ENGINEERING GEOLOGY

JUNIOR COURSE

2018-2019

Syllabus:

Chapter No.	Title
1	Engineering Geology and earth crust
2	Minerals
3	Factors affecting earth crust
4	Rocks, Types and Characteristics
5	Physical and engineering properties of rocks
6	Soils, origin and Characteristics
7	Physical and engineering properties of soils
8	Internal and external stresses is soils
9	Geological Maps
10	Contour Maps
11	Geophysical Investigations

References:

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1. Geology

It is the science which is devoted to the study of the earth and its components. It deals with all features of the earth's surface and with origin, composition, structure and inhabitant of the earth.

1.1 Branches of Geology:

The subject of geology is divided into several branches which are as follows:

1. **Physical Geology**: it is concerned with the work of natural processes which bring changes upon earth's surface.
2. **Petrology**: the discussion of the different kinds of rocks is known as petrology.
3. **Mineralogy**: it includes the study of minerals.
4. **Structural Geology**: it includes the study of the structures of the rocks in the earth's crust.
5. **Stratigraphy**: it is concerned with study of stratified rocks and their correlations.
6. **Paleontology**: it deals with the study of fossils. It the study of fossils (= preserved bones or shells) as a way of getting information about the history of life on Earth and the structure of rocks.
7. **Historical Geology**: it gives us a picture of the land, seas, climates and the life of early times upon the earth.
8. **Economic Geology**: it deals with the study of minerals of economic importance.
9. **Mining geology**: it is concerned with the study of application of geology to mining engineering.
10. **Engineering Geology**: it includes the study of application of geology in the engineering fields (and specifically in civil engineering).

The relationship between the Engineering Geologists and Civil Engineers:

The engineering geologist presents geological data and interpretations for use by the civil engineer. The civil engineers have to deal mostly with soil and rocks, timbers, steel, and concrete. In a great majority of civil engineering, projects and the designs, involve the soils and rocks almost directly.

The importance of engineering geology in civil engineering may briefly be summarized as follows:

Geology is important for successful geotechnical engineering practice. One of the primary tasks of a geotechnical engineer is to understand the character of the soil at a site.

Soils, derived from the weathering of rocks, are very complex materials and vary widely. There is no certainty that a soil in one location will have the same properties as the soil just a few centimeters away.

Unrealized geological formations and groundwater conditions have been responsible for failures of many geotechnical systems and increased construction costs. As a typical practical scenario, let us consider the design and construction of a bridge as part of a highway project. It is required to design the bridge foundation and abutment. To initiate a design of the foundation and the abutment, one has to know the geology of the site including the soil types, their spatial variations, groundwater conditions, and potential for damage from natural hazards such as earthquakes. You, perhaps working with geologists, will have to plan and conduct a site investigation and interpret the data.

1.2 Basic Geology:

Our planet Earth has an average radius of 6378 km and a mean mass density of 5.527 g/cm^3 compared with a mean mass density of soil particles of 2.7 g/cm^3 and water of 1 g/cm^3. Studies from elastic waves generated by earthquakes have shown that the earth has a core of heavy metals, mostly iron and nickel, of mass density 8 g/cm^3 surrounded by a mantle. The mantle consists of two parts, upper mantle and lower mantle. The upper mantle lies between (35-650) km depth and made of solid rock while the lower mantle lies between (650-2890) km depths and made of molten rock. Above the upper mantle is the crust, which may be as much as 50 km thick in the continental areas (Figure 1-1) and as little as 7 km thick in oceanic areas.

It is possible to distinguish two layers in the crust. The upper layer which is less dense (specific gravity=2.65), and granitic in character is known as the “sial"; while the lower layer which is basaltic in character (specific gravity=3.0) is known as" sima". The term sial represents rocks rich in silica and alumina and term sima represents rocks containing silica and magnesia. Under oceans only sima layer is found and sial layer appears to be absent.

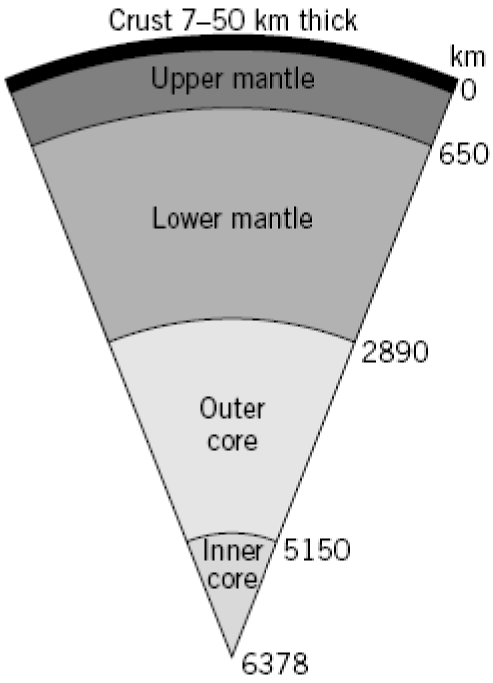


FIGURE 1-1: A SECTOR OF THE EARTH.

1.3 Minerals:

A "mineral "is a naturally occurring inorganic substance which has more or less definite chemical composition and definite atomic structure.

The minerals may be divided into TWO groups:

i. Rock forming minerals, and
ii. Ore-forming minerals.

"Rock forming minerals" are those which are found in abundance in the rocks of the earth's crust, while "ore-forming minerals" are those which are of economic value, and which do not occur in abundance in rocks. Approximately 200 different minerals are known, but most of them are rare. The minerals which occur in common rocks are small in numbers and they are divided into the following groups:

1. Oxides: Quartz, Magnetite, Hematite, limonite.
2. Carbonates: Calcite ($CaCO_3$).
3. Sulphides: Pyrite (Galena).
4. Sulphates: Gypsum ($CaSO_4.2H_2O$).
5. Chlorides: Rock salt (NaCl).
6. Silicates: Feldspars, Mica, Hornblende, Augite, Olivine.

1.3.1 Identification of minerals

Common minerals can be identified readily, if their ordinary physical properties are known. These include such properties as color, streak, luster, hardness, cleavage, fracture, form, specific gravity, tenacity, odor, feel, fluorescence, phosphorescence, magnetism, and crystal form.

The correct identification of minerals is made with polarizing microscope. This involves grinding the minerals or rocks into very thin slices and allowing polarized light to pass through them. In this way their optical properties are studied and the mineral are identified. Opaque minerals are studied under microscope by reflected light.

1.3.2 Physical properties of minerals

- **Color:**

  Some minerals possess a characteristic color e.g. the lead grey of Galena, the black of Magnetite, and the green of Chlorite. But in other cases such as Quartz, the color is variable and cannot be relied on as a guide to identify minerals. The variation in the color of a mineral may be due to: (a) isomorphs variations in composition, (b) minute colored inclusion, and (c) a small amount of some substance in solid solution.

  Some minerals when viewed in different directions show irregular changes in the color tints, it is called the "*play of color*". The term "opalescence" is applied to minerals which have milky appearance e.g. Opal. When bands of prismatic colors are seen on the surface of a mineral, it is said to show "iridescence".

- **Streak:**

  Streak is the color of mineral powder. The minerals are rubbed against unglazed porcelain plate (called streak plate) to obtain the streak. In some cases, the color of the streak differs remarkably from the color of the mineral. For example, the color of the Pyrite is brass yellow and its streak is dark green.

- **Luster:**

  Luster is the appearance of a mineral surface in reflected light. The various types of luster are as follows:

  i. Metallic luster: it is the luster exhibited by metals, e.g. Pyrite, Galena etc.
  ii. Vitreous luster: it is the luster exhibited by the broken surface of glass, e.g. Quartz.
  iii. Pearly luster: it is the luster exhibited by pearls, e.g. Mica.

iv. Silky luster: it is the luster exhibited by silk fibers, e.g. Asbestos.
v. Resinous luster: it is the luster exhibited by resin, e.g. Serpentine.
vi. Adamantine: it is the luster exhibited by Diamonds.
vii. Dull or earthy luster: minerals which have no luster described as dull or earthy, e.g. Kaolin.
Greasy, Waxy are the terms which are self-explaining.

- **Hardness:**

The hardness of a mineral is its resistance to scratching. It is determined by comparison with the standard minerals of the "*Mohs Scale of Hardness*". In this scale, there are ten minerals which are arranged in the order of their increasing hardness. The Moh's scale of hardness is given in Table 1-1. Note that a finger nail will scratch up to 2.5 (i.e. not Calcite), a window glass will scratch up to 5 (i.e. not Feldspar), and a pen knife will scratch up to about 6.5 (i.e. not Quartz). These can be used conveniently for determining the approximate hardness of minerals.

TABLE 1-1: MOH'S SCALE OF HARDNESS

1	Talc	Scratched by a finger nail
2	Gypsum	
3	Calcite	Scratched by a knife
4	Fluorite	
5	Apatite	
6	Orthoclase	Scarcely scratched by a knife
7	Quartz	Not scratched by a knife
8	Topaz	
9	Corundum	
10	Diamond	

- **Cleavage:**

It is the property of minerals to break more easily with smooth surfaces in certain directions. These directions lie parallel to the actual or possible crystal faces of the minerals, and there, cleavage is the property which is related to the atomic arrangement within the mineral. Galena has three cleavages at right angles forming cubes. Mica cleaves in one direction only, while in Calcite, cleavage planes meet in acute and obtuse angles giving a rhombohedral form. Quartz has no cleavage.

When minerals break with ease producing smooth lustrous faces, they are said to have perfect "cleavage". Interior degrees are described as good, distinct, indistinct, and imperfect.

- **Fracture:**

  The nature of a broken surface of a mineral is known as "fracture"; but the breaking should be in any other direction than the cleavage. Unlike cleavage, fracture does not produce smooth planes. The various types of fracture are as follows:

  i. Uneven Fracture: when the broken surface is rough or irregular, e.g. Apatite.
  ii. Even Fracture: when the mineral breaks with a flat surface, e.g. Flint.
  iii. Conchoidal Fracture: when the mineral breaks with curved surfaces often with concentric markings like a shell, e.g. Quartz.
  iv. Hackly Fracture: when the broken surface has a small sharp irregularity like broken metal, e.g. Native Copper.

- **Form:**

  Minerals may occur in the form of well developed “crystals" or they may be "massive"(without development of recognizable crystals). Besides these, the minerals may occur in a number of different forms. The important forms are as follows:

  i. Acicular: minerals showing needle like crystals, e.g. Natroflint.
  ii. Fibrous: minerals showing an aggregate of fibers, e.g. Asbestos.
  iii. Columnar: minerals which occur as columnar crystals, e.g. Tourmaline.
  iv. Bladed: minerals showing this form occur as small knife blades, e.g. Kyanite.
  v. Foliated: minerals having thin separable lamelle, e.g. Mica.
  vi. Granular: minerals which occur as aggregate of grains, e.g. Chromite.

- **Specific Gravity, Gs:**

  It is the weight of a mineral compared with the weight of an equal volume of water. Thus a mineral with specific gravity 4, is four times as heavy as water.

- **Odor:**

Some minerals give a characteristic smell when rubbed, breathed upon, or heated. The chief types of odor are as follows:

i. Arsenical: like the odor of garlic (Orpiment).
ii. Sulphurous: like the odor of burning sulphur (Pyrite).
iii. Argillaceous: like odor of clay.

- **Feel:**

  Feel is the sensation up on touching or handling minerals. The different types of feel are "greasy", "soapy", "rough", and "harsh".

- **Fluorescence:**

  Some minerals when exposed in sunlight or UV light produce a color, quite different from their own, and from that of the existing light. Thus green or colorless fluorite shows a blue or purple color in sunlight. This property of minerals is called “fluorescence".

- **Magnetism:**

  A few minerals are attracted by a magnet. Of these minerals, magnetite is the most common examples, which possesses attracting power and polarity is called "lodestone".

1.3.3 Common rock forming minerals:

Quartz, Kaolin, Gypsum, Calcite, Magnesium, Olivine, Halite (Rock salt)

1.3.4 Crystal Forms:

Most of the minerals are "*crystalline*" while a few are "*amorphous*"(non-crystalline). When minerals crystallize under favorable conditions, they take the form of crystals.

