CHAPTER 5

Rocks

In many instances geotechnical engineers work on rock problems. For example, locating the depth of bedrock is often an important part of any soil investigation. Rock slopes, rock tunneling, rock excavations, rock fill in dams, and foundations on rock are other examples of projects requiring the expertise of the geotechnical engineer. This chapter is intended to give the reader an overview of rocks, rock properties, and rock engineering. Further information and more detailed coverage of the topic should be sought in textbooks and other publications such as Goodman (1989).

5.1 ROCK GROUPS AND IDENTIFICATION

A *rock* is a mixture of minerals (Sorrell and Sandström 2001). You may wish to think of minerals as being the building blocks of the various rocks. The primary mineral groups forming rocks are silicates (e.g., feldspar and mica), oxides (e.g., quartz), carbonates (e.g., dolomite and calcite), and sulfates (e.g., gypsum). Some of the rare minerals are topaz, jade, and emerald (silicate); ruby and sapphire (oxides); and turquoise (phosphate). Diamond is pure carbon, so it is a basic element rather than a mineral. From the point of view of their origin, rocks are classified as igneous, sedimentary, or metamorphic.

Igneous rocks (Figure 5.1) are formed by the cooling process of magma (i.e., granite and basalt). Granite is formed when viscous lava cools slowly. It is light in color and contains large elements such as quartz and feldspar. Basalt is formed by the rapid cooling of fluid lava. It is dark-colored and contains fine-grained elements undetectable by the naked eye.

Sedimentary rocks (Figure 5.2) are formed by the weathering of a parent rock, when the weathered materials are transported and redeposited into a different setting and lithified back into rock by some form of cementation, or pressure, or a heat process. They are divided into *clastic rocks* (rocks made from particles of other rocks) and *nonclastic rocks* (rocks formed by chemical precipitates, often calcite). Sandstone, siltstone, mudstone, marl, and shale are clastic rocks, whereas limestone, dolomite, gypsum, lignite, and coal are nonclastic rocks.

Metamorphic rocks (Figure 5.3) are formed when the constituents of sedimentary and igneous rocks are changed by tremendous heat and pressure, with the possible influence of water and gases. The two main types of metamorphism processes involve temperature and pressure or temperature alone. Pressure alone is uncommon. In order of decreasing strength, marble, gneiss, slate, and schist are all metamorphic rocks.

For identification purposes, the charts in Figure 5.4 and 5.5a are very useful. Figure 5.4 helps in identifying the minerals that form a rock. It proceeds through a series of testing steps, including use of a hand lens to observe the rock-forming mineral; use of a knife and one's fingernail to test the strength; and observation of the cleavage, the color, and the luster. Figure 5.5a helps in identifying the rock itself. It distinguishes between rocks with a crystalline texture, rocks that have no grains visible and are uniformly smooth, and rocks with a clastic texture.

5.2 ROCK MASS VS. ROCK SUBSTANCE

Rock mechanics makes a major distinction between rock substance and rock mass. *Rock substance* refers to a piece of intact rock with no fissures; *rock mass* refers to the entire mass of rock, including fissures and joints. There is usually a big difference between the tensile strength of an intact piece of rock (rock substance), and a weathered mass of rock (rock mass). In most cases the rock mass is much weaker than the rock substance. Therefore, a description of the joint pattern is very important, and should include joint spacing (less than 50 mm for very fractured rock to more than 3 m for solid rock), joint width, joint roughness, joint direction (using a rose diagram), and joint strength.

Although it is easiest to measure the properties of the rock substance through laboratory testing, it is often more important to determine the behavior of the rock mass. This is the case for rock slopes, foundations on or in rock, and seepage through rock. An exception is the behavior of rock fill and rip rap, where the properties of the rock substance are critical.

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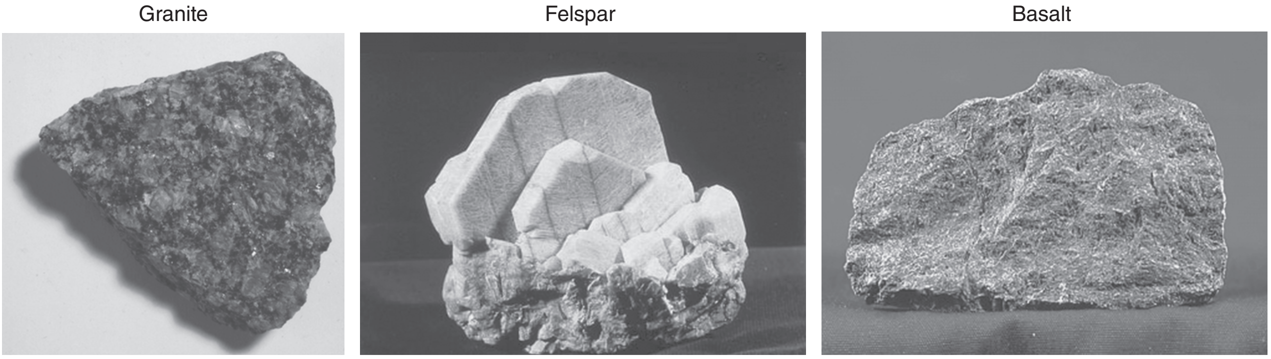
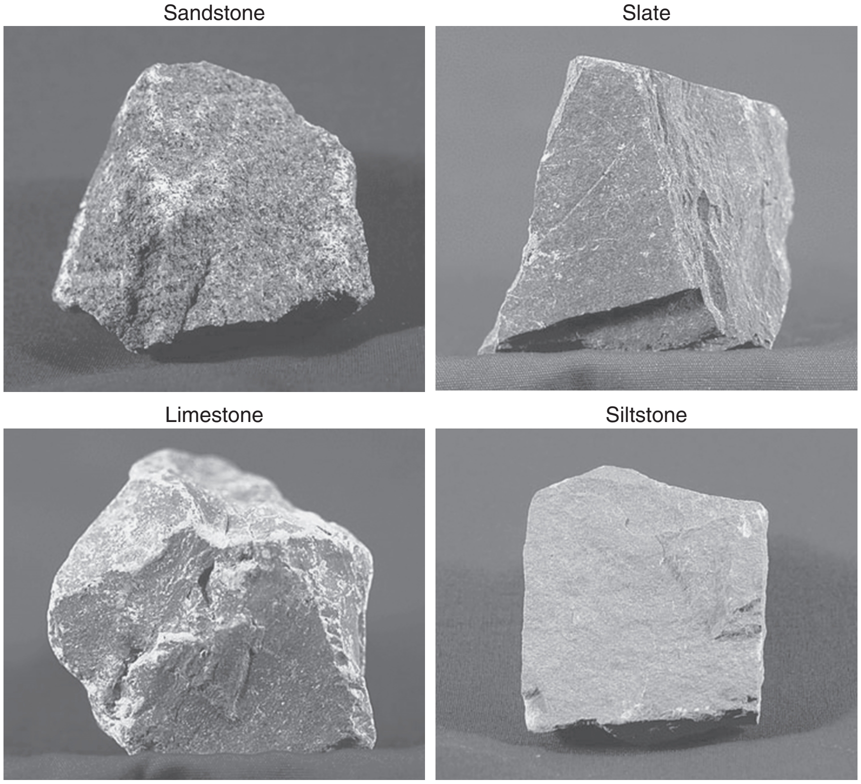


Granite

Felspar

Basalt

Figure 5.1 Igneous rocks: (*a*) granite, (*b*) feldspar, (*c*) basalt. (Courtesy of Mineral Information Institute, an affiliate of the SME Foundation.)



