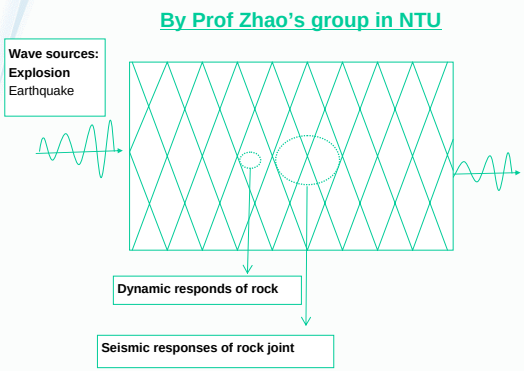
Some primary studies on response of rock structure under dynamic loads

Haibo Li

Institute of Rock and Soil Mechanics, CAS

Introduction

By Prof Zhao's group in NTU



Cavern/ Tunnel

Bedrock

Slope

Questions:

- What the mechanical properties of rock material and rock joint?
- How the shock wave propagate in rock mass?
- What the exact response of rock structures?

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Introduction

- Mechanical properties of rock material under dynamic loads
- Mechanical properties rock joints under dynamic loads
- Damage of bedrock under blasting excavation
- Response of rock slope under blasting excavation
- Response of rock slope under earthquake

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Mechanical properties of rock material under dynamic loads

Main works:

- **Experimental works :** shear, tensile, compressive, fracture toughness tests, study the change of strength of rock material with loading/strain rates (strain rate ranges: 10^{-4}-10^{1}/s, loading rate ranges: 10^{0}-10^{5}MPa/s)
- **Theoretical works :** sliding crack model is employed to simulate the mechanical properties of rock under dynamic compression

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Mechanical properties of rock material under dynamic loads

Rock dynamic testing system

Tension , compression, shear, fracture toughness test

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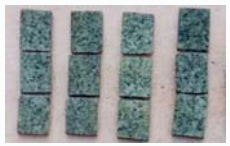
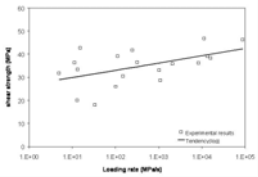
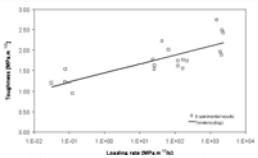
Mechanical properties of rock material under dynamic loads

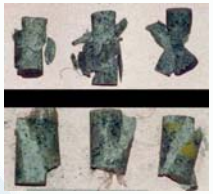


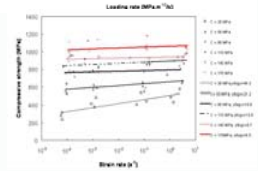


Dynamic shear test



Dynamic fracture toughness test





Dynamic compression test

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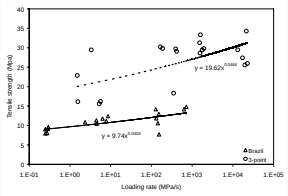
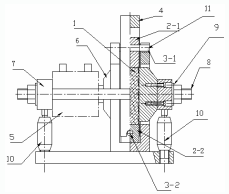
Mechanical properties of rock material under dynamic loads

Brazil method

3-piont bending method





Direct tension test with lateral compression(0-70MPa)

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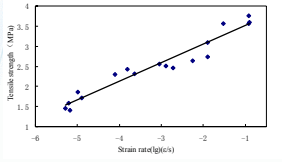
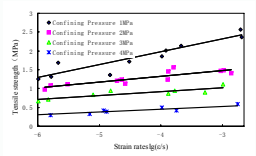
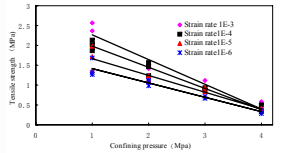
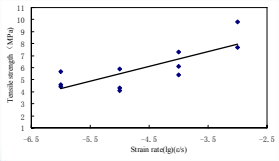
Mechanical properties of rock material under dynamic loads