A "*crystal*" is a solid having a definite atomic structure. It is bounded by smooth plane surfaces, called *faces*. The *crystal faces* are defined with reference to crystallographic axes, which are three or four in number. The "*crystallographic axes*" are imaginary lines which connect the centers of opposite faces, opposite corners, or opposite edges, and which intersect in a common origin within a crystal. All crystals of the same mineral possess the same degree of symmetry, and the same fixed angles between corresponding faces (interfacial angles). On the basis of the relations of the crystallographic axes, all the crystals may be grouped into six "*systems of crystallization*" which are given in the Table (1-2).

$$\alpha = b \ \Lambda \ c$$

$$\beta = a \ \Lambda \ c$$

$$\gamma = a \ \Lambda \ b$$

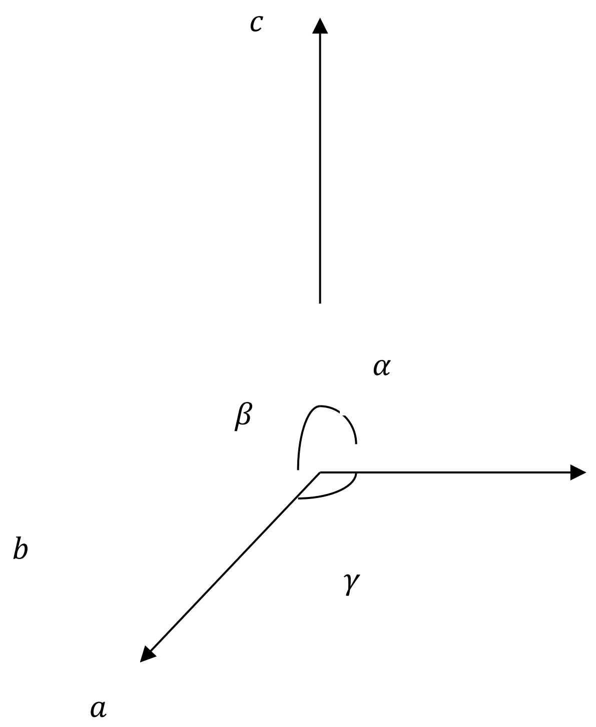


TABLE 1-2: SYSTEMS OF CRYSTALLIZATION

System	Crystallographic axes	Inter axial angles
Cubic (isometric)	a=b=c, a1=a2=a3	α=β=γ=90
Tetragonal	A=b≠c, a1=a2≠c	α=β=γ=90
Orthorhombic	a≠b≠c	α=β=γ=90
Hexagonal	a1=a2=a3≠c	a1^a2^a3^a1=120 c is perpendicular to the plane of the three axes(a1,a2,a3)
Monoclinic	a ≠ b ≠ c	α=γ=90; β≠90
Triclinic	a ≠ b ≠ c	α≠β≠γ≠90

TABLE 1-3: DIFFERENT TYPES OF SYMMETRY.

System	Axis of symmetry	Plane of symmetry	Center of symmetry
Cubic	13	9	1
Tetragonal	5	5	1
Orthorhombic	3	3	1
Monoclinic	1	1	1
Triclinic	0	0	1
Hexagonal	7	7	1

2. Rocks:

The rocks may be defined as aggregates of minerals. They form a major part of the earth's crust. On the basis of their mode of origin, rocks can be divided into three basic types: igneous, sedimentary, and metamorphic.

The rock cycle in nature is illustrated in Figure 2-1.

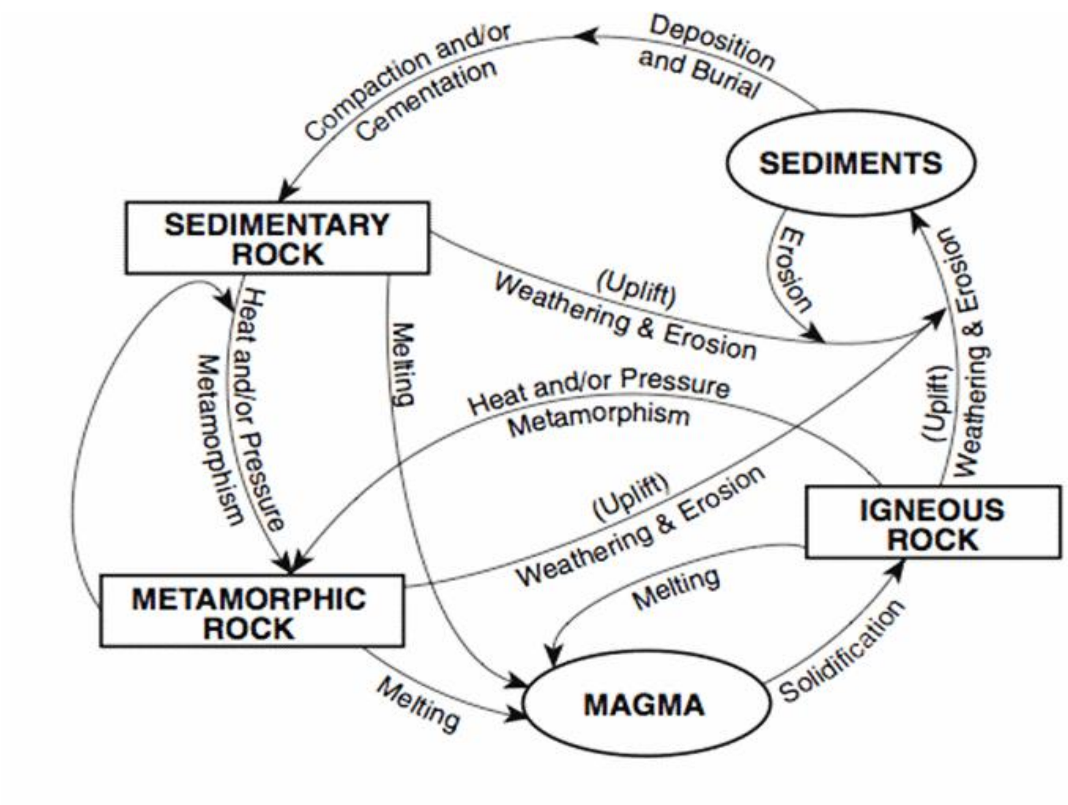


FIGURE 2-1: ROCK CYCLE IN NATURE.

2.1 Igneous Rocks:

Igneous rocks are formed by the cooling and solidification of magma. "Magma" is a hot, viscous, siliceous melts, containing gases. It comes from great depth below the earth's surface. When magma comes out upon the earth's surface, it is called" lava".

2.1.1 Acid and Basic Rocks:

The composition of igneous rocks depends upon the composition of the magma; from which they are originated. Magmas are of two types:

- Acid Magma, and
- Basic Magma.

Acid Magma: It is rich in Si, Na, K and poor in Ca, Mg, and Fe.

Basic Magma: It is rich in Ca, Mg, and Fe, and poor in Si, Na, and K.

In general, **acid igneous rocks** are light in color, low in specific gravity (2.7), and have high proportion of minerals like quartz, feldspar (alkali felspars) and some mica. An example of acid rock is granite.

Basic rocks, on the other hand, are usually dark in color (often black), relatively high in specific gravity (3.0, and are rich in minerals like Augite, hornblende, plagioclase, and iron ore. An example of basic rock is basalt.

On the basis of their silica content, the igneous rocks can be divided into the following groups:

a) Ultra-basic Rocks: These contain less than 45% silica, e.g. peridotite.
b) Basic Rocks: These contain silica between 45% and 55%, e.g. basalt.
c) Intermediate Rocks: These contain silica between 55% and 65%, e.g. diorite.
d) Acid Rocks: These contain more than 65% of silica, e.g. granite.

2.1.2 Textures of Igneous Rock:

"Texture" means the size, shape, and arrangement of mineral grains in a rock. The texture of a rock is governed by the cooling rate of the magma. In general, slower is the rate of cooling, the coarser is the grain of the rock. It is because; in slow cooling more opportunity is provided for crystals to grow to a large size. On the other hand, the glassy texture results from extremely rapid cooling. Between these two extremes there are fine grained and cryptocrystalline textures.

Igneous rocks, whose constituent mineral grains can be seen with the naked eyes, are described as "phaneric", while those, whose mineral grains are too small to be seen with the naked eyes, and are called "aphanitic".

Types of Texture:

The important textures found in igneous rocks are as follows.

1. Holo-crystalline: If a rock is made up entirely of crystalline material, it is said to be "holo-crystalline".
2. Coarse Grained: If the average grains or crystals of the minerals are more than 5 mm in diameter, the rock is said to be "coarse grained."
3. Fine Grained. If the grains are like granulated sugar where their average diameter is less than one millimeter, the rock is said to be "fine grained".
4. Cryptocrystalline. If the crystals are invisible to the naked eyes, and visible only under the microscope the rock is said to be "cryptocrystalline.
5. Glassy: If the magma is consolidated as an amorphous mass without any crystallization, the rock is said to be "glassy".
6. Porphyritic: sometimes an igneous rock shows relatively large crystals in a matrix, which is more finely crystalline or even glassy. Such a texture is called "porphyritic texture" and the rock is called a "porphyry". The large crystals in a porphyry are called "phenocrysts" and the finely crystalline uniform background is called the "groundmass."
7. Vesicular: volcanic rocks which have a glassy matrix often contain gas cavities, called. "Vesicles". Such rocks are said to have "vesicular texture."

2.1.3 Classification of Igneous Rocks:

On the basis of texture and mode of occurrence, the igneous rocks have been classified into three groups:

Plutonic Rocks: Plutonic rocks are formed when magma cools slowly at great depth with the retention of the volatiles. The textures of such rocks are coarse grained.

Volcanic Rocks: Volcanic rocks are formed when the magma erupts at the earth's surface and cools rapidly. The volatiles present in the magma escape into the atmosphere. The texture of such rocks are fine grained or glassy. Volcanic rocks often contain gas cavities called "vesicles". These rocks sometimes show "flow" structure" which is the result of movement in viscous lava. It is seen as lines or streaks of different color in a rock.

Hypabyssal Rocks: Hypabyssal rocks are formed when consolidation of magma takes place very close to the earth's surface.

Examples of such igneous bodies are dykes and sills. Hypabyssal rocks may be fine grained, or porphyritic, or even partly glassy. Within these three broad classes, there are so many different kinds of rocks, that it is necessary to classify them more closely on the basis of their composition and texture.

2.1.4 Mode of Occurrence:

The various forms in which igneous bodies occur are as follows:

Batholith: Batholiths are large intrusive igneous bodies which are granitic in composition. In plain view their outline is irregular and the area of outcrop exceeds 100 square kilometers. Most batholiths increase in size with depth and they are thought to be bottomless (Figure **2-2**).

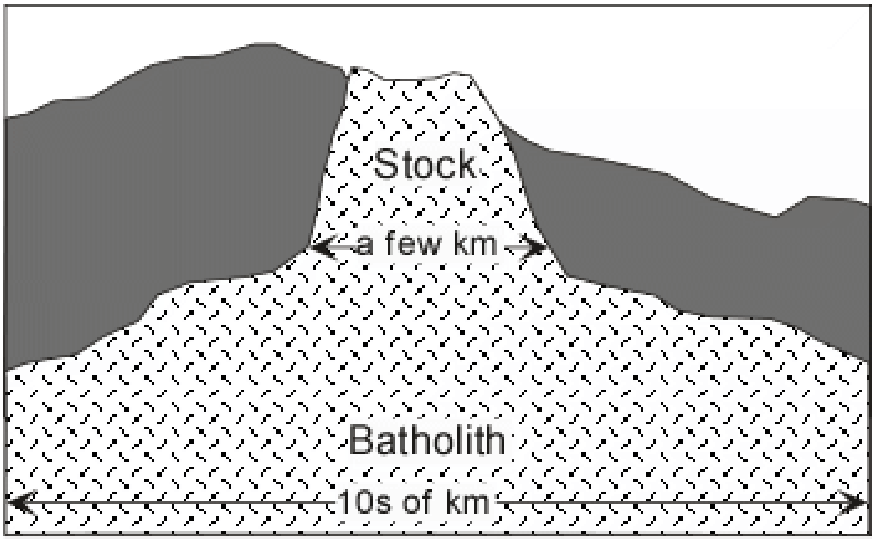


FIGURE 2-2: BATHOLITH.

