

EOSC433:
Geotechnical Engineering
Practice & Design

Lecture 9:
Deformation Analysis
and Elasto-Plastic
Yield

→ ← 1 of 51
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Numerical Modelling

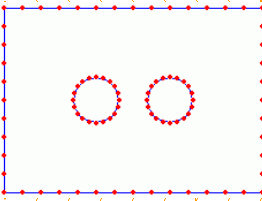
Numerical methods of stress and deformation analysis fall into two categories:

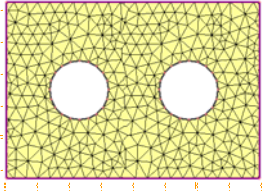
Integral Methods

Differential Methods

- incl. boundary-element method
- only problem boundary is defined & discretized
- Pro: more computationally efficient; Con: restricted to elastic analyses

- incl. finite-element/-difference & distinct-element methods
- problem domain is defined & discretized
- Pro: non-linear & heterogeneous material properties accommodated; Con: longer solution run times





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Numerical Analysis - Differential Methods

Differential methods are more difficult and time consuming than boundary analyses (BEM), both in terms of model preparation and solution run times. As such, they require special expertise if they are to be carried out successfully.

... finite-difference method	} continuum
... finite-element method	
... discrete-element method	} discontinuum
... distinct-element method	

New Considerations (relative to BEM):

- Division of problem domain (i.e. meshing efficiency & element types).
- Selection of appropriate constitutive models (i.e. stress-strain response of elements to applied forces).
- Determination of material properties for selected constitutive models (generally derived from lab testing with scaling to field conditions).
- Limiting boundary conditions and special loading conditions.



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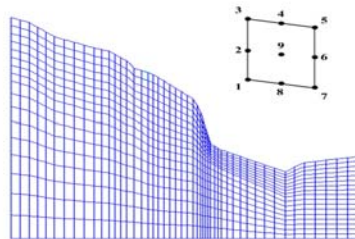
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Numerical Analysis - Differential Methods

Continuum Methods

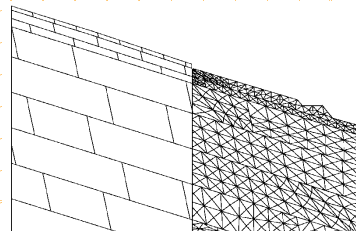
- ✓ Rock/soil mass behaviour represented as a continuum.
- ✓ Procedure exploits approximations to the connectivity of elements, and continuity of displacements and stresses between elements.



Stead et al. (2006)

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.

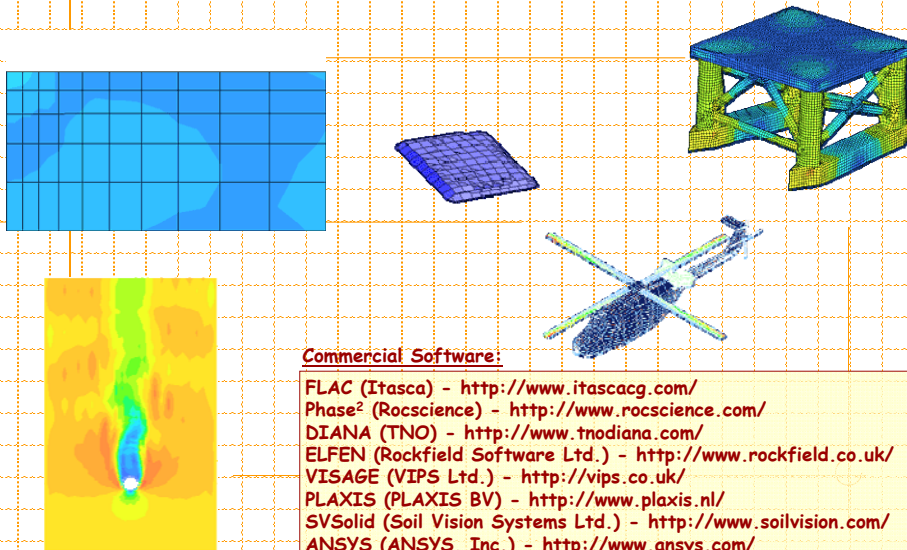


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Numerical Analysis - Continuum Methods



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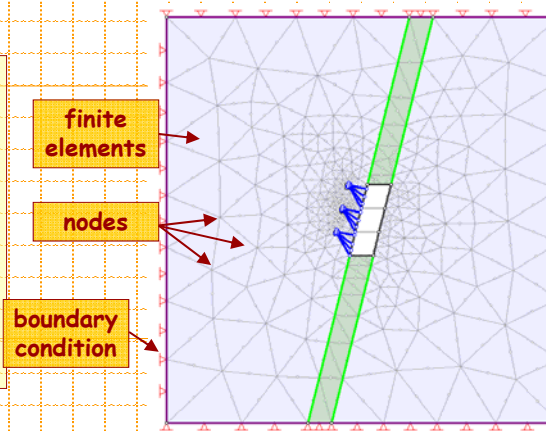
Continuum Analysis - The Basics

Continuum methods divide the rock mass into a set of simple sub-domains called "**elements**". These elements can be of any geometric shape that allows computation or provides the necessary relation to the values of the solution at selected points called "**nodes**".

This technique allows:

... accurate representation of complex geometries and inclusion of dissimilar materials.

... accurate representation of the solution within each element, to bring out local effects (e.g. stress or strain concentrations).



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Numerical Analysis - Continuum Methods

In geotechnical engineering, there are two key continuum-based differential approaches used (to find an approximate solution to a set of partial differential equations):

Finite-Difference

- method is an approximation to the differential equation
- solves a problem on a set of points that form a grid
- easier to implement, but approximation between grid points can be problematic.

Finite-Element

- method is an approximation to the solution of the differential equation
- solves a problem on the interiors of the grid cells (elements) and for the grid points
- can more easily handle complex geometries

FLAC - Fast Lagrangian Analysis of Continua (by Itasca)

finite difference

Phase² (by RocScience)

finite element



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Steps in a FEM Solution

Division of the problem domain into parts
(both to represent the geometry
as well as the solution of the problem)



Seek an approximate solution for each part
(using a linear combination of nodal values
and approximation functions)



Assemble the parts and solve for the whole
(by deriving the algebraic relations among the nodal values
of the solution over each part)



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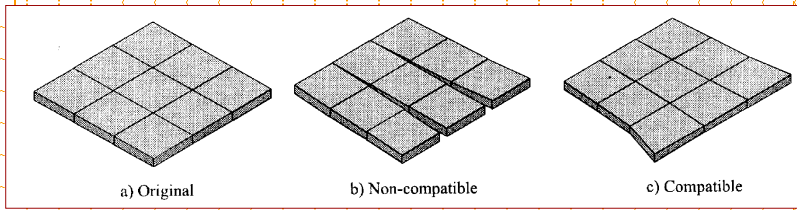
Basic Formulation of FEM Equations

Piece-wise approximation: The finite-element method has a central requirement that the field quantities (stress, displacement) vary throughout each element in a prescribed fashion using specific functions. As such, the problem domain is represented by an array of small, *interconnected subregions*.