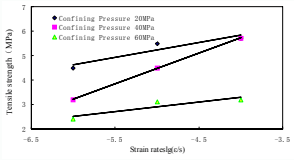


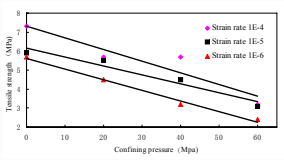




Gypsum samples







Granite samples

Direct tension test results

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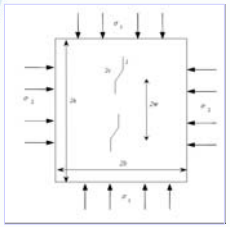
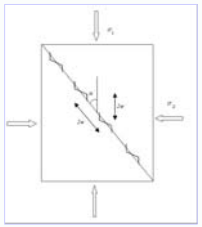
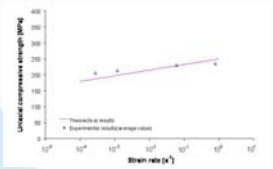
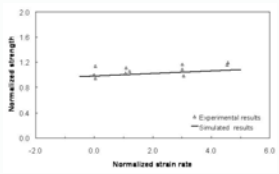
Mechanical properties of rock material under dynamic loads

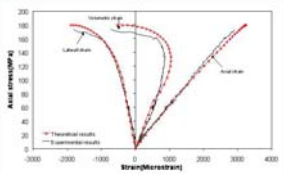




- ✓ Sliding crack model
- ✓ Simulate change of strength with strain rate and stress strain relation
- ✓ Study why and how the strength change with strain rate







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Mechanical properties of rock joint under dynamic loads

Main work:

- ✧ Experimental study on shear strength and stiffness of rock joint under different shear deformation velocities, undulation angles, normal stresses
- ✧ In order to simulate the mechanical properties of rock joint under earthquake

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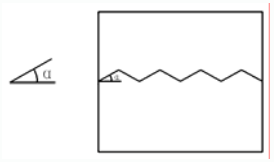
Mechanical properties of rock joint under dynamic loads



Artificial concrete rock samples

- ✓ Shear deformation velocities :0.02mm/s, 0.1mm/s, 0.4mm/s,0.8mm/s
- ✓ Normal stress: 1 MPa, 2 MPa and 3 MPa
- ✓ Undulation angle: 15°, 30 °, 45 °

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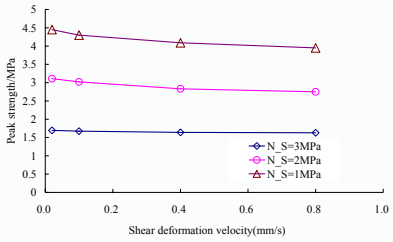
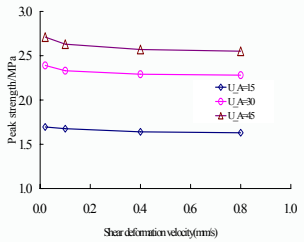
Mechanical properties of rock joint under dynamic loads



At different normal stresses (undulation angle=15°)



At different undulation angles (normal stress=1MPa)

Change of peak shear strength with shear deformation velocity

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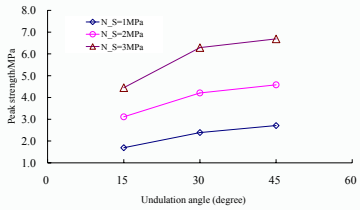
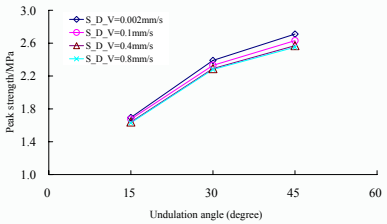
Mechanical properties of rock joint under dynamic loads



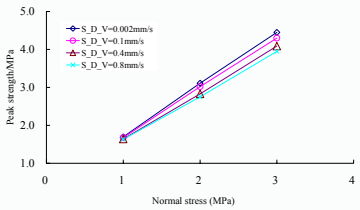
At different normal stresses
(shear deformation velocity=0.02mm/s)



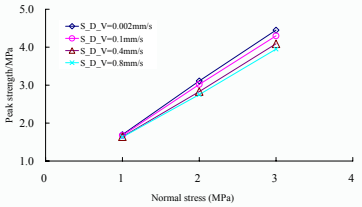
At different shear velocities
(normal stress＝1MPa)

Changes of peak shear strength with undulation angle

Mechanical properties of rock joint under dynamic loads



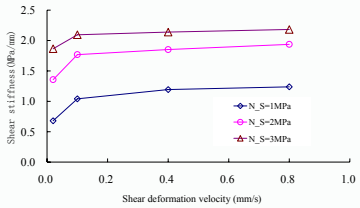
At different shear deformation velocities
(undulation angle＝15°)



