Geology 229
Engineering and Environmental Geology

Lecture 5

Engineering Properties of Rocks
(West, Ch. 6)
Outline of this Lecture

1. Triaxial rock mechanics test
   • Mohr circle
   • Combination of Coulomb shear failure criterion and Mohr circle
   • Expressing Coulomb criterion by principal stresses

2. Engineering classification of intact rock
3. Engineering tests for strength and durability
Triaxial Compression Test

In a triaxial compression test, the direction of the load is called the maximum principal direction and the direction of the confining pressure applied is the minimum principal direction. Attention should be exercised to the fact that the convention for defining the principal direction and principal stress may be different from earth science and physics. In physics, it is usually define the tensile stress, the extensional deformation as positive, whereas in earth science it is the opposite. We define compressive stress, and compressional deformation as positive, simply because the nominal status in the crust is compressive and compressional (think about a diver at the depth of 100 m, but the material is not water but rock now).
In the directions of the principal stresses ($\sigma_1$, and $\sigma_3$) there is no shear stress. Rock mechanic experiments show that the shear stress reaches its maximum in the direction of about 30 degrees from the maximum principle stress $\sigma_1$. Theoretical prediction is 45 degrees from the principle directions.
Mohr’s Circle

Mathematically, it can be shown that the normal stress $\sigma$ and the shear stress $\tau$ on any plane that has an angle of $\theta$ from the minimum principle stress $\sigma_3$ direction related to the maximum and minimum stress in the following equations. These relationships can also be expressed graphically by the Mohr’s Circle:

\[
\sigma = \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3) \cos 2\theta \\
\tau = \frac{1}{2}(\sigma_1 - \sigma_3) \sin 2\theta
\]
Mohr’s Circle (cont.)

In a triaxial test, the normal stress and shear stress on a given plane are the functions of $\sigma_1$ and $\sigma_3$ and fall on a circle.

Center:

$$\sigma_0 = \frac{1}{2}(\sigma_1 + \sigma_3)$$

Radius:

$$r = \frac{1}{2}(\sigma_1 - \sigma_3)$$
Mohr-Coulomb shear failure criterion

The combination of the Coulomb’s criterion on shear failure and the Mohr’s circle representation of the relationship between the principal stresses and the shear and normal stresses on a shear plane. Now we can examine not the $\tau - \sigma$ pair, but also the $\sigma_1 - \sigma_3$ pair to see if their relativity satisfies the stable/unstable condition.
Mohr-Coulomb shear failure criterion (cont.)

When $2\theta = 0.5\pi - \phi$, or $\theta = 0.25\pi - 0.5\phi$, $\tau = \tau_{ff}$, at this point the circle touches the straight line and this is the point of failure. Remember: $\theta$ is the angle of the shear plane with respect to the minimum compressive principal stress, on which the normal and shear stress are calculated, and $\phi$ is the angle of friction on the shear plane.
When shear failure is occurring, equivalent to express the failure criterion by the Coulomb criterion:

\[ \tau \geq S_0 + \mu \sigma \]

We can also find that the principal normal stresses are related as:

\[ \sigma_1 \geq C_0 + \sigma_3 \tan^2 \alpha \]

with

\[ C_0 = 2S_0 \tan \alpha, \text{ and } \alpha = \pi/4 + \phi/2 \]
Thus, when the circle touches the Coulomb failure criterion (the straight line) shear failure occurs. There are three ways for the circle reach the straight line to reach failure:

1) Increase $\sigma_1$;
2) Decrease $\sigma_3$;
3) Decrease both $\sigma_1$ and $\sigma_3$ at the same amount (equivalent to increase the pore pressure on the shear plane that we will discuss later)
Engineering classification of intact rock

There are two ways to classify the intact rock in terms of 2 parameters:

1) using compressive strength alone \((C_0)\)
2) use the ratio of \(E/ C_0\)
Engineering classification of intact rock (cont.)