Compatibility

Material Behaviour

Equilibrium



Potts & Zdravković (1999)

Unknowns: 6 stresses + 6 strains + 3 displacements = 15
Equations: 3 equilibrium + 6 compatibility = 9

To obtain a solution therefore requires 6 more equations. These come from the constitutive relationships.



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Basic Formulation of FEM Equations

FEM does not solve for a single element, it is assembled and solved as a whole (FDM, on the other hand, sweeps through a mesh and solves implicitly, element by element).

Compatibility

Material Behaviour

Equilibrium

matrix that relates the strains inside the element with the nodal displacements

matrix of material behaviour or the constitutive matrix for the element

interpolation of displacements across element (i.e. through shape functions matrix)

$$\epsilon = B \cdot a_e$$

strains

nodal displacements

$$\sigma = D \cdot B \cdot a_e$$

stress

strain

solved for

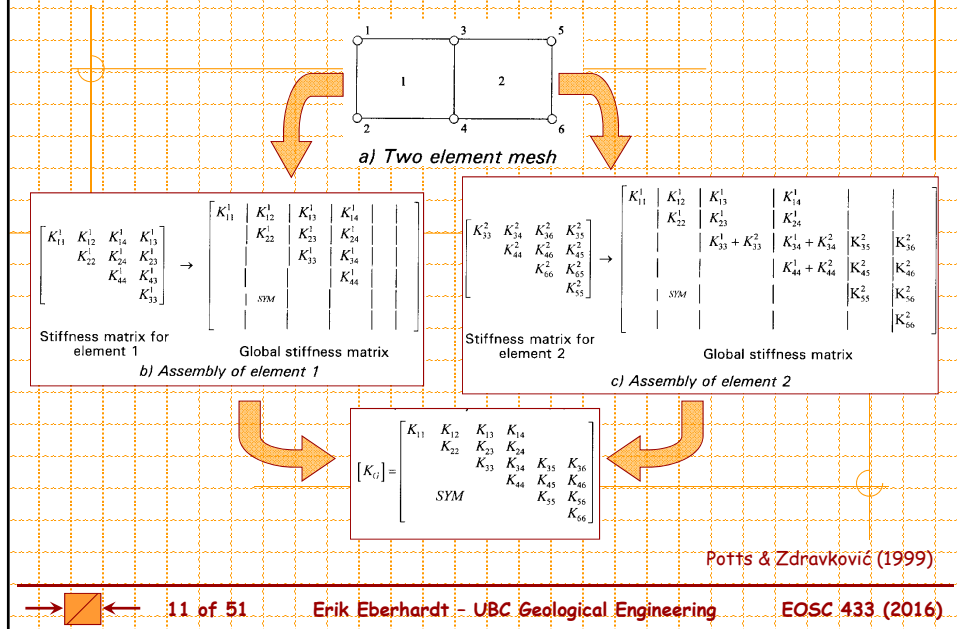


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Finite-Element Matrix Assembly



Potts & Zdravković (1999)

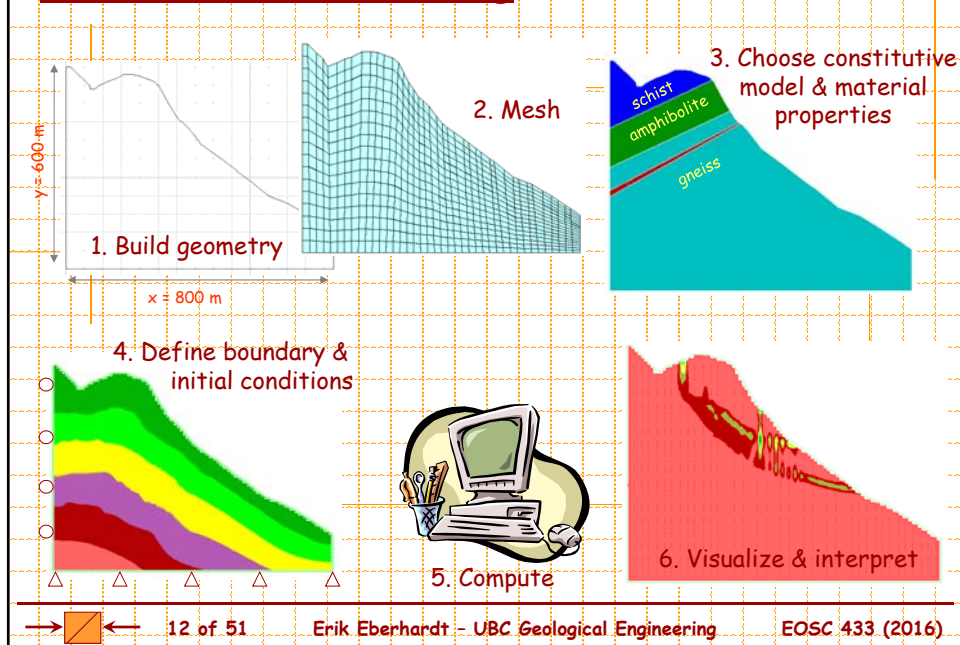


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Numerical Problem Solving



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Analysis in Geotechnical Design

Geotechnical analyses involve **complex** systems! Often, field data required for model input (e.g. *in situ* stresses, material properties, geological structure, etc.) are not available or can never be known completely/exactly. This creates **uncertainty**, preventing the models from being used to provide **design data** (e.g. expected displacements).

Such models, however, may prove useful in providing a picture of the **mechanisms** acting in a particular system. In this role, the model may be used to aid **intuition/judgement** providing a series of **cause-and-effect** examples.

