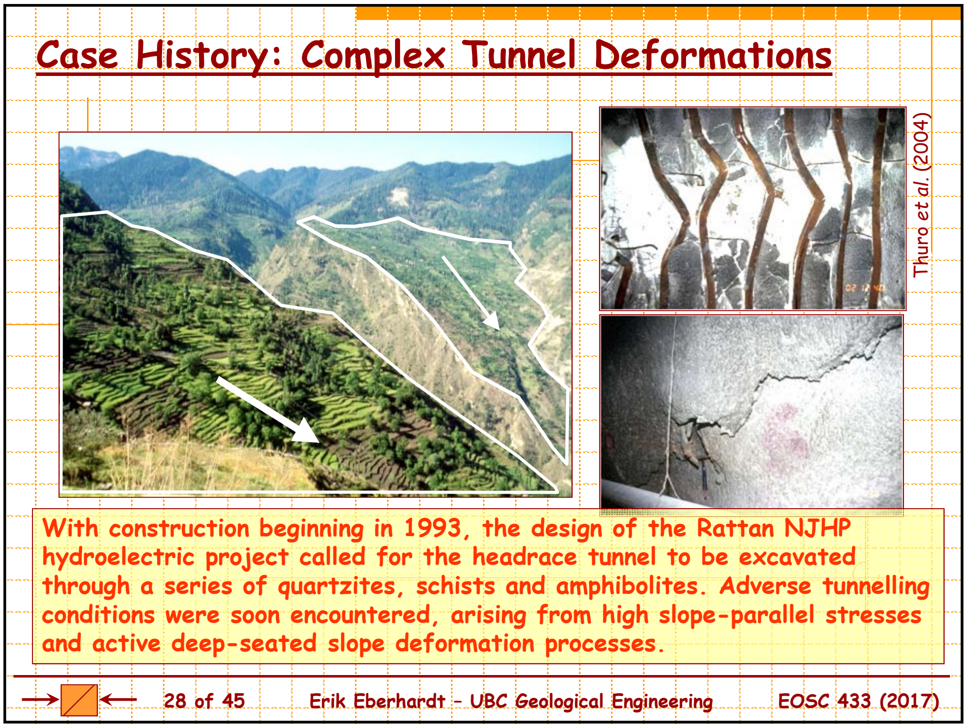
In any problem, there are certain variables that are of particular interest (e.g. displacements may be of concern in one problem, but stresses may be of concern in another). Liberal use should be made of the HIST command to track these important variables in the regions of interest. After some time-stepping has taken place, the plots of these histories often provide a means to find out what the system is doing.





Complex Tunnel Failure Mechanisms in Weak Rock

Nathpa Jhakri Hydroelectric Project, India …



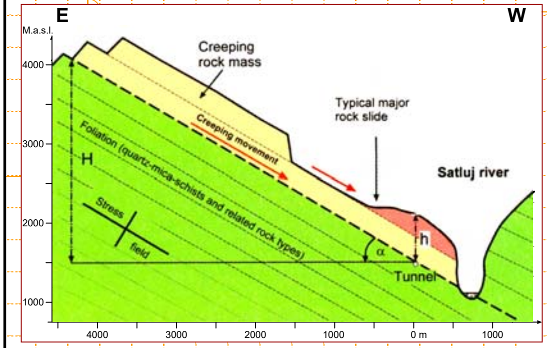
Case History: Complex Tunnel Deformations

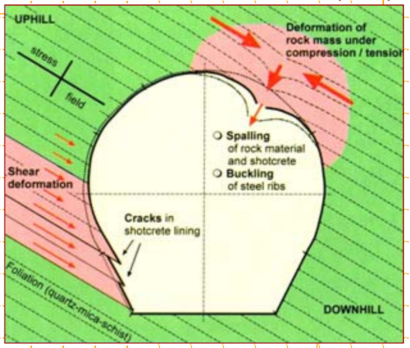
Thuro *et al.* (2004)

With construction beginning in 1993, the design of the Rattan NJHP hydroelectric project called for the headrace tunnel to be excavated through a series of quartzites, schists and amphibolites. Adverse tunnelling conditions were soon encountered, arising from high slope-parallel stresses and active deep-seated slope deformation processes.