Stock and Boss: A" stock" is a small batholith. Its area of outcrop is less than100 square kilometer. A stock having a circular outcrop is called a" boss".

Lopolith: It is a lenticular igneous body which is bent or sagged downward into a basin like shape (Figure 2-3).

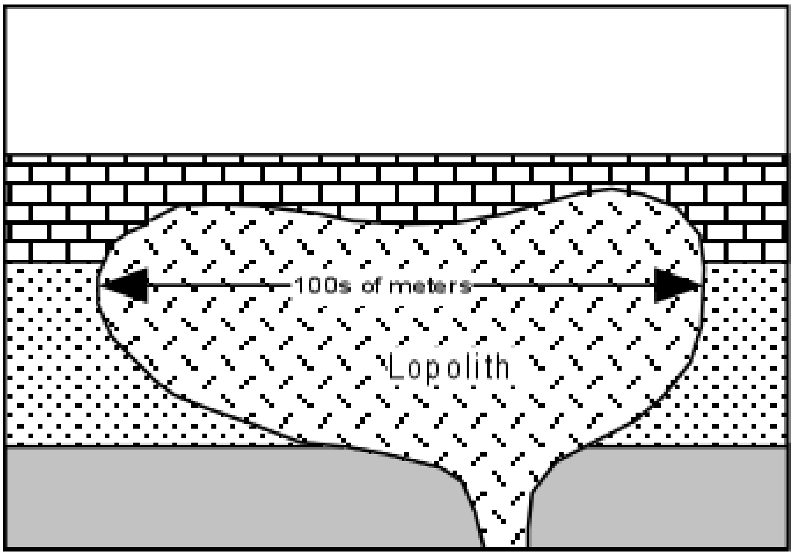


FIGURE 2-3: LOPOLITH.

Laccolith: Laccoliths arc plano-convex intrusive body which cause the overlying beds to arch in the shape of dome (Figure 2-4). A laccolith may be 2 to 3 km in diameter and several hundred meters in thickness. It differs from batholiths in being much smaller and having a known floor.

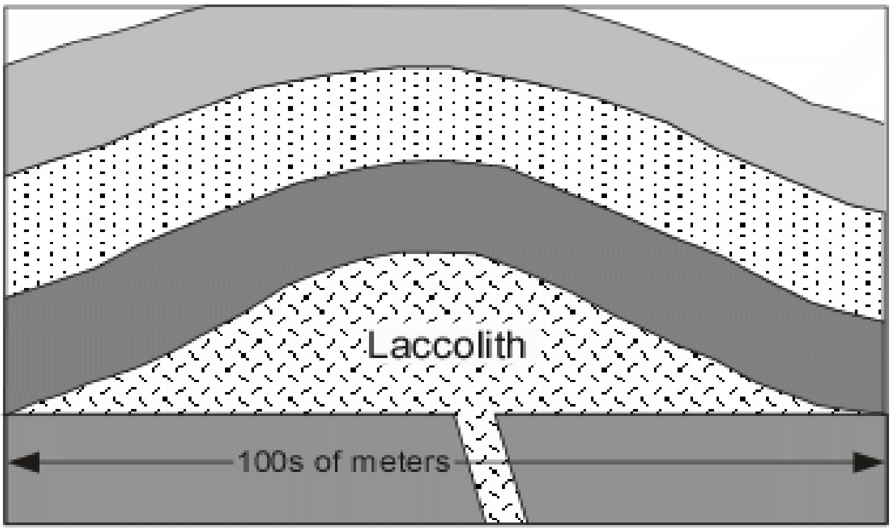


FIGURE 2-4: LACCOLITH

Phacolith: Phacoliths are intrusions of igneous rocks which occupy crests and troughs of folded strata as shown in Figure 2-5.

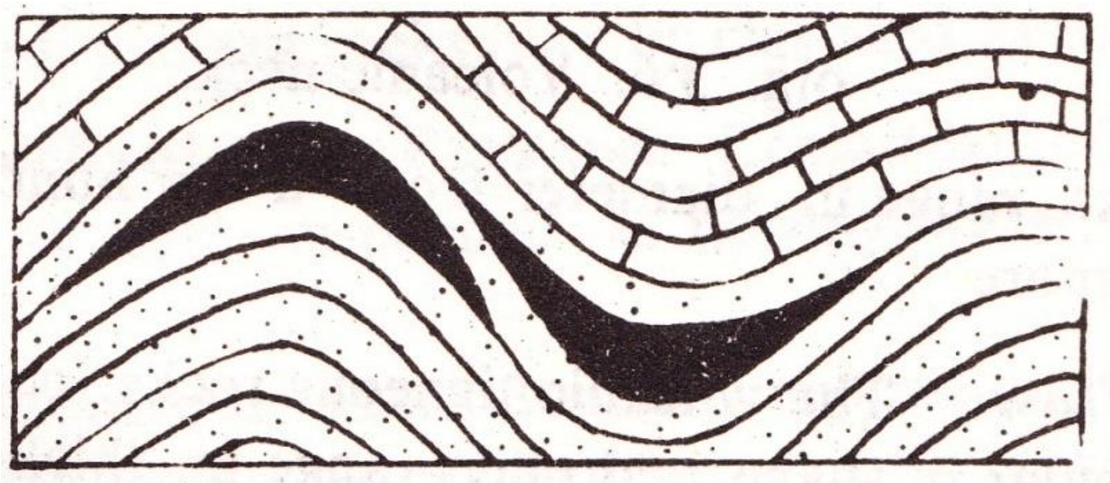


FIGURE 2-5: PHACOLITH

Sill: A sill is a sheet like igneous body which runs parallel to the bedding of the enclosing rock. They may be horizontal, inclined, or vertical depending upon the attitude of the strata in which they intruded. Sills vary in thickness from a few centimeters to several hundred meters, but they are always thin as compared to their length along the beds.

Dyke: A dyke is a more or less vertical wall-like igneous body that cuts across the bedding of the country rocks (Figure 2-6). The thickness of a dyke may vary from a few centimeters to a hundred meter or more. A dyke which has a circular outcrop and a conical form is called a "ring dyke". Dykes having inverted conical form and circular outcrops are described as "*cone sheets*". Dykes probably represent a crustal fracture into which the magma was injected.

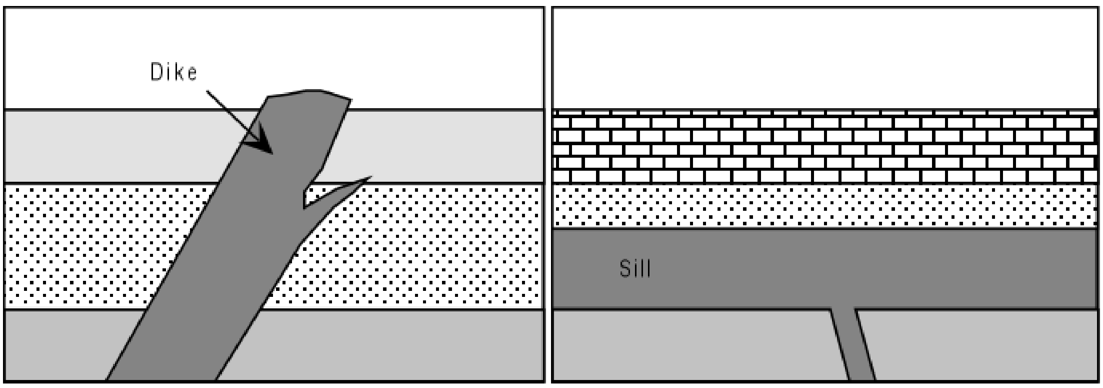


FIGURE 2-6: SILL AND DYKE.

Volcanic Neck or Plug: A volcanic neck or plug is a vertical Intrusion of igneous mass which has a roughly oval or circular cross section (Figure 2-7). It represents the event of an extinct volcano.

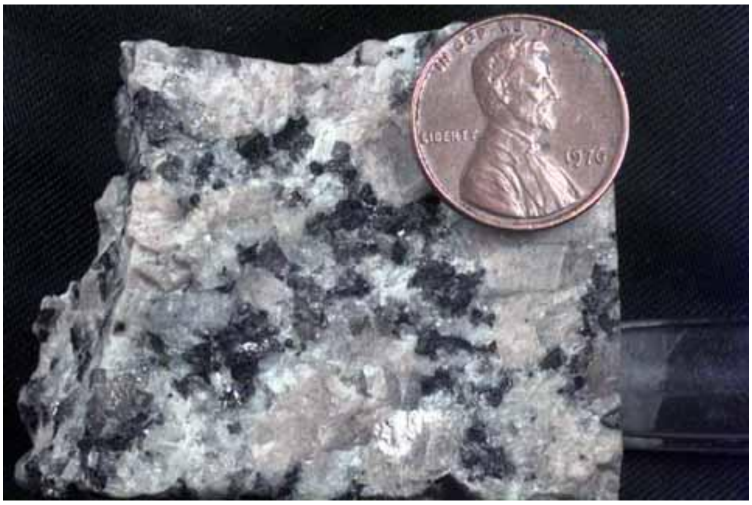
FIGURE 2-7: VOLCANIC NECK.

Volcanic necks range in diameter from a few hundred meters to a kilometer or more.

Lava Flow: The volcanic igneous rocks occur as lava flows. They are tabular in shape and may range in thickness from a few meter to several hundred meter. Lava flows are formed when lava breaks through the earth's crust along fissures kilometers in length, and very large quantities of it are poured out over the land.

2.1.5 Description of Common Rocks:

- **Granite:** It is a coarse grained rock which is composed of quartz, alkali felspars (orthoclase and microcline), and small amount of biotite or hornblende or both. The average granite contains 60% felspars, 30% quartz, and l0% ferromagnesian minerals. The granites are mostly light in color with a white or pink tint according to the color of the felspar.



Granite

- **Rhyolite:** Rhyolite is similar to granite in mineral composition but very different in texture. The texture is often porphyritic, which contains phenocrysts of quartz and felspar, set in a finely crystalline or glassy groundmass, the color of the rock is generally white, grey, or pink. Rhyolites may show "flow structure".
- **Pumice:** It is a cellular, volcanic froth of glassy texture which is so light that it floats on water. It is formed on the surface of acid lava.
- **Diorite:** It is a coarse grained rock which is mainly composed of plagioclase felspar and hornblende. However, in some varieties augite and biotite may occur. Most diorites contain little or no quartz.
- **Gabbro:** It is a coarse grained plutonic rock which is dark green or black in colour. It is composed of calcic-plagioclase (labradorite), augite (diallage), and magnetite.
- **Basalt:** Basalt is a dense looking black volcanic rock. Its texture is fine grained to glassy. It is composed of augite, plagioclase (labradorite) and iron-oxide. Basalt sometimes contains vesicles. Which have become filled with secondary minerals like quartz, calcite, zeolites, etc. and the rock is then said to have an "amygdaloidal structure".

Basalt

- **Dunite**: is a coarse grained rock which is composed almost entirely of olivine.

The difference between Granite and Basalt:

Basalt **a mafic rock**	**Granite** **a felsic rock**
1. Dark color 2. High specific gravity 3. Olivine/pyroxene/Calcic plagioclase rich 4. Fine grained - crystals only seen under high power. 5. Forms at the surface, principally in the ocean basins, but also in isolated "hot spots" on the continents.	1. Light color 2. Low specific gravity 3. Quartz and orthoclase and sodium plagioclase rich 4. Coarse grained - crystals large enough to see by eye 5. Forms on the continents deep underground

2.2 SEDIMENTARY ROCKS

The disintegrated products of pre-existing rocks are transported by water as sediment. This sediment is deposited in suitable depressions of the earth, where it gets consolidated and cemented to form "sedimentary racks". Sedimentary rocks occur in layers and frequently contain fossils.

2.2.1 Classification of Sedimentary Rocks:

The sedimentary rocks may be classified as follows:

1. ***Mechanically Formed***: Consisting of material (gravel, sand, silt and clay) suspended in flowing water. They are of three types:
    i. Rudaceous rocks: Bouldery deposit, e.g. conglomerate.
    ii. Arenaceous rocks: Sandy rocks, e.g. sandstone.
    iii. Argillaceous rocks: Clayey rocks, e.g. shale.
2. ***Organically Formed***: Consisting of accumulated animal or plant remains. These are of two types:
    i. Calcareous rocks: Limestone rocks.
    ii. Carbonaceous rocks: Coal seams.
3. ***Chemically Formed:*** Formed due to precipitation and accumulation of soluble constituents. These are of three types:
    i. Carbonate rocks: Limestone, dolomites.
    ii. Sulphate rocks: Gypsum rock.
    iii. Chloride rocks: Rock salt.