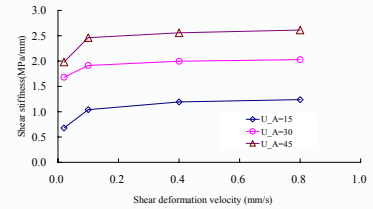
At different undulation angles (shear deformation velocity=0.02mm/s)

Change of peak shear strength with normal stress

Mechanical properties of rock joint under dynamic loads



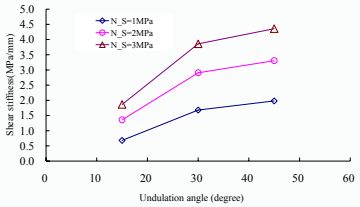
At different normal stresses
(undulation angle ＝15°)



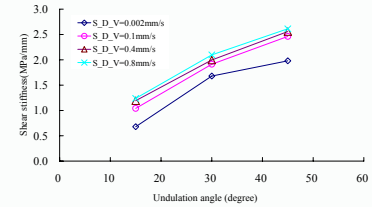
At different undulation angles
(normal stress＝1MPa)

Change of shear stiffness with shear deformation velocity

Mechanical properties of rock joint under dynamic loads



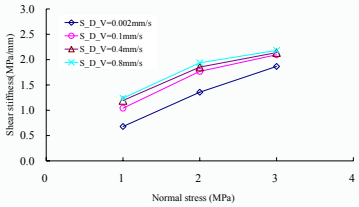
At different normal stresses
(shear deformation velocity = 0.02mm/s)



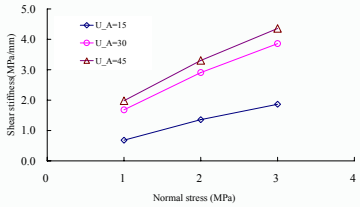
At different shearing deformation velocities
(normal stress＝1MPa)

Change of shear stiffness with undulation angle

Mechanical properties of rock joint under dynamic loads



At different shear deformation velocities (undulation angle=15°)



at different undulation angles (shear deformation velocity=0.02mm/s)

Change of shear stiffness of joints with normal stress

Mechanical properties of rock joint under dynamic loads

$$\tau_p = \sigma_n \tan(\phi_r + \alpha)$$

$$\tau_p = \sigma_n \tan\left[\phi_r + \alpha(\alpha_0)\right] f(\dot{u})$$

$$\tau_p = 0.883\sigma_n \tan\left[\phi_r + 7.526(\alpha_0)^{0.37}\right]\dot{u}^{-0.032}$$

Change of shear strength with normal stress, undulation angle and shear deformation velocity by regression

$$k_t = \frac{\partial\tau}{\partial u} = \frac{\tau_p}{L/100} = \frac{\sigma_n \tan\left[JRC\lg(\frac{JCS}{\sigma_n}) + \phi_r\right]}{L/100}$$

$$k_t = \frac{\sigma_n \tan\left[\phi_r + \alpha'(\alpha_0)\right]}{L/100} h(\dot{u})$$

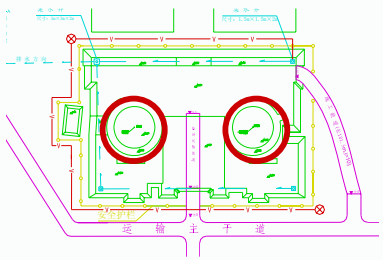
$$k_t = \frac{1.218\sigma_n \tan[\phi_r + 0.134\alpha_0^{1.466}]}{L/100}\dot{u}^{0.045}$$

Change of shear stiffness with normal stress, undulation angle and shear deformation velocity by regression