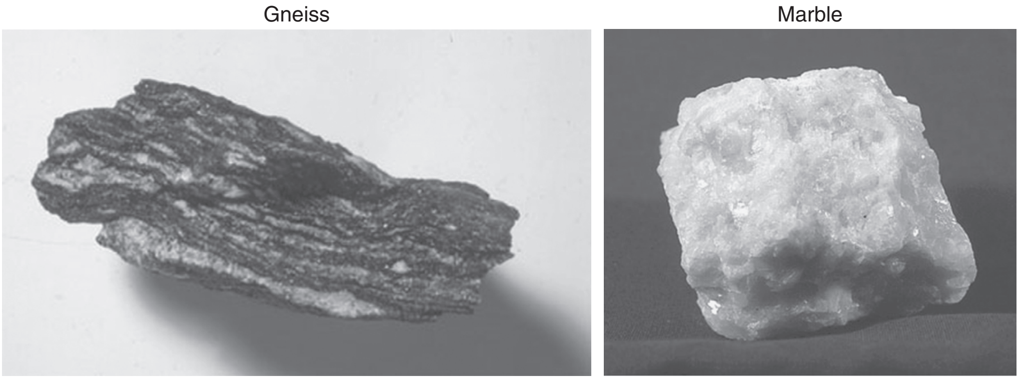
Sandstone

Slate

Limestone

Siltstone

Figure 5.2 Sedimentary rocks: (*a*) sandstone, (*b*) slate, (*c*) limestone, (*d*) siltstone. (Courtesy of Mineral Information Institute, an affiliate of the SME Foundation.)



Gneiss

Marble

Figure 5.3 Metamorphic rocks: gneiss, marble. (Courtesy of Mineral Information Institute, an affiliate of the SME Foundation.)

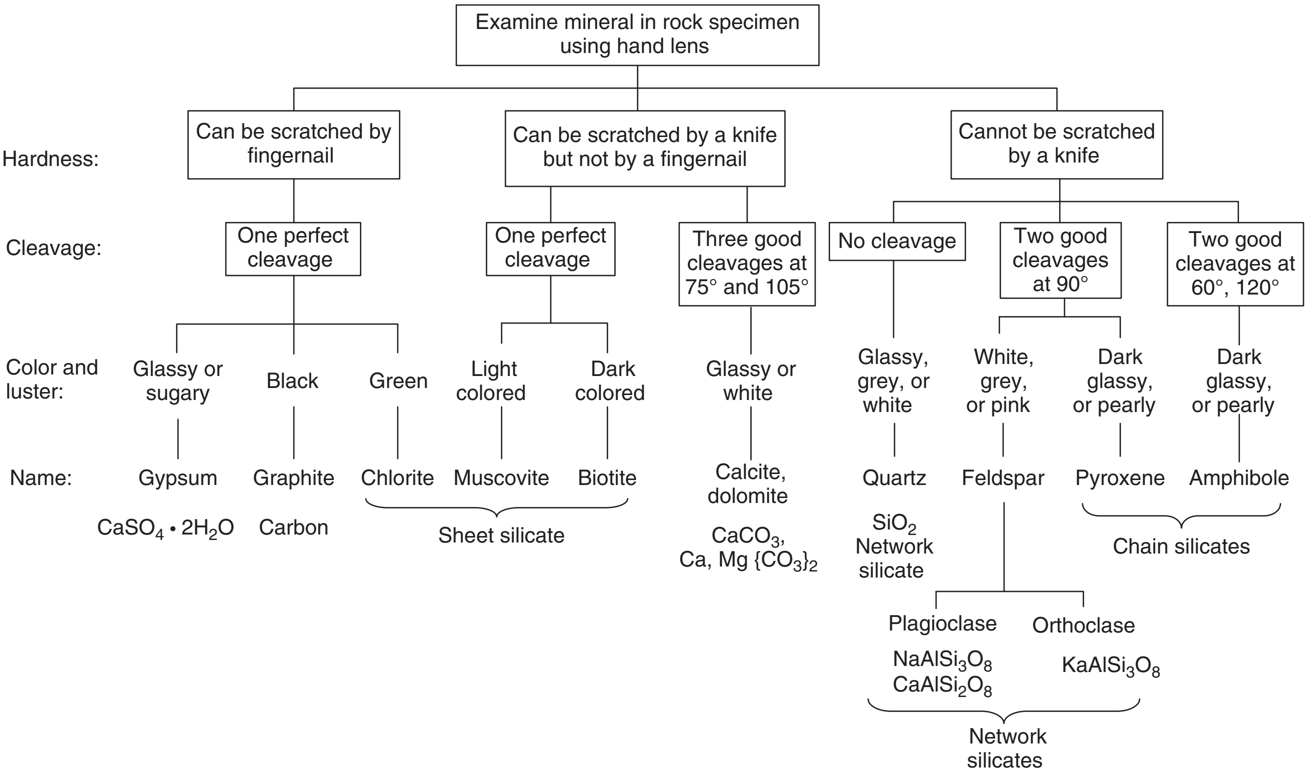
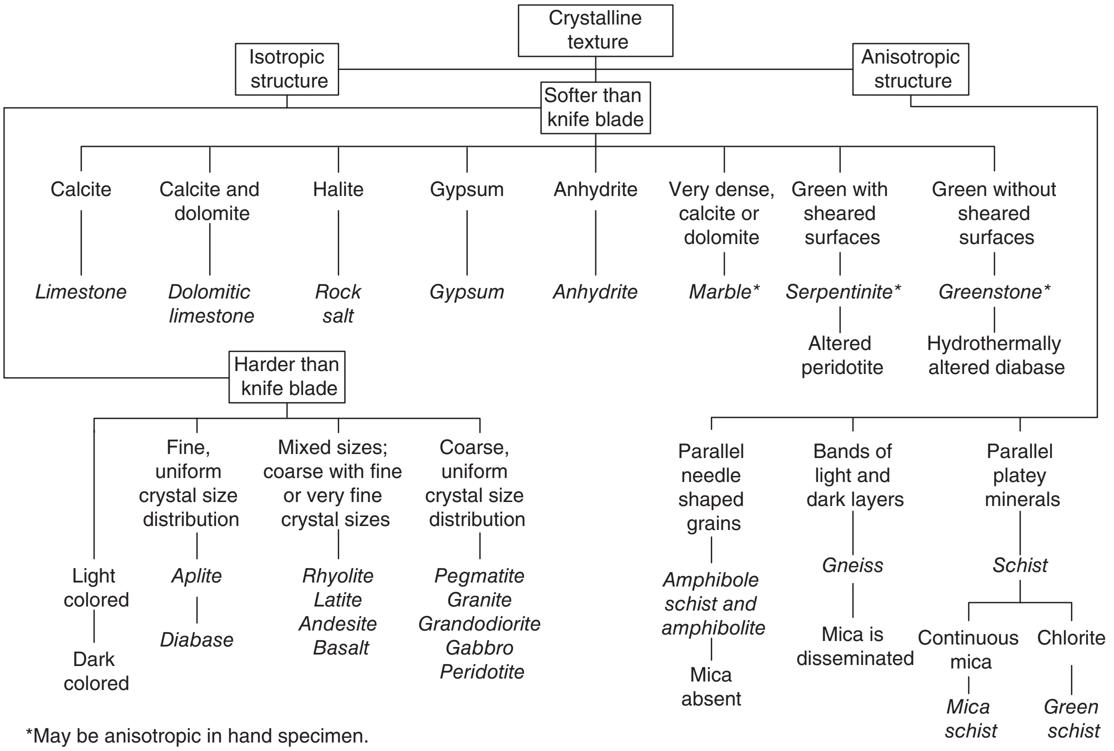


Figure 5.4 Identifying rock minerals. (From Goodman, 1989. Reprinted with permission of John Wiley & Sons, Inc.)



*May be anisotropic in hand specimen.

Figure 5.5a Identification of rocks with crystalline texture. (From Goodman, 1989. Reprinted with permission of John Wiley & Sons.)

