CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

TRIP REPORT

SUBJECT: Short course on rock fracture mechanics offered by the University of Victoria, Canada. (20-3702-072)

DATE/PLACE: September 4-7, 1990 at the Empress Hotel, Victoria, British Columbia, Canada.

AUTHOR: Mikko Ahola

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TRIP REPORT

SUBJECT: Short Course on rock fracture mechanics offered by the University of Victoria, Canada. (20-3702-072)

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PERSON PRESENT: Mikko Ahola

BACKGROUND AND PURPOSE OF MEETING:

The purpose for attending the course was to enhance my background in the mechanics of rock fracture and its applications in geomechanics, geophysics, and mining engineering.

SUMMARY:

The course began with a brief review of the basic principles of solid mechanics in both two and three dimensions as background material for the fracture mechanics theory. Both linear and non-linear material models were discussed including linear elasticity, plasticity, and viscoelasticity. The majority of course was spent in the area of linear elastic fracture mechanics, however, a brief introduction was given to elastic-plastic fracture mechanics. The three basic fundamental modes of fracture include 1) mode I - tensile or opening mode, 2) mode II - in-plane shear or sliding mode, 3) mode III - anti-plane shear or tearing mode. In general, fracture mechanics problems may consist of one mode or a combination of fracture modes. For example, the propagation of a fault is usually considered a combination of fracture modes I and II, depending on the confinement pressures. Solution to these types of mixed mode problems requires the use of the principle of superposition to obtain an accurate description of the stress field and deformation around the crack tip. In addition, the solution of any fracture mechanics problem requires the calculation of the applicable stress intensity factors K_I, K_{II}, and K_{III}, corresponding to the three modes of fracture. These stress intensity factors are the magnitude of the crack tip stress field for a particular mode and depend on such factors as the applied load, the shape of the body, and the crack length.

The course covered some basic principles of laboratory testing for rock properties, including methods for determining the fracture toughness. The concept of subcritical crack growth was also introduced. This phenomena can result in significant rates of crack extension at critical stress levels substantially lower than

that predicted from the classical fracture mechanics theory. This is common in materials subjected to long-term loading, especially if high temperatures or reactive environments exist. Subcritical crack growth has recently been used as a mechanistic explanation for time dependent earthquake phenomena and the stability of hydrofractures. This has stimulated numerous laboratory studies of subcritical crack growth in minerals and rocks. Some experimental data on subcritical crack growth in rocks was presented, the majority of which has been done on quartz. Some fracture mechanics parameters have been determined for Nevada tuff. In general, the factors influencing subcritical crack growth in geologic materials include (1) the stress intensity factor, (2) temperature, (3) chemical equilibrium of any fluid present, (4) pressure, (5) rock microstructure, and (6) residual stresses remaining from tectonic activity.

Another topic covered in the course was wave propagation and dynamic crack analyses. The types of waves covered included P-waves, S-waves, Rayleigh-waves and Love-waves. Photoelasticity was used to show the results of lab experiments on wave propagation and crack-wave interaction. From the photoelastic fringe patterns at various times, one could easily visualize the different arrival times of the P and S-waves on a preexisting crack and their effect towards further propagating the crack. Rayleigh waves could also be seen propagating along the free surface of the crack.

Some examples of fracture mechanics principles applied to several geologic problems were discussed in the course. For example, the propagation of a fault was described earlier as being mixed mode in nature. The mode of crack or fault propagation is determined by the relative values of the shear and tensile stress intensity factors, denoted as K_{II} and K_I respectively. Most seismic faulting deep in the earth's crust is thought to involve processes of shear fracture and frictional sliding rather then tensile fracture. However, in areas of low lithostatic pressure near the earth's surface, out-of-plane tensile cracking has been observed at the ends of strike-slip faults. Laboratory experiments have shown that most shear fractures are unstable in the sense that they tend to propagate out of their original plane thus forming tensile cracks. However, under high confining pressures as would be expected deep underground, the shear stress intensity factor K_{II} can become several order of magnitudes greater than the tensile stress intensity factor K_I, causing the out of plane tensile cracking to be eliminated.

Hydraulic fracturing and geothermal energy projects are areas where fracture mechanics principles have proven to be most effective. However, a great deal of fracture mechanics research in geophysics has now focused on the study of earthquake rupture.

IMPRESSIONS/CONCLUSIONS:

Overall, the course was very informative in presenting the current state-of-the-art in rock fracture mechanics and areas of future

research. Fracture mechanics theory is now being used to address the mechanisms as well as the mechanics of crack growth. However, for the case of repository materials which would be subjected to long term loading, in addition to high temperatures and possible chemical reagents in the groundwater, the classical fracture mechanics theory breaks down. Much more experimental data on subcritical crack growth is needed to determine fracture parameters for these types of materials subjected to long term loadings and under the influence of extreme conditions.