Situation	<ul style="list-style-type: none"> ✧ complicated geology ✧ inaccessible ✧ no testing budget 	↔	<ul style="list-style-type: none"> ✧ simple geology ✧ \$\$\$ spent on site investigation
Data	none	↔	complete (?)
Approach	investigation of failure mechanism(s)	↔	predictive (design use)



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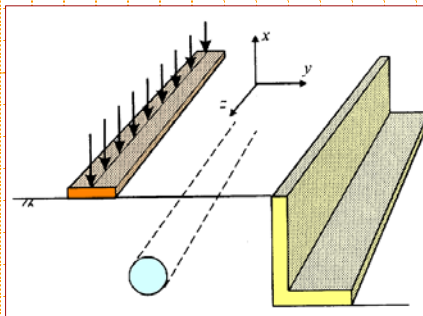
Problem Solving: 2-D or 3-D?

Many geotechnical problems can be assumed to be plane strain (2-D assumption) without significant loss of accuracy of the solution.

... in plane strain, one dimension must be considerably longer than the other two;

... strains along the out-of-plane direction can be assumed to be zero;

... as such, we only have to solve for strains in one 2-D plane.



Potts & Zdravković (1999)



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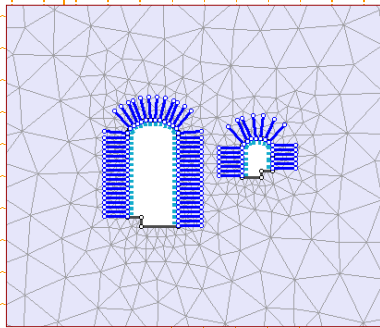
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Problem Solving: Meshing

The intention of grid generation is to fit the model grid to the physical domain under study. When deciding on the geometric extent of the grid and the number of elements to specify, the following two aspects must be considered:

1. How will the location of the grid boundaries influence model results?
2. What density of zoning is required for an accurate solution in the region of interest?



Do's and Don'ts

- The density of elements should be highest in regions of high stress or strain gradients.
- The greatest accuracy is achieved when the element's aspect ratio is near unity; anything above 10:1 is potentially inaccurate (5:1 for FDM).
- The ratio between adjacent elements should not exceed 4:1 (using a smooth transition to zone from fine to coarse mesh).



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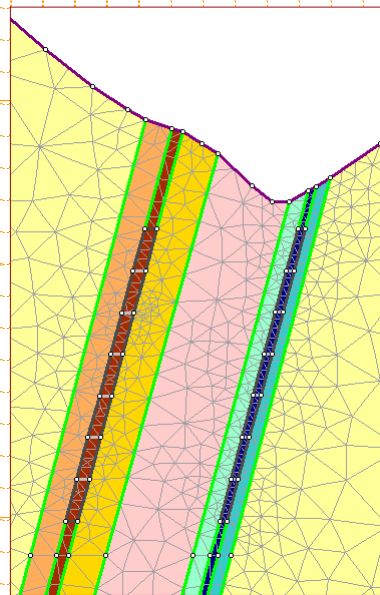
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Material Properties

A key advantage of differential methods over integral methods is that by discretizing the problem domain, the assignment of **varying material properties** throughout a heterogeneous rock mass is permitted.

Material properties required by the chosen constitutive stress-strain relationship are generally derived from **laboratory testing programs**. Laboratory values should be extrapolated to closely correlate with the **actual *in situ* conditions**.



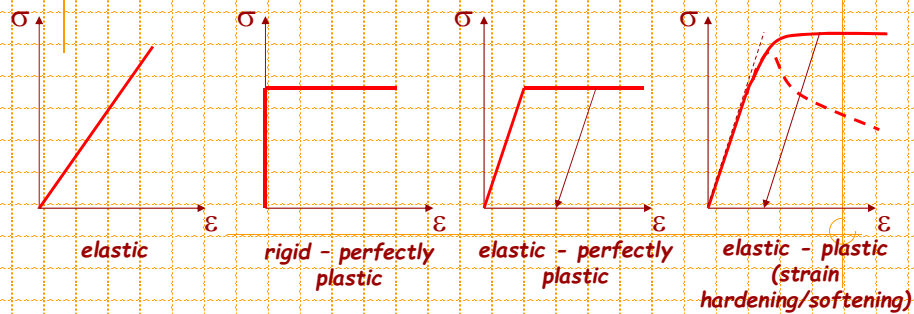
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Problem Solving: Constitutive Models

During deformation, solid materials undergoes irreversible strains relating to slips at grain/crack boundaries and the opening/closing of pore space/cracks through particle movements. Constitutive relations act to describe, in terms of phenomenological laws, the stress-strain behaviour of these particles in terms of a collective behaviour within a continuum.



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Constitutive Models

"Most fundamental ideas of science are essentially simple and may, as a rule, be expressed in a language comprehensible to everyone".

Einstein

... the more complex the constitutive model, the more the number of input parameters it requires and the harder it gets to determine these parameters without extensive, high quality (and of course, expensive) laboratory testing;

... as such, one should always begin by using the simplest model that can represent the key behaviour of the problem, and increase the complexity as required.

*"Everything should be made as simple as possible...
but not simpler".*

Einstein



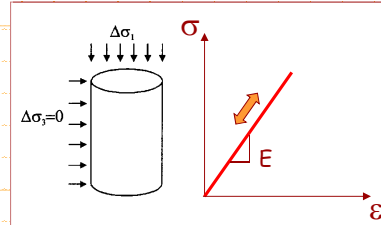
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Constitutive Models for Geomaterials

- ✓ Linear elastic (isotropic)
- ✓ Linear elastic (anisotropic)
- ✓ Viscoelastic
 - influence of rate of deformation
- ✓ Elastic-perfectly plastic
 - von Mises
 - Drucker-Prager
 - Mohr-Coulomb
- ✓ Elasto-plastic
 - Cam-clay
 - strain softening



$$\begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{zz} \\ \epsilon_{xy} \\ \epsilon_{yz} \\ \epsilon_{zx} \end{bmatrix} = \frac{1}{E} \begin{bmatrix} 1 & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1 & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1+\nu) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+\nu) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1+\nu) \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix}$$

symmetric



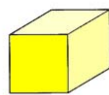
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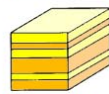
The Elastic Compliance Matrix - Isotropy

Isotropy assumptions used for rock:



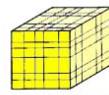
Perfectly isotropic rock

2 elastic constants:
1 Young's modulus, 1 Poisson's ratio



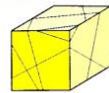
Transversely isotropic rock
(one axis of symmetry, e.g. similar to a rock mass with distinct laminations or with one main fracture set)

5 elastic constants:
2 Young's moduli, 2 Poisson's ratios, and 1 shear modulus



Orthotropic rock
(three axes of symmetry, e.g. similar to a rock mass with three orthogonal fracture sets)

9 elastic constants:
as in the matrix above — 3 Young's moduli, 3 Poisson's ratios and 3 shear moduli



General anisotropic rock

21 elastic constants:
all the independent S_{ij} in the S matrix. Because the matrix is symmetrical, there are 21 rather than 36 constants.

