ISRM ROCK MECHANICS CURRICULUM GUIDE

PREFACE

It was as long ago as in the early 1990s that the ISRM Commission on Education, chaired at that time by Dr John A. Franklin, compiled the "Geotechnical Curriculum Guide". The Guide was a set of course outlines whose purpose was to assist in the planning and updating of curricula in the earth sciences, geotechnical engineering, and mining. The courses included: (a) Geology for Engineers, (b) Basic Geological Engineering, (c) Soil Mechanics, (d) Rock Mechanics, (e) Surface Geo-engineering, (f) Underground Geo-engineering, and (g) Mining.

Standardization was not the intent, nor did the ISRM Commission on Education suggest that the Guide could serve as anything more than an indication of the course content needed for accreditation. The main objective was to help teachers identify overlooked topics, and eliminate some items and/or include others to achieve a more comprehensive and better-balanced curriculum. It was also believed that a well-organized course outline could help the student grasp the interrelationship between courses and the scope and structure of such a complex subject.

The "Geotechnical Curriculum Guide" was disseminated amongst almost all university professors involved in teaching rock mechanics, rock engineering and related subjects at geological, civil and mining engineering departments all over the world. For many years (1997-2005) it was also available on the home page of the ISRM Commission of Education on the Internet.

When the Joint Technical Committee on Education and Training (JTC3) was established under the umbrella of the Federation of International Geo-engineering Societies (FedIGS), a decision was taken in 2006 to develop Guidelines on Education and Training in Engineering Geology, Rock Mechanics, Soil Mechanics and Geotechnical Engineering. Consequently, an campaign was undertaken by core members of JTC3 representing the ISRM to update and extend the rock-mechanics-related part of the existing "Geotechnical Curriculum Guide" with the aim of covering applications of rock mechanics not only to mining engineering (which was first proposed by Prof. Z. T. Bieniawski) but also to civil engineering and petroleum engineering, with a focus on engineering design to make rock mechanics more relevant to industrial practice. Subjects of engineering geology and soil mechanics were left to colleagues representing the International Association of Engineering Geology (IAEG) and the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), respectively. As a result, the ISRM Rock Mechanics Curriculum Guide, which includes syllabi or course outlines in General Rock Mechanics, Civil Rock Mechanics, Mining Rock Mechanics and Petroleum Rock Mechanics, has been developed. The draft version of the Guide is presented below for critical review and discussion. Comments and suggestions for improvement are welcome and will be gratefully appreciated.

M. Kwaśniewski, JTC3 Core Member (ISRM)

Gliwice, May 2nd, 2009

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GENERAL ROCK MECHANICS

PREREQUISITES: Geology for engineers course or equivalent, an introductory differential equations course, and a course in statics and dynamics of deformable materials.

COURSE CONTENT: Review of design principles in geomaterials; origins and measurement of rock stress; strength and yield, including effects of normal stress and pore pressure; mechanisms of rupture and yield; deformability of rock and rock masses including dilation, strain, creep, brittle and ductile mechanisms, thermal and swelling properties; testing and constitutive representation of rock behavior; testing in the field for yield and deformability behavior. The last third of the course addresses methods of analysis in rock mechanics using the basic cases of a petroleum reservoir being depleted, a rock slope stability study, and a circular opening (borehole or tunnel) in a rock mass.

SKILLS: Students graduating from this course should be able to define the constitutive behavior of brittle and ductile rock materials and the jointed rock mass, and apply the methods of limiting equilibrium, finite-, boundary-, and distinct-element modeling to elementary design of rock excavations.

CONCEPTS: Continuum and discontinuum mechanics; fracture initiation and propagation; brittle-ductile transition as a function of temperature and pressure; principles of groundwater flow through fissured media; nature and causes of rock stress; mechanics of faulting and earthquakes.

LECTURES: This is a two-semester course (semester A & semester B; 30 weeks in total) involving at minimum one 2-hour lecture per week plus at least six 2-hour laboratory sessions, for a total of 120 hours of education, including laboratory and project tutorials, and discussion of assignments. Students are required to read ahead of lectures.

PROJECTS AND ASSIGNMENTS: Students work together in groups of 3-4 to carry out a small software development project e.g. a simple expert system to aid in a design problem, coding of closed-form equations for use by the engineer. About five assignments are marked on professionalism and presentation as well as technical content.

LABORATORY PRACTICALS: Six to eight laboratory sessions to be selected from the list given in the Course Outline below. Students work together in groups of 3-4 to complete a comprehensive set of tests on a single rock type, leading to a formal report analyzing the data. Alternatively, a special program of tests on samples of different rock types to explore fundamental aspects of rock behavior.

ASSESSMENT: Projects and assignments (35%), laboratory practicals (25%) and final examination (40%).

COURSE OUTLINE: GENERAL ROCK MECHANICS

Semester A

INTRODUCTION TO ROCK MECHANICS

ROCK MECHANICS & ROCK ENGINEERING

Course content in relation to prerequisite courses
Scope, capabilities & applications of rock mechanics

DESIGN PRINCIPLES

Uncertainties in design, concept of modeling, types of model
Introduction to probabilistic concepts in design
Safety factors in civil, mining and petroleum engineering
Conceptual, mathematical, empirical, physical, probabilistic models
Representation of materials, continua and discontinua (constitutive laws)
Parametric studies (sensitivity analyses) as a design tool
Empirical design & expert systems; use of knowledge sources and data bases
Analog and physical models; assessment of mechanisms
Analytical solutions & numerical modeling
Limitations and role of laboratory and field testing in rock mechanics