Case History: Complex Tunnel Deformations

Thuro *et al.* (2004)





… the unfavourable orientation of the schistosity, relative to the slope-parallel major principal stress and deep-seated slope movements, led to numerous ground control issues in the headrace tunnel, resulting in costly delays, interference with construction logistics and potentially shortening the life span of the final structure.

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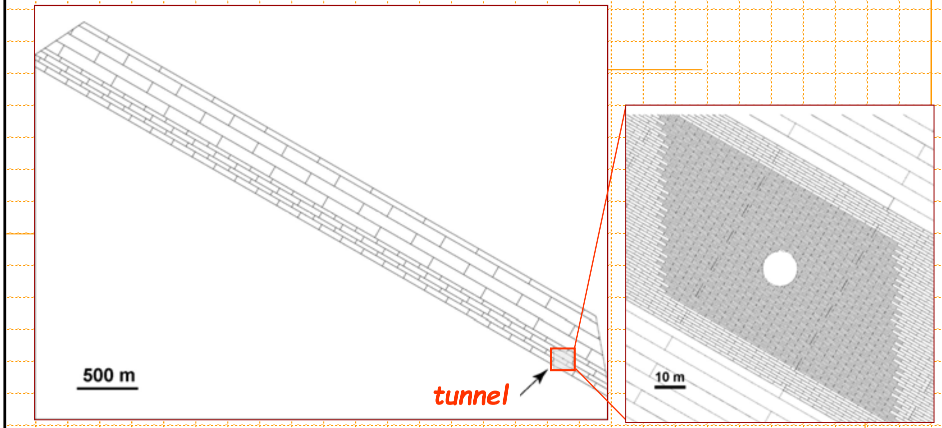
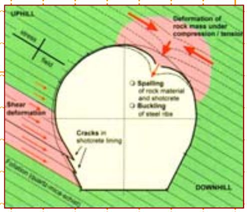
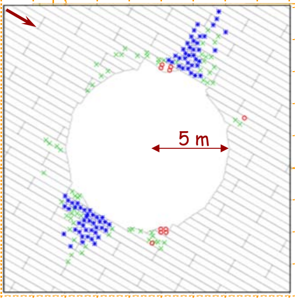


Distinct-element modelling was carried out to investigate the instability mechanism further, as the influence of the schistosity and jointing together with the deep-seated slope movements were not properly accounted for in the continuum finite-element analyses that were initially carried out.

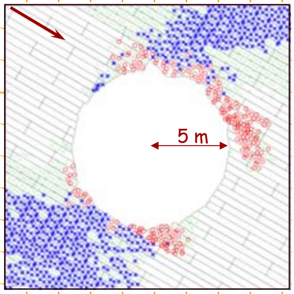
Case History: Complex Tunnel Deformations

Modelling of tunnel damage due to creeping slope …

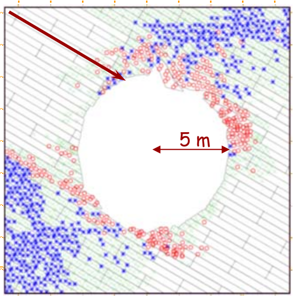




slope displacement = 0.05 m



slope displacement = 0.5 m



slope displacement = 1.0 m

Thuro *et al.* (2004)

Good Modelling Practice

Field Constraints
(be aware of reality)

Software/Hardware Availability
(choose right technique)

Basic Knowledge of Software
(know limitations)

Information Update

Simplicity

Experience and Judgment

Curiosity and Patience

Practicality
(time and $$$)

Availability of Data
(deterministic/probabilistic)

Application of Distinct-Element Modelling to Geotechnical Analysis

Lecture References

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Hart, RD (1993). An introduction to distinct element modeling for rock engineering. In *Comprehensive Rock Engineering: Principles, Practice & Projects*. Pergamon Press, Oxford, **2**: 245-261.

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