2.2.2 Particle Size in Sediments:

The constituent particles of sediments may be classified into gravel and pebble, sand, silt, and clay, and each of these give rise to a particular type of rock, Table 2-1.

TABLE 2-1: PARTICLE SIZE IN SEDIMENTS

Grade	Grain size	Type of rock
Gravel or Pebble	2 mm and over	Conglomerate
Sand	0.l mm to 2 mm	Sandstone
silt	0.01 mm to 0.l mm	Siltstone
Mud or Clay	Less than 0.01 mm	Mudstone, shale, clay

2.2.3 Consolidation:

Consolidation is a process by which soft and loose sediments are converted into hard and firm rocks. There are mainly three methods of consolidation:

2. ***Compaction and Dehydration***: When a bed is buried under more sediment, it is consolidated due to the pressure of the overlying mass. The excess of water is squeezed out and the cohesion is developed between the grains of sediments. Fine grained sediments like clays are consolidated most effectively by this process.
3. ***Cementation:*** Coarse grained sediments (conglomerates and sandstones) are mostly consolidated by cementation. These being porous, water circulates through them and the dissolved mineral matter may be precipitated between the grains thereby causing cementation. The most common cementing materials are silica, calcium carbonate, iron-oxides, and clay minerals.
4. ***Crystallization:*** Chemically formed sedimentary rocks such as limestone, dolomites, salt, gypsum etc. are consolidated chiefly by the crystallization of their constituents.

2.2.4 Structural Features:

Structural features of sedimentary rocks are of great value in determining their origin. The chief sedimentary structures are as follows:

1. Stratification,
2. Lamination,
3. Cross-bedding,
4. Graded bedding,

5. Ripple marks,
6. Marks in desiccated sediments, and
7. Concretions.

Stratification:

The deposition of sediments into layers or beds is called "stratification". The thickness of a single bed may vary from a few centimeters to many meters. The planes dividing different beds are called "bedding planes". The stratification is formed due to the following:

i. Differences in the kinds of material deposited, e.g. shale and limestone beds.
ii. Differences in the size of particles deposited, e.g. coarse grained and fine grained sandstone beds.
iii. Differences in the color of the material deposited, e.g. light grey, and dark grey layers of limestone.

Lamination:

Thin bedding, less than one centimeter in thickness, are called "lamination". It is usually found in fine grained sedimentary rocks like shale.

Cross-bedding:

It is also called current bedding or false bedding. Cross bedding are the minor bedding or laminations which lie at an angle to the planes of general stratification. This structure is found in shallow water and wind formed deposits.

Graded bedding:

When a sedimentary bed shows a gradation in grain size from coarse below to fine above, it is said to be graded. Such type of bedding is called "graded bedding". This structure is commonly found in greywacke.

Ripple Marks:

Ripple marks are the wavy undulations that may be seen on the surface of some sedimentary deposit. These are produced by the action of waves and currents in shallow water. They may also be formed on the deposits formed by wind. Ripple marks are of two types:

a) Asymmetrical or current ripple marks, and
b) Symmetrical or oscillation ripple marks (Fig. 3-9). The oscillation ripple marks are useful in determining tops and bottoms of deformed beds.

Marks in Desiccated sediments:

The sediments which have undergone repeated wetting and drying may show "mud cracks", "tracks of terrestrial animals", "percussion marks of hail and rain", and "impressions of ice or salt crystals". These markings are most commonly preserved as casts.

Concretions:

Concretions are variously shaped masses or nodules of mineral matter found within a sedimentary rock. Their shape may be round, elliptical, oval, lenticular, or irregular. Concretions generally consist of calcium carbonate, or silica and often possess an internal radiating or concentric structure. They are formed by the deposition of mineral matter from percolating solutions about a nucleus.

2.2.5 Factors Affecting variety of Sedimentary Rocks

Three main factors are affecting the variety of sedimentary rocks; these are:

1. ***Type of the Original Rock Material***: Where chemical weathering of calcareous rocks produces calcareous rocks too, and physical weathering of sandstone produces sandstone too. Whereas, chemical and physical weathering of igneous and metamorphic rocks produces different rocks.
2. ***Type of Transportation:*** Different deposits formed with different agent of transportation (wind, water and glaciers).
3. ***Environment of Deposition:*** Different environments results in different sedimentations. Thus it may be described according to the type of environment in which it accumulated:

   (a): Continental deposits: If it were laid down on land or in a lake by rivers, ice or wind. If the agents are rivers, wind and glaciers, their result will be fluviatile deposits, Aeolian deposits and glacial deposits, respectively.

(b): Transitional (Intermediate) deposits: If it were laid down in an estuary or delta deposits formed in delta (deltaic) and deposits formed in estuaries of rivers (estuarine).

(c): Marine deposits: These deposits formed along coastlines, shores, continental shelves and deposits formed in the abyssal areas of deep oceans (under greater depth of water) are abyssal deposits.

2.2.6 Description of Common Rocks

- ***Conglomerate:*** The pebbles and gravels on consolidation and cementation produce a rock known as conglomerate. The pores of a conglomerate are filled up with a matrix, which is composed of fine sands, rock particles, and some cementing material.
- ***Breccia:*** A breccia is a rock resembling conglomerate but having angular fragments instead of rounded pebbles. Sandstone is mainly composed of sand size grains of quartz, which are cemented together. The cementing material may be silica, calcite, iron-oxide or, clay Depending up on the nature of cementing material, sandstones may-be classified as follows:
  1. Siliceous sandstone. Sandstone in which the cementing material is silica.
  2. Calcareous sandstone. Sandstone in which the cementing material is calcium carbonate.
  3. Ferruginous Sandstone. Sandstone in which the cementing material is iron-oxide.
  4. Argillaceous Sandstone. Sandstone in which the cementing material is clay.
- ***Greywacke:*** Greywacke is a grey colored rock. In addition to quartz, it contains fragments of rock and some ferromagnesian minerals, which are embedded in a matrix of clay and chlorite materials.
- ***Shale:*** It is a laminated fine grained sedimentary rock which is mainly composed of clay minerals and some silt-size grains of quartz. Shale may be calcareous, carbonaceous, and ferruginous depending upon whether they contain calcium carbonate, carbonaceous matter, or iron-oxide. Shale are often soft and can be scratched by a knife.

- ***Limestone:*** Limestone consists chiefly of calcite and dolomite with varying amounts of impurities such as chalcedony or clay. Some limestones may also contain calcareous shells of marine organisms. Limestones are very fine grained and show in some cases pisolitic or oclitic structures. Limestone is identified by their softness, their fossil content, and by their effervescence in dilute hydrochloric acid.
- ***Marl:*** Impure limestones which contain mixture of clay and calcareous matter, are known as marls.
- ***Dolomite:*** Dolomite is a Magnesian limestone which is composed of double carbonate of calcium and magnesium (Ca Mg(CO3)2). It is distinguished from ordinary limestone by its greater hardness, greater specific gravity, and inferior solubility in hydrochloric acid.
- ***Flint and Chert:*** These are cryptocrystalline forms of silica found in limestones and chalks in the form of nodules and bands.

2.3 METAMORPHIC ROCKS

When the pre-existing rocks are subjected to increased temperature, pressure, and action of chemically active fluids, "metamorphic rocks" are formed.

During metamorphism re-crystallization of the mineral constituents takes place, as a result new minerals and new textures are produced.

2.3.1 Agents of Metamorphism:

The agents which bring about metamorphism of rocks are as follows:

1. Physical agents: Heat, uniform pressure, and directed pressure.
2. Chemical agents: Chemically active water and gases.

In the sedimentary or igneous rocks these agents produce changes that are either physical, chemical or both. Physical changes produce new texture whereas chemical changes cause the formation of new minerals.

The changes in the texture is produced by the process of "re-crystallization" in which the original minerals undergo a change in their structure, i. e. they are flattened or elongated.

Chemical changes during metamorphism involve the exchange of elements and compounds which result in the formation of new minerals.

2.3.2 Types of Metamorphism:

Depending upon the don above agents, the metamorphism:

1. Thermal metamorphism.
2. Dynamo-thermal metamorphism
3. Cataclastic metamorphism
4. Metasomatism.

Thermal Metamorphism: In thermal metamorphism the changes brought about in rocks are mainly due to heat, but heated magmatic waters or vapors carrying mineral matter in solution also play important part when the thermal metamorphism occurs in the immediate vicinity of igneous intrusions, it is called, contact metamorphism", and when it occurs on a regional scale at depth, it is called " plutonic metamorphism".

In thermal metamorphism uniform pressure predominates which favors reduction of volume. Hence during re-crystallization, the minerals that develop will be dense and equidimensional, and the metamorphic rock thus produced, will have non-foliated even grained texture.

By thermal metamorphism clays and shales may change into Porcellanite, Hornfelse, or even Mica-Schist, while sandstones and limestones may form quartzite and marble respectively.

Dynamo-thermal Metamorphism: This type of metamorphism is also called "regional metamorphism. It is caused when directed pressure and heat act together. It leads to more or less complete re crystallization of rocks combined with the production of new structures.

The directed pressure involves movement and shearing, and therefore, it is the main factor in forming foliated, handed, and cleavable rocks. The new minerals that develop under directed pressure are usually flat, tabular, elongated, bladed, or flaky in nature. Examples of such minerals are Muscovite, Biotite, Chlorite, and Talc.

These minerals develop with their flat sides at right angles to the direction of pressure. Thus the directed pressure causes the flaky minerals to arrange themselves parallel or sub parallel to each other, thereby producing foliation in the metamorphic rocks. The foliated rocks include slates, schists, and gneisses. Dynamo-thermal metamorphism takes place in fold mountain regions.

Cataclastic Metamorphism: In this type of metamorphism mainly directed pressure or stress predominates. The stress produces shearing movements in the rocks and causes crushing, granulation, and powdering. Therefore, the cataclastic rocks show mainly mechanical breaking with little new mineral formation. Cataclastic metamorphism occurs in the higher levels of the earth's crust where rocks are mostly hard and brittle. Examples of cataclastic rocks are Mylonites and fault Breccia. "Mylonite" is a microbreccia which is produced by granulation of the original rock grains.

Metasomatism: The metasomatic replacement of rocks is brought about by deposition from hydrothermal solutions (hot magmatic waters). The replacement takes place molecule by molecule so that as new mineral is added, the old is removed and the volume of the rock remains unchanged. The new rock frequently produces all the textural details of the original rock. The example of metasomatic replacement is petrified wood. The metasomatic replacement is often accompanied by deposition of metallic ores.

2.3.3 Metamorphic Zones:

The degree or intensity of metamorphism generally increases with depth because as the depth increases temperature and pressure also increase. From the earth's surface downwards, there are three metamorphic zones:

a) "epizone" or upper zone;
b) "mesozone" or intermediate zone, and
c) "Katazone" or lower zone.

Epizone: The epizone lies near the earth's surface where temperature is low (300^{o}C) and directed pressure is high. In this zone cataclastic metamorphism takes place. The alteration in rocks is weak and phyllites are the typical rocks.

Mesozone: It is an intermediate zone where temperature is of the order of 300^{o}C to 500^{o}C. The directed pressure is also high and therefore, dynamo-thermal metamorphism takes place. Schists are the typical rocks of mesozone.

Ketazone: It is the bottom most zone where directed pressure is absent, uniform pressure is high, and temperature is also high (500^oC to 800^oC). In the ketazone plutonic metamorphism predominates which produces even grained rocks.

2.3.4 Description of Common Rocks:

- ***schist:*** A rock having well developed schistose structure is known as a schist. Schists arc largely composed of flaky minerals such as muscovite, biotite, hornblende, chlorite, talc etc. Depending upon the type of flaky mineral present, the schists are described as Muscovite-Schist, Biotite-Schist, Hornblende-Schist, Chlorite-Schist, Talc-Schist etc. When the content of quartz increases, mica-schist passes into quartz-schist and micaceous quartzite.
- ***Marble:*** Marbles are produced by the metamorphism of limestones and dolomites. They contain interlocking grains of calcite or dolomite minerals and here their structure is said to be granulose.
- ***Quartzite:*** Metamorphosed sandstones having granulose structure are called quartzite. They are mainly composed of quartz with a small amount of mica, tourmaline, graphite or iron-minerals.
- ***Slate:*** Slates are produced by the metamorphism of shales. They are fine grained rocks having slaty structure due to which they split into thin smooth plates. They are composed of very fine grained mixture of quartz, chlorite, sericite, and felspar.

