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Rock Dynamics Research at NTU

presented by

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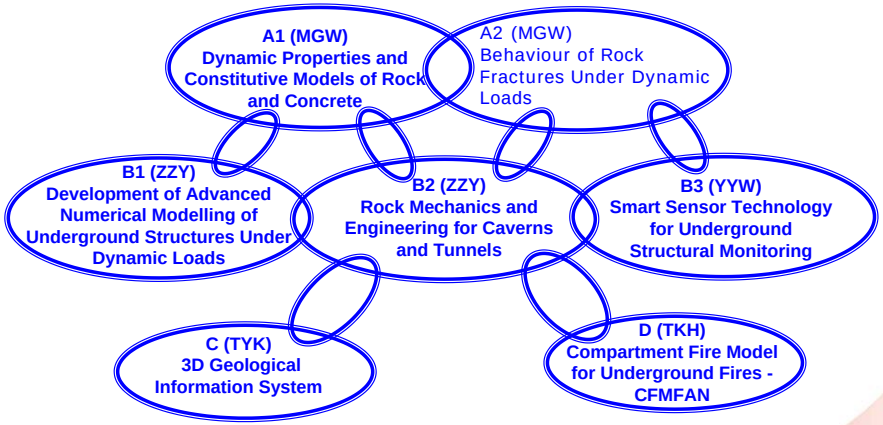
Nanyang Technological University, Singapore

Underground Technology and Rock Engineering



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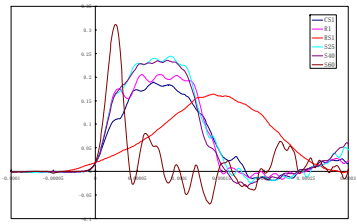
Rock Dynamic Properties and Constitutive Models

SHPB

Pneumatic Gun

Pulse shape effects



Waveforms with different strikers

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Static and Dynamic Tests for Granite

Static compression

Dynamic compression

Lower strain rate

Medium strain rate

Higher strain rate

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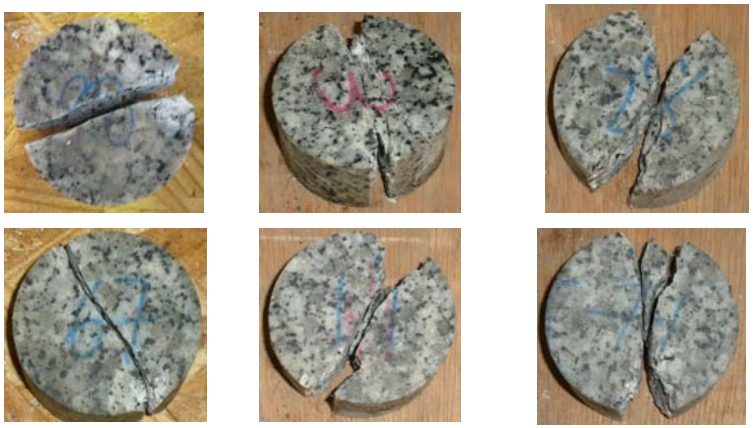
Brazilian Splitting tests for granite



Quasi-static load | With lower dynamic load | With higher dynamic load

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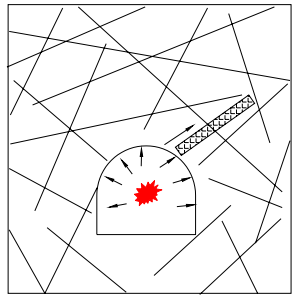
Rock Joint Dynamic Properties

Joins in rock mass



Stress wave propagation in rock mass

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Stress Wave Propagation in Rock Mass

- Two granite pressure bars
- A discontinuous layer between the pressure bars
- Aperture and water content effects

- Multiple joint layers

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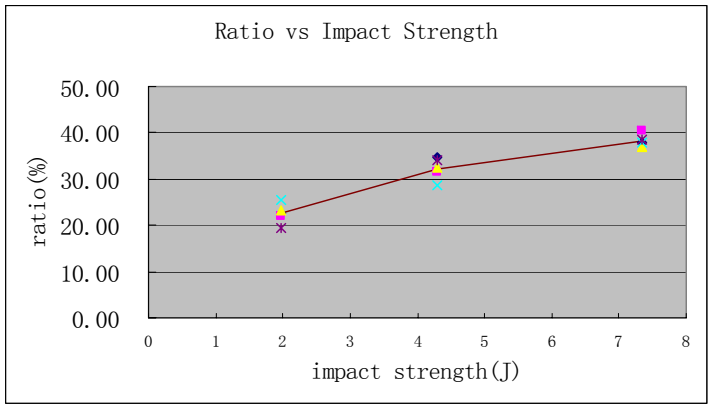
Impact Energy Effect