A copy of the course outline is attached, and detailed course notes are available in my office for any one interested.

PROBLEMS ENCOUNTERED: NONE.

PENDING ACTIONS: NONE.

SIGNATURE

Mikko Ahola — Date: 10/16/90

CONCURRENCE

Sui-Min Hsieh for Asadul H. Chowdhury, Manager, RDCO — Date: 10/16/90

Allen R. Whiting, Diretor WSE&I — Date: 10/16/90

University Extension & Community Relations
UNIVERSITY OF VICTORIA

presents

Rock Fracture Mechanics

A Professional Development Short Course
in
Advanced Fracture Mechanics
Applied to Geomechanics and Mining

September 4 to 7, 1990

Presenters:

Dr. Hans Peter Rossmanith, Vienna University of Technology
Dr. Joanne Wegner, University of Victoria

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UNIVERSITY OF VICTORIA

ROCK FRACTURE MECHANICS

- Detailed Course Contents -

1. Introduction to fracture mechanics and its geomechanical and mining engineering applications

2. Elements of solid mechanics
2.1 Geomechanics convention for displacement, strain, and stress
2.1.1 Force and stress
2.1.2 Stress transformation
2.1.3 Stress in 3 dimensions
2.1.4 Stress transformation in 3 dimensions
2.1.5 Stress deviation
2.1.6 Differential equations of static equilibrium
2.1.7 Displacement and strain
2.1.8 Principal strains, strain transformation, volumetric strain and deviator strain
2.1.9 Strain compatibility equations
2.1.10 Stress-strain relations
2.2 Methods of stress analysis
2.2.1 Principles of classical stress analysis
2.2.2 Circular excavation
2.2.3 Zone of influence of an excavation
2.2.4 Effect of planes of weakness on elastic stress distribution
2.2.5 Elliptical excavation
2.3 Nonlinear Material Behaviour
2.3.1 Linear elasticity of rocks
2.3.2 Nonlinear elasticity of rocks
2.3.3 Deformation Plasticity of rocks
2.3.4 Flow plasticity of rocks
2.3.5 Progressively fracturing theory of rocks
2.3.6 Linear viscoelasticity of rocks
2.3.7 Elastoviscoplasticity of rocks
2.3.8 Endochronic plasticity of rocks
2.3.9 Endochronic viscoplasticity of rocks
2.4 Friction
2.4.1 Friction of rocks
2.4.2 Phenomena with smooth surfaces
2.4.3 Sliding on a plane of weakness: 2 dimensional theory
2.4.4 The study of friction in triaxial apparatus
2.4.5 Sliding on a plane of weakness: 3 dimensional theory
2.4.6 The effects of time and relative displacement on rock friction
2.5 Elasticity and strength of rock
2.5.1 The stress-strain curve
2.5.2 Types of fracture
2.5.3 The Coulomb criterion
2.5.4 Mohr's hypothesis
2.5.5 The plane Griffith criterion

3. Stress
3.1. The state of stress underground
3.2 The influence of confining stress on fracture
3.3 The stress circle
3.3.1 Applications
3.4 Fracture of anisotropic rock
3.5 Role of fluid in the fracture of rock
3.6 Effect of preexisting fractures
3.7 Brittle plastic transition
3.7.1 Cylindrical polar coordinates
3.8 General deformation of released energy
3.8.1 Mining consequences of energy changes
3.8.2 Thin tabular excavations
3.9 Rock mass response to mining
3.9.1 Stratified rock
3.9.2 Jointed rock
3.9.3 Identification of potential failure modes

4. Engineering rock fracture mechanics
4.1 Linear elastic fracture mechanics
4.1.1 Stresses and displacements for the near crack-tip field
4.1.2 Mixed-mode fracture
4.2 Elastic-plastic fracture mechanics
4.2.1 The J-integral
4.2.2 Crack extension laws
4.2.3 Process zone
4.2.4 Crack tip opening displacement
4.2.5 Simplification and constraint of stress state
4.2.6 Crack growth resistance curves
4.3 Mechanics of shear rupture applied to earthquake zones
4.3.1 Shear fracture mechanics
4.3.2 The J-integral
4.3.3 Slip-weakening of shear rupture
4.4 Stress criterion
4.5 Stress and displacement distribution around a crack Plane problem mode I and II
4.5.1 Anti-plane strain - Mode III
4.5.2 Boundary conditions
4.5.3 Geophysical modelling and interpretations
4.5.4 The Westergaard stress function approach
4.5.5 Displacement field
4.5.6 Geological considerations
4.5.7 The stress field
4.5.8 Special regions in the vicinity of the crack