Damage of bedrock under blasting excavation

⇦ Lingdong nuclear power plant

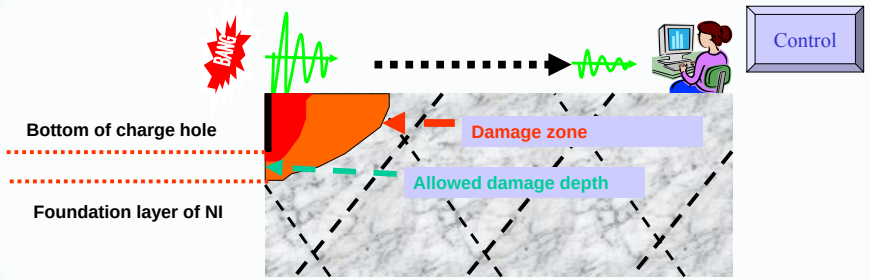
⇩ Hongyanhe nuclear power plant



Rock foundation of nuclear island

Damage of bedrock under blasting excavation

- ✓ **Bedrock is granite, blasting excavation, should be extremely controlled to ensure the integrity of bedrock**



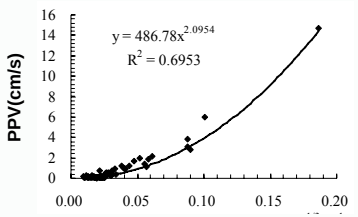
- ✓ **Should control the blasting excavation to ensure the allowed damage depth of the blasting not up to foundation layer of NI**

Damage of bedrock under blasting excavation

Main works:

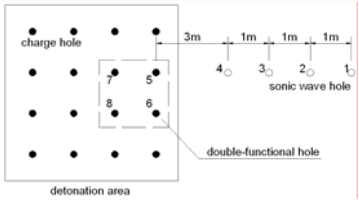
- ✧ **Study the damage of bedrock for nuclear island under blasting excavation**
- ✧ **Provide the safety threshold velocity to control the blasting excavation**
- ✓ **Site monitoring: blasting vibration monitoring, sonic wave test**
- ✓ **Numerical simulation**

Damage of bedrock under blasting excavation

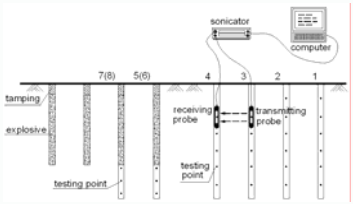


Blasting vibration monitoring

Damage of bedrock under blasting excavation



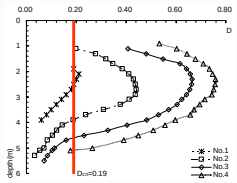
Sonic test layout

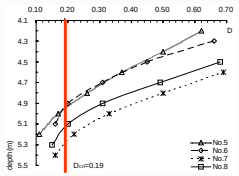


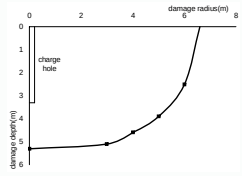
Sonic test system

Conduct sonic wave test before and after blasting to study the damage of rock mass