3. Secondary Geological Structures

3.1 DIP AND STRIKE

Dip: It is the angle of inclination of a rock bed with the horizontal plane. The dip includes both the direction and the angle. The dip direction is measured by its compass bearing, and the angle of dip with a clinometer.

Apparent Dip and True Dip:

The "true dip" is the maximum angle which an inclined bed makes with the horizontal. It is measured at right angles to the strike in a vertical plane. If the angle is measured in any other direction, it will have a value less than the true dip. Such partial dip angles are called "apparent dips." So the apparent dip may be defined as the inclination of bed to the horizontal in any other direction than the direction of the true dip.

Strike: It is the direction of a line formed by the intersection of the plane of a bed with a horizontal plane. The strike is always at right angles to the true dip. The direction of strike is determined by compass with reference to the true north and south. The illustration of the dip and strike is given in Figure 3-1below.

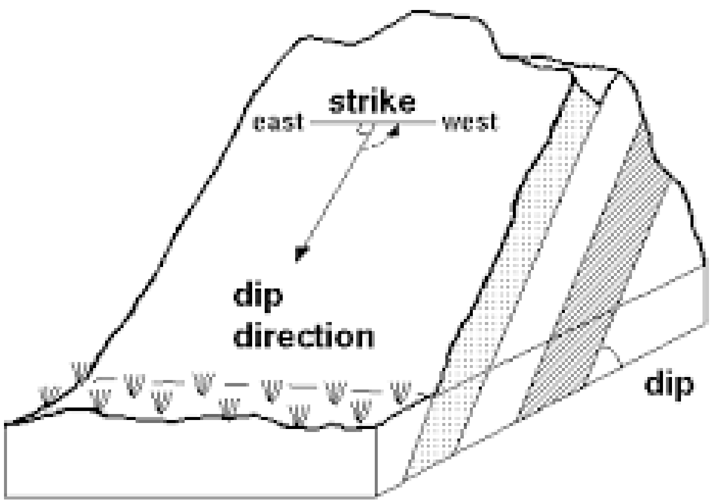


FIGURE 3-1: DIP AND STRIKE

3.2 Folds:

The wavy undulations in the rock beds are called "folds". They consist of arches and troughs in alternate manner. The size of folds varies greatly. Width of some folds are measured in kilometers while those of others in meters or centimeters. The details of the fold's terminology are shown in Figure 3-2.

3.2.1 TERMINOLOGY:

- ***Anticline***: It is on up fold where the limbs dip away from the axis.
- ***Syncline:*** It is a down fold where the limbs dip towards the axis.
- ***Limb:*** The sloping side of a fold from crest to trough is called the "limb".
- ***Axial Plane:*** It is an imaginary plane or surface which divides the fold into two equal halves.
- ***Axis:*** The line of intersection of the axial plane with the surface of any of the constituent rock beds is known as the "axis" of the fold.

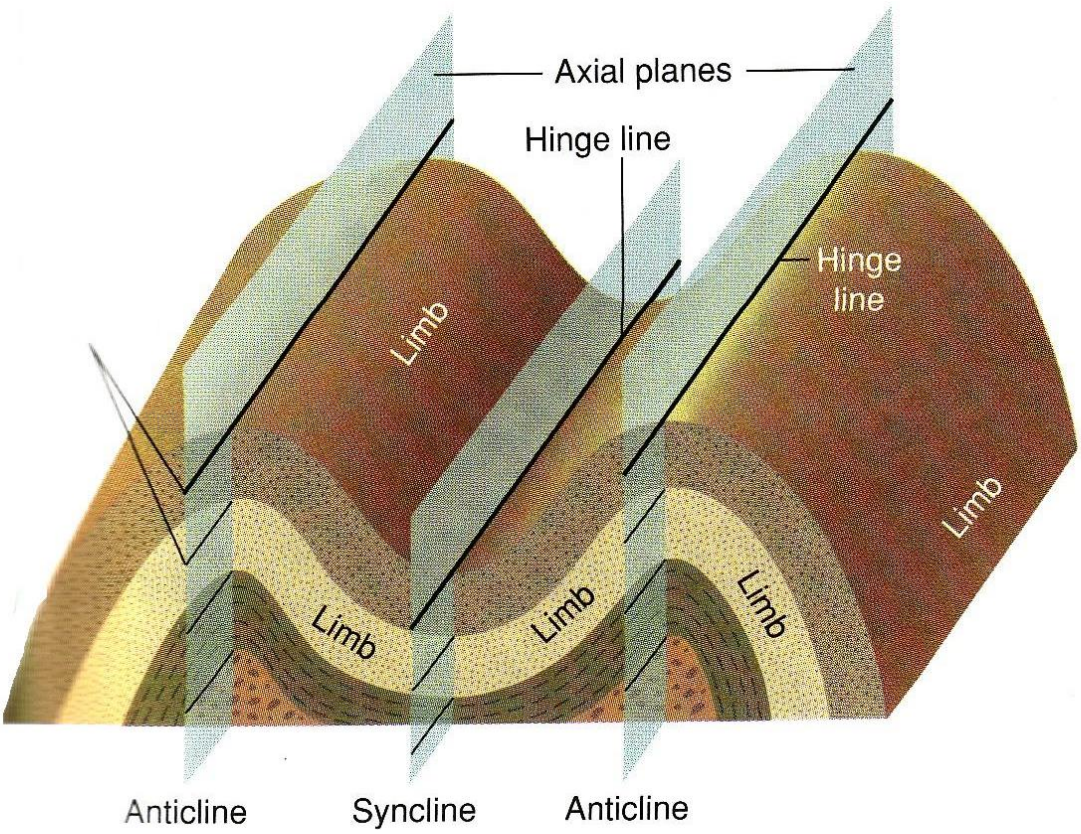


FIGURE 3-2: FOLDS

3.2.2 Types of Fold:

- **Symmetrical Fold:** A" Symmetrical fold" is one where the axial plane is vertical and the two limbs have the same amount of dip Figure **3-3**.
- **Asymmetrical Fold:** An "asymmetrical fold" is one where the axial plane is inclined and the limbs dip at different angles, and in opposite directions.
- **Overturned Fold:** "Overturned fold" is one in which the axial plane is inclined and one limb is turned past the vertical. In this case both the limbs dip in the same direction and one of the limbs is turned upside down.
- **Recumbent Fold:** In "recumbent folds" the folding is so intense that axial plane becomes almost horizontal and the lower limb, which also becomes nearly flat, gets overturned.

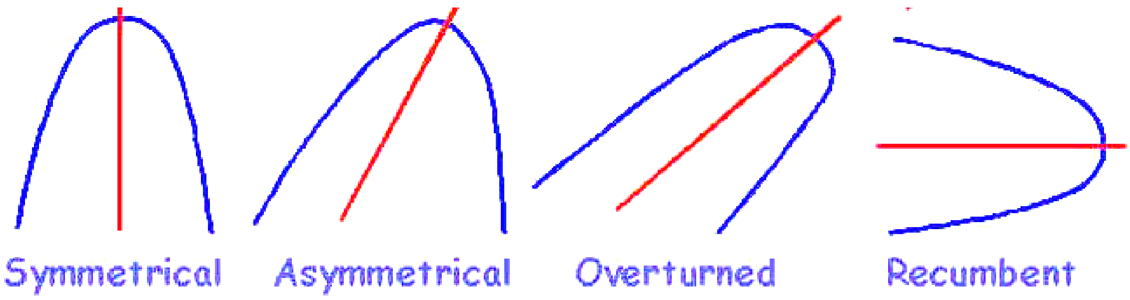


FIGURE 3-3: SOME TYPES OF FOLDS.

In such folds, fractures may develop across bends and thrusting of the recumbent rock mass may take place, please see Figure **3-4**.

- **Isoclinal Fold:** This type of fold shows parallel limbs which dip at the same angle and in the same direction.
- **Dome and Basin:** When the strata have been subjected to folding in two directions at right angles, each anticline is converted into a "dome", and each syncline is converted into a "basin". In domes the beds dip away from a central point. In basins, the beds dip downwards a central point.

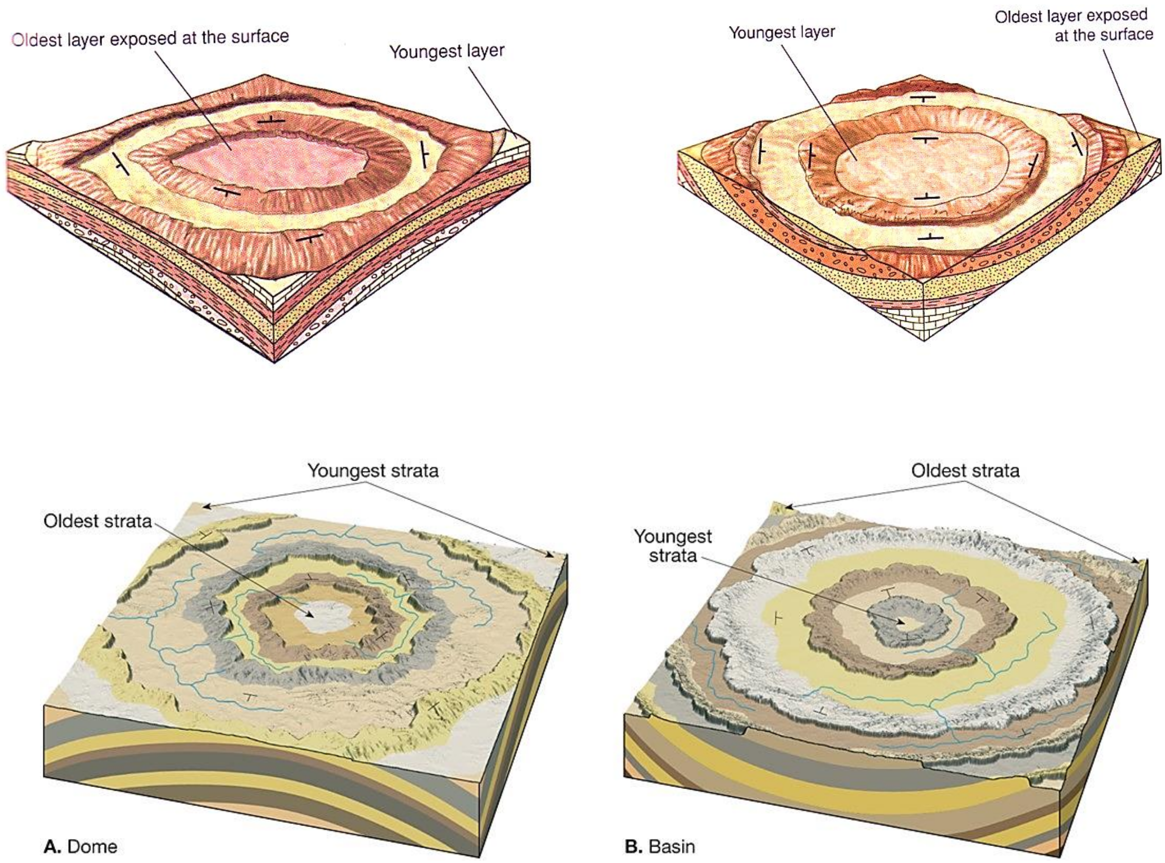


FIGURE 3-4: DOME AND BASIN FOLDS

3.3 FAULTS

A fault is a fracture along which there has been relative displacement of beds, which were once continuous (Figure 3-5). The fracture surface is called "fault plane". The displacement along a fault may be less than a meter, several hundred meters, or many kilometers.

3.3.1 TERMINOLOGY:

- **Strike of a Fault:** It is the direction of the line of intersection of a fault plane and horizontal plane.
- **Hade:** The hade of a fault is the angle of inclination of the fault plane measured from the vertical (DCE in Figure).
- **Hanging Wall and Foot Wall:** When the fault plane dips at any angle other than 90", one face of the rock mass will lie above the fault, and the other will be below it. The block of rock which is on the upper side of the fault plane, is called the "hanging wall", and the block which lies below the fault plane is called "foot wall".