GENERAL APPROACH TO PROBLEM SOLVING IN ROCK MECHANICS

Definition of the initial state of the rock mass (pressure, stress, temperature, ...)
Delineating the geometry of the rock mass (strata, geotechnical units, ..); and of the structure
Estimation of the past and future load history and geometry evolution
Development of a sufficient behavioral law for the problem to be addressed
Choice of a method for analyzing the problem
Confirmation of the design validity and continued optimization by monitoring and re-analyzing

ROCK STRESSES

FORCE AND STRESS

Mass and weight, forces, stresses and strengths, vectors & tensors
Calculation of total and effective stresses in sedimentary basins

BEHAVIOR OF STRESSED ROCK MASSES

Slow compaction and lithification of sediments, continental drift and mantle processes
Earthquakes, rockfalls and rockbursts, squeeze in tunnels
Slow movement, including creep on faults, creep of salt

STRESSES IN THREE DIMENSIONS

Stress on a surface & elemental cube; determination of shear and normal stresses on an arbitrary plane
The stress tensor, principal stresses
Uniaxial, biaxial, & triaxial stress states, hydrostatic stress, deviatoric stress

NATURE AND CAUSES OF ROCK STRESS

Gravitational stresses, effects of depth and topography
At-rest stress state, loading and unloading effects, stress history and diagenesis
Tectonic stresses, "fossilized" stresses, intercrystalline stress, core microfracturing and

discing
Limits to earth stresses, active and passive limits for sediments, effect of cohesion
Limits to stresses in jointed rocks, slip of joints, effect of fissured masses
Measured soil & rock stress trends, unloading of strata
Stresses in creeping rock strata such as shale and halite
Stresses near the earth's surfaces and at depth; depth and intensity of earthquakes

EXCAVATION-INDUCED STRESSES

Non-uniform stress, concept of a stress concentration around an opening
Concept of a zone of stress relief such as on top of a slope, near a trench top
Stress trajectories in the earth, changes because of tectonic and volcanic effects
Principal stress directions near free surfaces that are excavated (borehole, slope,...)
Typical stress concentration regions around openings, slopes, foundations
Stress concentrations in mining pillars, leading to yield or bursting

STRESS MEASUREMENT

Estimation of stress states in sedimentary basins using basin models and structural geology principles
Stress measurement methods in soils & rocks: nulling methods, strain-relief methods, direct measures
Strain relief: rock overcoring, USBM, "doorstopper", Lisbon, CSIR and CSIRO methods
Nulling methods: slotting stressmeter, undercoring & flat jack methods
Direct measures: liquid inclusion in halites, hydraulic fracturing & hydraulic tests on preexisting fissures
Other methods: dilatometer (sleeve fracturing), soft inclusions in soft rocks
Correlations to stress using sonic velocity methods, shear wave anisotropy
Stress orientations: tectonic state models, wellbore breakouts, stress relaxation (DSCA) & Kaiser effect

STRENGTH AND YIELD

INTRODUCTION

Definitions of strength & yield criteria; peak strength and ultimate strength
The difference between residual mineral strength and ultimate rock mass strength
Strength & yield criteria in 3-D stress space
Failure modes: tensile, bending, buckling, toppling, shearing, crushing

TESTING TO DEFINE STRENGTH & YIELD CRITERIA FOR INTACT ROCK

Uniaxial, biaxial, polyaxial, hydrostatic compression tests
Axisymmetric triaxial test, continuous failure state testing
Effect of scale on strength, large scale triaxial tests in the laboratory
Direct & indirect tensile tests, beam bending, torsion and hollow cylinder tests
The problem with defining tensile strength of a lab specimen and comparing to the mass

TESTS TO DEFINE SHEAR STRENGTH & YIELD CRITERIA FOR DISCONTINUITIES

Tilt tests on blocks & core
Triaxial testing of discontinuities - limitations

Sampling of jointed rock & filling materials, taking and testing replicas
Direct shear test with laboratory & field-portable apparatus
In situ tests on blocks, slopes and underground testing
Estimating shear strength from back analysis

FACTORS AFFECTING STRENGTH OF ROCKS
The effects of increasing normal stress on porous and non-porous rocks
Moisture conditions and their effect on strength (tensile fissure)
Dilatant behavior & i-angle
Scale & roughness effects on strength of a rock joint
Effects of infillings on joint strength
Joint creep, and the effect of strain rate

STRENGTH AND YIELD CRITERIA
Shear strength criteria, Mohr-Coulomb strengths of joints and fillings
Attributes of the strength surface
Mohr-Coulomb criterion, Griffith criterion and extensions
Curvilinear criteria: Ladanyi and Archambault, Barton
Empirical criteria: Hoek and Brown, Johnston

BRITTLE BEHAVIOR (FRACTURE) OF ROCKS
Crack initiation & propagation, Griffith crack theory
Modes of rupture & yield associated with brittle behavior and different stresses
"Flaking" of rock in a stressed vertical wall, longitudinal fractures parallel to pillar surfaces
Rock bursting mechanisms
Fracture toughness tests for fracture mechanics
Extensional strain fracture criteria
Mechanisms of brittle rupture in blasting, hydraulic fracture

DEFORMABILITY

STRAIN AND DEFORMATION: CONCEPTS & MEASUREMENT
Definitions: strain, displacement, stiffness, deformability, plasticity, elasticity, linearity, hysteresis
Elastic and inelastic, linear and non-linear behavior
Strain and deformation, reversible and irreversible straining, non-linearity of deformation processes
Strain localization because of weakening, localization of slip along joints in a rock mass
Measurement of strain, electrical resistance strain gages, interferometry, holography
Hooke's law, and derivation of various compressibilities
Strain paths for 2-D cases in typical situations such as mining a free vertical face
Rocks as materials that remember their strain history (permanent fabric alterations)
Anisotropy of rock deformability: principal directions of stiffness, example of shales

LABORATORY STRESS-STRAIN TESTS TO ESTIMATE DEFORMABILITY
Uniaxial compression test & derivation of elastic parameters

