深地科学论坛（第四十八讲）：深地岩石力学特性及模拟方法

时间：2022 年 12 月 20 日 20:00-22:30（GMT+8）

地点：腾讯会议直播（ID 号：625-932-229）

邀请人：鞠明和、胡李华

报告人	报告人单位	报告题目
白庆升	德国弗莱贝格大学岩土研究所	基于原位应力路径的真三轴声发射和波速变化研究 -- 以 Mine-by 隧道为例
李晓锋	加拿大多伦多大学土木工程系	OpenFDEM 开源程序开发及其在岩石动力学和多物理场耦合中的应用

欢迎全校教师及同学参加！

深部岩土力学与地下工程国家重点实验室

深部地下工程学科创新基地

《深地科学（英文）》

力学与土木工程学院

江苏省岩土力学与工程学会

2022. 12. 20

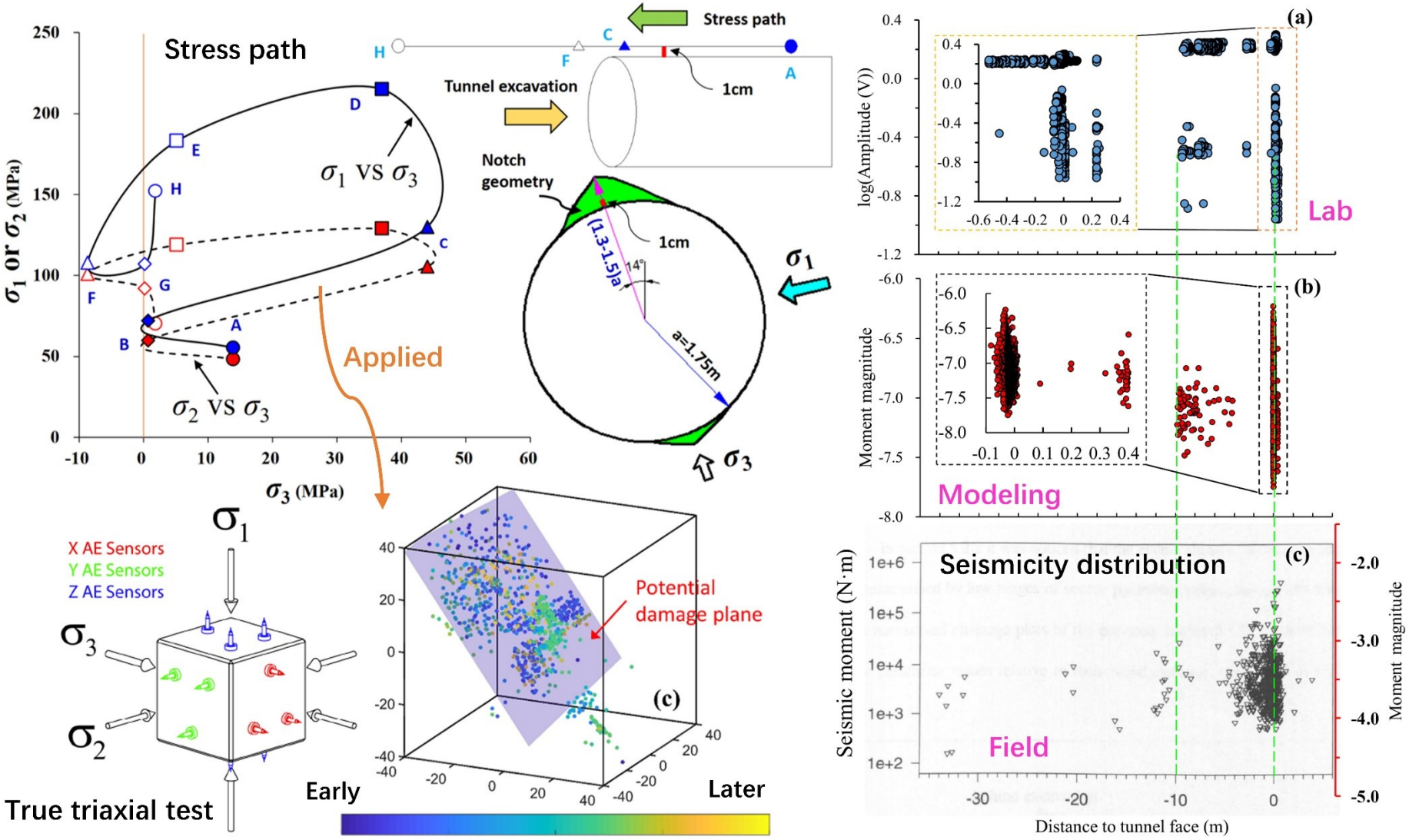
报告人简介：

白庆升，博士，副教授，现为弗莱贝格工业大学岩土研究所 PI。主要从事岩石力学和岩石工程方面的研究工作。现任 SCI 期刊《Journal of Geophysics and Engineering》和《Advances in Civil Engineering》编委。入选“2016 年博士后国际交流派出计划（2016-2018）”、“德国洪堡学者（2020-2021）”。主持或参加国家重点研发计划、国家自然科学基金、德国科学基金会（DFG）项目以及与企业合作科研项目 10 余项，获省部级奖 8 项。在 Geophysical Research Letters、International Journal of Rock Mechanics and Mining Sciences、Rock Mechanics and Rock Engineering 等期刊发表 SCI/EI 学术论文 60 余篇，文章被引 1400 余次(https://scholar.google.com/citations?user=REayZYgAAAAJ&hl=zh-CN&oi=ao)。授权国家发明专利 3 项，实用新型专利 12 项。

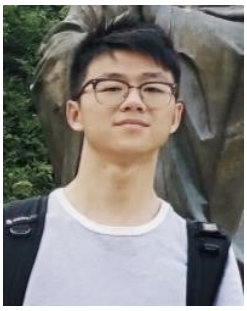
基于原位应力路径的真三轴声发射和波速变化研究 -- 以 Mine-by 隧道为例

报告摘要：