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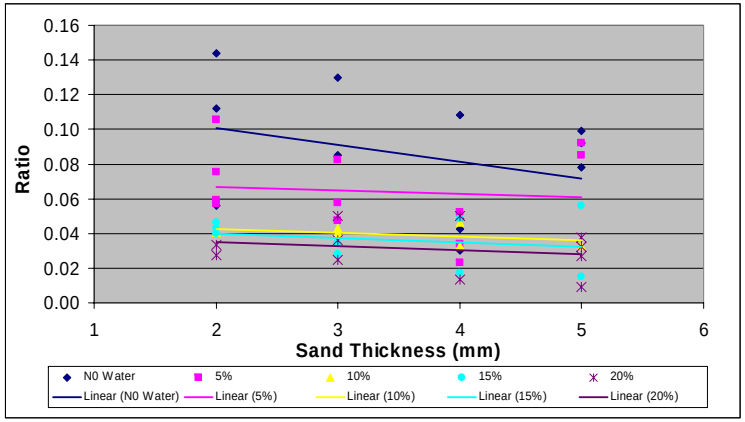
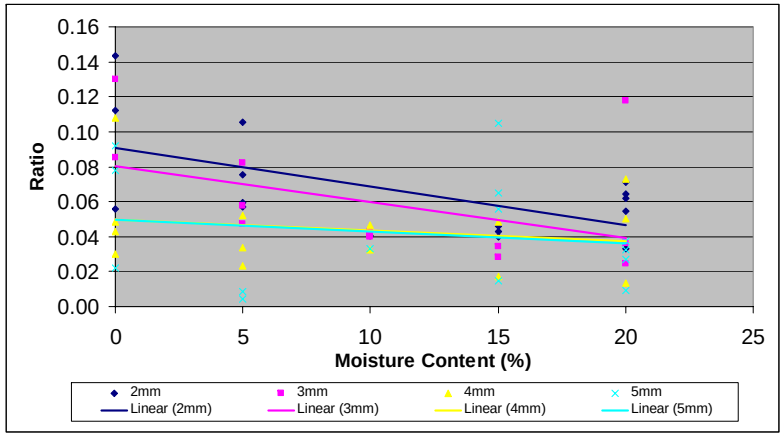
Aperture effects

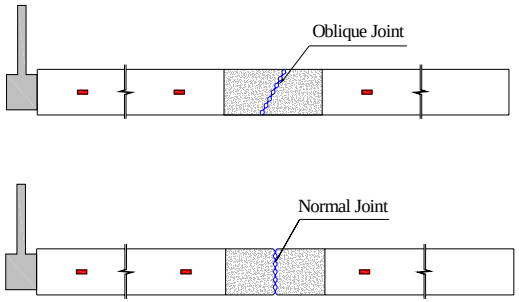


Effect of Water Content

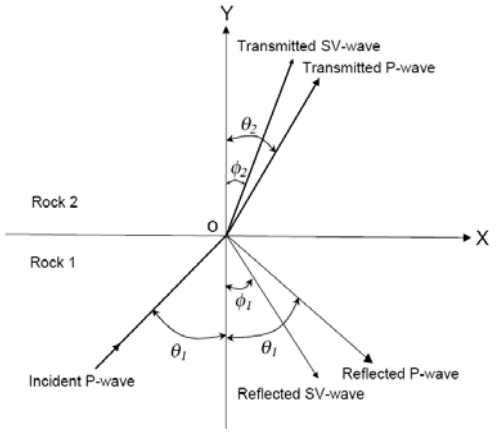


SHPB tests for oblique joint

- Effect of joint orientation on wave transmission and reflection



Wave Propagation Across Single Joint



$$\sigma_{yy}^{-} = \sigma_{yy}^{+}$$

$$\tau_{xy}^{-} = \tau_{xy}^{+}$$

$$\Delta v = v^{-} - v^{+} = \frac{\sigma_{yy}}{k_n}$$

$$\Delta u = u^{-} - u^{+} = \frac{\sigma_{xy}}{k_\tau}$$

2-D P-wave propagation Displacement discontinuity theory

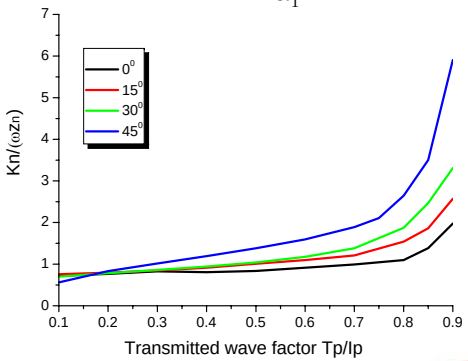
Different Joint Orientation Cases

incident p-wave

$$w_{Ip} = -Ie^{-i\omega t}\{\cos\theta_1 \cdot \exp[(\frac{i\omega}{\alpha_1}) \cdot (x\sin\theta_1 - z\cos\theta_1)]\}$$

$$u_{Ip} = Ie^{-i\omega t}\{\sin\theta_1 \cdot \exp[(\frac{i\omega}{\alpha_1}) \cdot (x\sin\theta_1 - z\cos\theta_1)]\}$$