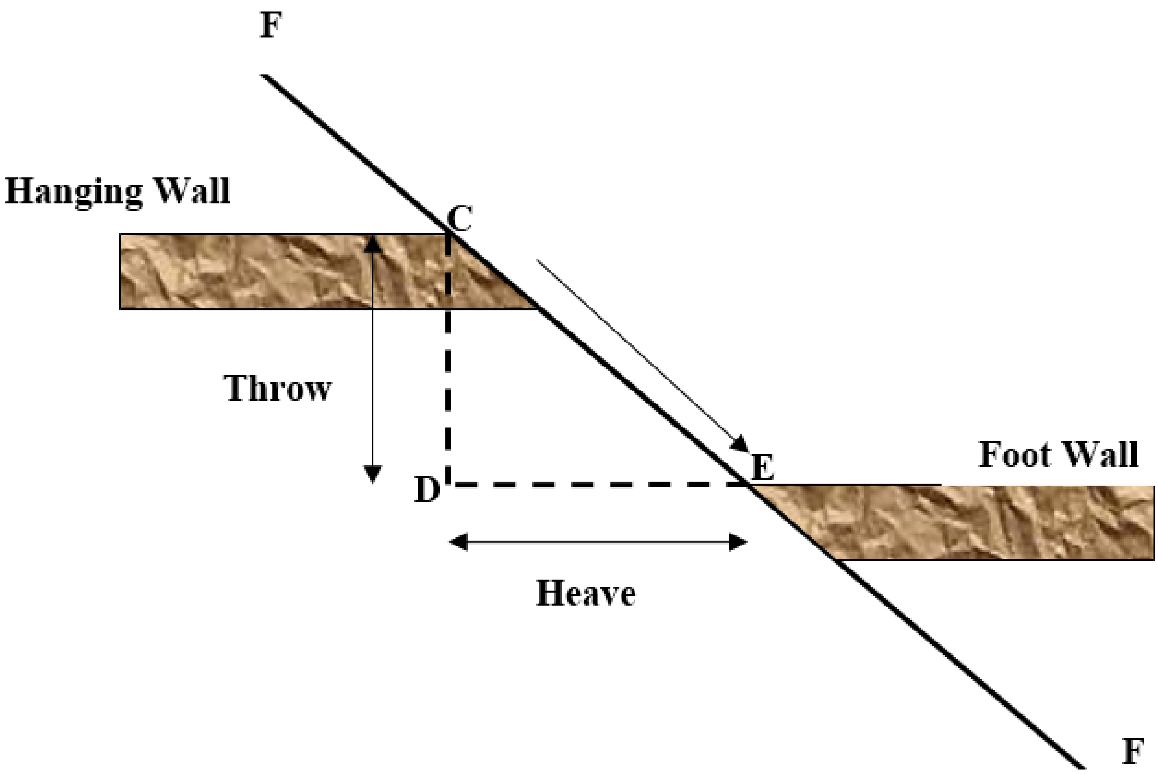


FIGURE 3-5: PARTS OF FAULT.

- **Throw:** The vertical displacement (CD in Figure 3-5.) of the fractured beds is called the "**throw**" of the fault. The side on which the strata appear to have thrown down, is known as the "down throw side", while the other side on which they appear to have gone up is called the "up throw side".
- **Heave:** The horizontal displacement of strata as seen in a section of a fault, is called heave (DE in Figure 3-5).
- **Fault Slip:** The amount of movement which results from faulting, is described by measurements between points which were originally in contact. The total displacement is called the "net slip".

3.3.2 CLASSIFICATION OF FAULTS:

With reference to relative movement, faults are classified as follows:

1. **Normal Fault:** A normal fault is one in which hanging wall appears to have moved downward relative to foot wall. It is called "gravity fault".

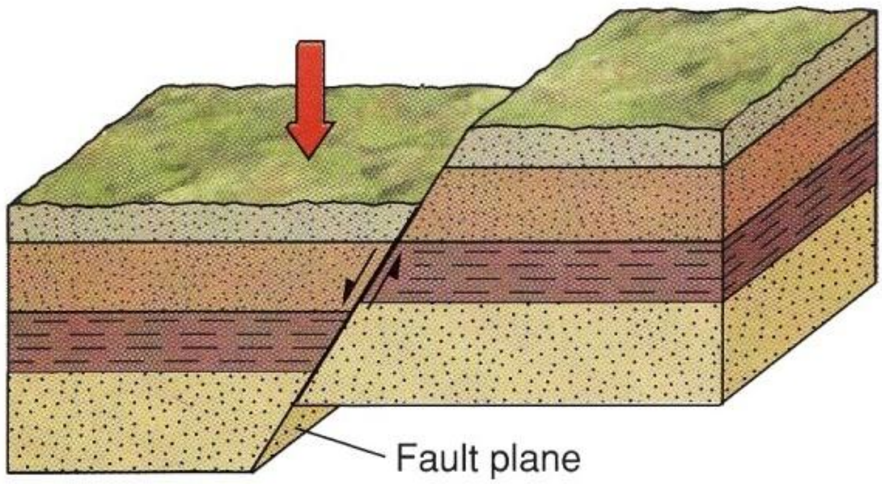


FIGURE 3-6: NORMAL FAULT

2. **Reverse fault:** A reverse fault is one in which hanging wall appears to have moved upward relative to the foot wall.

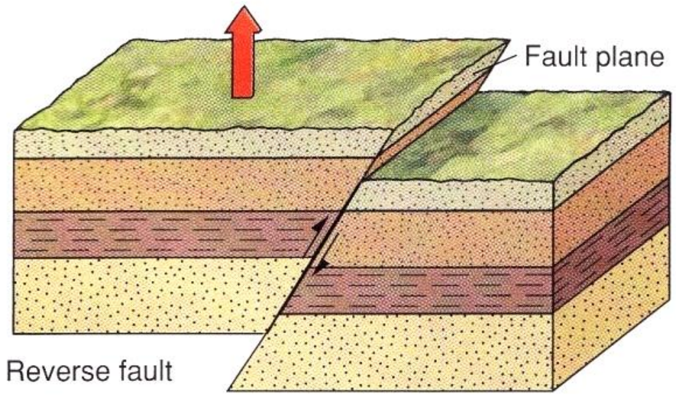


FIGURE 3-7: REVERSE FAULT

3. **Graben or rift fault:** when normal faults hade towards each other as shown in Figure **3-8** and the beds between them are thrown down in the form of a wedge, the structure is called "Graben" or "Rift fault".

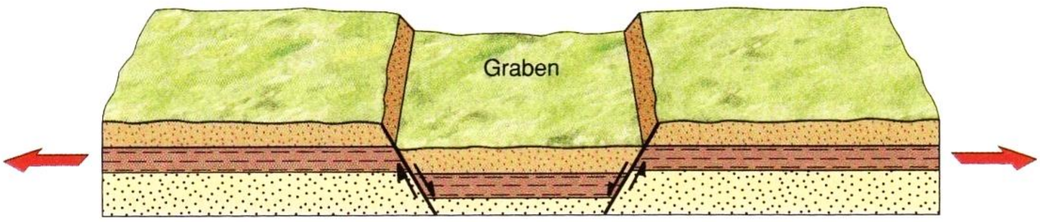


FIGURE 3-8: GRABEN FAULT

4. **Horst:** a horst consists of a central block on the both sides of which adjacent beds appear to have been faulted down (Figure **3-9**).

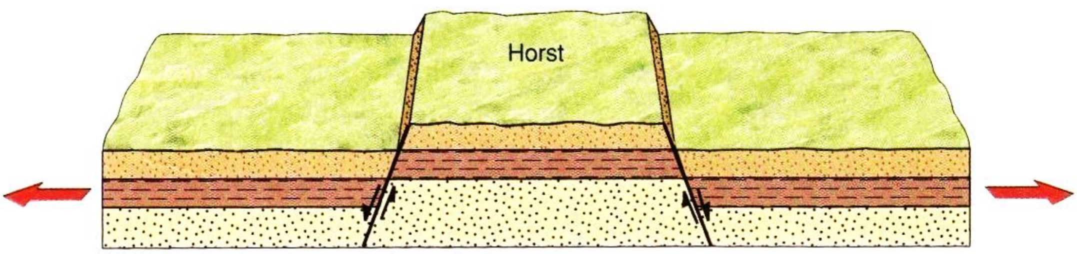


FIGURE 3-9: HORST FAULT

5. **Radial Faults:** A number of faults exhibiting a radial pattern are described as "radial faults".

3.4 JOTNTS

Joints: Joints are cracks or fractures present in the rocks along, which there has been no displacement. Joints occur in all types of rocks. They may be vertical, inclined, or even horizontal. Their dip and strike are measured in the same way as that of sedimentary strata.

Joints are formed as a result of contraction due to cooling or consolidation of rocks. They are also formed when the rocks are subjected to compression or tension during earth movements.

Commonly a large number of joints lie parallel to one another. These parallel joints together form a "joint set". A "joint system" consists of two or more joint sets.

CLASSIFICATION OF JOINTS:

On the basis of the origin, joints may be classified into two groups:

i. Tension joints, and
ii. Shear joints.

Tension Joints: Tension joints are those which are formed as a result of tensional forces. These joints are relatively open, and have rough and irregular surfaces. The columnar joints in lava flows, and longitudinal joints in the anticlines, that run parallel to the axis of fold.

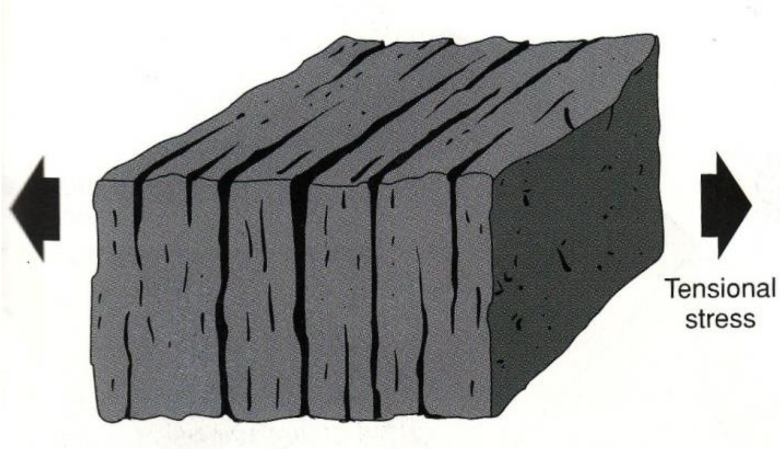


FIGURE 3-10: JOINTS

Shear Joints: Shear joints are those which are formed due to shearing stresses involved in the folding and faulting of rocks. These joints are rather clean cut and tightly closed. Shear joints occur in two sets which intersect at a high angle to form a "conjugate joint system".

On the basis of their attitude and geometry, they may be classified as follows:

- Strike Joints: Joints which are parallel to the strike of rocks are called "strike joints".
- Dip Joints: Joints which are parallel to the dip of rocks are called "dip joints".
- Oblique Joints: Joints which run in a direction that lies between the strikes and dip directions of the rock beds are called "oblique joints".
- Bedding Joints: Joints which are parallel to the bedding planes in sedimentary rocks, are called "bedding joints".
- Master Joints: In sedimentary rocks the joints usually run in two directions at nearly right angles. One set of joints run parallel to the dip direction and the other parallel to the strike. Of these. One set of joints is commonly more strongly developed than the other, and extends for long distances. Such well-developed joints are called "master joints".
- Mural Joints: Granites show three sets of joints mutually at right angles which divide the rock mass into more or less cubical blocks. Such joints are called "mural joints".
- Sheet Joints: Sheet joints are often seen in the exposures of granites. These joints run in the horizontal direction and are formed as tension cracks during cooling of the rock. The sheet joints are somewhat curved and are essentially parallel to the topographic surface. They are more conspicuous and closer together near the ground surface.
- Columnar Joints: Columnar joints are formed in tabular igneous masses such as dykes, sills, and lava flows. These joints divide the rock into hexagonal columns which are arranged at right angles to the chief cooling surface.