Strain measurements in the axi-symmetric triaxial test
Volumetric strain measurements in triaxial tests, dilation of rock matrix and joint surfaces
Cyclic testing and permanent strain determination in triaxial tests
Stiff test machines to measure post-peak behavior of fractured rock
Joint stiffness & compliance, shear stiffness versus shear displacement

FIELD TESTS OF ROCK AND ROCK MASS DEFORMABILITY
Flexible CSM dilatometer & rigid Goodman Jack
Plate loading tests, surface & underground, rigid & flexible plates
Large flat jack tests, block tests
Radial jacking & pressure tests in tunnels

STRESS-STRAIN CURVES FOR ROCKS
Typical static-elastic parameters & behavior of various rock types
Dilatancy suppression as the effect of normal stress; increasing damage with dilatancy reduction
Comparison of laboratory & field results

DYNAMIC-ELASTIC BEHAVIOR
Stress waves and their velocities in different rocks
Measurement of wave velocity & dynamic elastic parameters
Typical dynamic elastic properties, difference between static & dynamic values

VISCOUS, THERMAL & SWELLING BEHAVIOR

CREEP BEHAVIOR
Time- and temperature-dependence of strength and strain
Hydrostatic creep of porous media, deviatoric creep of rocks
Creep micro-mechanisms: crack growth, dislocations, pressure solution, cataclasis
Conventional "primary-secondary-tertiary" creep concepts
The concept of steady-state fabric and increasing damage in covalent bonded rocks

TESTING OF CREEP BEHAVIOR
Laboratory uniaxial & triaxial creep tests
Stress relaxation & strain-rate controlled tests
Field tests & back analysis; trial rooms and convergence measurements

RHEOLOGICAL MODELS FOR TIME-DEPENDENT MATERIALS
Rheological elements & simple rheological "bodies"
Non-linear elastic, plastic (slip and rupture), and viscous parameters
Creep behavior of typical soft & hard rocks

HEAT FLOW AND THERMAL PROPERTIES
Thermal conductivity: definition, typical values
Specific heat: definition, typical values
Thermal coefficient of expansion: definition, typical values
Heat flow calculations and similarity to consolidation equation (Fick's Law)

Testing of thermal properties in the laboratory; saturation effect
Frost action on rocks; crack propagation
Thermal considerations of radioactive waste disposal

SWELLING ROCKS: ROCK TYPES AND MECHANISMS
Swelling clay minerals: smectite family, vermiculite; effect of stress
Deterioration of the strength of smectitic clay shales and mudstones in mining
Anhydrite-gypsum reaction
Pyrite & marcasite reactions in the presence of oxygen; black shales
Index tests for durability and swelling potential
Unconfined swelling tests, oedometric & ring swell tests
Dry-wet cycling and its effects of argillaceous rocks

Semester B

ANALYSIS METHODS IN ROCK MECHANICS

ANALOG AND PHYSICAL MODELS
Electrical & photoelastic analogs for complex elastic problems
Base friction models to study mechanisms of deformation and yield
Physical models, materials & methods, centrifuge tests
Physical simulations in cases where scaling criteria cannot be all fulfilled

DISCONTINUUM MODELS: VECTOR ANALYSIS AND LIMITING EQUILIBRIUM METHODS
The infinite slope sliding along a pressurized basal plane
Stability of a block on a slope; cohesion, earthquakes, pore pressure, cable anchors
Vectorial analysis using forces, development of equations, design charts
Rock slope stability equations for a planar slope with tension crack
Design charts and making a problem dimensionless for plotting
Incorporating the effects of rock improvement

CLOSED-FORM AND SEMI-ANALYTIC CONTINUUM SOLUTIONS
Closed-form solution derivations for the lateral stresses in a petroleum reservoir
Subsidence, the Ekofisk case history
The effect of changes of pore pressure and temperature on reservoir lateral stresses
Approaching the yield state because of heating or injection of fluids
Closed-form solutions for foundations - Boussinesq and Cerrutti solutions
Superposition of elastic solutions for point loads
Closed-form solutions for circular openings in elastic rock
The hollow cylinder equations, Kirsch solution for tunnels, boreholes, etc.
Derivation of the hydraulic fracture equations for an impermeable, pressurized elastic borehole
State of stress in the elastic tunnel or borehole wall in a deviatoric stress field
Combining the Kirsch solution with the presence of a fault, with a yield criterion for the fault
The closed-form solution for thermal stresses on the wall of a circular opening

Stresses in cases of elastoplasticity and damages tunnels and borehole walls
Stresses resulting from slip along joints

NUMERICAL MODELING APPROACHES FOR CONTINUA
Advantages of numerical models and pitfalls associated with their use
Finite difference & finite element methods in geomechanics (worked examples)
Boundary element, displacement discontinuity and boundary integral methods (worked examples)

NUMERICAL MODELING APPROACHES FOR DISCONTINUOUS MEDIA
Distinct element methods for jointed rock (worked examples)
Key block methods: formalization of discontinuous mass analysis, arch formation and destruction
Distinct element models for particulate (granular) media (worked examples)
Network models, truss models

ROCK MECHANICS LABORATORY SESSIONS:

1. Rock sample preparation
2. Strain gaging
3. Uniaxial compression test to determine ultimate strength, Young's modulus and Poisson's ratio
4. Uniaxial compression test for the complete (pre- and post-failure) strain-stress curve
5. Uniaxial loading-unloading-reloading compression test for susceptibility of rocks to bursting
6. Index properties test (e.g. point load strength test)
7. Triaxial compression tests for a strength criterion and the corresponding material parameters
8. Tensile tests (direct tension test and/or the Brazilian test)
9. Creep test under uniaxial compression conditions
10. Rock swelling test
11. Slake-durability test
12. Rock hardness test
13. Fracture toughness test
14. Rock permeability test
15. Shear test on rock joint for joint deformability and strength

Notice: It is recommended that field tests be included in the rock mechanics course wherever possible.