Damage of bedrock under blasting excavation





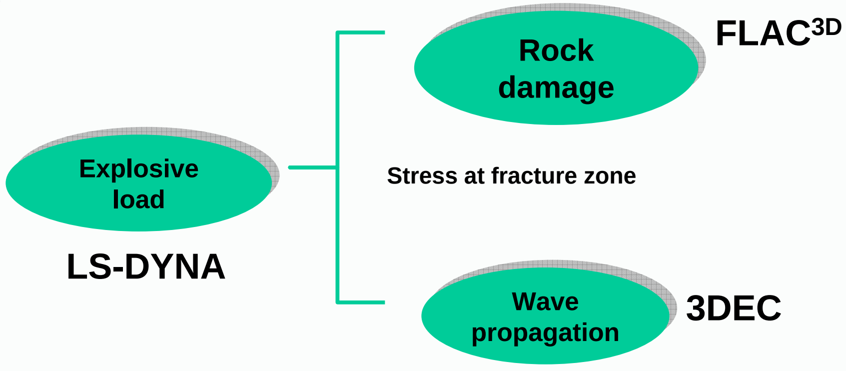


$$D = 1 - \frac{E}{E_0} = 1 - \left(\frac{c}{c_0}\right)^2 = 1 - (1-\eta)^2$$

Damage contour of rock mass around detonation area

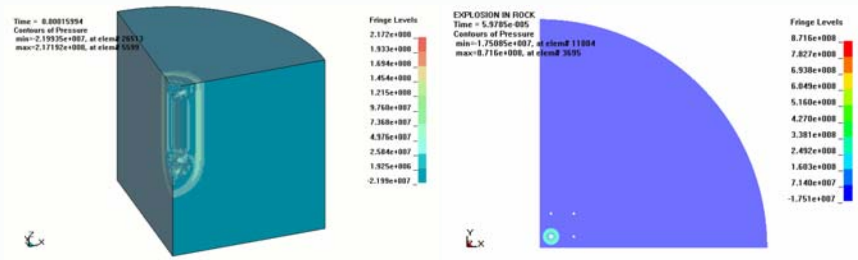
- ✓ **According to the sonic wave test results, the change of elastic modulus of rock mass before and after blasting can be also obtained**
- ✓ **D , damage variable, defined as the change of elastic modulus**
- ✓ **According to the technical regulation of China, decreasing ratio of the wave speed of rock mass before(c_0) and after explosion (c) should be less than 10%, change of elastic modulus is then less than 19%, damage threshold D_{cr} is 0.19**

Damage of bedrock under blasting excavation



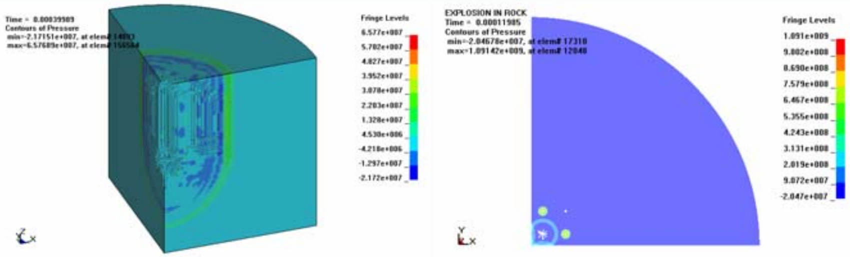
Numerical simulation

Damage of bedrock under blasting excavation



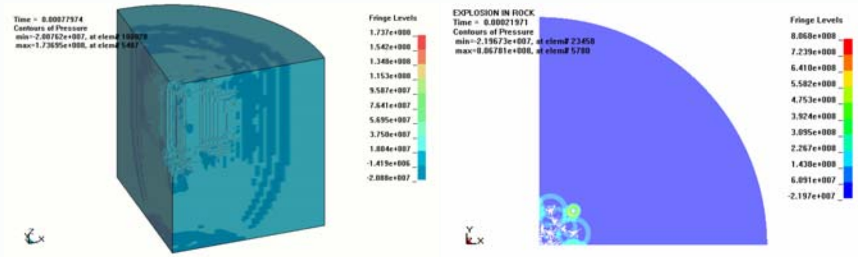
Shock stress propagation

Damage of bedrock under blasting excavation



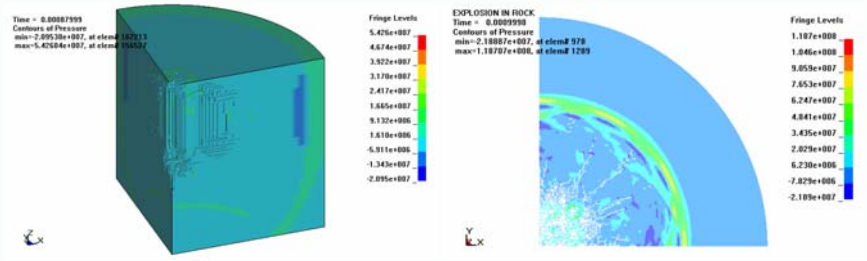
Shock stress propagation

Damage of bedrock under blasting excavation



Shock stress propagation

Damage of bedrock under blasting excavation



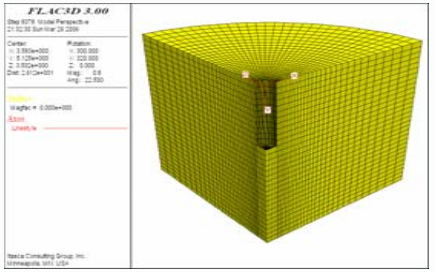
Shock stress propagation

Damage of bedrock under blasting excavation

- Damage variation: micro crack based presented by Yang R, Bawden W.F, Katsabanis P.D.
- Damage threshold: 0.2

$$D_i = p_f = 1 - e^{-C_{di}^2}$$

$$C_{di} = \begin{cases} \alpha_i(\varepsilon_i - \varepsilon_{cri})^{\beta_i} \cdot t & \varepsilon_i > \varepsilon_{cri} \\ 0 & \varepsilon_i \le \varepsilon_{cri} \end{cases}$$