Normal stiffness



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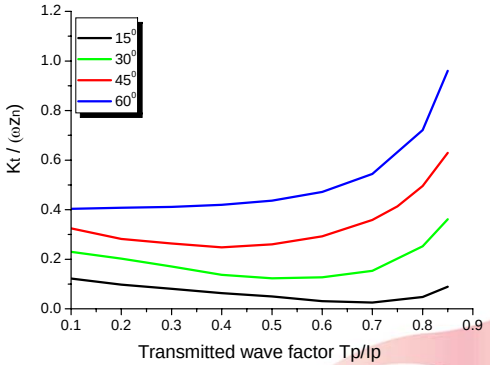
Different Joint Orientation Cases

incident p-wave

$$w_{Ip} = -Ie^{-i\omega t}\{\cos\theta_1 \cdot \exp[(\frac{i\omega}{\alpha_1}) \cdot (x\sin\theta_1 - z\cos\theta_1)]\}$$

$$u_{Ip} = Ie^{-i\omega t}\{\sin\theta_1 \cdot \exp[(\frac{i\omega}{\alpha_1}) \cdot (x\sin\theta_1 - z\cos\theta_1)]\}$$

Tangent stiffness



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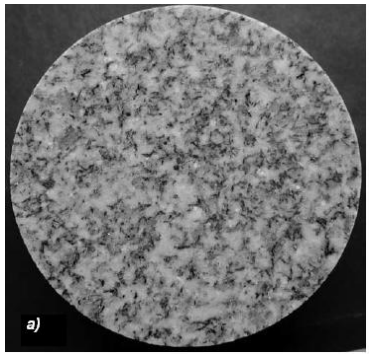
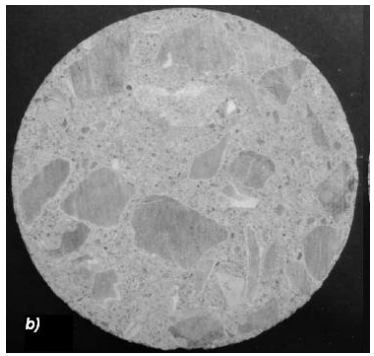
Modeling Heterogeneity Effect



Granite sample



Concrete sample

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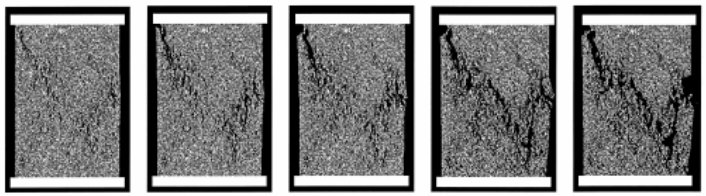
Modeling Material Heterogeneity

- Weibull Distribution
  - Statistical method
  - Describes the microstructures well
  - Adopted in numerical simulations in FEM

    Rock Failure Process Analysis (RFPA) ,Tang et al.(2000)



Simulations on rock failure under compression considering material heterogeneity by Tang et al. (2000)

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SPH Method

- Approximations of SPH
  - Kernel (smoothing) Function
    - Delta function property
    - Normalization
    - Compactly supported
    - Smoothing property
  - Kernel approximation

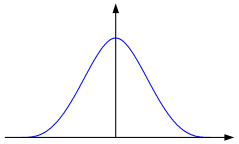
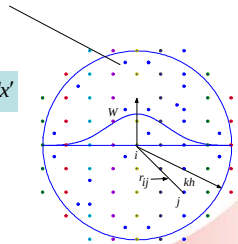


Illustration of one kernel function in 1-D

$$f(x)=\int f(x')W(x-x',h)dx' \qquad \nabla f(x)=\int f(x')\nabla W(x-x',h)dx'$$

Supporting domain



  - Particle approximation

$$f_i=\sum_{j=1}^{N}\left(\frac{m_j}{\rho_j}\right)f_j W(x_i-x_j,h) \qquad \nabla f_i=\sum_{j=1}^{N}\left(\frac{m_j}{\rho_j}\right)f_j \nabla_i W(x_i-x_j,h)$$

Illustration of SPH approximations

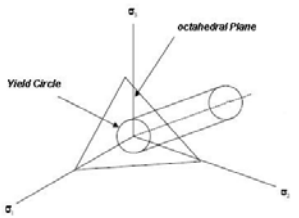
SPH Method

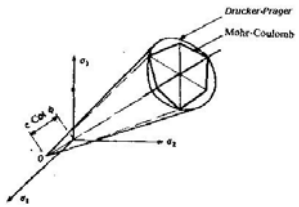
- Governing equations & SPH approximations