TEXTBOOKS AND MATERIALS:

Amadei B. & Stephansson O.: *Rock Stress and Its Measurement.* Chapman & Hall, London 1997.

Bieniawski Z.T.: *Rock Mechanics Design in Mining and Tunneling.* A. A. Balkema, Rotterdam 1984.

Bieniawski Z.T.: *Engineering Rock Mass Classifications.* John Wiley & Sons, New York 1989.

Bieniawski Z.T.: *Design Methodology in Rock Engineering.* A. A. Balkema, Rotterdam 1992.

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Cristescu N.: *Rock Rheology.* Kluwer Academic Publishers, Dordrecht 1989.

Cristescu N.D. & Hunsche U.: *Time Effects in Rock Mechanics.* John Wiley & Sons, Chichester 1998.

Desai C.S. & Siriwardane H.J.: *Constitutive Laws for Engineering Materials with Emphasis on Geologic Materials.* Prentice-Hall, Inc., Englewood Cliffs 1984.

Dunnicliff J.: *Geotechnical Instrumentation for Monitoring Field Performance.* John Wiley & Sons, Inc., New York 1988.

Farmer I.: *Engineering Behaviour of Rocks* (2nd edn). Chapman and Hall Ltd, London 1983.

Franklin J.A. & Dusseault M.B.: *Rock Engineering.* McGraw-Hill, New York 1989.

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Herget G.: *Stresses in Rock.* A. A. Balkema, Rotterdam 1988.

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Jing L. & Stephansson O.: *Fundamentals of Discrete Element Methods for Rock Engineering – Theory and Applications.* Elsevier, Amsterdam 2007.

Jumikis A.R.: *Rock Mechanics* (2nd edn). Trans Tech Publications, Clausthal-Zellerfeld 1983.

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Mogi K.: *Experimental Rock Mechanics.* Taylor & Francis/Balkema, Leiden 2006.

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Pande G.N., Beer G. & Williams J.R.: *Numerical Methods in Rock Mechanics.* John Wiley & Sons Ltd, Chichester 1990.

Paterson M.S. & Wong T.-f.: *Experimental Rock Deformation – The Brittle Field* (2nd edn). Springer-Verlag, Berlin Heidelberg 2005.

Parry R.H.G.: *Mohr Circles, Stress Paths and Geotechnics* (2nd edn). Spon Press, London 2004.

Priest S.D.: *Discontinuity Analysis for Rock Engineering.* Chapman & Hall, London 1993.

Singh B. & Goel R.K.: *Rock Mass Classification.* Elsevier Science Ltd, Oxford 1999.

Stavrogin A.N. & Tarasov B.G.: *Experimental Physics and Rock Mechanics (Results of Laboratory Studies).* A. A. Balkema Publishers, Lisse 2001.

Ulusay R. & Hudson J.A.: *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006.* The ISRM Turkish National Group, Ankara 2007.

Whittaker B.N., Singh R.N. & Sun G.: *Rock Fracture Mechanics – Principles, Design and Applications.* Elsevier Science Publishers B.V., Amsterdam 1992.

Wittke W.: *Rock Mechanics, Theory and Applications with Case Histories.* Springer-Verlag, Berlin 1990.

Wyllie D.C. & Mah C.W.: *Rock Slope Engineering: Civil and Mining* (4th edn). Spon Press, London and New York 2004.

Additionally, see ISRM Bibliography of Textbooks and Journals, and the educational software for finite element, finite difference, boundary element, distinct element and limit equilibrium analysis.

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CIVIL ROCK MECHANICS

PREREQUISITES: The course is for civil engineering students already equipped with an understanding of basic geological concepts as well as the principles of statics/dynamics, mechanics of deformable bodies and strength of materials.

COURSE CONTENT: Rock mechanics fundamentals and rock engineering applied to underground and surface civil works. Design and stability analysis of excavations in rock and foundations on rock. Emphasis on applications in engineering practice, case studies and quantitative methods in design. See Course Outline.

SKILLS: Students graduating from this course should be competent to perform basic tasks as civil ground control engineers. They should be able to select and apply an appropriate combination of empirical, analytical and numerical methods to plan and rationally design stable structures in and on rock.

CONCEPTS: The concepts, from prerequisite courses, of strength of materials and mechanics, plus an in-depth appreciation of the impact of geological conditions on civil works; the applications and limitations of analytical and numerical modeling techniques to civil engineering; and the tests needed for rock characterization and design.

LECTURES: This is a two-semester course (semester A & semester B; 30 weeks in total) involving at minimum one 2-hour lecture per week plus at least six 2-hour laboratory sessions, for a total of 120 hours of education, including laboratory and project tutorials, and discussion of assignments. Students are required to read ahead of lectures.

LABORATORY PRACTICALS: Six to eight laboratory sessions to be selected from the list given in the Course Outline below. It is important that laboratory sessions are aimed not at parameter measurement only, but also at illustrating the factors which affect rock strength and deformability in order to impart an understanding of the rock mechanics principles.

PROJECTS AND ASSIGNMENTS: Three individually completed mini-design projects on, for example, design of a dam foundation, design of a highway cut in rock, design and analysis of an underground tunnel. Reports are expected to meet professional standards. Numerous homework assignments.

METHOD OF ASSESSMENT: 15% for each of three mini-design reports, plus 20% for laboratory assignments and homework exercises, plus 35% for examinations.