Rock damage simulation model

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Damage of bedrock under blasting excavation

Vertical direction **Horizontal direction**

Damage growth

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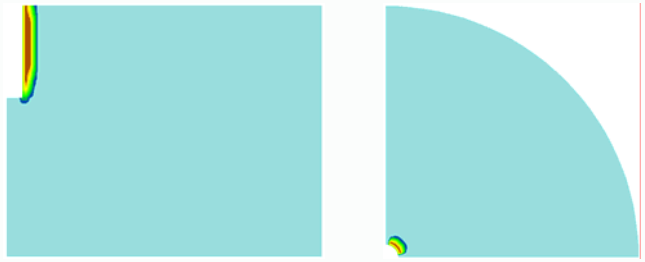

Vertical direction **Horizontal direction**

Damage growth

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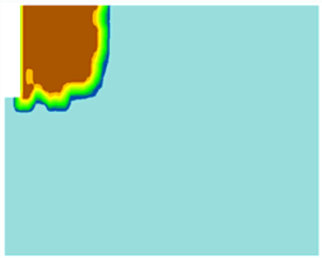
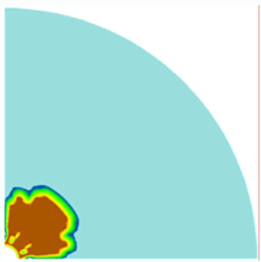
Damage of bedrock under blasting excavation



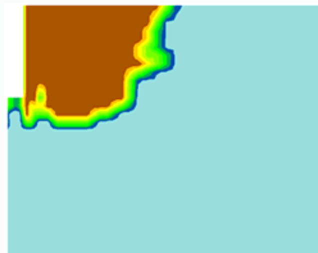
Vertical direction



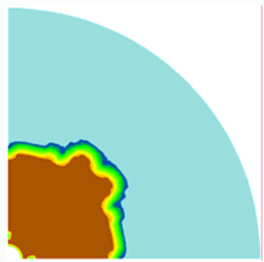
Horizontal direction

Damage growth

Damage of bedrock under blasting excavation



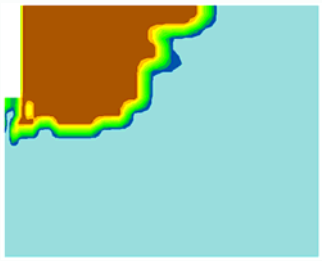
Vertical direction



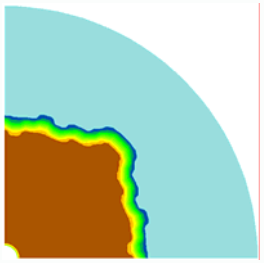
Horizontal direction

Damage growth

Damage of bedrock under blasting excavation



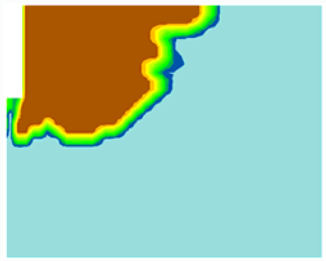
Vertical direction



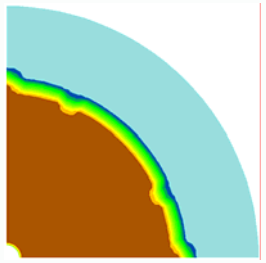
Horizontal direction

Damage growth

Damage of bedrock under blasting excavation



Vertical direction



Horizontal direction

Damage growth

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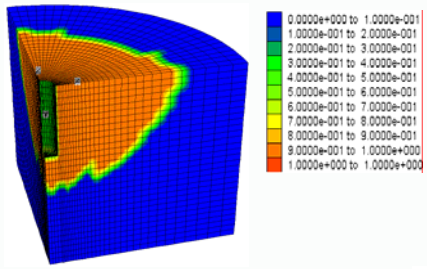
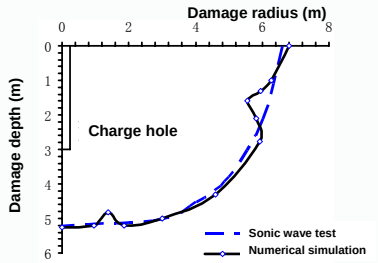