$$\begin{cases}\dfrac{d\rho}{dt}=-\rho\cdot\dfrac{\partial v^{\alpha}}{\partial x^{\alpha}}\\ \dfrac{dv^{\alpha}}{dt}=-\dfrac{1}{\rho}\cdot\dfrac{\partial \sigma^{\alpha\beta}}{\partial x^{\beta}}\\ \dfrac{de}{dt}=-\dfrac{\sigma^{\alpha\beta}}{\rho}\cdot\dfrac{\partial v^{\alpha}}{\partial x^{\beta}}\end{cases} \Rightarrow \begin{cases}\dfrac{d\rho_i}{dt}=\rho_i\sum_{j=1}^{N}\dfrac{m_j}{\rho_j}v_{ij}^{\ \alpha}\dfrac{\partial W_{ij}}{\partial x_i^{\ \alpha}};\ \ \rho_i=\sum_{j=1}^{N}m_j W_{ij}\\ \dfrac{dv^{\alpha}}{dt}=-\sum_{j=1}^{N}m_j\left(\dfrac{\sigma_i^{\ \alpha\beta}}{\rho_i^{\ 2}}+\dfrac{\sigma_j^{\ \alpha\beta}}{\rho_j^{\ 2}}\right)\dfrac{\partial W_{ij}}{\partial x_i^{\ \beta}}\\ \dfrac{de_i^{\ \alpha}}{dt}=\dfrac{1}{2}\sum_{j=1}^{N}m_j v_{ij}^{\ \beta}\left(\dfrac{\sigma_i^{\ \alpha\beta}}{\rho_i^{\ 2}}+\dfrac{\sigma_j^{\ \alpha\beta}}{\rho_j^{\ 2}}\right)\dfrac{\partial W_{ij}}{\partial x_i^{\ \beta}}\end{cases}$$

SPH Method

- Constitutive model
  - Elasto-plastic constitutive model
  - Failure criterions
    - von Mises yield criterion
    - Mohr-Coulomb criterion



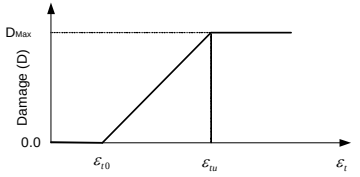


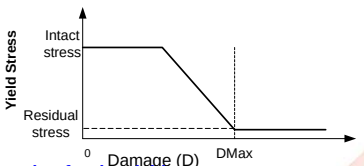
Geometrical representation of the von Mises (left) and Mohr-Coulomb (right) yield surfaces in principal stress space

SPH Method

- Isotropic tensile damage model

$$D=\begin{cases}0 & ,\ \varepsilon_t<\varepsilon_{t0}\\ D_{Max}\left(\varepsilon_t-\varepsilon_{t0}\big/\varepsilon_{tu}-\varepsilon_{t0}\right) & ,\ \varepsilon_{t0}\le\varepsilon_t<\varepsilon_{tu}\\ D_{Max} & ,\ \varepsilon_t\ge\varepsilon_{tu}\end{cases} \qquad \varepsilon_{t0}=f_{t0}\big/E_0 \qquad \varepsilon_{tu}=\lambda_u\varepsilon_{t0}$$





Isotropic tensile damage model (left); Illustration for the yield stress degraded with the damage (right) in uniaxial stress state

Modeling Material Heterogeneity

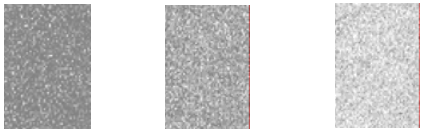
- Weibull distribution equation

$$f(T)=\frac{\beta}{\mu}\left(\frac{T}{\mu}\right)^{\beta-1} e^{\left[-\left(\frac{T}{\mu}\right)^{\beta}\right]} \quad ;T\geq 0,\ \mu>0,\ \beta>0$$

μ: seed parameter, β: homogenous index

- Implementation

- Numerical specimens



β =1 β =2 β =5

Distributions by different heterogeneous indices

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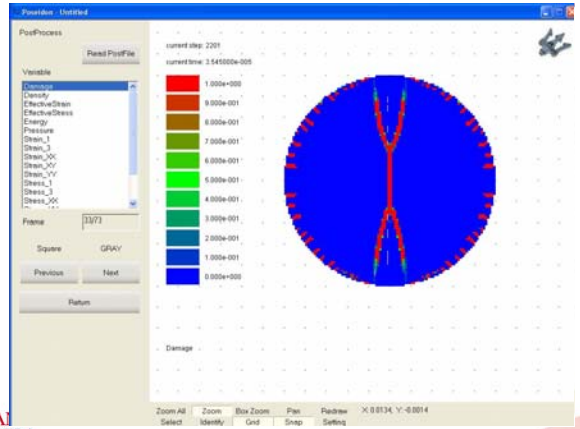
Program Implementation & Calibration

- Program Implementation with pre-processor & post-processor



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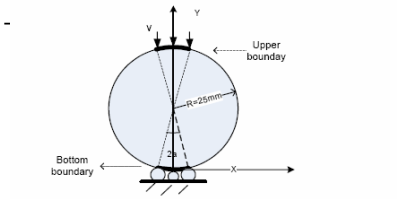
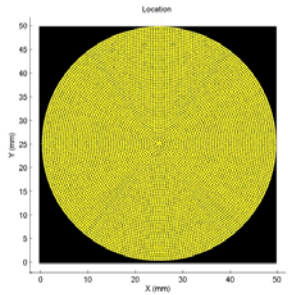
Simulations on Brazilian Splitting Test

- Numerical Model Configuration
  - Elasto-plastic model with M-C criterion
  - Isotropic tensile damage model
  - Tensile strength as a critical parameter to investigate heterogeneous effects