工程岩体的损伤与破坏行为与其所经历的应力路径息息相关。在实验室中，经常采用加载的方法来测试岩石的力学特性；但工程实践中，由卸荷造成的岩石破坏经常发生，比如开挖边界的片帮行为。因此，采用加载的方法无法真实的反映现场实际。本研究根据加拿大地下实验室 Mine-by 隧道开挖实际，获取了 Mine-by 隧道顶板在开挖过程中的应力变化情况。开展了开挖应力路径下花岗岩损伤特征的真三轴实验和离散元数值模拟研究，基于声发射监测结果分析了该加载应力路径下花岗岩的损伤演化过程；从震源机制和裂隙破裂规律角度，揭示了卸荷诱发花岗岩损伤并形成宏观破裂的微观机制。研究了加卸载过程中三个方向波速的变化情况；数值模拟研究了中间主应力卸载对微观裂隙发育的影响。该方法突破了以往实验研究的局限性，对指导和寻求更加真实模拟工程实际的实验方法具有重要的理论和实践意义。


Stress path
σ_1 or σ_2 (MPa)
σ_3 (MPa)
σ_1 VS σ_3
σ_2 VS σ_3
Applied
Stress path
Tunnel excavation
1cm
Notch geometry
(1.3-1.5)a
14°
a=1.75m
σ_1
σ_3
X AE Sensors
Y AE Sensors
Z AE Sensors
σ_1
σ_3
σ_2
True triaxial test
Potential damage plane
(c)
Early
Later
(a)
log(Amplitude (V))
Lab
(b)
Moment magnitude
Modeling
Seismicity distribution
(c)
Seismic moment (N·m)
Moment magnitude
Field
Distance to tunnel face (m)

报告人简介：



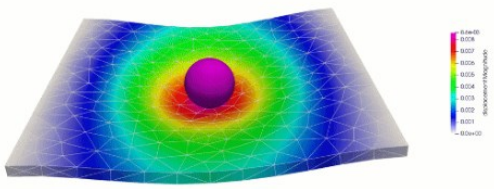
李晓锋，博士，现为多伦多大学土木工程系高级研究助理，主要从事岩石动力学及连续-非连续计算方法方面的研究。中国岩石力学与工程学会岩石动力学专委会副秘书长，J Rock Mech Geotech 科学编辑。2019 年度中国科学院院长特别奖、中国科学院百篇优秀博士论文获得者。自主开发了 OpenFDEM 连续非连续计算程序，形成了 2D/3D、热、流体、爆炸、颗粒离散元、相场及 CFD 等求解器集成的免费计算平台(https://xiaofengli-uoft.github.io/Mainpage/)。先后获得 2020 度中国岩石力学与工程学会优秀博士论文(排名第 1)，2021 年度国际岩石力学学会 Rocha 奖银奖，2022 年度美国岩石力学学会未来领袖计划、湖北省科技进步一等奖(2/15)。以第一作者或通讯作者在 Comput Method Appl M、Int J Rock Mech Min 等期刊发表 SCI/EI 论文 30 余篇，Scopus 引用 1100 余次，论文入选 2020 年度陈宗基讲座优秀论文、中国精品科技期刊领跑者 5000。