Hudson & Harrison (1997)



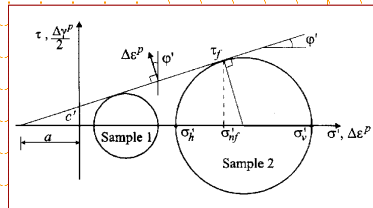
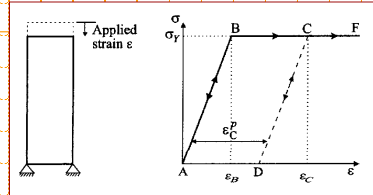
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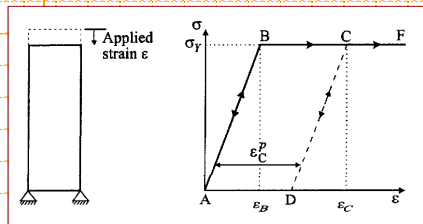
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Plasticity: An Introduction

Elastic materials have a unique stress-strain relationship given by the generalized Hooke's law. For many materials, the overall stress-strain response is not unique. Many states of strains can correspond to one state of stress and vice-versa. Such materials are called inelastic or plastic.



... when load is increased, material behaves elastically up to point B, and regains its original state upon unloading.

... if the material is stressed beyond point B up to C, and then unloaded, there will be some permanent or irrecoverable deformations in the body, and the material is said to have undergone plastic deformations.



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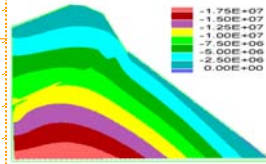
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Plasticity & Yield

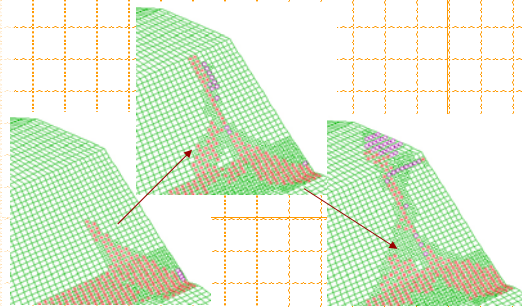
When run **elastically**, yield and/or failure within the model are not considered/enabled.

An **elasto-plastic** model allows and solves for **yielding** within the model (and the resulting displacements that arise). All plastic models potentially involve some degree of permanent, path-dependent deformations. Once an element has reached it's yield state, further increases in stress must be supported by neighbouring elements, which in turn may yield, setting off a chain reaction leading to localization and catastrophic failure.

Solution Step 1 - Initial stress state.



Solution Step 2 - Disequilibrium condition.



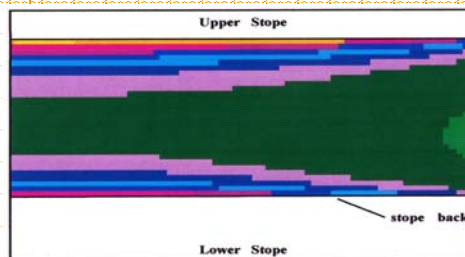
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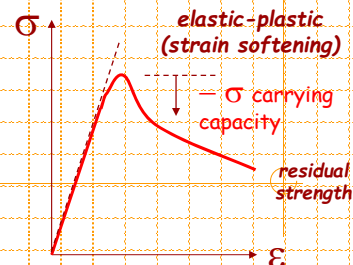
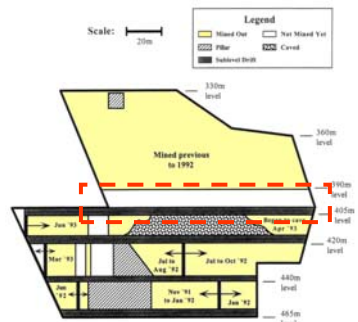
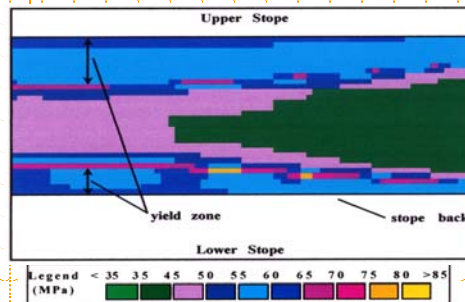
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Plasticity & Yield

Elastic Analysis



Elasto-Plastic Analysis



Eberhardt et al. (1997)

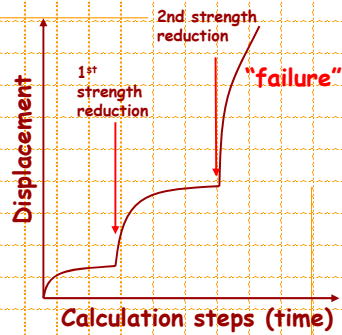
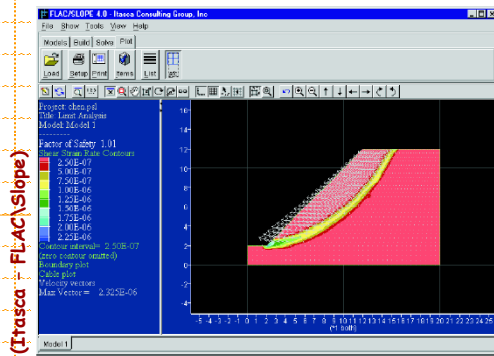


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Shear Strength Reduction



Strength reduction:

$$c_{mob} = c/F \quad \phi_{mob} = \phi/F$$

The shear strength is reduced until collapse occurs, from which a factor of safety is produced by comparing the estimated shear strength of the material to the reduced/increased shear strength at failure.