-



Geometry and loading condition for disc specimen under the dynamic load (R=25mm, α=6.9°)



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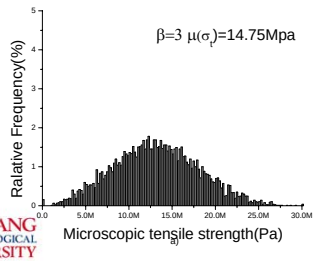
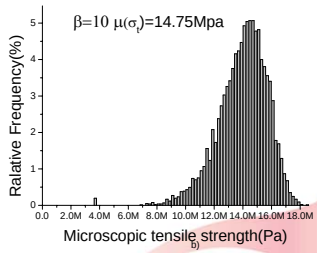
Simulations on Brazilian Splitting Test

- Cases Under Low Loading Rate (v=-0.1m/s)
  - Heterogeneity model setting

Case No.	σ_{t0} *(MPa)*		ρ, ν, E, c, ϕ
	β	$\mu(\sigma_{t0})$	β
1	**3**	**14.75**	**50**
2	**10**	**14.75**	**50**





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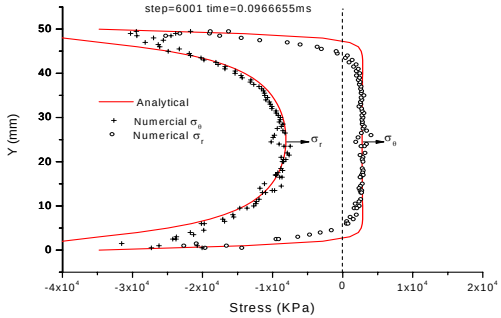
Simulations on Brazilian Splitting Test

- Cases Under Low Loading Rate (v=-0.1m/s)

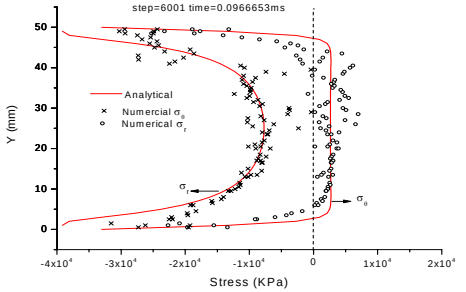


Analytical and simulated stress distributions along the loading axis

Case 2 β =10

Simulations on Brazilian Splitting Test

- Cases Under Low Loading Rate (v=-0.1m/s)

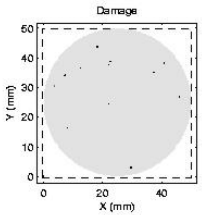


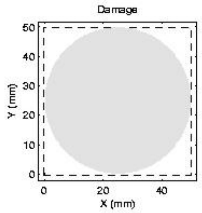
Analytical and simulated stress distributions along the loading axis

Case 1 **β =3**

Simulations on Brazilian Splitting Test

- Cases Under Lower Loading Rates





Case 1 β =3 **Case 2 β =10**

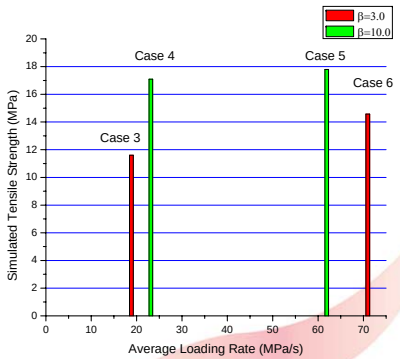
Variations of damage distribution during the fracture process

Simulations on Brazilian Splitting Test

- Cases Under Higher Loading Rates
  - Loading rates and simulated tensile strengths
    - Simulated tensile strength

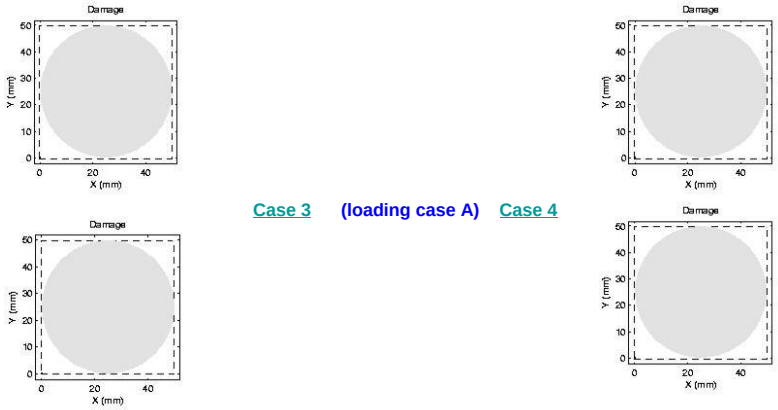
$$\sigma_x \approx -\frac{P}{\pi RL}$$

    - Strength gets increased with the Loading Rate
    - Improvement was affected by the material heterogeneity



Simulations on Brazilian Splitting Test

- Cases Under High Loading Rates (Fracture processes)



Case 3 (loading case A) Case 4

Case 5 (loading case B) Case 6

Variations of damage distribution during the fracture process

Simulations on Brazilian Splitting Test

- Cases Under High Loading Rates (Final Fracture patterns)