COURSE OUTLINE: CIVIL ROCK MECHANICS

Semester A

ROCK MECHANICS FUNDAMENTALS and LABORATORY

FUNDAMENTAL MECHANICS PRINCIPLES

Stresses and strains in three dimensions

Strength and yield concept
Fracture mechanics concepts
Basics of rheology
Friction and sliding
Effective stress concept
Ground stresses and stress distributions
Basic rock mechanics instrumentation

ROCK PROPERTIES AND THEIR USE

Rock material properties, strength and deformability
Swelling properties
Stress wave propagation in rocks
Time-dependent behavior of rocks
Properties of discontinuities in rock
Rock mass properties and in-situ testing

STRENGTH THEORIES AND FAILURE CRITERIA

Mechanisms of rock failure
Stress, strain and strain energy strength theories
Mohr-Coulomb criterion
Hoek & Brown criterion
Mogi criterion
Strength of anisotropic and jointed rocks
Effect of pore pressure

FLUID FLOW IN ROCK

Hydraulic permeability and conductivity
Flow through single discontinuities
Flow through discontinuity networks

ROCK MECHANICS FIELD INSTRUMENTATION

Rock stress and deformation measurements
Rock bolt pullout testing and monitoring
Applications of field measurements

ROCK MECHANICS LABORATORY SESSIONS:

1. Rock sample preparation
2. Strain gaging
3. Uniaxial compression test to determine ultimate strength, Young's modulus and Poisson's ratio
4. Uniaxial compression test for the complete (pre- and post-failure) strain-stress curve
5. Uniaxial loading-unloading-reloading compression test for susceptibility of rocks to bursting
6. Index properties test (e.g. point load strength test)
7. Triaxial compression tests for a strength criterion and the corresponding material parameters
8. Tensile tests (direct tension test and/or the Brazilian test)
9. Creep test under uniaxial compression conditions

10. Rock hardness test
11. Fracture toughness test
12. Rock permeability test
13. Shear test on rock joint for joint deformability and strength

Notice: It is recommended that field tests be included in the rock mechanics course wherever possible.

Semester B

ROCK ENGINEERING

DESIGN PRINCIPLES AND METHODOLOGY
- Engineering design fundamentals
- Empirical, observational and analytical design methods

SITE INVESTIGATIONS
- Exploration and drilling techniques
- Geophysical logging and downhole observations
- Engineering geological mapping

INSTRUMENTATION AND MONITORING
- Geotechnical instrumentation for monitoring field performance
- Monitoring of excavations during construction
- Monitoring of excavations after construction

ROCK MASS PROPERTIES AND CLASSIFICATIONS
- Strength and deformability
- Rock Mass Rating (RMR) system
- Q - system
- Geological Strength Index (GSI) system

DESIGN AND MODELING OF UNDERGROUND EXCAVATIONS
- Stress distributions around underground excavations
- Underground excavation failure mechanisms
- Optimum shape and orientation of excavations
- Analytical and numerical modeling of underground excavations

DESIGN AND MODELING OF SURFACE EXCAVATIONS
- Stress distributions around underground excavations
- Underground excavation failure mechanisms
- Optimum shape and orientation of excavations
- Analytical and numerical modeling of underground excavations

FOUNDATION ENGINEERING
- Rock foundations
- Stresses and deflections in rock under footings
- Bearing capacity of rock

Deep foundations in rock

ROCK SLOPE ENGINEERING
Modes of slope failure in hard rock
Kinematic analysis of slopes
Limiting equilibrium analysis of slopes
Numerical simulations for slope stability analysis
Probabilistic methods

DESIGN OF ROCK REINFORCEMENT
Rock bolting and rock anchors
Grouting and liners
Steel arches
Other stabilization techniques

SPECIAL TOPICS
Rock blasting in underground and surface excavations
Design of underground hydrocarbon storage caverns
Geomechanical aspects of the underground nuclear waste disposal
Geomechanical aspects of the geological sequestration of carbon dioxide

TEXTBOOKS AND MATERIALS:

Amadei B. & Stephansson O.: *Rock Stress and Its Measurement.* Chapman & Hall, London 1997.

Bieniawski Z.T.: *Rock Mechanics Design in Mining and Tunneling.* A. A. Balkema, Rotterdam 1984.

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Stavrogin A.N. & Tarasov B.G.: *Experimental Physics and Rock Mechanics (Results of Laboratory Studies).* A. A. Balkema Publishers, Lisse 2001.

Ulusay R. & Hudson J.A.: *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006.* The ISRM Turkish National Group, Ankara 2007.

Whittaker B.N., Singh R.N. & Sun G.: *Rock Fracture Mechanics – Principles, Design and Applications.* Elsevier Science Publishers B.V., Amsterdam 1992.

Wittke W.: *Rock Mechanics, Theory and Applications with Case Histories.* Springer-Verlag, Berlin 1990.

Wyllie D.C. & Mah C.W.: *Rock Slope Engineering: Civil and Mining* (4th edn). Spon Press, London and New York 2004.

Additionally, see ISRM Bibliography of Textbooks and Journals, and the educational software for finite element, finite difference, boundary element, distinct element and limit equilibrium analysis.

ISRM ROCK MECHANICS CURRICULUM GUIDE

MINING ROCK MECHANICS

PREREQUISITES: The course is for mining engineering students already equipped with an understanding of basic geological concepts as well as the principles of statics/dynamics, mechanics of deformable bodies and strength of materials.

COURSE CONTENT: Rock mechanics fundamentals and rock engineering (called "ground control" or "strata control" in mining) applied to underground and surface mining works. Design, excavation and support of mine openings. Emphasis on applications in engineering practice, case studies and quantitative methods in design. See Course Outline.

SKILLS: Students graduating from this course should be competent to perform basic tasks as mine ground control engineers. They should be able to select and apply an appropriate combination of empirical, analytical and numerical methods; and to plan and control the geomechanical aspects of mining works.

