Dr. C. Arson
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Tunneling and Mining: Mechanics and Engineering – Spring 2017

Meeting Times: Tuesday & Thursday, 1.35pm-2.55pm
Classroom: ES&T L1125
Office Hours: Monday & Tuesday, 3pm-4pm

Prerequisites: COE undergraduate coursework. Recommended: CEE 4405 Geotechnical Engineering.

Scope of the course: The course focuses on the fundamental principles of tunnel and underground mining design. Background lectures will review basic rock physics and mechanics, fracture characterization, fluid flow in porous media and fracture networks. Emphasis will be put on the following design issues: site geology and tunnel alignment, excavation plans, support techniques, drainage systems, long-term behavior. Applications will include the prediction of settlements and subsidence and the optimization of energy geotechnologies, e.g., heat and fluid extraction, mine excavation, Compressed Air Energy Storage (CAES), nuclear waste disposal.

Learning Objectives:
1. Design a laboratory test plan to determine rock physical and mechanical properties
2. Calculate stresses around cavities and excavations
3. Calculate the displacements at a tunnel wall, in the short and long terms
4. Recommend excavation support and drainage systems
5. Design an excavation plan
6. Simulate rock deformation and damage with Finite Element Methods
7. Predict the response of rock to Thermo-Hydro-Mechanical coupled stresses around cavities used for energy and waste storage

Outline & Schedule (tentative – subject to minor changes)

1. <u>How do excavations disturb the stress field in elastic rock</u>? [Week 1-3, Homework 1 due]
   - 1.1. Relating rock history to rock in situ stress
     Stress induced by erosion and cooling
   - 1.2. Direct methods for determining rock in situ stress
     Strain rosette, flat jack, hydraulic fracturing, borehole breakout
   - 1.3. Examples of underground cavities in the U.S.
   - 1.4. Stress around cavities in elastic rock
     Plane strain analysis of circular excavations, complex variable method, Kirsch equations, Leeman & Hayes's solution for stress distributions around cavities subject to 3D stress
   - *1.5.* Using analytical stress distributions for design
     Zone of influence of an excavation, effect of planes of weakness, optimal shape of an excavation, zone of fracture initiation and damage, zone of rock failure and spalling

2. <u>How to design mining supports to avoid failure</u>? [Weeks 4-7, Homeworks 2-3 due]
   - 2.1. Rock deformation and failure
     Definitions, phenomenological failure models (Tresca's theory, Mohr-Coulomb's theory, Hoek and Brown's model), Drucker-Prager's elasto-plasticity model, mechanistic models of fracture propagation
   - 2.2. Tunneling: convergence-confinement method
   - 2.3. Mining: design of rock reinforcements and supports
     Pillars, backfill

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3. How to design tunnels and mines in fractured rock? [Week 8-10, Homework 4 due, Mid-Term Exam]
   3.1. Excavation design in stratified rock
   Roof sag, roof separation, bolting strata
   3.2. Excavation design in blocky rock
   Theory of blocks
   3.3. Mining subsidence
   Troughs, discontinuous subsidence, crown holes, pillar collapse, chimney caving

4. What is the impact of pore water on mining? [Week 11-16, Homework 5 due, Res. & Design Projects due]
   4.1. Fluid flow in porous media
   Permeability-porosity relationships, flow in fracture networks
   4.2. Introduction to thermo-poro-elasticity
   The two first laws of thermodynamics, thermo-poro-mechanical constitutive relationships, Water Retention Curve, damaged rock thermo-poro-elastic properties
   4.3. Design applications
   Hydraulic fracturing, drainage systems

Course Assessment:

Five individual homeworks will include calculus, analysis and design. A mid-term examination will test the ability of students to do rapid hand calculations and make design recommendations based on basic rock mechanics and engineering principles. There will not be any final examination. Instead, students will have to complete an individual research project and a design project in groups of 2-3 students. Syllabi specifically dedicated to the mid-term exam, the research project and the design project will be posted later.