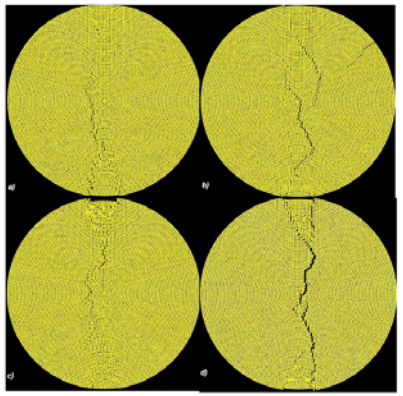
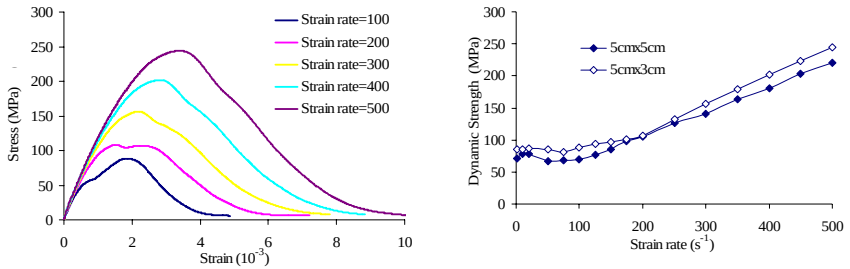
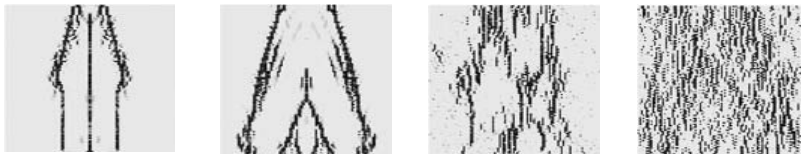


Figure 5-24 Cracks simulated in Case 3, 4, 5 and 6, from a) to d),

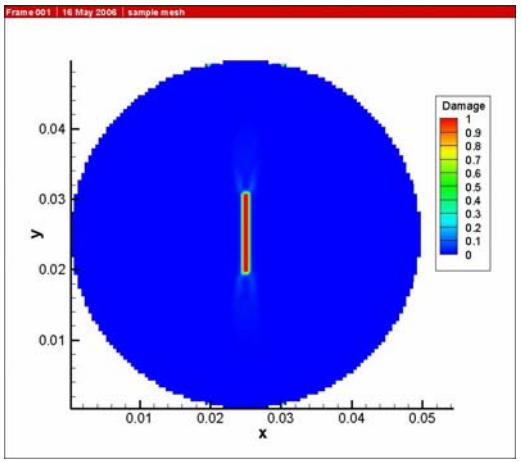
Strain Rate Effect





Strain rate increase

Ongoing Works – Advanced Constitutive Model



Ongoing Works – 3D Model

- Rock splitting simulations in 3-D

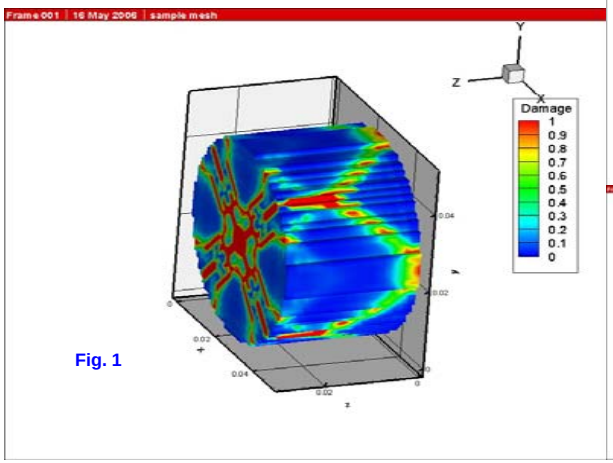


Fig. 1

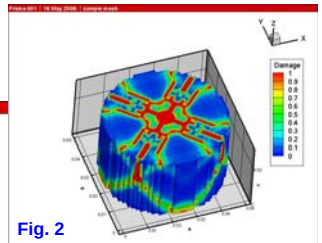


Fig. 2

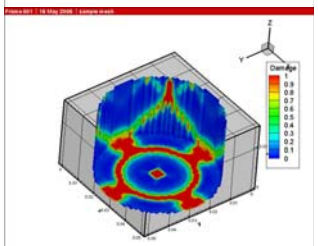
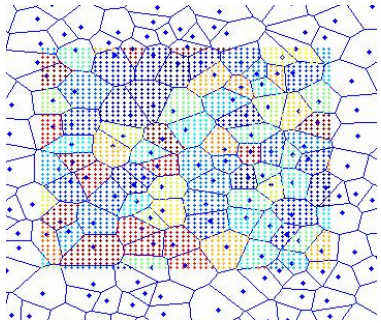


Fig. 3

Ongoing work – Generalized SPH Method

- Considering material heterogeneity
  - Using Voronoi polygons
    - Aggregates, composites
    - Rock joints, discontinuum