Simulated damage contours

Simulated results and sonic wave test results



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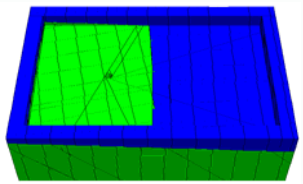
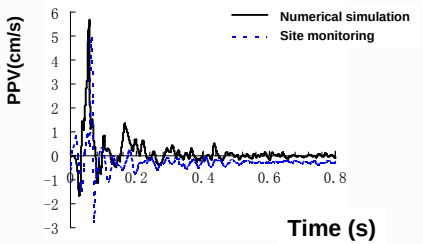
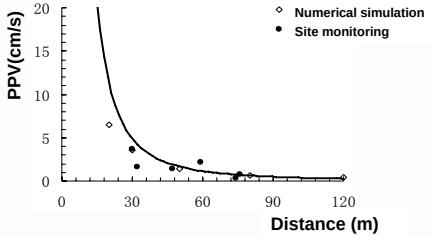


3DEC model



Wave propagation simulation



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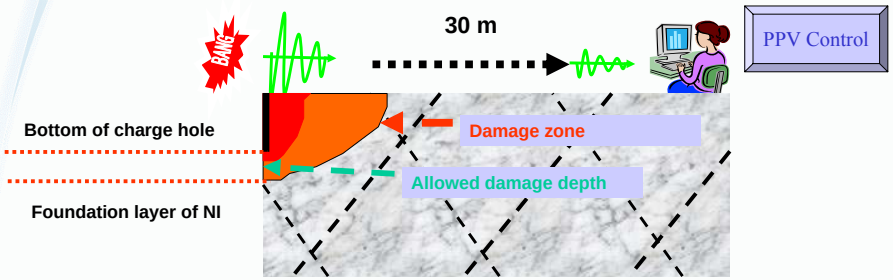
Damage of bedrock under blasting excavation



PPV at 30m are employed to control the rock damage , when the PPV at 30m is less than a certain value, the damage depth is within allowed damage depth

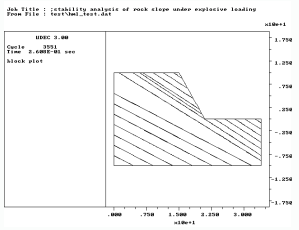
Project	Allowed damage depth	Threshold PPV at 30 m
Lingdong	1.5m	5cm/s
Hongyanhe	1.15m	2.5cm/s

Response of rock slope under explosion

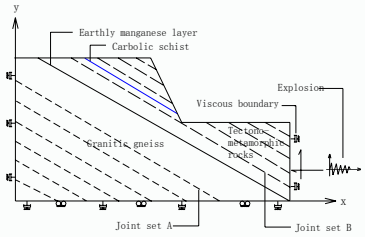
Huangmailin Phosphorite mine

- Based on the Huangmailin Phosphorite mine project
- Main problem: how to guarantee the stability of the rock slope under blasting excavation?
- Safety threshold velocity should be presented to control the blasting excavation

Response of rock slope under explosion



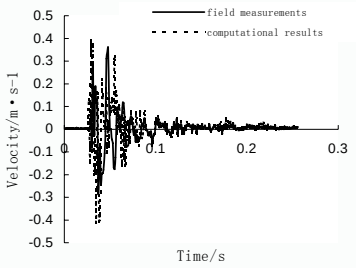
UDEC model of the rock slope



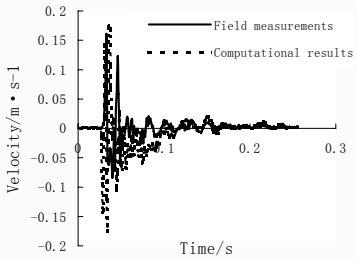
Boundary conditions of the model

- UDEC is employed to simulate the response of the rock slope under blasting excavation

Response of rock slope under explosion

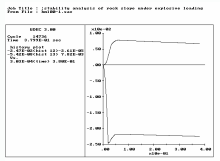
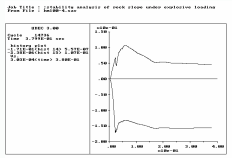
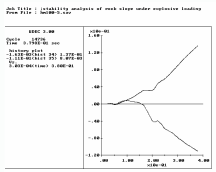


Vertical velocity history of the slope toe obtained by computation and site monitoring