Individual research project: Students will prepare a short paper (5,000 words) and a 10 minute presentation to explain geological and design constrains encountered in an area of energy geotechnology, review the state-of-the-practice from 7-10 publications (e.g. academic journal papers, technical reports, press articles), compare models proposed in the state-of-the art, and highlight potential research areas. Possible project topics include: cyclic loading of salt caverns (Compressed Air Energy Storage, hydrogen storage, natural gas and oil storage); nuclear waste disposal (long-term thermo-hydro-mechanical rock behavior, excavation damaged zone); geothermal energy extraction; carbon dioxide sequestration.

Design project: Each group will prepare a report (20-30 pages) and a 20 minute presentation to explain tunnel design options at an actual tunnel site located in the U.S. Examples treated in the past years include: Peachtree Center Station (Atlanta, GA); Devil's Slide Tunnels (CA); Port of Miami Tunnel; Addison Airport toll tunnel (Dallas, TX); Elizabeth River Tunnels Project (Norfolk and Portsmouth, VA); Caldecott Tunnel Fourth Bore (Oakland, CA). Computation and programming tools used for the project shall include at least one of the following: MATLAB, PLAXIS, COMSOL, ABAQUS, ANSYS, Fortran. Grading will be based on the following rubrics: Introduction (10 pts): site description and purpose of the tunnel; Literature review (20 pts): geological data and engineering specifications; Hand calculations and analyses (20 pts): in situ stress, expected plastification, anticipated reinforcements and supports; Numerical simulations with the Finite Element Method (40 pts): geometry, material properties, boundary conditions, calculations for several design options, result interpretations; Conclusions (10 pts): recommendations for design and further in situ measurements or numerical analyses, as needed.

Grading: Final grade: $F<60\%\leq D<70\%\leq C<80\%\leq B<90\%\leq A\leq 100\%$
5 homeworks @ 8% each: 40%. Mid-term exam: 20%. Research project: 15%. Design project: 25%.

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Recommended references:

For rock engineering design:

- B.H.G. Bradi, E.T. Brown. *Rock Mechanics for Underground Mining, third edition*. Springer, 2004.

…with examples from:

- J.A. Hudson, J.P. Harrison. *Engineering Rock Mechanics, An Introduction to the Principles*. Pergamon, 1997.
- W.G. Pariseau. *Design Analysis in Rock Mechanics.* Taylor & Francis, 2007.

For general rock mechanics:

- E. Hoek, *Practical Rock Engineering*, e-notes, 2007 http://www.rocscience.com/education/hoeks_corner
- J.C. Jaeger, N.G.W. Cook, R.W. Zimmerman. *Fundamentals of rock Mechanics, fourth edition.* Blackwell Publishing, 2007.

For fluid flow and poromechanics:

- O. Coussy, *Mechanics and Physics of Porous Solids*, Wiley, 2010.
- Y. Guéguen, V. Palciauskas. *Introduction to the Physics of Rocks*, Princeton University Press, 1994.

Academic Honor Code:

- The design project is a group assignment, but the research project and the homeworks are individual. Working in group on the homework is allowed (and encouraged). However, each student must write up and turn in his/her own solutions.
- Use of any previous semester course materials is allowed for this course; however, it is reminded that while they may serve as examples, they are not guidelines for any tests, quizzes, homework, projects, or any other coursework that may be assigned during the semester.
- Plagiarizing is defined by Webster's as "to steal and pass off (the ideas or words of another) as one's own: use (another's production) without crediting the source." If caught plagiarizing, you will be dealt with according to the GT Academic Honor Code. Quote and attribute any words that are not your own. Do not cut and paste more than 10% of your paper; any percentage more than this will be considered plagiarism.
- Full compliance with the GT Academic Honor Code is expected. For any questions involving these or any other Academic Honor Code issues, please consult me or go to: www.honor.gatech.edu