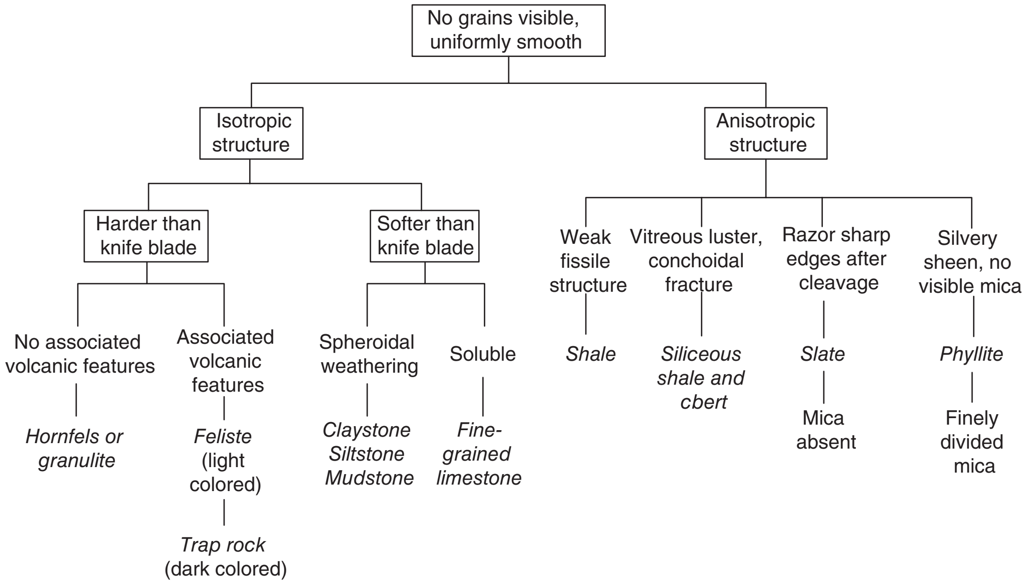


Figure 5.5b Identification of rocks with no grains visible. (From Goodman, 1989. Reprinted with permission of John Wiley & Sons.)

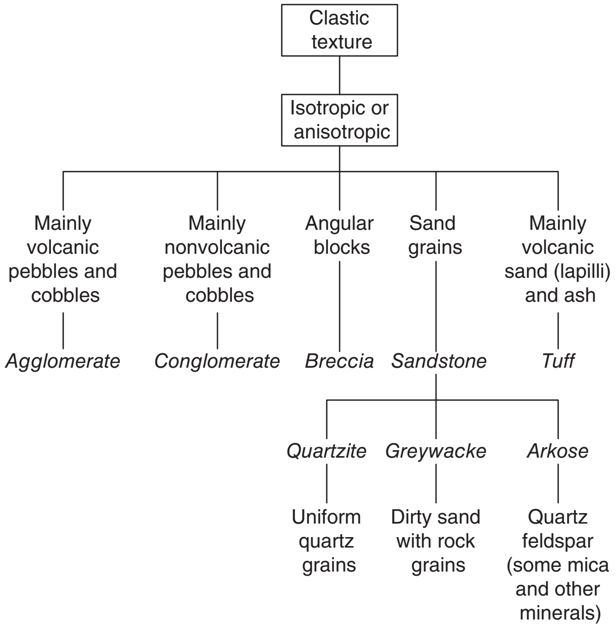


Figure 5.5c Identification of rocks with clastic texture. (From Goodman, 1989. Reprinted with permission of John Wiley & Sons.)

5.3 ROCK DISCONTINUITIES

Rocks usually exhibit a network of discontinuities that significantly affect the mass behavior. Many words exist to refer to these discontinuities: fissures, cracks, fractures, joints, and faults (Priest 1993). *Fissures* are the smallest and *faults* are the largest (Figure 5.6 and Figure 5.7). Nonetheless, the two main types are joints and faults. *Joints* are created over geologic time by bending of the rock mass, by vertical expansion, by horizontal stress relief (e.g., cliffs), by temperature differences, and sometimes by chemical action. Joints tend to exhibit a pattern. Faults are due to the movement of rock plates on a large scale and tend to be singular elements. These discontinuities introduce nonlinearities in behavior, stress dependency and anisotropy in properties, and weaknesses with regard to deformation and strength. Cementation in clastic rocks also significantly influences a rock's properties; often the properties of the binder control the behavior of the rock, much as cement controls the behavior of concrete. If the network of joints is random (rare), it weakens the rock evenly, but if the joints are directional (common), the weakness is accentuated in the direction of the joints in shear and reduces the shear strength to the strength of the joint surfaces. The tensile strength of the rock mass perpendicular to the joint direction is reduced to a small fraction of the intact rock strength. Compression perpendicular to joints increases deformation compared to the intact rock but has little influence on strength.

Another type of discontinuity is cavities and voids in the rock mass. These cavities most commonly form in limestone, dolomite, gypsum, and salt. Sinkholes in limestone occur in karst regions and can reach impressive dimensions.

5.4 ROCK INDEX PROPERTIES

Rock index properties include the dry unit weight of the rock substance and the porosity of the rock substance. The dry unit weight of the rock substance varies from a possible 21 kN/m^3 for a shale or a limestone to a possible 27 kN/m^3 for a marble or a granite. The most common values are between 25 and

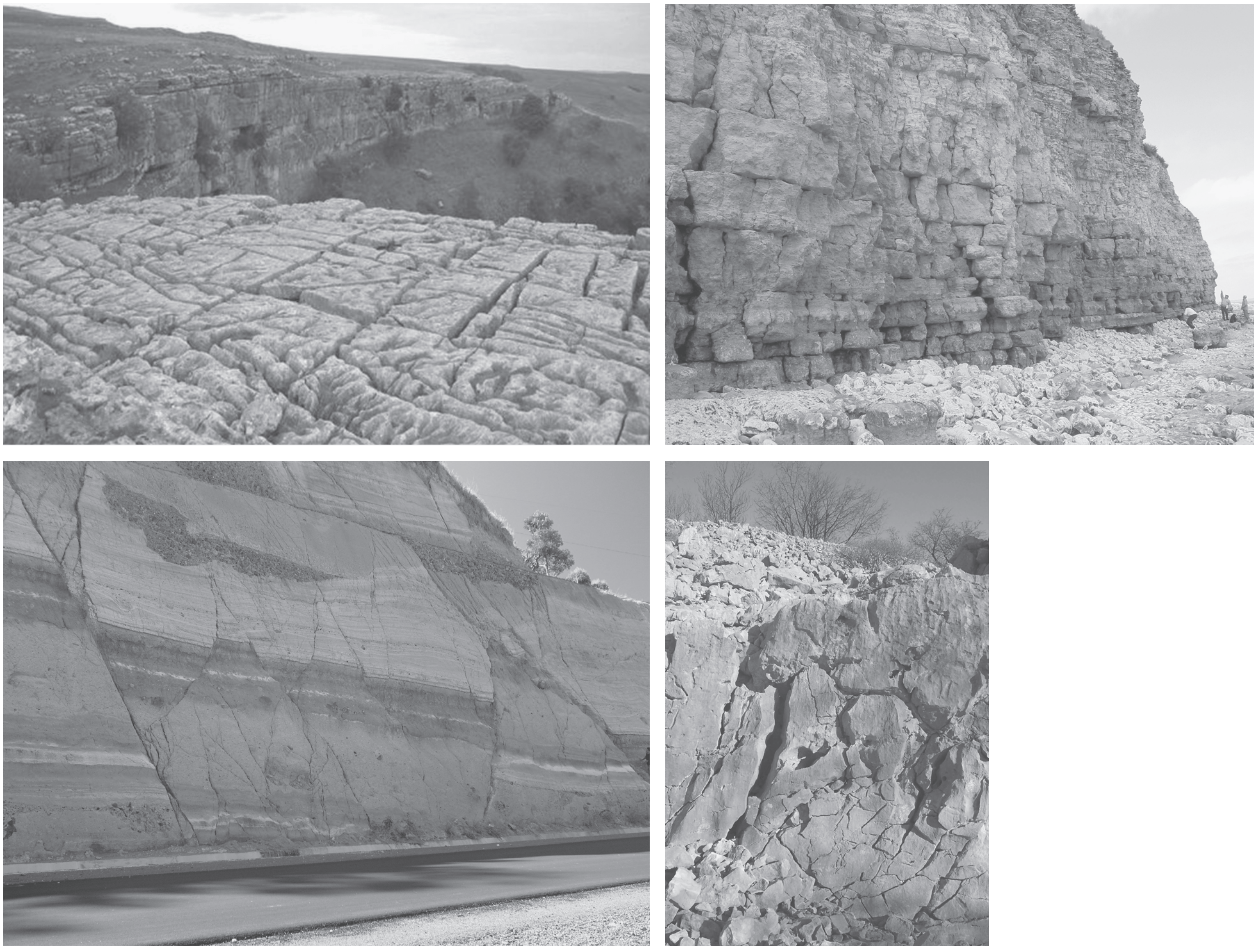


Figure 5.6 Fissures and joints. (a: Courtesy of Lupin. c: Courtesy of Charles DeMets, University of Wisconsin-Madison. d: Courtesy of Alex Brollo.)