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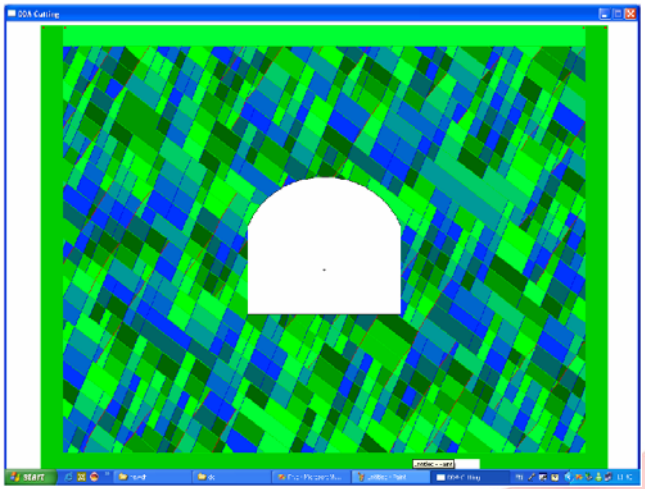
Ongoing Work – Application of Manifold Method



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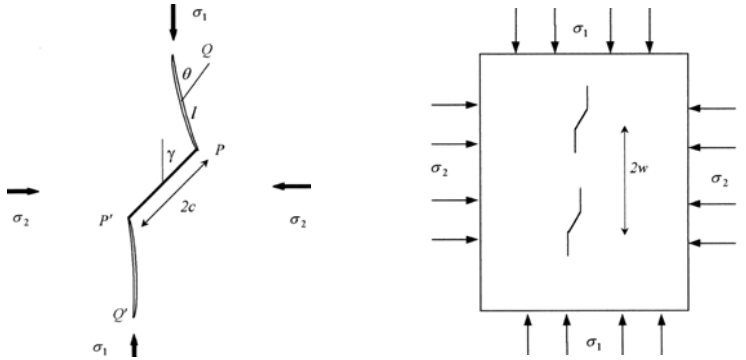
The Role of Fracture Mechanics –Sliding Crack Model



Wing-crack model and simplified model for array preexisting crack

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The Role of Fracture Mechanics –Sliding Crack Model

45^0, v=0.5m/s , length of preexisting crack=1.0cm

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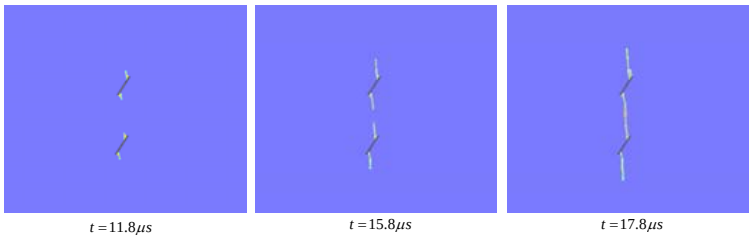
The Role of Fracture Mechanics –Sliding Crack Model

Effect of different orientation and strain rate on crack growth



60^0, v=1.0m/s , same preexisting cracks=1.0cm

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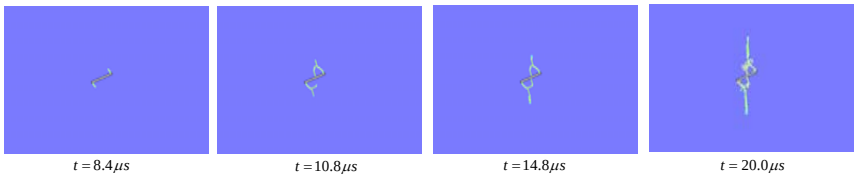
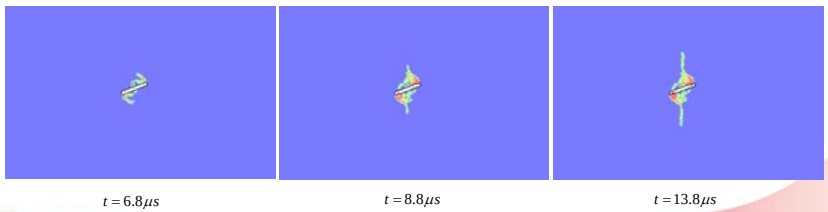
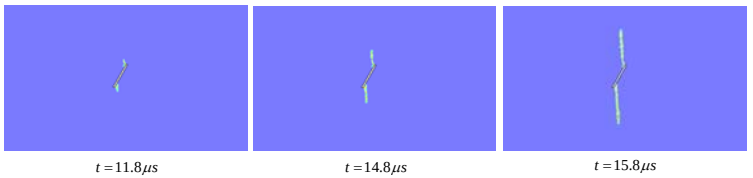