5. The theory of subcritical crack growth with applications to minerals and rocks
5.1 Process or damage zone theories
5.2 overview of experimental data
5.2.1 Quartz
5.2.2 Quartzites and sandstones
5.2.3 Granitic rock
5.2.4 Basic rocks
5.2.3 Marbles and limestones
5.2.6 General remarks
5.3 Factors influencing subcritical crack growth
5.3.1 Influence of stress intensity factor
5.3.2 Influence of temperature
5.3.3 Influence of pressure
5.3.4 Influence of microstructure
5.3.5 Influence of residual strains

5.3.6 Subcritical crack growth limit and crack healing
5.4 Continuum damage models
5.4.1 Basic elements
5.4.2 Microcrack damage
5.4.3 Evolution of damage

6. Laboratory testing
6.1 Classical testing of strength
6.1.1 Results of triaxial tests
6.1.2 Diametral compression of cylinders
6.1.3 Dynamic methods
6.2 Stiff and servo-controlled testing machines
6.3 Fracture toughness testing of rock
6.3.1 On specimen geometries
6.3.2 Specific work of fracture
6.3.4 Fracture toughness
6.3.5 J-integral resistance
6.3.6 Anisotropy effects
6.3.7 Rock fracture toughness testing specimens
6.3.8 Crack resistance measurements in core specimens
6.3.9 Conclusions

7. Rock dynamics
7.1 Wave propogation
7.1.1 Waves in unbounded media
7.1.2 Superposition of elastic waves
7.1.3 Boundary effects
7.1.4 Plate waves
7.1.5 Surface waves
7.1.6 Non-planar wave fronts at boundaries and interfaces
7.1.7 Dynamic layer detachment and spallation
7.2 Dynamic crack analysis
7.2.2 The constant speed running crack
7.2.3 Non-uniformly moving cracks
7.2.4 The fundamental solution
7.2.5 Discontinuous change of crack speed
7.3 Crack wave interaction
7.3.1 Phenomenological investigations of crack-wave propogation
7.3.2 Interface cracks and joints
7.3.3 Double crack at a bondline
7.3.4 Fracture network development from multiple bondline cracks
7.3.5 Transmission of waved and cracks across interfaces
7.3.6 Dissimilar media interface cracking
7.3.7 Interface cracking
7.4 Cracks subjected to stress wave loading (theory)

8. Conceptual methods of stress analysis
8.1 The boundary element method
8.2 The finite element method
8.2.1 Displacement variation
8.2.2 Stress within an element
8.2.3 Solution for nodal displacements
8.3 Distinct element method
8.3.1 Force displacement laws
8.3.2 Law of motion
8.3.3 Computational scheme
8.4 Hybrid computational schemes
8.5 Numerical modelling of crack initiation and propogation
8.5.1 Fracture process zone
8.5.2 Numerical fracture modelling under mixed mode conditions

9. Applications
9.1 Geological applications
9.1.1 Normal fault quasistatic propogation
9.1.2 Fault filled with thin compressible material
9.1.3 Effect of fault filling material
9.1.4 Fault growth direction
9.2 Overview of geophysical applications
9.2.1 Fault mechanics and deformation of the lithosphere
9.2.2 Displacements near the San Andreas fault (following the 1906 earthquake)
9.2.3 Veins and solution surfaces at terminations of small faults
9.2.4 Spacing of joints in layered rock
9.3 Fracture mechanics of hydraulic fracturing and hot dry rock geothermal energy
9.3.1 Fracture mechanisms treatment of hydraulic fracturing
9.3.2 Fracture mechanics applied to hot dry rock geothermal energy
9.4
9.4.1 Fracture control blasting
9.4.2 Fragmentation studies with small flaws
9.4.3 Fracture initiated by reflected stress waves
9.4.4 Fragmentation studies with large flaws
9.5 Longwall mining
9.5.1 Longwall coal mining
9.5.2 Block caving
9.5.3 Pillar fracture and collapse
9.5.4 Discontinuous subsidence associated with caving methods of mining
9.5.5 Future perspectives

10. Advanced dynamic photoelasticity
10.1 Basics of photoelasticity
10.1.1 Basic equations of photoelasticity
10.2 High-speed photography and requirements of an optimum photographic system in dynamic photoelasticity
10.3 High-speed recording systems
10.3.1 Cranz-Schardin Camera
10.4 Examination of dynamic photoelastic fringe patterns
10.4.1 Identification of isochromatic fringes
10.4.2 Analysis of dynamic photoelastic data
10.4.3 Fracture analysis using photoelastic data