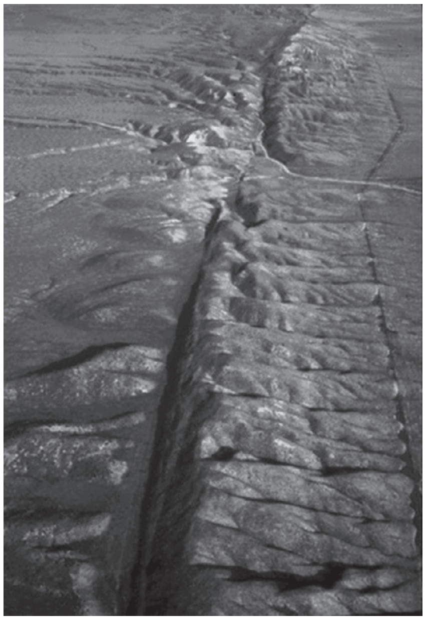


Figure 5.7 A fault. (Courtesy of The United State Geological Survey USGS, USA)

26 kN/m^3. The porosity of rock substance is at most a few percent; exceptions include shale, sandstone, and schist, for which the porosity can reach that of soils at several tens of percent. The degree of weathering significantly affects the rock mass unit weight and porosity, with the lowest unit weights and highest porosities for the highest degree of weathering.

5.5 ROCK ENGINEERING PROPERTIES

Engineering properties of the rock substance include durability, hardness, permeability, modulus, and strength (Waltham 1994). Although it is generally more important to know the properties of the rock mass, the first step is to find out the properties of the rock substance. An exception to this “rule” is when rip rap or rock fill has to be used for protection, as in scour or stability in rock-fill dams.

The *durability* of a rock is measured by a test called the *slaking durability test*. Ten pieces of rock are weighed and placed in a rotating drum lined with a 2 mm opening mesh. The drum is slowly rotated through a water bath for

10 minutes and the rock pieces remaining after the test are weighed again. The ratio in percent of the weight after and before the test is the slaking durability index I_{sd}. Rocks typically have I_{sd} values in excess of 90%. Values below 70 are undesirable for rip-rap applications.

Hardness is a measure of how hard a surface is. For rocks, it may refer to the hardness of the parent mineral or the rock surface. Talc is one of the softest minerals, whereas diamond is the hardest known mineral. On Mohs scale of hardness, talc has a rating of 1, gypsum 2, quartz 7, and diamond 10. The hardness of a rock surface can be measured by using a Schmidt hammer. The Schmidt hammer generates an impact on the rock surface and the mass that impacts the surface rebounds to a measured height. The rebound height divided by the maximum height is called the rebound value R. The rebound value has been correlated to the unconfined compression strength and the modulus of rocks.

The hydraulic conductivity, k, of a rock can be measured in the laboratory on an intact sample or in the field on the rock mass. The results are usually extremely different, with the field values being 10 to 100,000 times (or even more) larger than the laboratory values depending on the extent of the network of discontinuities in the rock mass. The densest intact rocks will have k values in the 10^{-10} to 10^{-15} m/s range, but volcanic intact rocks can have hydraulic conductivities in the range of 10^{-3} m/s. In the field, the hydraulic conductivity is drastically increased compared to the intact rock, as water could be gushing out of the joints of the rock mass. The k value can exhibit significant anisotropy depending on the direction of the joints.

The modulus of deformation, E, of the rock substance is measured on samples in the laboratory, most commonly using the unconfined compression test. In the field, the plate test, the half cylinder test, or the pressuremeter test can be used. Values of E for intact rock or rock substance are in the range of 2000 MPa to 100,000 MPa (concrete is around 20,000 MPa). The softer rocks include chalk and shale; the stiffer ones include granite and marble. The Poisson's ratio of rocks is relatively small, with values ranging from 0.15 to 0.3.

The strength of the intact rock, as measured by unconfined compression tests, can vary from more than 200 MPa for very hard rock to less than 10 MPa for very soft rock. Concrete has an unconfined compression strength of 20 MPa. Therefore, concrete is a soft to medium rock.

The ratio between the rock modulus of deformation E and the unconfined compression strength q_u is in the range of 150 to 600, with an average of 350. The lower values are found for the softer rocks (sandstone, shale), while the higher values are found for the harder rocks (marble, granite).

The tensile strength of a rock can be measured indirectly by using a special splitting test called the Brazilian test. The values range from less than 1 MPa for a shale up to about 15 MPa for granite. The shear strength of intact rocks leads to cohesion intercepts in the range of 5 to 40 MPa and friction angles in the range of 30 to 50 degrees.

5.6 ROCK MASS RATING

Rock masses are rated by using indices that help in evaluating the relationship between the rock substance properties and the rock mass properties.

Samples of rock are obtained by coring the rock, a process which consists of rotating an open steel tube or barrel with a coring bit (diamond) on the end of the steel tube wall. The tube is rotated into the rock at high speed while water is simultaneously injected for lubrication and cooling. Cores are retrieved and placed in core boxes. The recovery ratio (RR) is the ratio expressed in percent of the length of the core recovered divided by the length cored. The rock quality designation (RQD) is the ratio of the length obtained by adding all the pieces of core longer than 100 mm over the length cored. The *velocity index* I_v is also a useful index to evaluate the difference between the rock substance properties and the rock mass properties. It is defined as the ratio of the square of the compression-wave velocity of the rock mass in the field to the square of the compression-wave velocity of the intact rock in the laboratory. Rock mass quality is excellent for an RQD higher than 90% and a velocity index higher than 0.8. Rock mass quality is very poor for an RQD less than 25% and a velocity index less than 0.2.

The Unified Rock Classification System or URCS (Williamson 1984) was developed to parallel the Unified Soil Classification System (USCS). It provides a systematic and reproducible method of describing rock weathering, strength, discontinuities, and density in a manner directly usable by engineers. The URCS is described in ASTM D5878.

In 1989, Bieniawski proposed the rock mass rating (RMR) by combining several indicators of rock mass features. They include the strength of the rock substance (q_u), the rock quality designation (RQD), the joint spacing, the joint condition, the joint orientation, and the groundwater conditions. Table 5.1 shows the RMR categories. The RMR value is obtained by adding the ratings defined in each category. Rock mass classes I through V correspond to RMR values between 80–100, 60–80, 40–60, 20–40, and 0–20, respectively. A class I rock mass would be labeled a very good rock, whereas a class V rock mass would be considered very poor rock. Such classes can be correlated to estimated values of rock mass strength and safe bearing pressures, for example. Another and similar rock mass rating system exists and is called the Norwegian Q system. This system, created in 1974, is credited to Barton, Lien, and Lunde of the Norwegian Geotechnical Institute (1974). It is based primarily on the analysis of tunneling case histories and uses six parameters to assess the rock mass quality. The parameters are the RQD, the joint set number J_n, the roughness of the joints J_r, the degree of alteration and filling of the joints J_a, the water inflow J_w, and the stress reduction factor *SRF*. Using these six parameters, the Q factor is derived with the following equation:

$$Q = \frac{RQD \times J_r \times J_w}{J_n \times J_a \times SRF}$$

Table 5.1 Rock Mass Rating (RMR) Geomechanics System (Waltham 1994)

Parameter	Assessment of values and rating				
Intact rock USCS, MPa	>250	100–250	50–100	25–50	1–25
rating	15	12	7	4	1
RQD %	>90	75–90	50–75	25–50	>25
rating	20	17	13	8	3
Mean fracture spacing	>2 m	0.6–2 m	200–600 mm	60–200 mm	<60 mm
rating	20	15	10	8	5
Fracture conditions	Rough tight	Open <1 mm	Weathered	Gouge <5 mm	Gouge >5 mm
rating	30	25	20	10	0
Groundwater state	Dry	Damp	Wet	Dripping	Flowing
rating	15	10	7	4	0
Fracture orientation	Very favorable	Favorable	Fair	Unfavorable	Very unfavorable
rating	0	−2	−7	−15	−25

Rock mass rating (RMR) is sum of the six ratings. Note that orientation ratings are negative.