Horizontal velocity history of the slope toe obtained by computation and site monitoring

Response of rock slope under explosion

stable condition → Limit equilibrium condition → unstable condition

- In simulation, amplifying the magnitude of the explosive loads, the stable and unstable condition of the rock slope can be obtained according to the convergent and scatter condition of displacement
- The safety threshold velocity of the rock slope under explosion can be obtained, as 30cm/s at slope toe

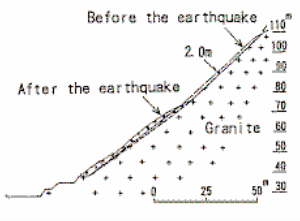
Response of rock slope under earthquake

Landslide triggered by earthquake

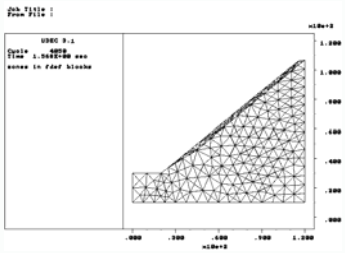
- Two parameters are usually employed to evaluate the response of rock slope under earthquake
- ✓ Permanent displacement ?
- ✓ Factor of safety ?

Response of rock slope under earthquake

- UDEC is employed to study the displacement properties of rock slope under earthquake



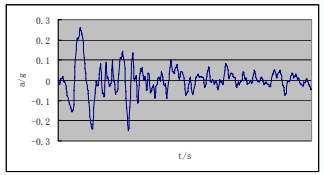
Rokko landslide



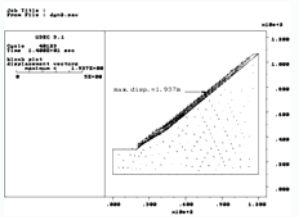
UDEC model

Okimura T., Yamugami T., Vagi K. Slope failure during the 1995 south Hyogo earthquake in Japan

Response of rock slope under earthquake



Input earthquake load

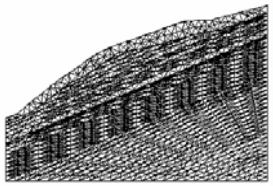


Displacement vector of the Rokko landslide

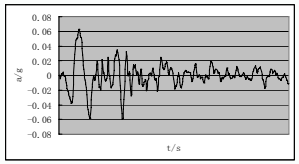
	Site monitoring	UDEC Modeling	Nemark method
Permanent Displacement (cm)	200.09	160.3	59.0

Response of rock slope under earthquake

Zhongjiawan rock slope



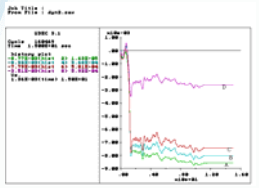
UDEC model



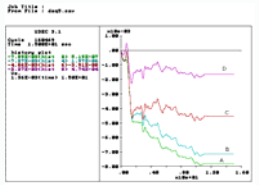
Input earthquake load

- UDEC is also employed to study the safety factor of rock slope under earthquake
- Based on project: Shanghai-Chendu highway

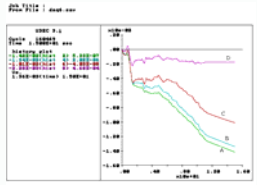
Response of rock slope under earthquake



stable condition
K=1.0



Limit equilibrium condition
K=1.12



unstable condition
K=1.13

- In simulation, strength reduction method is used. $c_k = \frac{c}{K}$ $\phi_k = \arctan\frac{\tan\phi}{K}$
- By reduction the strength of rock structure, the stable and unstable condition of the rock slope can be obtained according to the convergent and scatter condition of displacement

Response of rock slope under earthquake

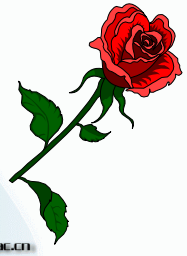
Earthquake intensity =6.0

	Static load equilibrium method	Pesudo static equilibrium method	UDEC modeling
Factor of Safety	1.18	1.07	1.12

Conclusion remarks

- Some research works have been done related to rock dynamics
- Include: mechanical properties of rock material and rock joint, damage of bedrock under blasting excavation, response of rock slope under blasting and earthquake
- Most of them are the primary and trial works, need more further and thoroughgoing works

Thank for your attention !



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