CONCEPTS: The concepts, from prerequisite courses, of strength of materials and mechanics, plus an in-depth appreciation of the impact of geological conditions on mining works; the applications and limitations of analytical and numerical modeling techniques to mining works; and the tests needed for ground characterization and design.

LECTURES: This is a two-semester course (semester A & semester B; 30 weeks in total) involving at minimum one 2-hour lecture per week plus at least six 2-hour laboratory sessions, for a total of 120 hours of education, including laboratory and project tutorials, and discussion of assignments. Students are required to read ahead of lectures.

LABORATORY PRACTICALS: Six to eight laboratory sessions to be selected from the list given in the Course Outline below. It is important that laboratory sessions are aimed not at parameter measurement only, but also at illustrating the factors which affect rock strength and deformability in order to impart an understanding of the rock mechanics principles.

PROJECTS AND ASSIGNMENTS: Three individually completed mini-design projects on, for example, rock support design, mine pillar design, underground mining design for reduction of subsidence effects or rock slope design. Reports are expected to meet professional standards. Numerous homework assignments.

METHOD OF ASSESSMENT: 15% for each of three mini-design reports, plus 20% for laboratory assignments and homework exercises, plus 35% for examinations.

COURSE OUTLINE: MINING ROCK MECHANICS

Semester A

ROCK MECHANICS FUNDAMENTALS and LABORATORY

FUNDAMENTAL MECHANICS PRINCIPLES

Stresses and strains in three dimensions

Strength and yield concept
Strain energy
Fracture mechanics concepts
Basics of rheology
Concepts of controlled and uncontrolled failure
Ground stresses and stress distributions
Basic rock mechanics instrumentation

ROCK PROPERTIES AND THEIR USE

Rock material properties, strength and deformability
Swelling properties
Time-dependent behavior of rocks
Ability of rocks to store the elastic strain energy
Cuttability of rocks
Properties of discontinuities in rock
Rock mass properties and in-situ testing

STRENGTH THEORIES AND FAILURE CRITERIA

Mechanisms of rock failure
Stress, strain and strain energy strength theories
Mohr-Coulomb criterion
Hoek & Brown criterion
Mogi criterion
Strength of anisotropic and jointed rocks
Effect of pore pressure

ROCK MECHANICS FIELD INSTRUMENTATION

Rock stress and deformation measurements
Borehole penetrometer testing
Rock bolt pullout testing and monitoring
Applications of field measurements

ROCK MECHANICS LABORATORY SESSIONS:

1. Rock sample preparation
2. Strain gaging
3. Uniaxial compression test to determine ultimate strength, Young's modulus and Poisson's ratio
4. Uniaxial compression test for the complete (pre- and post-failure) strain-stress curve
5. Uniaxial loading-unloading-reloading compression test for susceptibility of rocks to bursting
6. Index properties test (e.g. point load strength test)
7. Triaxial compression tests for a strength criterion and the corresponding material parameters
8. Tensile test (direct tension test and/or the Brazilian test)
9. Creep test under uniaxial compression conditions
10. Rock hardness test
11. Shear test on rock joint for joint deformability and strength
12. Field measurements (stress, load and convergence)

Semester B

ROCK ENGINEERING (GROUND CONTROL)

DESIGN PRINCIPLES AND METHODOLOGY
- Engineering design fundamentals
- Empirical, observational and analytical design methods

SITE INVESTIGATIONS
- Exploration and drilling techniques
- Geophysical logging and downhole observations
- Engineering geological mapping

ROCK MASS CLASSIFICATIONS
- Rock Mass Rating (RMR) system
- Q - system
- Geological Strength Index (GSI) system

DESIGN AND MODELING OF MINE OPENINGS
- Stress distributions around mine openings
- Design of mine pillars
- Analytical and numerical modeling of mining structures

DESIGN OF ROCK REINFORCEMENT
- Rock bolting and rock anchors
- Grouting and liners
- Steel arches

LONGWALL MINING AND SURFACE SUBSIDENCE
- Geomechanics principles of panel layout design
- Caving mechanics
- Design of abutment and yield pillars
- Subsidence: mechanisms, prediction, control

DYNAMIC MANIFESTATIONS OF ROCK PRESSURE
- Rock spalling
- Rock bursts and coal bumps
- Gas and coal outbursts

ROCK BLASTING
- Mechanics of explosive rock breaking
- Design of blasting patterns
- Rock damage

DESIGN OF ROCK SLOPES
- Plane and wedge failure

Circular failure
Limiting equilibrium analysis
Probabilistic methods

SPECIAL TOPICS
Disposal of mine wastes
Geotechnical hazards in abandoned mines

TEXTBOOKS AND MATERIALS:

Amadei B. & Stephansson O.: *Rock Stress and Its Measurement.* Chapman & Hall, London 1997.

Bieniawski Z.T.: *Rock Mechanics Design in Mining and Tunneling.* A. A. Balkema, Rotterdam 1984.

Bieniawski Z.T.: *Strata Control in Mineral Engineering.* A. A. Balkema, Rotterdam 1987.

Bieniawski Z.T.: *Engineering Rock Mass Classifications.* John Wiley & Sons, New York 1989.

Bieniawski Z.T.: *Design Methodology in Rock Engineering.* A. A. Balkema, Rotterdam 1992.

Brady B.H.G. & Brown E.T.: *Rock Mechanics for Underground Mining* (3rd edn). Springer, Dordrecht 2006.

Bräuner G.: *Rockbursts in Coal Mines and Their Prevention.* A. A. Balkema, Rotterdam 1994.

Desai C.S. & Siriwardane H.J.: *Constitutive Laws for Engineering Materials with Emphasis on Geologic Materials.* Prentice-Hall, Inc., Englewood Cliffs 1984.