In 1994, Hoek introduced the geologic strength index (GSI) to rate jointed rock masses. The GSI takes into consideration the interlocking of rock pieces or "blockiness" of the rock mass on the one hand and the condition of the rock surfaces or joints on the other (Figure 5.8). Then the GSI is used to extrapolate from the intact rock strength and modulus to the strength and modulus of the rock mass.

5.7 ROCK ENGINEERING PROBLEMS

Some common rock engineering problems include allowable pressures for foundations, ultimate side shear and ultimate point pressure for bored piles, slope stability, tunneling, excavations, blasting, rippability, and scour.

The allowable pressure for shallow foundations in rock is sometimes used prescriptively. These values vary significantly and depend on the quality of the rock mass, which can be described by the RMR classes of the geomechanics system. Estimates of these allowable values are from 6000 to 10,000 kPa for a very good rock (Class I), 4000 to 6000 kPa for a good rock (Class II), 1000 to 4000 kPa for a fair rock (Class III), 200 to 1000 kPa for a poor rock (Class IV), and less than 200 kPa for a very poor rock (Class V). The settlement associated with these allowable pressures is usually calculated using elasticity theory; the main issue is obtaining the right modulus of deformation for the rock mass.

The columns of the World Trade Center towers were on shallow foundations on rock (Figures 5.9, 5.10, and 5.11). The towers weighed approximately 4500 MN each, were 417 m high, and had a footprint of 62 m × 62 m. The mica schist bedrock was found at a depth of about 21 m and exhibited inclined joints. Excavation took place so the shallow foundations could rest directly on the rock. The rock substance modulus was determined through laboratory tests that gave an average of 80,000 MPa. The rock mass was tested by a full-scale footing test which gave a rock mass modulus equal to 1400 MPa or 1/57 of the rock substance value, due to the presence of joints. The design pressure for the footings was approximately 3000 kPa and the maximum pressure applied during the full-scale footing test was well over 3000 kPa.

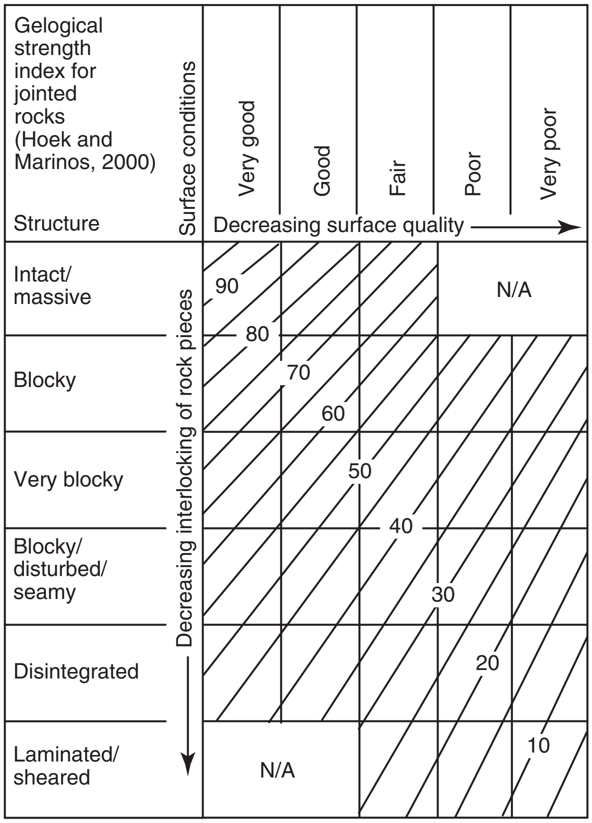


Figure 5.8 Geologic strength index (GSI) for jointed rock masses. (After Marinos and Hoek, 2000.)

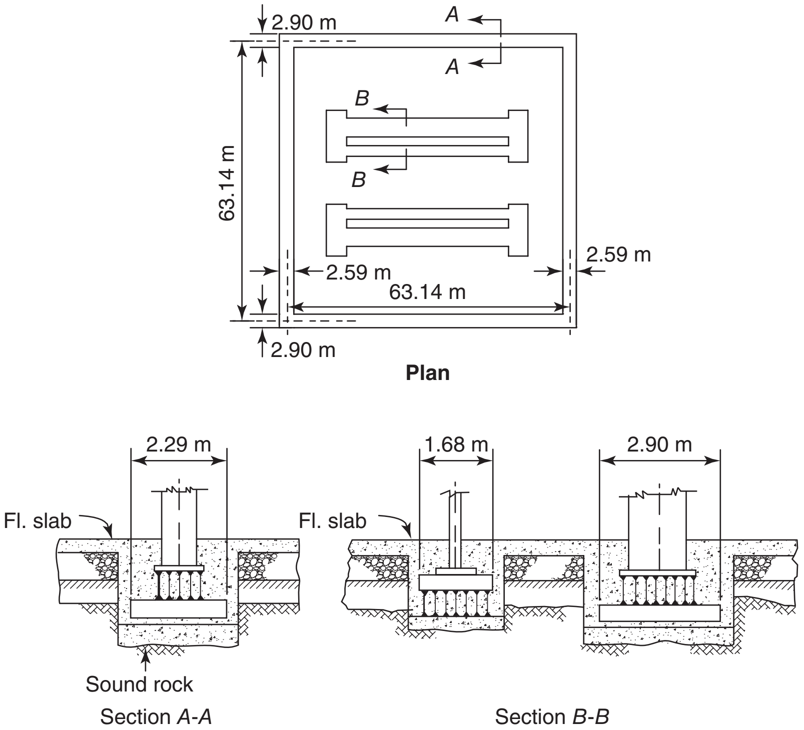


Figure 5.9 Foundation plan for the World Trade Center. (Courtesy of the Port Authority of New York and New Jersey.)

Figure 5.10 Photo of the foundation for the World Trade Center. (Courtesy of the Port Authority of New York and New Jersey.)

The shallow foundations are shown on Figure 5.8 and 5.9; the total area was 1426 m^2. The calculated settlement for the foundation elements using elasticity theory and the measured modulus was very small, varying from 6 to 12 mm. Most of this settlement is likely to have happened during construction.

The cliffs at the Pointe du Hoc site in Normandy, France, are made of interbedded layers of limestone and sandstone. These cliffs are eroded at their base by wave action from the sea; caverns develop at the base as a result of this wave action (Figure 5.12). When the caverns become deep enough, the overhanging rock mass fails. These failures allow back-calculation of the tensile strength of the rock mass. The tensile strength of the rock substance tested in the laboratory by the Brazilian test (Figure 5.13) gave an average tensile strength of 3400 kPa in the limestone and 4500 kPa in the sandstone. The average tensile strength of the rock mass back-calculated from the overhang failures (Figure 5.14) indicated 40 kPa tensile strength, or about 1/100 of the rock substance value.

Recommendations for the ultimate side shear values for a bored pile socketed in rock range from 300 kPa for a weak, fractured, decomposed rock (say, RQD = 20%) to 3000 kPa for a massive competent rock. Common formulas

Figure 5.11 Photo of the World Trade Center twin towers. (Courtesy of the Port Authority of New York and New Jersey.)