Using compressive strength alone \( (C_0) \) we can classify the rocks into 5 classes:

A, B, C, D, E

For rocks with very high compressive strength to very low compressive strength.
Engineering classification of intact rock (cont.)

Using the ratio of Young’s modulus to the compressive strength $E/C_0$ we can classify the rocks into 3 classes:

- H (for high);
- M (for mediate);
- L (for low).

So by combining the 2 methods we may have rocks classified as BH, BM, CM, etc.
### Engineering Classification of Intact Rock Based on Compressive Strength

<table>
<thead>
<tr>
<th>Class</th>
<th>Level of Strength</th>
<th>Strength in psi</th>
<th>Strength in MPa</th>
<th>Representative Rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Very high</td>
<td>32,000</td>
<td>220</td>
<td>Quartzite, diabase, and dense basalt</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>16,000-32,000</td>
<td>110-220</td>
<td>Most igneous rocks, most limestones, and dolomite, well-cemented sandstones and shales</td>
</tr>
<tr>
<td>C</td>
<td>Medium</td>
<td>8,000-16,000</td>
<td>55-11</td>
<td>Most shales, porous sandstones, and limestones</td>
</tr>
<tr>
<td>D</td>
<td>Low</td>
<td>4,000-8,000</td>
<td>27.5-55</td>
<td>Friable sandstones, porous tuff</td>
</tr>
<tr>
<td>E</td>
<td>Very low</td>
<td>4,000</td>
<td>25.5</td>
<td>Clay-shale, rock salt</td>
</tr>
</tbody>
</table>
### Engineering Classification of Intact Rock Based on E/C₀

<table>
<thead>
<tr>
<th>Class</th>
<th>Level of Strength</th>
<th>E/C₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>High</td>
<td>500</td>
</tr>
<tr>
<td>M</td>
<td>Medium</td>
<td>200-500</td>
</tr>
<tr>
<td>L</td>
<td>Low</td>
<td>200</td>
</tr>
</tbody>
</table>
FIGURE 6.6  Engineering classification for intact rock-summary plot, igneous rocks.
FIGURE 6.7  Engineering classification for intact rock-summary plot, sedimentary rocks.
FIGURE 6.8  Engineering classification for intact rock-summary plot, metamorphic rocks.
Aggregate are the most frequently used engineering materials for construction.

What is Aggregate?

An aggregation of sand, gravel, crushed stone slag; Used in cement concrete, mortar, asphalt pavement, etc., or used along in railroad ballast.

By surface excavation we can get these materials.

Quarry: - production of bedrocks; Pit: - production of gravel, sand, or other unconsolidated materials.
For rock as engineering material we care about its strength and durability.

For getting the strength test we can use abrasion test.

For durability test we can use the sulfate soundness test and freezing and thawing test.
Abrasion resistance test:

Sample weight 5 kg, specific size gradation specific number of steel spheres, interior projecting shelf, 500 revolutions, then use #12 sieve with $d=0.141$ mm.

Percent loss = (material finer than #12 sieve) / (original weight)

For highway construction, we need percent loss less than 35 – 50 %. 
For durability test there are two major methods:

1) sulfate soundness:

Soaking the material under test into sulfate solution and put it into oven for drying to crystal for 5 cycles, then use the same sieve and get the percent loss;

2) freezing-thawing test:

Freezing and thawing the material for 25 cycles, then use the same sieve and get the percent loss;

For highway construction material, the maximum loss for concrete aggregate is 12-15%, and for base course this number is 15-18%.
For durability Concern, different geographic regions may have different emphases. For example, in Florida, the heating-cooling, wetting-drying are the main processes for material deterioration; while in our New England, freezing-thawing, and the chemical reaction caused by road salt are the major damager for road material.
Readings:
Ch. 6, 7

Homework:
Chapter 6, Problems:
5, 6, 7, 8, 9