OpenFDEM 开源程序开发及其在岩石动力学和多场耦合中的应用

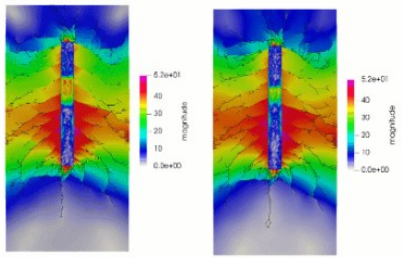
报告摘要：

Rock deformation and breakage behaviour under dynamic loads cover a wide range of areas including tunnelling, earthquake, projectile penetration, and exploration drilling in petroleum and nuclear waste deposits. In this presentation, the dynamic fracturing of rock spanning from mineral scale to laboratory scale is characterized, and the mechanism of rate dependency leaded by the transition from intergranular fracturing to transgranular fracturing is revealed. The rate dependency of the characteristic size, debris distribution and pulverization law of rocks are discussed. Two typical failure types are proposed and a novel energy-based fragment model is carried out to address the underlying mechanism of pulverization of rock under high strain rate.

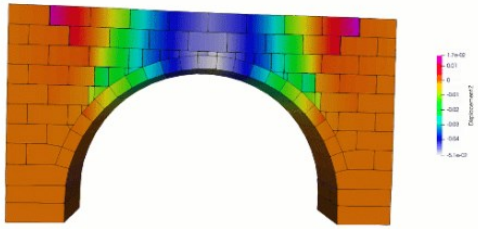
OpenFDEM is a free finite and discrete element solver with object-oriented architecture for solving multiscale, multiphase and multiphysics (3M) problems that operates on various platforms. The applications are, but not limited to, mechanical, thermal and fluid problems. Additional acceleration techniques are used to boost the calculation as well. OpenFDEM is a portable kernel, which contains static, nonlinear static and dynamic(explicit) solvers, it has a friendly preprocessing module to generate mesh, which supports to import over 6 formats, e.g. geo, .inp, .msh, .stl, .step, .igs, .dxf, .jpg and .tess . The solver is composed by FEM, DEM, thermal, hydro, phasefield, particulate DEM, CFD and MPM kernels. OpenFDEM supports 26 element types and 17 materials, which can be used for brittle, ductile, phasefield, nonlocal, viscous and fatigue problems. The supporting modules, e.g. documentation, GUI, coupling interface and particle library are also built to extend the application. In this presentation, I will give an overview of the development and functionalities of the OpenFDEM.



E1. Large deformation with hyperelastic mat



E2. Detonation in explosive, JWL mat



E3. Arch bridge failure, build by Hexahedron (polyhedron) , geometry from itasca

Element type (26)

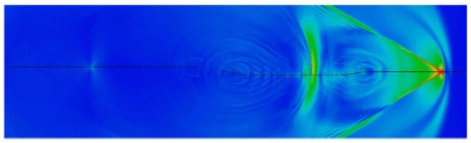
- Linear element: TRIANGLE 3, QUADRILATERAL 4, TETRAHEDRON 4, HEXAHEDRON 8, PRISM 6, PYRAMID 6
- Quadratic element: TRIANGLE 6, QUADRILATERAL 9, TETRAHEDRON 10, HEXAHEDRON 27, PRISM 18, PYRAMID 14
- Reduced integration: QUADRILATERAL 8, HEXAHEDRON 20, PRISM 15, PYRAMID 13,
- Interface element: COH 3, COH 7, COH 4, COH 8, COH 9
- Structure element: POINT 0, LINE 2, LINE 3
- Others: POLYGON, POLYHEDRON