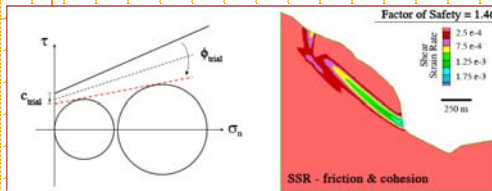
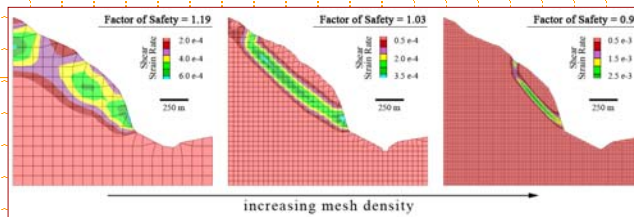
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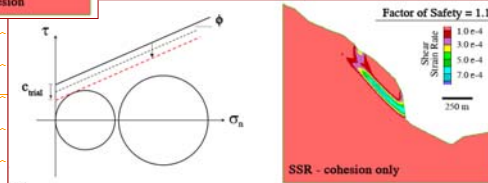
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Understanding Shear Strength Reduction

mesh dependency



modelling "failure"



Eberhardt (2008)



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Case History #1: Cause of Fatal Landslide

Lutzenberg (2002) - 3 deaths



Although this slide occurred during a period of heavy rain, the investigation uncovered the presence of a broken water pipe suspiciously located in the head of the slide.



This led to questions of whether the pipe ruptured during "a rainfall-triggered landslide", or whether non-critical slope movements caused the pipe to rupture and the leaking pipe was responsible for the landslide.

Valley et al. (2004)



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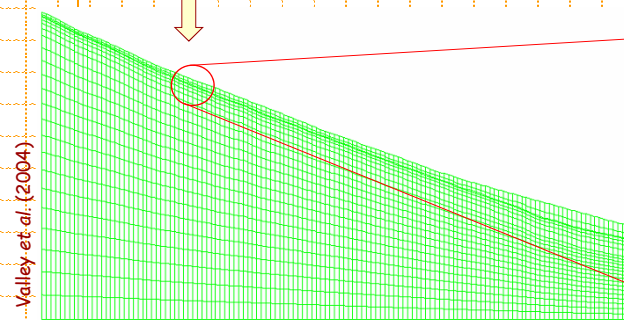
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Case History #1: Cause of Fatal Landslide



In-situ mapping and testing for shear strength properties.



Valley et al. (2004)

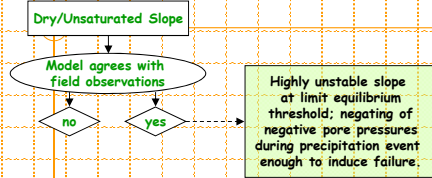


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Lutzenberg: H-M Coupled FEM Analysis

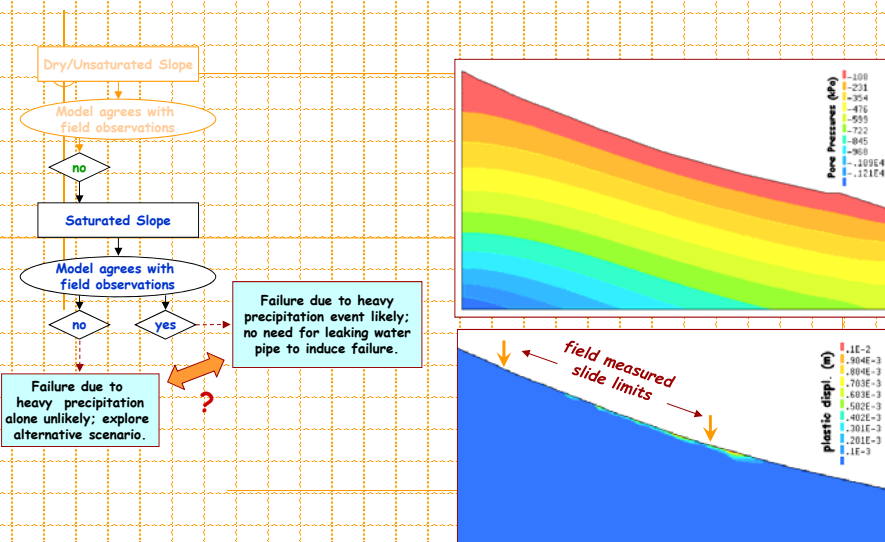


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Lutzenberg: Coupled H-M FEM Analysis



Valley et al. (2004)

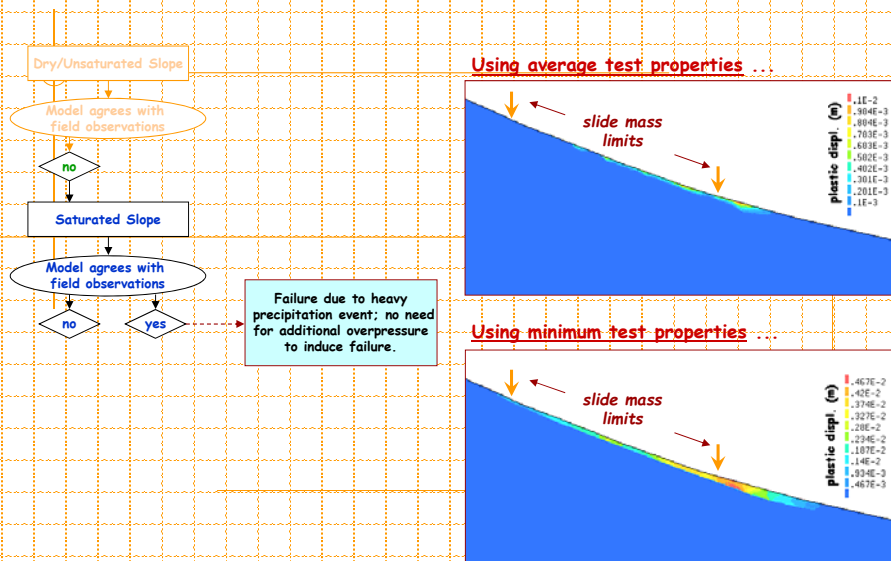


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Lutzenberg: H-M Coupled FEM Analysis

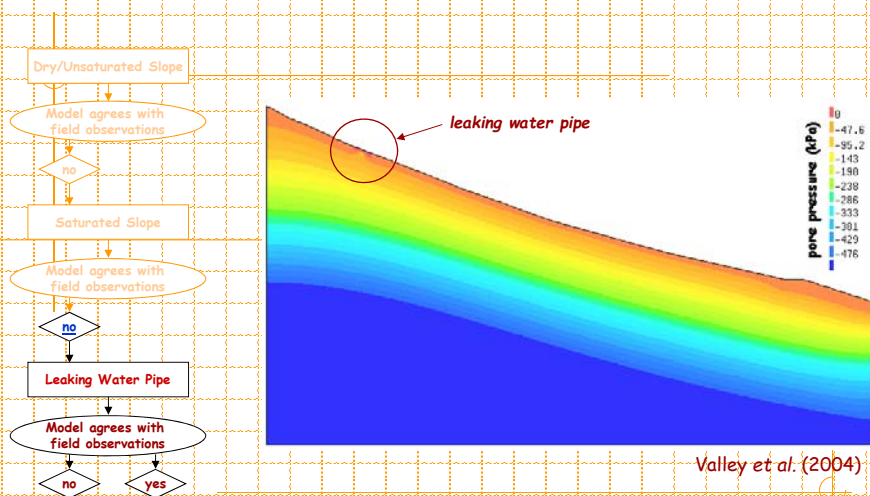


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Lutzenberg: Coupled H-M FEM Analysis