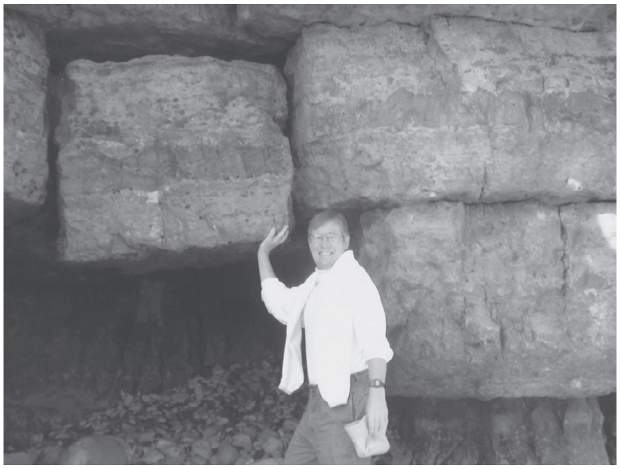


Figure 5.12 Jointed rock mass and caverns at Pointe du Hoc.

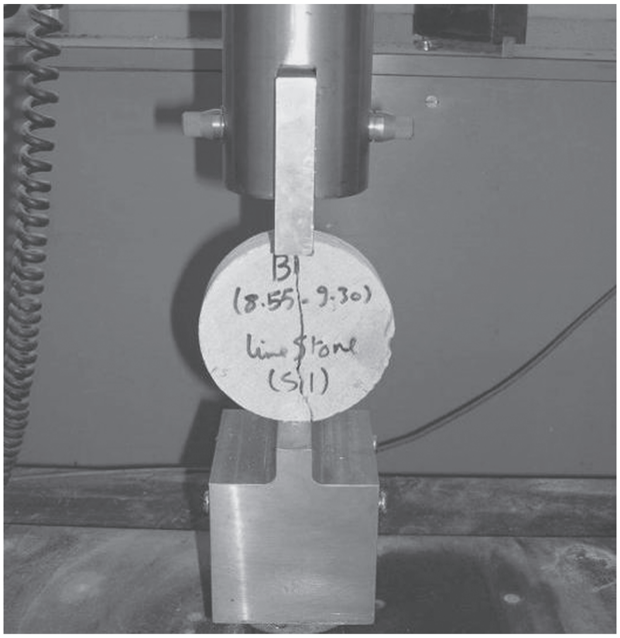


Figure 5.13 Brazilian tension test on Pointe du Hoc limestone.

equate the ultimate side shear with the square root of the unconfined compression strength diminished by additional factors that take the rock mass quality into consideration. The ultimate bearing pressure at the bottom of a bored pile or a driven pile to rock can range from 4000 kPa for a poor rock mass quality to 400,000 kPa for a massive competent rock with a high strength. Of course, the ultimate bearing capacity may be limited by the strength of the pile itself. The ultimate bearing pressure is usually given as proportional to the unconfined compression strength of the intact rock diminished by a coefficient that takes the rock mass quality into consideration.

In rock slope stability, the main influencing factors are the direction of the joints compared to the direction of the potential failure surface, the shear strength of the joints, and the water pressures in the joints. Failure analyses usually use planar surfaces and wedges following the joints' contours. The failing mass is analyzed using fundamental laws and constitutive laws to give a factor of safety. The *factor of safety* is defined as the ratio of the resisting moment or resisting force in the direction of sliding over the driving moment or driving force in the direction of sliding.

Figure 5.14 Massive collapse of rock cliff at Pointe du Hoc.

Other rock engineering problems include tunneling, excavations, blasting, rippability, and scour.

5.8 PERMAFROST

In areas of the Earth where the mean annual temperature of the air does not get above 0° Celsius, the soil may be permanently frozen down to a certain depth. These areas include the North Pole, the South Pole, and any mountain above about 5000 m high (Figure 5.15). The permafrost can be shallow (a few meters) or deep (several hundred meters). Because permafrost is rich in ice, its properties are very much tied to the properties of the ice. This implies that, much like ice, the strength and modulus of permafrost increase when the temperature decreases and are rate dependent. Note that the influence of temperature is much more important than the influence of rate effect. Permafrost also exhibits creep under sustained loading. Because ice is the binder that strengthens permafrost, like cement for concrete, the higher the degree of saturation of permafrost, the stronger the permafrost is. For construction on permafrost, it is best to isolate the building or structure from the permafrost so as to minimize the temperature changes incurred in the permafrost. Indeed, when permafrost melts, it loses tremendous strength. This is why buildings and pipelines are elevated above permafrost ground through the use of piles (Figure 5.16).

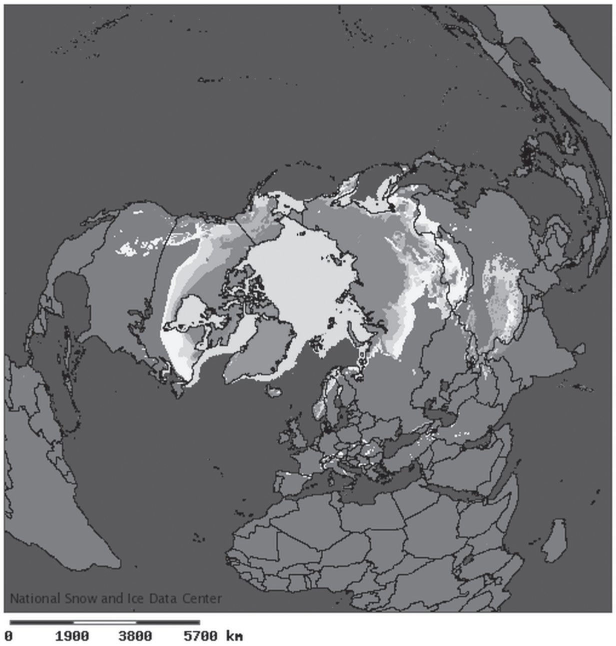


Figure 5.15 Zones of permafrost in the Northern hemisphere. (Courtesy of NSIDC.)

Figure 5.16 Elevated structure on permafrost. (Courtesy of Anadarko Petroleum Corporation.)

PROBLEMS

5.1 Answer the following questions:
  a. What are the three main categories of rocks?
  b. Are granite, feldspar, and basalt igneous, metamorphic, or sedimentary rocks?
  c. Are sandstone, shale, limestone, and lignite igneous, metamorphic, or sedimentary rocks?
  d. Are gneiss and marble igneous, metamorphic, or sedimentary rocks?

5.2 Is diamond a rock or a mineral? Is there any rock harder than diamond? Is there anything harder than diamond?

5.3 What is the difference between rock mass and rock substance, and how does this difference affect the engineering properties?

5.4 What is the typical range of values for the dry unit weight and porosity of a rock substance?

5.5 How is the durability of a rock substance measured? Describe the test.

5.6 What are the typical range of modulus and Poisson's ratio values for rock substance? How do this range and values compare with concrete?

5.7 What is the typical range of unconfined compression strength for rock substance and its ratio to the rock substance modulus? What is the typical range of tensile strength for rock substance? How does this compare with concrete?

5.8 Explain what the RR, the RQD, and the I_v are and use the words *excellent, good, fair, poor*, or *very poor* to qualify ranges of values of these various indices.

5.9 Explain what the RMR and the GSI are and how they are obtained.

5.10 Attempt a correlation between the safe pressure for a foundation on rock using the rock substance strength on the one hand and the RMR or GSI on the other.