20^0, v=0.1m/s , length of preexisting crack=1.0cm

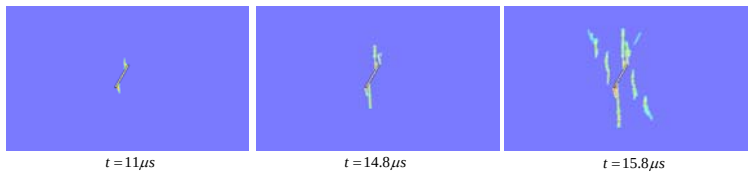


NANYANG TECHNOLOGICAL UNIVERSITY 20^0, v=0.5m/s , length of preexisting crack=1.0cm

The Role of Fracture Mechanics –Sliding Crack Model



60^0, v=0.5m/s , length of preexisting crack=1.0cm



60^0, v=1.5m/s , length of preexisting crack=1.0cm

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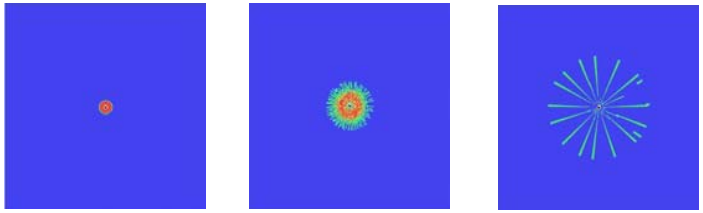
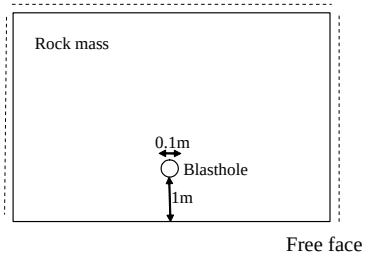
Borehole Blast Simulation: Influence of Loading Rate



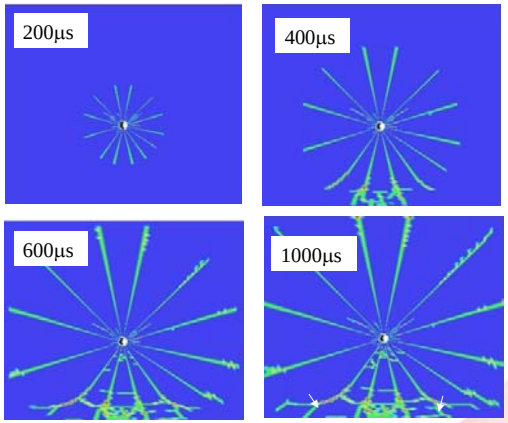
(a) 20 MPa/μs (b)10 MPa/μs (c)1.0 MPa/μs

Fracture pattern under different loading rate

Borehole Blast Simulation

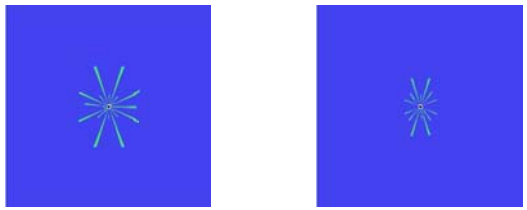


Blasthole model



Fracture Process

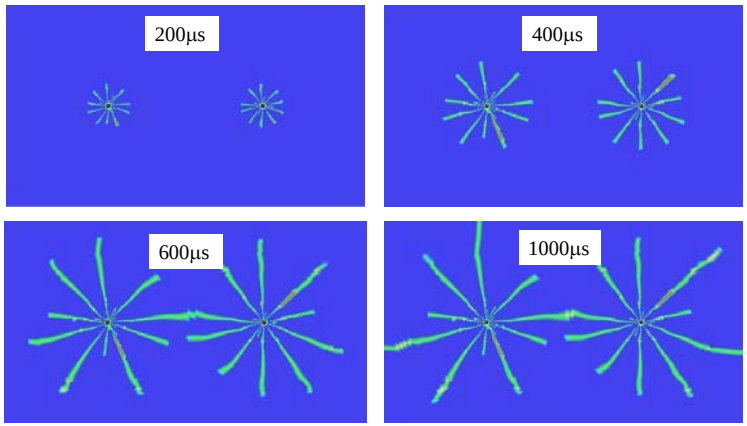
Influence of Pre-existing Stress



(a) 2 MPa (b) 10 MPa

(c) 30 MPa (d) 50 MPa

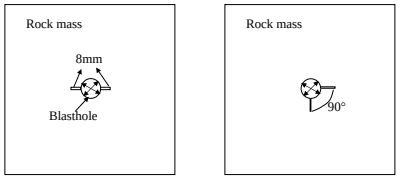
Crack Connections



Effectiveness of Blast damage control

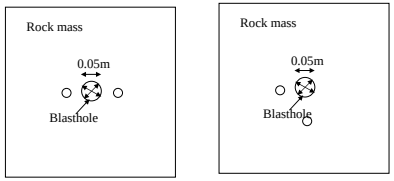
Control I

Blasthole with notches



Control II

Blasthole with concurrent holes



Control III

Charge holder with slits

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Summary

- Rock and rock joint dynamic properties.
- Mechanism of strain rate effect on rock dynamic failure.
- Modeling heterogeneity effect.
- Fracture mechanics versus damage mechanics.
- Continuum model versus discontinuous model.
- Rock engineering applications.

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Thank you !

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