Material library (24)

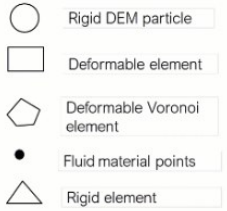
- Matrix material: elastic, hyperelastic, transverse, Mohr-Coulomb plastic, Drucker–Prager plastic, Viscous Burgers, Viscous Power law, Mazars damage, CDP, JH2, JWL, phasefield, nonlocal damage
- Interface material: Evans-Marathe, anisotropic, heterogenous, Ortiz-Pandolfi, rate-dependet, linear, Fatigue
- Contact material: Mohr-Coulomb, hertz, RSF, dilation shear, dynamic friction

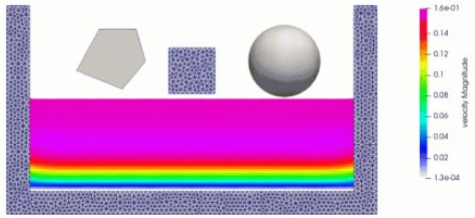
Contact

- Rough search: NBS, Cell-based, time-dependent cell method
- Contact type: Triangle-Triangle, Quad-Triangle, Quad-Quad, quadratic contact pair, Line-Arbitary, Arbitary-Arbitary
- Potential model: Munjiza potential, Yuntian potential, penalty method



E4. Supershear friction in two adjacent faults, RSF contact model





E5. Toys in a tank

OpenFDEM kernel

Mesh generator

Blast solver

Hydro solver

Thermal solver

FDEM kernel

Particle DEM solver

CFD solver

Parallelization

Material library

Documentation

open source initiative
Opensource

Cross-platform

Portable

Supporting module

Website and repository

GUI

Coupling interface

Particle library

Capabilities	OpenFDEM	vs.	Other codes
Ability to simulate the fracturing from continuum to discontinuum	✓		✓
High order element types	✓		✓ *1
Fruitful material library, supporting over 24 materials	✓		
Time-dependent contact detection algorithm	✓		✓ *2
Arbitrary-arbitrary contact type	✓		
Hydro module (including gas flow)	✓		✓ *3
Thermal module and THM coupling (include contact thermal)	✓		✓ *4
Fluid-Solid interaction (computational fluid dynamic)	✓		✓ *5
Blast and explosive EOS support	✓		
Built-in DFN generation (2D and 3D)	✓		✓ *6
Grain based model and image identification	✓		
Built-in module to create geometry, mesh and preprocessing	✓		✓ *7
Particulate DEM	✓		
Parallelization (GPU, CPU and clusters)	✓ *8		✓ *8
GUI			✓ *9
Structure			✓ *10

- OpenFDEM supports 17 element materials spanning elastic, hyperelastic, plastic, damage, nonlocal, viscous and phasefield models, supports 7 cohesive materials spanning static, dynamic and fatigue problems. It also contains 6 contact models including Mohr-coulomb friction, hertz contact, rate friction, rough dilation shear law and so on.
- high-order integration schemes and solving methods are used to seek more reliable numerical results which are comparable to theoretical solutions. The element type has a maximum order of three to rebuild the large deformation within the entity.
- Arbitrary-arbitrary contact type is available for OpenFDEM, a very general kernel for contact problem.

*1 Solidity supports ten-node tetrahedron.
*2 YH-FDEM has contact activation algorithm.
*3 MultiFracs and IRAZU have hydro module, IRAZU also has gas flow.
*4 Only MultiFracs and IRAZU have THM coupling.
*5 Only Solidity and HOSS have CFD. Solidity is coupled with Fluidity and HOSS uses built-in module.
*6 IRAZU has built-in function to create 2D DFNs, OpenFDEM supports create 3D DFNs.
*7 Only IRAZU and YH-FDEM support mesh generation, OpenFDEM supports 2D and 3D mesh generation both.
*8 IRAZU, YH-FDEM, MultiFracs have GPU parallelization, Hoss has MPI parallelization and OpenFDEM has OpenMP parallelization, OpenFDEM has OpenMP.
*9 IRAZU has strong UI, YH-FDEM also supports UI.
*10 IRAZU, MultiFracs and Y-geo support different structure element types.