5.11 Calculate the settlement of the foundation of the World Trade Center towers (Figure 5.1s).

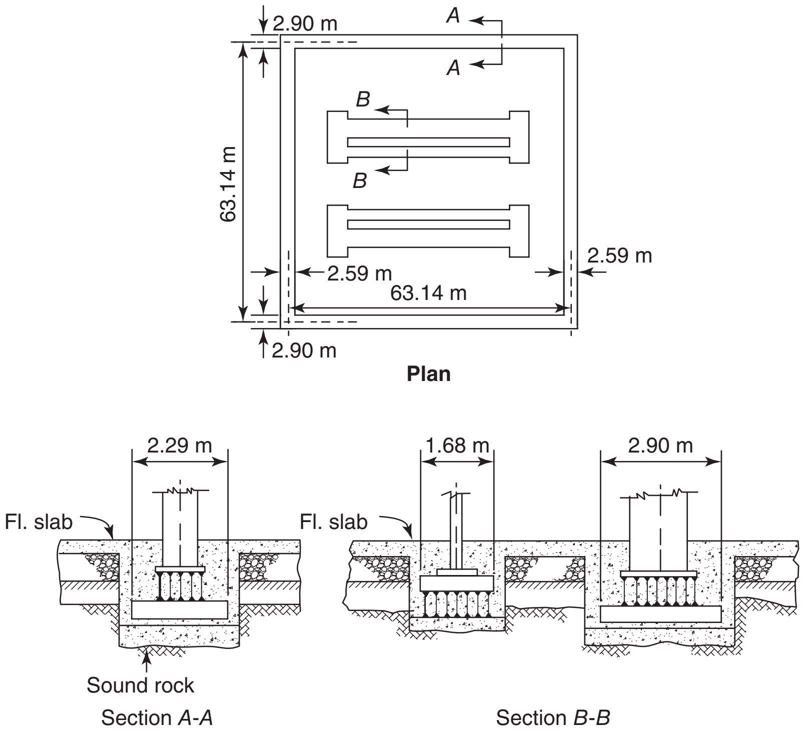


Figure 5.1s World Trade Center foundations section.

5.12 Calculate the stress distribution along the plane of failure for the cliff overhang in Figure 5.2s. Give the solution if the stresses are in the elastic range and assume that there is no failure due to tensile stress (no crack). Find the maximum stress when the cliff is 30 m high and the cave is 4 m deep and 3 m high.

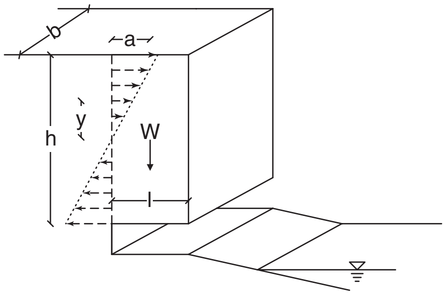


Figure 5.2s Geometry of the cliff.

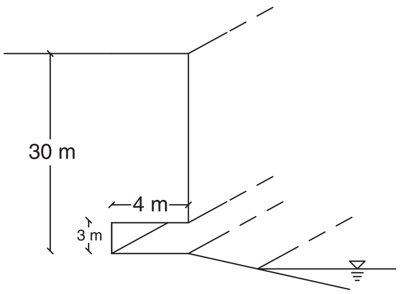


Figure 5.3s Dimensions of the cliff.

5.13 What is the best way to design a foundation on permafrost?

Problems and Solutions

Problem 5.1

Answer the following questions:

a. What are the three main categories of rocks?
b. Are granite, feldspar, and basalt igneous, metamorphic, or sedimentary rocks?
c. Are sandstone, shale, limestone, and lignite igneous, metamorphic, or sedimentary rocks?
d. Are gneiss and marble igneous, metamorphic, or sedimentary rocks?

Solution 5.1

a. From the point of view of their origin, rocks are classified as igneous, sedimentary, or metamorphic.
b. Granite, feldspar, and basalt are igneous rocks.
c. Sandstone, shale, limestone, and lignite are sedimentary rocks.
d. Gneiss and marble are metamorphic rocks.

Problem 5.2

Is diamond a rock or a mineral? Is there any rock harder than diamond? Is there anything harder than diamond?

Solution 5.2

Diamond is pure carbon, so it is a basic element and is classified as a mineral. Diamond is the hardest mineral on the Mohs scale of mineral hardness, based on its resistance to scratching. There is no rock or other natural material harder than diamond. A few manmade materials—all made of carbon—have been claimed to be harder than diamond.

Problem 5.3

What is the difference between rock mass and rock substance, and how does this difference affect the engineering properties?

Solution 5.3

Rock substance refers to a piece of intact rock with no fissures; *rock mass* refers to a large volume of rock, including the fissures and joints. In most cases, the rock mass is much weaker than the rock substance. The presence of fissures and joints weakens the rock mass and affects all its engineering properties.

Problem 5.4

What is the typical range of values for the dry unit weight and porosity of a rock substance?

Solution 5.4

The dry unit weight of rock substance varies from about 21 kN/m^3 (e.g., a shale or a limestone) to about 27 kN/m^3 (e.g., a marble or a granite). The most common values are between 25 and 26 kN/m^3. The porosity of rock substance is very low except for shale, sandstone, and schist, for which the porosity can reach that of soils (several tens of percent).

Problem 5.5

How is the durability of a rock substance measured? Describe the test.

Solution 5.5

The durability of a rock is measured by a test called the slaking durability test. Ten pieces of rock are weighed and placed in a rotating drum lined with a 2 mm opening mesh. The drum is slowly rotated through a water bath for 10 minutes and the dry weight of the rock pieces remaining after the test is measured again. The ratio in percent of the weight after and before the test is the slaking durability index I_{sd}. Rocks typically have I_{sd} values in excess of 90%. Values below 70% are undesirable for rip-rap applications.

Problem 5.6

What are the typical range of modulus and Poisson's ratio values for rock substance? How do this range and values compare with concrete?

Solution 5.6

Values of the modulus of deformation for rock substance range from 2000 MPa to 100,000 MPa and the Poisson's ratio values of rock substance range from 0.15 to 0.3. By comparison, concrete has a modulus of 20,000 MPa, equivalent to that of a soft to medium rock.

Problem 5.7

What is the typical range of unconfined compression strength for rock substance and its ratio to the rock substance modulus? What is the typical range of tensile strength for rock substance? How does this compare with concrete?

Solution 5.7

The typical range of unconfined compression strength for rock substance is from 10 MPa for very soft rock to 200 MPa for very hard rock. By comparison, concrete has an unconfined compression strength of 20 MPa, equivalent to the strength of a soft rock.

The ratio between the rock modulus of deformation E and the unconfined compression strength q_u is in the range of 150 to 600, with an average of 350.

The typical range of tensile strength for rock substance is 1 MPa to 15 MPa. The average tensile strength for concrete is about 2.5 MPa, so concrete is equivalent to a soft rock.

Problem 5.8

Explain what the RR, the RQD, and the I_v are and use the words *excellent, good, fair, poor*, or *very poor* to qualify ranges of values of these various indices.

Solution 5.8

The recovery ratio (RR) is the ratio of the length of the core recovered divided by the length cored, expressed in percent.

The rock quality designation (RQD) is the ratio of the length obtained by adding all the pieces with length longer than 100 mm over the length cored, expressed in percent.

The velocity index I_v is used to evaluate the difference between the rock substance properties and the rock mass properties. It is defined as the ratio of the square of the compression-wave velocity of the rock mass in the field to the square of the compression-wave velocity of the rock substance.

Rock Quality	RR	RQD (%)	$\mathbf{I}_v$
Excellent	97–100	90–100	>0.8
Good	90–97	75–90	0.6–0.8
Fair	67–90	50–75	0.4–0.59
Poor	35–67	25–50	0.2–0.39
Very poor	<35	<25	<0.2

Problem 5.9

Explain what the RMR and the GSI are and how they are obtained.

Solution 5.9

The rock mass rating (RMR) is a value defined as the sum of ratings for several indicators of rock mass features. These indicators are the strength of the rock substance (q_u), rock quality designation (RQD), joint spacing, joint condition, joint orientation, and the groundwater conditions.

Rock Quality	RMR
Excellent	81–100
Good	61–80
Fair	41–60
Poor	21–40
Very poor	0–20

The geologic strength index or GSI is used to rate jointed rock masses, taking into consideration the interlocking of rock pieces or blockiness of the rock mass on the one hand and the condition of the rock surfaces or joints on the other.

The RMR and GSI can be used to extrapolate from the strength and modulus of the rock substance to the strength and modulus of the rock mass.

Problem 5.10

Attempt a correlation between the safe pressure for a foundation on rock using the rock substance strength on the one hand and the RMR or GSI on the other.