Farmer I.: *Engineering Behaviour of Rocks* (2nd edn). Chapman and Hall Ltd, London 1983.

Franklin J.A. & Dusseault M.B.: *Rock Engineering.* McGraw-Hill, New York 1989.

Franklin J.A. & Dusseault M.B.: *Rock Engineering Applications.* McGraw-Hill, New York 1991.

Goodman R.E.: *Introduction to Rock Mechanics* (2nd edn). John Wiley & Sons, New York 1989.

Franklin J. (ed.): *Mine Monitoring Manual.* The Canadian Institute of Mining and Metallurgy, Montréal 1990.

Herget G.: *Stresses in Rock.* A. A. Balkema, Rotterdam 1988.

Hoek E. & Brown E.T.: *Underground Excavations in Rock.* Institution of Mining and Metallurgy, London 1980.

Hoek E., Kaiser P.K. & Bawden W.F.: *Support of Underground Excavations in Hard Rock.* A. A. Balkema, Rotterdam 1995.

Hudson J.A. (ed.): *Comprehensive Rock Engineering* (5 vols). Pergamon, Oxford 1993.

Jaeger J.C., Cook N.G.W. & Zimmerman R.W.: *Fundamentals of Rock Mechanics* (4th edn). Blackwell Publishing, Malden 2007.

Jeremic M.L.: *Strata Mechanics in Coal Mining.* A. A. Balkema Publishers, Rotterdam 1985.

Jeremic M.L.: *Ground Mechanics in Hard Rock Mining.* A. A. Balkema, Rotterdam 1987.

Jumikis A.R.: *Rock Mechanics* (2nd edn). Trans Tech Publications, Clausthal-Zellerfeld 1983.

Linkov A.M.: *Dynamic Phenomena in Mines and the Problem of Stability.* Secretariat of the ISRM, LNEC, Lisboa 1994.

Mogi K.: *Experimental Rock Mechanics.* Taylor & Francis/Balkema, Leiden 2006.

Nagaraj T.S.: *Principles of Testing Soils, Rocks and Concrete.* Elsevier Science Publishers B.V., Amsterdam 1993.

Pande G.N., Beer G. & Williams J.R.: *Numerical Methods in Rock Mechanics.* John Wiley & Sons Ltd, Chichester 1990.

Pariseau W.G.: *Design Analysis in Rock Mechanics.* Taylor & Francis/Balkema, Leiden 2007.

Peng S.S.: *Coal Mine Ground Control* (3rd edn). Syd. S. Peng publisher, 2008.

Priest S.D.: *Discontinuity Analysis for Rock Engineering.* Chapman & Hall, London 1993.

Singh B. & Goel R.K.: *Rock Mass Classification.* Elsevier Science Ltd, Oxford 1999.

Stavrogin A.N. & Tarasov B.G.: *Experimental Physics and Rock Mechanics (Results of Laboratory Studies).* A. A. Balkema Publishers, Lisse 2001.

Ulusay R. & Hudson J.A.: *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006.* The ISRM Turkish National Group, Ankara 2007.

Whittaker B.N. & Reddish D.J.: *Subsidence – Occurrence, Prediction and Control.* Elsevier Science Publishers B.V., Amsterdam 1989.

Whittaker B.N., Singh R.N. & Sun G.: *Rock Fracture Mechanics – Principles, Design and Applications.* Elsevier Science Publishers B.V., Amsterdam 1992.

Wyllie D.C. & Mah C.W.: *Rock Slope Engineering: Civil and Mining* (4th edn). Spon Press, London and New York 2004.

Additionally, see ISRM Bibliography of Textbooks and Journals, and the educational software for finite element, finite difference, boundary element, distinct element and limit equilibrium analysis.

ISRM ROCK MECHANICS CURRICULUM GUIDE

PETROLEUM ROCK MECHANICS

PREREQUISITES: The course is for petroleum engineering students already equipped with an understanding of basic geological concepts as well as the principles of statics/dynamics, mechanics of deformable solids, strength of materials, thermodynamics and fluid mechanics.

COURSE CONTENT: Rock mechanics fundamentals and rock engineering applied to borehole stresses and wellbore integrity analysis, hydraulic fracturing and well stimulation, sand production and reservoir compaction. Emphasis on applications in engineering practice, case studies and quantitative methods in design. See Course Outline.

SKILLS: Students graduating from this course should be competent to perform basic tasks as petroleum ground control engineers. They should be able to select and apply an appropriate combination of empirical, analytical and numerical methods; and to plan and control the geomechanical aspects of petroleum works.

CONCEPTS: The concepts, from prerequisite courses, of structural geology, strength of materials, mechanics of deformable solids and fluid mechanics, plus an in-depth appreciation of the impact of geological conditions on petroleum works; the applications and limitations of analytical and numerical modeling techniques to petroleum works; and the tests needed for ground characterization as well as wellbore design and reservoir production.

LECTURES: This is a two-semester course (semester A & semester B; 30 weeks in total) involving at minimum one 2-hour lecture per week plus at least six 2-hour laboratory sessions, for a total of 120 hours of education, including laboratory and project tutorials, and discussion of assignments. Students are required to read ahead of lectures.

LABORATORY PRACTICALS: Six to eight laboratory sessions to be selected from the list given in the Course Outline below. It is important that laboratory sessions should aim not at parameter measurement only, but also at illustrating the factors which affect rock strength and deformability in order to impart an understanding of the rock mechanics principles.

PROJECTS AND ASSIGNMENTS: Three individually completed mini-design projects on borehole stability during drilling, wellbore stability, hydraulic fracturing and well stimulation. Reports are expected to meet professional standards. Numerous homework assignments.

METHOD OF ASSESSMENT: 15% for each of three mini-design reports, plus 20% for laboratory assignments and homework exercises, plus 35% for examinations.