4. ROCK WEATHERING AND SURFACE PROCESSES

4.1 BASIC DEFINITIONS:

Weathering: The rocks break and undergo decay under the influence of the atmospheric factors like wind, sun, frost, water, and organisms and then produce soil. This phenomenon is called *"weathering".*

The weathering, includes two processes: (i) *disintegration* or physical breaking, and *(ii) decomposition* or chemical decay,

Erosion: Erosion involves the transportation and removal of weathering products from the place of their formation.

Denudation: The combined effect of weathering and erosion is called *"denudation"* which involves the general wearing down of the earth's surface.

4.2 PHYSICAL WEATHERING:

Physical weathering or disintegration is the mechanical breaking fill rocks to form particles of smaller size, without change in composition. The principal agents of physical weathering are as follows:

Frost: The freezing of water in the cracks of rocks tend to disintegrate them because water on freezing expands about one eleventh of its volume and therefore, exerts great pressure on the walls of the cracks. *By this process angular fragments of rocks are broken from the high mountain ranges*. These fragments of rocks roll down the hill slope, and accumulate at the bottom to form *"talus"* deposit.

Heating and Cooling: The heating and cooling of rock masses occur due to daily and seasonal temperature changes. The heat causes them to expand and cooling causes them to contract. The repeated expansion and contraction tend to develop cracks in the rocks. In desert areas, the coarse grained rocks, like granite, disintegrate soon into their constituent crystals, and become desert sands as a result of temperature variation;

Organisms: Plants and animals also play important part in the physical weathering of rocks. Plant roots grow into cracks and joints, and push the rock fragments apart. The burrowing of animals such as earth worms, ants, and rodents also contribute to the disintegration of rocks. Man also breaks the rocks by making road cuts, tunneling, quarrying, mining, and cultivating the land.

4.3 CHEMICAL WEATHERING:

Chemical weathering or decomposition is a process in which rocks are broken down by chemical decay of minerals. The chief agents of chemical weathering are as follows:

Water: The chemical weathering of rocks is done mainly by rain water. The processes involved are:

i. Oxidation,
ii. Hydration,
iii. Carbonation, and
iv. Solution.

Oxidation:

The oxygen, in the presence of water, readily unites with the iron present in the minerals such as pyroxenes, amphiboles, and olivine, and converts it to iron oxide (hematite) or to hydroxides (limonite). The oxidation of pyrite leads to the formation of limonite and weak solution of sulphuric acid. This acid is a powerful chemical agent, which attacks the rocks and develops solution pits. The iron oxides and hydroxides are the very common products of oxidation, which impart the red and yellow colors to soils.

Hydration:

Hydration is the process in which water molecules combine chemically with the minerals to produce new compounds. The formation of gypsum ($CaSO_4.2H_2O$) from anhydrite ($CaSO_4$) is a good example of hydration. Carbonation frequently occurs together with hydration. Thus orthoclase feldspar, a mineral that is abundant in granite, is decomposed and converted into kaolin by hydration and carbonation. Other hydrous silicates formed by hydration of the primary silicates (pyroxenes, amphiboles, olivine etc.) include chlorite, serpentine, talc, and zeolites.

Carbonation:

When minerals containing calcium, magnesium, sodium, or potassium ions react with water containing carbon dioxide, carbonates and bicarbonates are formed which are taken into solution. This, process of decomposition is called carbonation. The calcium feldspars may break down to form clay and calcium carbonate by carbonation.

Solution:

The process of solution and carbonation goes on together. The limestone, dolomites; rock salt, and gypsum are particularly susceptible to solution when they are attacked by water containing carbon dioxide.

4.4 WORK OF WIND:

The air current in motion is called *"wind"*. The wind is an important agent of erosion, transport, and deposition. Its work is particularly seen in arid regions.

4.4.1 Geological Work of Wind:

Erosion by Wind: Wind does erosion in three ways:

a) Deflation,
b) Abrasion, and
c) Attrition.

Deflation: Wind lifts and removes the loose particles from an area and cause lowering of the land surface by a process. In many deserts, deflation produces hollows or basins with their bottoms at 'water table. Such basins containing some water are called "oases".

Abrasion: During Dust Storms, minute grains of sand are carried in suspension by the wind. They dash and collide against the exposed rock masses and cause erosion. This process, in which sand grains are used as tools for eroding rocks, is called *"abrasion"*.

Attrition: The particles that travel with wind collide against one another. These mutual collisions lead to their further break down and the process is called *"attrition".*

4.4.2 Transport by Wind:

The finer dust particles (size 0.02 mm or less) are generally lifted up in the air and are transported in *"suspension",* whereas the sands are transported in a series of jumps or these merely roll along the ground. The process by which sand particles travel in a series of jumps is called *"saltation".* The greater parts of the sand grains are transported very near the ground surface and they are seldom lifted more than two meter above the ground.

4.4.3 Deposition by Wind:

The materials deposited by wind are called *"Aeolian deposits".* The rock particles in the Aeolian deposits are generally well rounded and are sorted according to their size and weight. The important wind deposits are:

1. Sand dunes, and
2. Loess.

Sand Dune: The sand travelling as bed load in wind accumulates wherever it meets any obstruction, such as a boulder or a bush. Mounds of windblown sand heaped up in this manner are called *"sand dunes".* On the windward side, a sand dune shows a long gentle slope at an angle of about 5°to 15° from the horizontal, and on the leeward side, the slope angle is usually 20° to 30°. The sand dunes may migrate slowly in the direction of wind movement. The migrating sand dunes may advance and cover farmland, railroad's, highways, and other valuable property. Their movement may be checked by planting vegetation.

Loess: The suspended load transported by wind consists mainly of silt and dust particles. When it settles, it forms a blanket deposit of silt, known as *"loess".* These deposits are typically non-stratified and have a grayish yellow color. Loess is composed of many minerals including quartz, feldspar, hornblende, and calcite. Deposits of loess are very fertile. Loess deposits in some parts of China approach a thickness of 300 meter or more.

4.5 WORK OF RIVERS

The geological work of rivers is to *"erode"* the valleys *"transport"* the material thus eroded, and *"deposit"* the same in the lower reaches at favorable sites.

4.5.1 Geological Work of River:

River Erosion: The rivers do erosion in four ways:

1. Chemical action;
2. Hydraulic action,
3. Abrasion, and
4. Attrition.

Chemical Action: It includes the solvent and chemical action of water on country rocks.

Hydraulic Action: Swiftly flowing water hammers the uneven faces of rocks exposed along its channel and removes the rock fragments. This process of erosion is Called *"hydraulic action".*

Abrasion: The flowing water uses pebbles, gravels, sands etc. as a tool for scratching and breaking the sides and floor of the valley. This process of erosion is called *"abrasion".*

Attrition: It is the breaking of the transported material themselves due to mutual collision. As a result of attrition the rock, particles become more rounded and smaller in size.

4.5.2 River Transportation:

The amount of solid material transported by a river is called its *"load".* It is transported mainly in three ways:

1. Soluble material as "solution".
2. Heavy material as *"bed load",* which rolls and slides along the river bottom.
3. The finer particles as *"suspension".*

4.5.3 River Deposition:

The loose rock materials transported by a river downstream are deposited where the velocity of flowing water is reduced. The sorting of the material takes place automatically, as the larger and heavier particles settle quickly, while smaller and lighter ones continue their journey further ahead. The deposits made by rivers ate called *"alluvial* deposits".

4.6 WORK OF GLACIERS

Glacier: The glaciers are the rivers of ice, which move over the ground under the influence of gravity. Most of glaciers move at the rate of a few meters per day.

4.6.1 Geological Work of Glaciers:

Erosion by Glaciers: The glaciers cause erosion in three ways:

1. By plucking or quarrying;
2. By abrasion, and
3. By frost wedging.

Plucking or Quarrying: The glacial ice adheres to large blocks of jointed bedrock, pulls them out and carries them along.

Abrasion: The moving ice grinds and polishes the rocks with the help of rock fragment, which are held firmly within the body of the glacier.

Frost Wedging: The thawing and freezing of water in the cracks and joints of rocks are breaking them by wedge action.

4.6.2 Transport by Glaciers:

The rock debris produced due to glacial erosion is transported by ice in three ways:

1. *Super Glacial Load:* The rock debris, which is present on the surface of the glacier, is called *"super glacial load".*
2. *Englacial Load:* The rock debris present within the ice is called *"englacial load".*
3. *Subglacial Load:* The rock debris present at the bottom of the glacier is called "*subglacial load".*

4.6.3 Deposition by Glaciers:

The loose rock material deposited by the ice is called *"glacial deposits".* The *fluvioglacial deposits"* are those, which are made by the water formed by the melting of the ice. The term *"glacid drift"* is commonly applied to all the material that is transported and deposited by glaciers. It is also called *"boulder clay"* or *"till".* The boulder clay or drift is mainly composed of fine clay and sand, with striated pebbles and boulders. This material, in general, is heterogeneous and unsorted, with no stratification. The glacial drift does not exhibit chemical weathering.

Glaciers may transport huge rock boulders, many thousands of tones in weight. When ice melts, they are left behind great distances away from their natural bedrock. Such boulders are called *"erratic boulders".*

4.7 WORK OF SEA

The profile of the sea floor from the coast up to the deep sea has been divided into four zones:

1. ***Littoral Zone:*** The littoral zone is also called *"shore zone".* This includes the area between the levels of the high tide and low tide. The littoral zone separates the coastal land mass from the sea. This zone contains the sediment derived from the land.
2. ***Continental Shelf Zone:*** This is a submerged platform, which slopes gently towards sea. The maximum depth of water on the continental shelf does not exceed 200 meter. The sediment is mostly terrigenous. Coral islands are commonly formed in this zone.
3. ***Continental Slope:*** This lies between the continental shelf and deep-sea zone. The depth of water varies from 200 to 900-meter. The sediments here are very fine, which includes black mud, 'blue mud, green mud, coral mud, and volcanic mud.
4. ***Deep Sea Zone:*** It includes the deep sea floor that lies at a depth of 900 to 4000 meter. The deep-sea zone contains very fine sediments of inorganic and organic origin, which are called *"ooze".* Radiolarian ooze, foraminiferal ooze, diatomaceous ooze, and red clay are the important types of the deep-sea deposits.

4.7.1 Geological Work of Sea Water

Erosion by Sea: The destruction of shores by sea waves is caused in four ways:

1. *Hydraulic Impact:* The sea waves generated by strong winds dash against the steep rocky shore where fractured and jointed rocks are destroyed very quickly.
2. *Abrasion:* The sea waves pick up rock fragments like pebbles and sands, and strike them against the cliffs. A great deal of erosion is done in this way.
3. *Attrition:* The pebbles and sand, moving to and fro along with the sea waves are further broken down to smaller sizes due to mutual collision.
4. *Chemical Action of Water:* The chemical action of sea water is seen only where coasts are composed of readily soluble rocks, such as limestone and dolomite.

4.7.2 Transportation by Sea:

The products of erosion are transported by undertow currents and longshore currents, in suspension and solution.

4.7.3 Deposition by Sea:

The products of erosion are sorted by waves and currents of the sea, and then deposited mostly in shallow water.

4.8 GROUND WATER

All water occurring beneath the earth's surface is known as "ground water". The chief source of ground water is the downward percolation of the rain water.

4.8.1 Geological Work of Ground Water

Erosion: The ground water does erosion mainly by chemical action. The mechanical erosion is negligible as the ground water moves very slowly through the rocks. The erosive action of groundwater is most conspicuous in limestone regions where the water charged with carbon dioxide dissolves calcium carbonate very easily.

4.8.2 Transportation of Ground Water

The materials dissolved by ground water are carried in solution until they are deposited. Some materials may also reach sea through underground percolation thereby increasing the salinity of seawater.

4.8.3 Deposition of Ground Water

The deposition of the dissolved materials from the ground water takes place by:

1. Loss of CO_2 from water,
2. Evaporation,
3. Decrease of temperature,
4. Fall of pressure, or
5. Chemical reaction.

SOILS: FORMATION, TYPES AND PHYSICAL PROPERTIES

5.1 INTRODUCTION:

The word 'soil' has different meanings for different professions. To the agriculturist, soil is the top thin layer of earth within which organic forces are predominant and which is responsible for the support of plant life. To the geologist, soil is the material in the top thin zone within which roots occur. From the point of view of an engineer, soil includes all earth materials, organic and inorganic, occurring in the zone overlying the rock crust.