Solution 5.10

It has been suggested (Sjoberg 1997) that GSI can be related to RMR by GSI = RMR − 5 for rock masses with RMR larger than 25. Therefore, the following correlation between the safe pressure and the RMR or GSI may be developed:

Pressure (kPa)	RMR	GSI
6, 000 ∼ 10, 000	Class I (81 ∼ 100)	76 ∼ 95
4, 000 ∼ 6, 000	Class II (61 ∼ 80)	56 ∼ 75
1, 000 ∼ 4, 000	Class III (41 ∼ 60)	36 ∼ 55
200 ∼ 1, 000	Class IV (21 ∼ 40)	21 ∼ 35
<200	Class V (0 ∼ 20)	0 ∼ 20

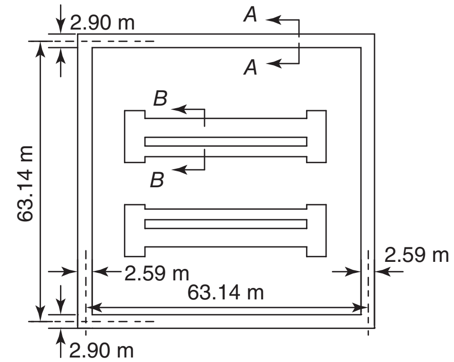
Sjoberg, J. 1997.

Problem 5.11

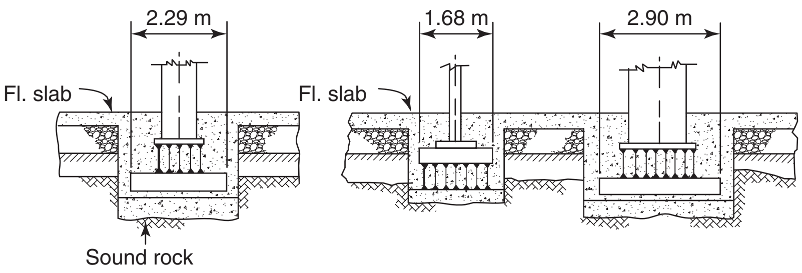
Calculate the settlement of the foundation of the World Trade Center towers.

Solution 5.11

The sections of the World Trade Center foundations are shown in Figure 5.1s.



Plan



Section *A-A* Section *B-B*

Figure 5.1s World Trade Center foundations section.

The pressure acting on the shallow foundation is $p = 3.0 \times 10^6 Pa$, and the rock mass modulus is $E = 1.4 \times 10^9 Pa$. The ratio between the effective length and the effective width of the foundation (L'/B') is 10.0, and Poisson's ratio (ν) of the rock is 0.3. The settlement of the foundation, assuming that the thickness of the bedrock layer is infinite, is given by the following equation:

$$s = C_s pB\left(\frac{1-\nu^2}{E}\right)$$

where C_s is the shape factor (2 for a rigid foundation with an L/B = 10.0, Fang 1991). Therefore, the settlement is:

$$s(\text{mm}) = 2 \times 3 \times 10^6 \cdot B \cdot \left(\frac{1-0.3^2}{1.4 \times 10^9}\right) \times 1000 = 3.9 \cdot B$$

For B = 2.29 m, $S_1 = 8.93$ mm.

For B = 1.68 m, $S_2 = 6.55$ mm.

For B = 2.9 m, $S_3 = 11.31$ mm.

Problem 5.12

Calculate the stress distribution along the plane of failure for the cliff overhang in Figure 5.2s. Give the solution if the stresses are in the elastic range and assume that there is no failure due to tensile stress (no crack). Find the maximum stress when the cliff is 30 m high and the cave is 4 m deep and 3 m high.

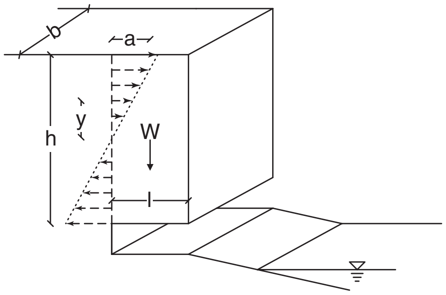


Figure 5.2s Geometry of the cliff.

Solution 5.12

The weight W of the rock overhang above the cave is:

$$W = \gamma \times b \times h \times l$$

where Y is the unit weight of the cliff rock, b is the unit width, h is height of the overhang, and l is the depth of the cave. The bending moment due to this mass of rock is:

$$M = W \times a$$

With $a = l/2$

The stress distribution in the cliff due to the bending moment is:

$$\sigma = \frac{M \times y}{I}$$

where I is the moment of inertia of the cliff section and y is the vertical distance from the neutral axis (Figure 5.2s). The moment of inertia of the cliff section is:

$$I = \frac{b \times h^3}{12}$$

Combining the previous equations gives the equation for the normal stress distribution in the cliff section:

$$\sigma = \frac{12 \times \gamma \times l \times a}{h^2} \times y$$

Numerical application:

$$h = 27 \text{ m}$$
$$l = 4 \text{ m}$$
$$a = 2 \text{ m}$$
$$b = 1 \text{ m}$$
$$Y = 26 \times 10^3 \text{ N/m}^3$$

Weight per meter of cliff above the cave:

$$W = 26 \times 10^3 \times 27 \times 4 = 28.08 \times 10^5 \text{ N/m}$$

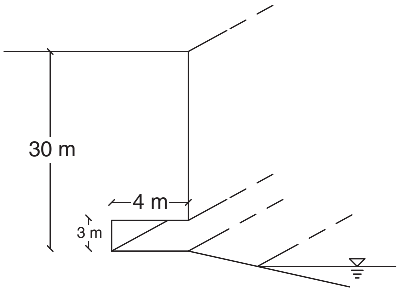


Figure 5.3s Dimensions of the cliff.

The moment due to the cliff mass above the cave:

$$M = 28.08 \times 10^5 \times 2 = 56.16 \times 10^5 \text{ N.m/m}$$

The moment of inertia of the cliff section:

$$I = 27^3/12 = 1640 \text{ m}^4/\text{m}$$

The stress at the top and bottom of the section is:

$$\sigma = \frac{12 \times 26 \times 10^3 \times 4 \times 2}{27^2} \times \frac{27}{2} = 46.22 \times 10^3 \text{ Pa} = 46.22 \text{ kPa}$$

The tension capacity of the intact rock varied between 2 and 20 MPa, yet the cliffs failed when the depth of the caverns reached about 4 m. Therefore, the rock mass tensile strength must have been about 46 kPa, or less than about 2% of the intact rock strength.

Problem 5.13

What is the best way to design a foundation on permafrost?

Solution 5.13

The best way to design a foundation on permafrost is to provide a space between the foundation slab and the soil layer (Figure 5.4s). That way air can circulate and prevent building-generated heat from thawing out the soil layer below and thereby dramatically decreasing the soil strength.

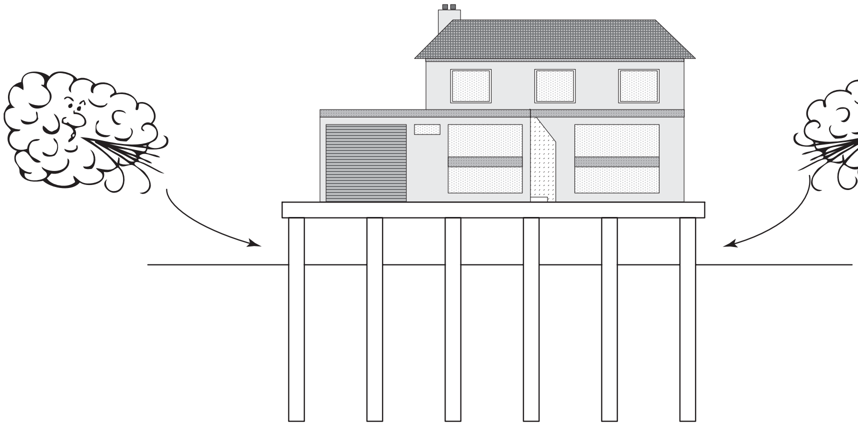


Figure 5.4s Solution for designing a foundation on permafrost.