COURSE OUTLINE: PETROLEUM ROCK MECHANICS

Semester A

ROCK MECHANICS FUNDAMENTALS and LABORATORY

FUNDAMENTAL MECHANICS PRINCIPLES
Stresses and strains in three dimensions

Strength and yield concepts
Fracture mechanics concepts
Basics of rheology
Poroelasticity and the effective stress concept
In-situ stresses and formation pressures
Basic rock mechanics instrumentation

ROCK PROPERTIES AND THEIR USE

Rock material properties, strength and deformability
Thermal and swelling properties
Hydraulic permeability and conductivity
Stress wave propagation in rocks
Time-dependent behavior of rocks
Properties of discontinuities in rock
Rock mass properties and in-situ testing

CONSTITUTIVE MODELING OF ROCK BEHAVIOR

Linear elasticity (advantages and limitations)
Plastic flow; strain softening/hardening
Poroelastoplasticity
Viscoelastic and viscoplastic models

STRENGTH THEORIES AND FAILURE CRITERIA

Mechanisms of rock failure
Stress, strain and strain energy strength theories
Mohr-Coulomb criterion
Hoek & Brown criterion
Mogi criterion
Strength of anisotropic and jointed rocks
Effect of pore pressure

ROCK MECHANICS FIELD INSTRUMENTATION

Rock stress and deformation measurements
Hydrofracturing of rocks
Applications of field measurements

ROCK MECHANICS LABORATORY SESSIONS:

1. Rock sample preparation
2. Strain gaging
3. Uniaxial compression test
4. Index properties test (e.g. point load strength test)
5. Conventional triaxial compression test
6. Tensile tests (direct tensile test and/or the Brazilian test)
7. Acoustic wave velocity measurement test
8. Hydrostatic compression (compressibility) test
9. Rock permeability test
10. Fracture toughness test
11. Rock drillability test

Notice: It is recommended that field tests be included in the rock mechanics course wherever possible.

Semester B

ROCK ENGINEERING (GROUND CONTROL)

DESIGN PRINCIPLES AND METHODOLOGY
- Engineering design fundamentals
- Empirical, observational, analytical and computer-aided design methods
- Basics of well planning and design

SITE INVESTIGATIONS
- Exploration and drilling techniques
- Geophysical logging and downhole observations
- Engineering geological mapping

BOREHOLE AND WELLBORE STABILITY
- Stresses around boreholes
- Borehole failure criteria and failure modes
- Borehole collapse - causes and effects
- Stability during drilling
- Stability of a producing well

SAND PRODUCTION
- Mechanisms of sand production
- Sand production control
- Modeling of sand production
- Sanding prediction

HYDRAULIC FRACTURING
- Mechanics of hydraulic fracturing; fracture initiation, propagation and closure
- Physical processes in hydraulic fracturing
- HF geometrical models
- Principles for fracture design

RESERVOIR COMPACTION AND SURFACE SUBSIDENCE
- Compaction of oil and gas reservoirs
- Impact of compaction on well productivity
- Subsidence: mechanisms, prediction and control

RESERVOIR MONITORING
- Microseismics
- Tiltmeters
- InSAR and GPS

SPECIAL TOPICS

Waste disposal in deep geological formations
Carbon dioxide sequestration in depleted oil/gas reservoirs
Geothermal engineering

TEXTBOOKS AND MATERIALS:

Amadei B. & Stephansson O.: *Rock Stress and Its Measurement.* Chapman & Hall, London 1997.

Charlez Ph.A.: *Rock Mechanics,* Vol. 1 – *Theoretical Fundamentals.* Éditions Technip, Paris 1991.

Charlez .A.: *Rock Mechanics,* Vol. 2 – *Petroleum Applicatiols.* Éditions Technip, Paris 1997.

Committee on Fracture Characterization and Fluid Flow, U.S. National Committee for Rock Mechanics: *Rock Fractures and Fluid Flow.* National Academy Press, Washington, D.C., 1996

Desai C.S. & Siriwardane H.J.: *Constitutive Laws for Engineering Materials with Emphasis on Geologic Materials.* Prentice-Hall, Inc., Englewood Cliffs 1984.

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Goodman R.E.: *Introduction to Rock Mechanics* (2^{nd} edn). John Wiley & Sons, New York 1989.

Fjæer E., Holt R.M., Horsrud P., Raaen A.M. & Risnes R.: *Petroleum Related Rock Mechanics* (2^{nd} edn). Elsevier Science Publishers B.V., Amsterdam 2008.

Jaeger J.C., Cook N.G.W. & Zimmerman R.W.: *Fundamentals of Rock Mechanics* (4^{th} edn). Blackwell Publishing, Malden 2007.

Mogi K.: *Experimental Rock Mechanics.* Taylor & Francis/Balkema, Leiden 2006.

Paterson M.S. & Wong T.-f.: *Experimental Rock Deformation – The Brittle Field* (2^{nd} edn). Springer-Verlag, Berlin Heidelberg 2005.

Priest S.D.: *Discontinuity Analysis for Rock Engineering.* Chapman & Hall, London 1993.

Ulusay R. & Hudson J.A.: *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006.* The ISRM Turkish National Group, Ankara 2007.

Whittaker B.N. & Reddish D.J.: *Subsidence – Occurrence, Prediction and Control.* Elsevier Science Publishers B.V., Amsterdam 1989.

Whittaker B.N., Singh R.N. & Sun G.: *Rock Fracture Mechanics – Principles, Design and Applications.* Elsevier Science Publishers B.V., Amsterdam 1992.

Zoback M.D.: *Reservoir Geomechanics.* Cambridge University Press, Cambridge 2007.

Additionally, see ISRM Bibliography of Textbooks and Journals, and the educational software for finite element, finite difference, boundary element and distinct element analysis.