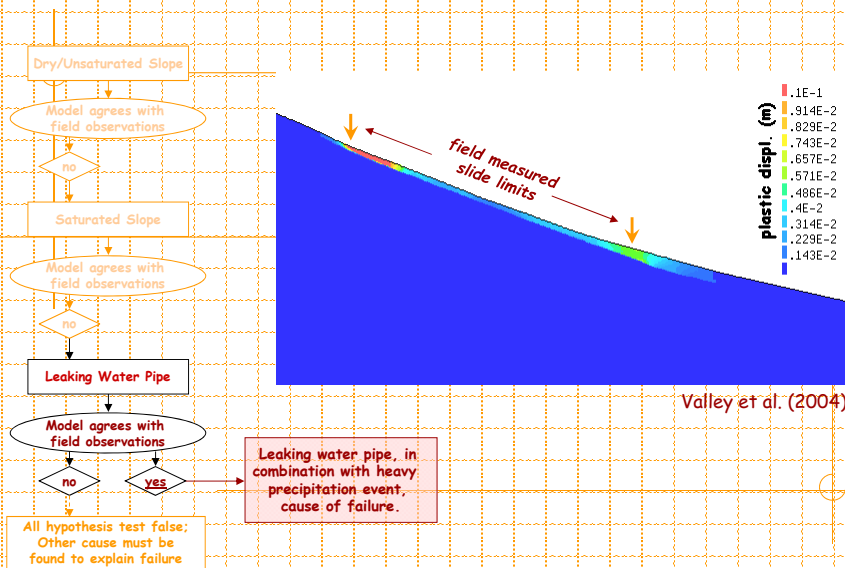


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Lutzenberg: Coupled H-M FEM Analysis



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Good Modelling Practice

The modelling of **geomechanical processes** involves special considerations and a design philosophy different from that in other fields of **applied mechanics**. This is because situations in earth materials often involve limited amounts of input data.

As such, the model should never be considered as a "black box" that accepts data input at one end and produces a prediction at the other. The model should instead be prepared carefully and tested several times in progression of **increasing difficulty** to gain a full understanding of the problem.

In order to perform a successful numerical study, several steps are recommended:

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



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Input & Assumptions

The fundamental requirement for a meaningful modelling study should include the following steps of data collection/evaluation:

- site characterization (geological and hydrogeological conditions);
- groundwater conditions (pore pressure model);
- geotechnical parameters (strength, deformability, permeability);
- instability mechanisms (kinematics or potential failure modes).

"if you do not know what you are looking for,
you are not likely to find much of value"

R. Glossop, 8th Rankine Lecture, 1968



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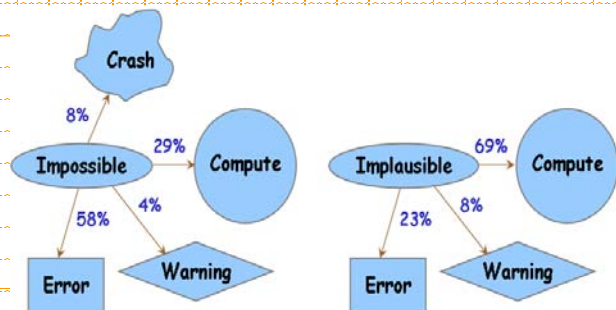
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Good Modelling Practice

"numerical modelling should not be used as a
substitute for thinking, but as an aid to thought "

... results of a survey
of nine commonly
used geotechnical
modelling programs
and their response to
impossible (e.g. $E < 0$)
and implausible
($E_{\text{soil}} > E_{\text{rock}}$) input
data.



Crilly (1993)

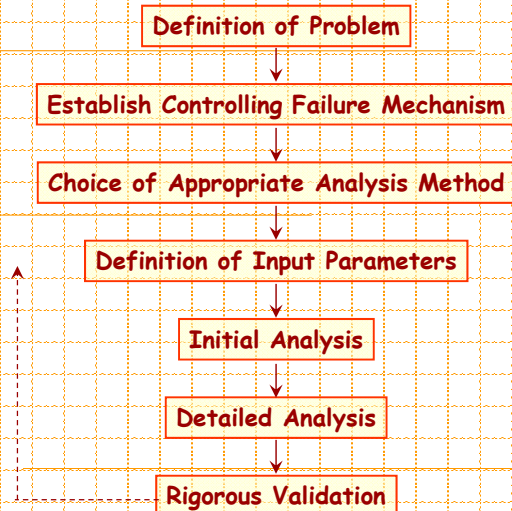


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Good Modelling Practice



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Case History #2: Verification & Validation

Palabora: Managing geo-risk through improved data integration, model input and constraint of 3-D model uncertainty.



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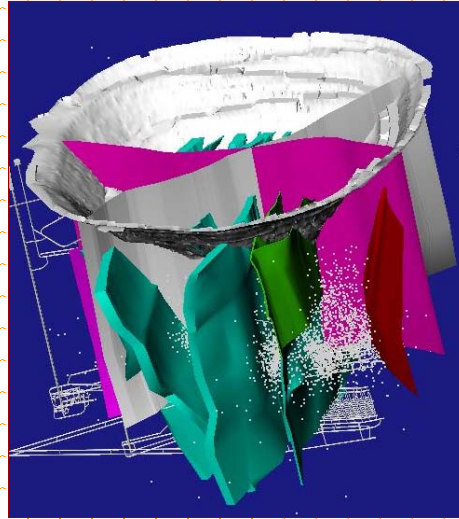
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Case History #2: Verification & Validation

Collect mine data
(problem geometry, geology &
model constraints)

Build 3-D data
model



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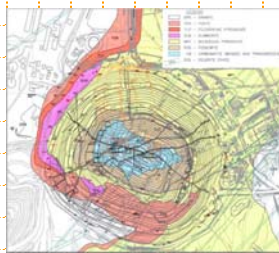
Case History #2: Verification & Validation

Collect mine data
(problem geometry, geology &
model constraints)

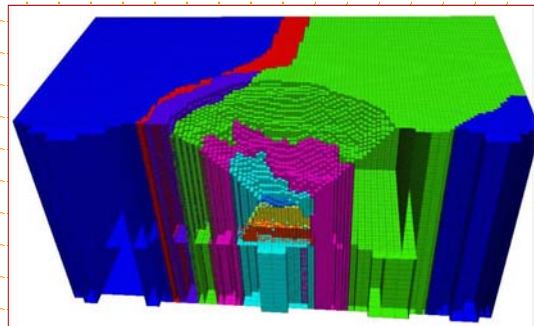
Build 3-D data model



Build 3-D
numerical model



Woo et al. (2011)



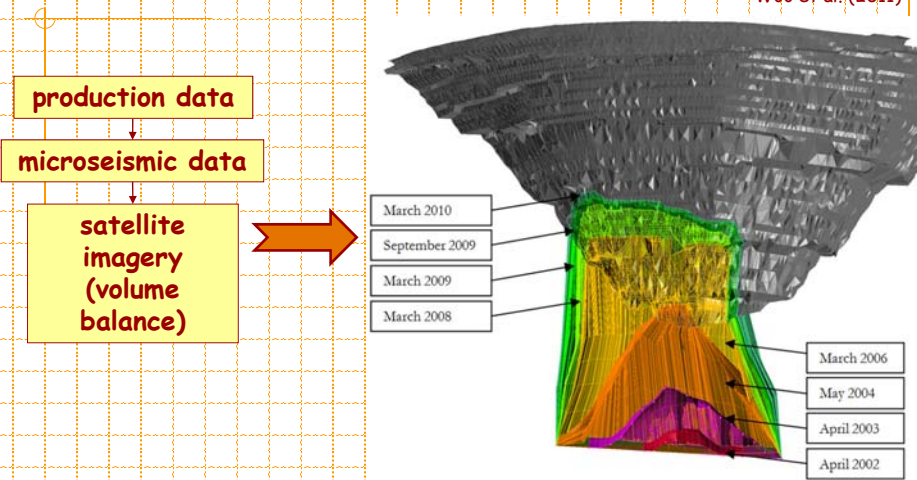
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Case History #2: Verification & Validation

Woo et al. (2011)

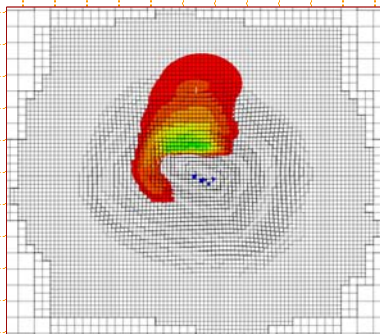


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Case History #2: Verification & Validation



Woo et al. (2011)



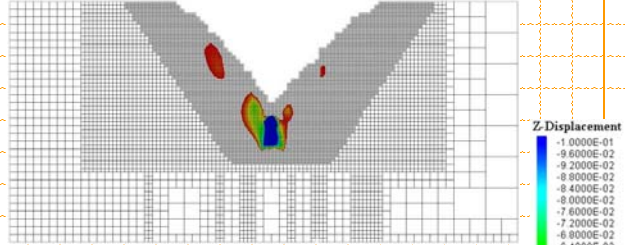
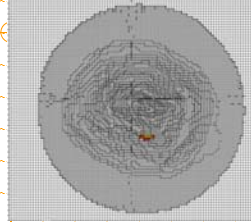
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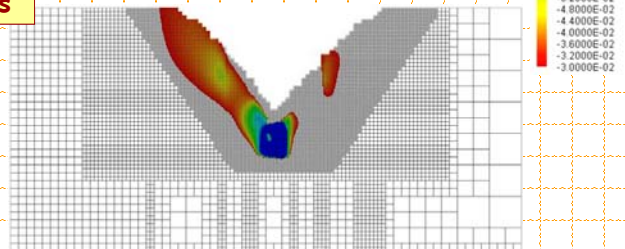
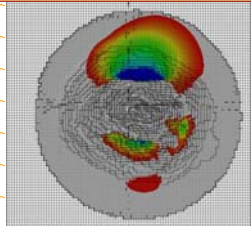
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Case History #2: Verification & Validation

average properties



lower-bound properties



Woo et al. (2011)



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Case History #2: Verification & Validation

Model Inputs	Input Confidence	
Surface topography	Good	Digital mine plans
Model boundaries	Good	
Material boundaries	Good	
Cave geometry	Marginal	Limited data
Mesh controls	Good	
Constitutive model (for each rock unit)	Poor	Geological uncertainty
Rock mass properties (for each rock unit)	Poor	
In-situ stresses	Marginal	Inconclusive field data



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Case History #2: Verification & Validation

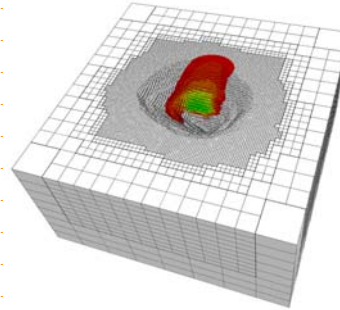
Collect mine data
(problem geometry, geology
& model constraints)

Build 3-D data model

Build 3-D numerical
model

Carry out parametric
and constitutive
analyses

Calibrate and
constrain models



ELASTIC
↓
ELASTO-PLASTIC
↓
UBIQUITOUS JOINT
↓
STRAIN SOFTENING



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Case History #2: Verification & Validation

second pass:
measures phase (ϕ_1) for
each pixel for time t_1

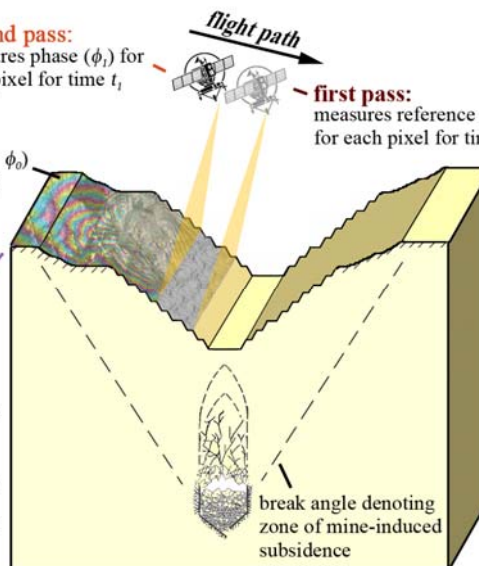
first pass:
measures reference phase (ϕ_0)
for each pixel for time t_0

InSAR image:
phase difference ($\phi_1 - \phi_0$)
for each pixel during
time interval ($t_1 - t_0$)

phase (ϕ):
each colour represents
the phase (ϕ) of a wave

displacement:
pixels move relative to
previous image resulting
in phase shift

displacement toward satellite
0 2.83 cm
← radar wavelength →



Rabus et al. (2009)

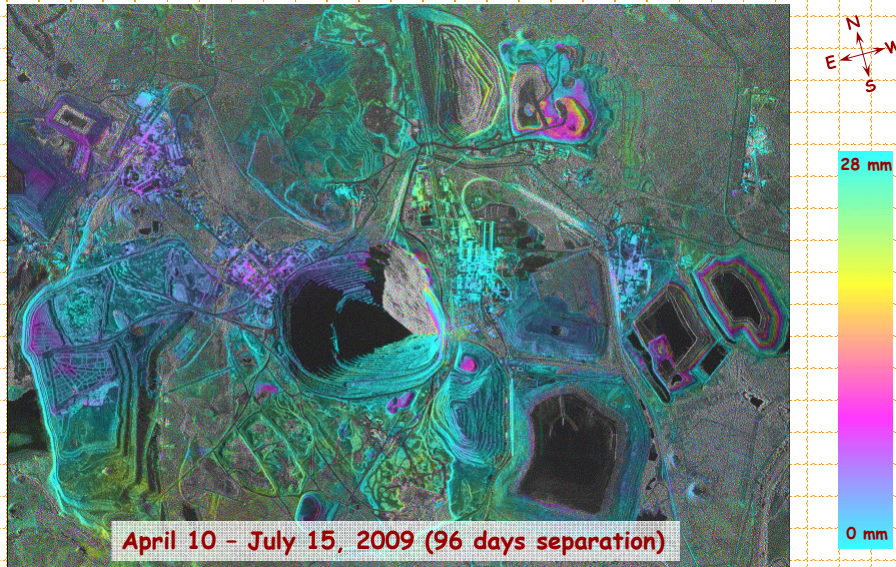


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Case History #2: Verification & Validation



Data courtesy of MDA



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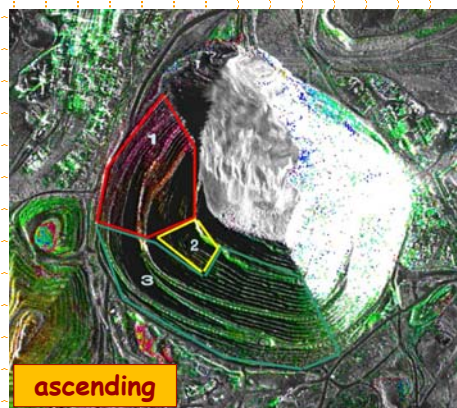
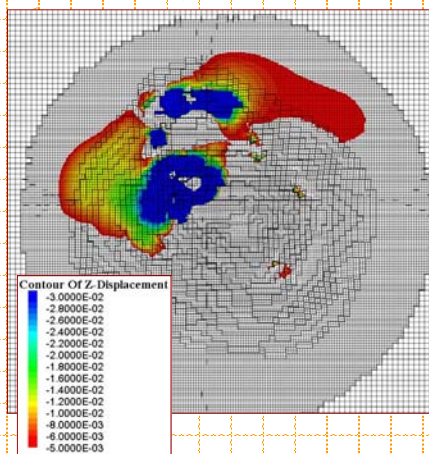
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Case History #2: Verification & Validation

Forward Analysis: Predictive Model (2009-2010)

Woo et al. (2011)



10-40mm (red)

10-20mm (yellow)

0-10mm (green)



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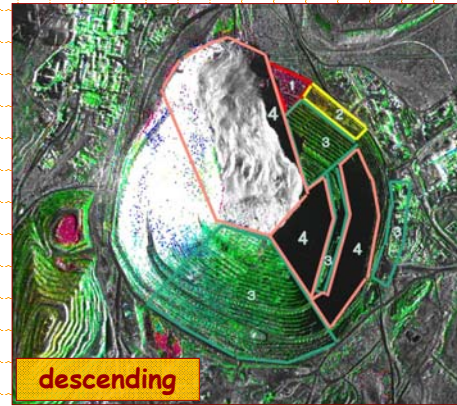
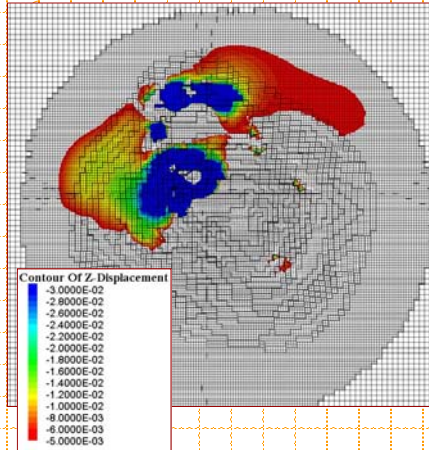
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Case History #2: Verification & Validation

Forward Analysis: Predictive Model (2009-2010)

Woo et al. (2011)



10-40mm (red)
10-20mm (yellow)
0-10mm (green)



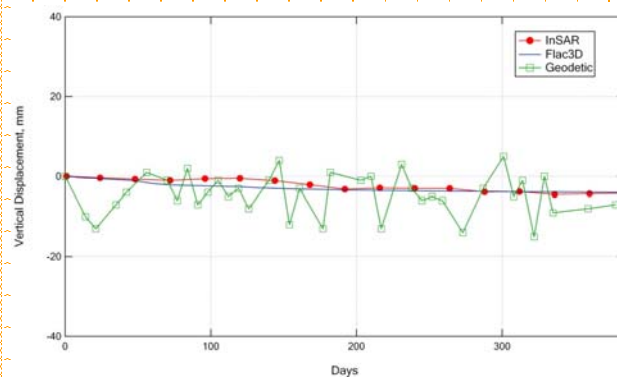
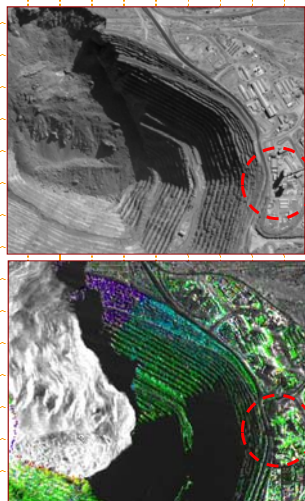
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Case History #2: Verification & Validation

Forward Analysis: Predictive Model (2009-2010)



Woo et al. (2011)



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