The behavior of a structure depends upon the properties of the soil materials on which the structure rests. The properties of the soil materials depend upon the properties of the rocks from which they are derived. A brief discussion of the parent rocks is, therefore, quite essential in order to understand the properties of soil materials.

5.2 FORMATION OF SOILS

Soil is defined as a natural aggregate of mineral grains, with or without organic constituents, which can be separated by gentle mechanical means such as agitation in water. By contrast, rock is considered a natural aggregate of mineral grains connected by strong and permanent cohesive forces. The process of weathering of the rock decreases the cohesive forces binding the mineral grains and leads to the disintegration of bigger masses to smaller and smaller particles. Soils are formed by the process of weathering of the parent rock. The weathering of the rocks might be by mechanical disintegration, and/or chemical decomposition.

5.3 SOIL TYPES

Geologists classify soils into two major categories: residual soils and transported soils. Different types of soils under these categories are described next. Also, note that geotechnical engineers use different soil classification systems for engineering purposes.

5.3.1 Residual soils:

The soil type depends on the characters of the parent rocks. For example, *decomposed granite* is sandy residual soils derived from the weathering of *granitic rocks*. As well as, shale that is sedimentary rocks consists of clayey minerals are weathered to form clayey residual soils. The most important characteristics of residual soils are:

- This type of soil is formed when the rock weathering process is faster than the transport processes.
- This soil type retains many of the characteristics of the parent rock.
- The transition with depth from soil to weathered rock to fresh rock is gradual with no distinct boundaries.
- In tropical regions, residual soils are very thick; meanwhile in cooler and more arid regions it has thin layers and may be no residual soils at that area.
- The engineering properties of residual soils are range from poor to good and generally improved with depth.

5.3.2 Transported soil

This type of soil is formed by the deposition of sediments that have been weathered and transported from their places of origin. The famous types and properties of transported soils are summarized below.

Glacial soils:

- This type of soils is formed due to glaciers activities. It is well known that glacial are not stationary and moves along the ground.
- Glaciers grind down the rock and soil, and transport these materials over long distance even hundreds of kilometers, hence the resulting deposits often contain a mixture of different materials origin, hardness and sizes.
- Such soils contain different grain size that reduces the void ratio. Therefore; the glacial soils are difficult to compress and possess high shear strength.

Alluvial soils (or fluvial soils or alluvium):

- These soils are transported to their present position by rivers and streams.
- This soil type always contains extensive groundwater aquifers.
- This soil type contains alternating horizontal layers of different soil types.
- The properties and size of particles is highly dependent on the quantity and velocity of the stream.
- The change in the profile of such soils is not sharp; but it happens gradually.
- The grains of such soil type are called gravel, sand and fines.
- The alluvial soil possesses high void ratio. Hence it is having high compressibility and low shear strength.

Aeolian soils:

- These soils are transported and deposited by wind.
- The method of deposition causes the soil structure to be weak (poorly graded soils).
- Due to the loose state of packing, such soils have poor engineering properties.

The most popular types of Aeolian soils are:

Dune sand*: it consists of fine to medium, rounded and dry sand particles. This soil types always characterized to have nearly same size particles. The size of particles transported by wind depends on the wind speed and its predominated direction.

*State the problems of dune sand and methods of treatment

Loess Aeolian soils: this soil type transported by wind and mainly composed of silt size particles of shape edges. This soil may have cohesion that enables engineers to make excavations of up to ten meters.

Organic soils:

- In this soil large amounts of organic materials are presents within soil mass.
- This soil is always regarded as a problematic soil in civil engineering projects *due to its high compressibility and low shear strength*.

Marine soils: formed by decomposition in the seas.

Some Soils that are generally used in Practice:

Bentonite is clay formed by the decomposition of volcanic ash with a high content of montmorillonite. It exhibits the properties of clay to an extreme degree.

Kaolin, China Clay is very pure forms of white clay used in the ceramic industry.

Calcareous Soil is a soil containing calcium carbonate. Such soil effervesces when tested with weak hydrochloric acid. Marl consists of a mixture of calcareous sands, clays, or loam.

Peat is a fibrous aggregate of finer fragments of decayed vegetable matter. Peat is very compressible and one should be cautious when using it for supporting foundations of structures.

Loam is a mixture of sand, silt and clay.

Loess is a fine-grained, air-borne deposit characterized by a uniform grain size, and high void ratio. The size of particles ranges between about 0.01 to 0.05 mm. The soil can stand deep vertical cuts because of slight cementation between particles. It is formed in dry continental regions and its color is yellowish light brown.

Shale is a material in the state of transition from clay to slate. Shale itself is sometimes considered a rock but when it is exposed to the air or has a chance to take in water, it may rapidly decompose.

5.4 SOIL PHASE RELATIONSHIPS

Soil mass is generally a three phase system. It consists of solid particles, liquid and gas. For all practical purposes, the liquid may be considered to be water (although in some cases, the water may contain some dissolved salts) and the gas as air. The phase system may be expressed in SI units either in terms of mass-volume or weight-volume relationships. The inter relationships of the different phases are important since they help to define the condition or the physical make-up of the soil.

5.4.1 Mass-Volume Relationship:

In SI units, the mass M, is normally expressed in kg and the density ρ in kg/m^3. Sometimes, the mass and densities are also expressed in (g) and (g/cm^3) or (Mg) and (Mg/m^3) respectively. The density of water ρ_w at 4 °C is exactly 1.00 g/cm^3 (= 1000 kg/m^3 = 1 Mg/m^3). Since the variation in density is relatively small over the range of temperatures encountered in ordinary engineering practice, the density of water pw at other temperatures may be taken the same as that at 4 °C. The volume is expressed either in (cm^3) or (m^3).

5.4.2 Weight-Volume Relationship:

Unit weight or weight per unit volume is still the common measurement in geotechnical engineering practice. The density ρ may be converted to unit weight, by using the relationship:

$$\gamma = \rho\, g$$

The 'standard' value of (g) is 9.807 m/s^2 (= 9.81 m/s^2 ≈10.0 m/s^2 for all practical purposes).

5.4.3 THE PHASE RELATIONSHIP OF SOIL:

The phase-relationships in terms of mass-volume and weight-volume for a soil mass are shown by a block diagram shown in Figure 5-1. A block of unit sectional area is considered. The volumes of the different constituents are shown on the right side and the corresponding mass/weights on the right and left sides of the block. The mass/weight of air may be assumed as zero.

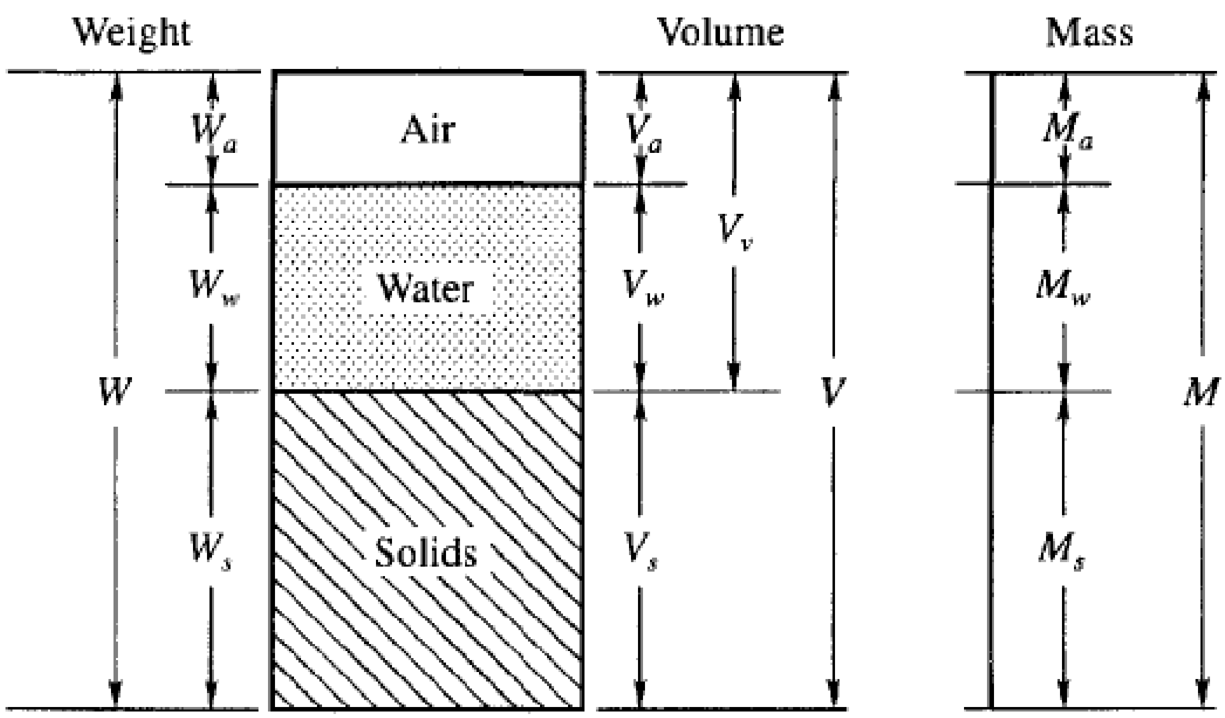


FIGURE 5-1: BLOCK DIAGRAM—THREE PHASES OF A SOIL ELEMENT

5.4.3.1 Volumetric Relations:

There are different relations between different volumes of soil sample constituents. Three volumetric relations are useful in geotechnical engineering that can be determined directly from the phase diagram presented in Figure 5-1.

1. The ***void ratio**, e,* is defined as the ration between the volume of voids and the volume of soils and expressed as:

$$\boldsymbol{void\ ratio, e = \frac{Volume\ of\ voids}{Volume\ of\ solids} = \frac{V_v}{V_s}}$$

Where, *Vv* = volume of voids, and *Vs* = volume of the solids.

The void ratio *e* is always expressed as a *decimal.*

2. The ***porosity**, n* is expressed as:

$$\boldsymbol{Porosity, n = \frac{Volume\ of\ voids}{Total\ volume\ of\ sample} \times 100}$$

$$\boldsymbol{n = \frac{V_v}{V} \times 100}$$

Where, *V* = total volume of the soil sample.

The *porosity n* is always expressed as a *percentage.*

3. The ***degree of saturation*** *S* is expressed as:

$$\boldsymbol{Degree\ of\ Saturation, S = \frac{Volume\ of\ voids\ filled\ with\ water}{Volume\ of\ voids} \times 100}$$

$$\boldsymbol{S = \frac{V_w}{V_v} \times 100}$$

Where, V_w = volume of water.

It is always expressed as a percentage. When S = 0%, the soil is completely dry, and when S = 100%, the soil is fully saturated.

5.4.3.2 Mass Relations:

The other aspects of the phase diagram connected with mass or weight can be explained with reference to Figure 5-1. The most important mass relationship is the water content.

The Water Content, ω:

The water content, ω of a soil mass is defined as the ratio of the mass of water, M_w in the voids to the mass of solids, Ms, that means:

$$\omega = \frac{M_w}{M_s} \times 100$$

The water content, which is usually expressed as a percentage, can range from zero (dry soil) to several hundred percent. The natural water content for most soils is well under 100%, but for the soils of volcanic origin (for example bentonite) it can range up to 500% or more.

5.4.3.3 The Mass or weight-volume Relations:

1. **Density, ρ:**

Another very useful concept in geotechnical engineering is density (or, unit weight) which is expressed as mass per unit volume. There are several commonly used densities. These may be defined as the total (or bulk), or moist density,γ (or ρ_{moist}); the dry density, γ_d (or ρ_d); the saturated density, γ_{sat} (or ρ_{sat}); the density of the particles, solid density, ρ_s; and density of water ρ_w. Each of these densities or unit weight is defined as follows with respect to Figure 5-1.

$\gamma_{bulk} = \frac{W}{V} = \frac{\gamma_w G_s + \gamma_w eS}{1+e} = \frac{\gamma_w (G_s + eS)}{1+e}$ =bulk, total and wet unit weight

$\gamma_{sat} = \frac{\gamma_w (G_s + e)}{1+e}$ Saturated unit weight

$\gamma_{dry} = \frac{\gamma_w G_s}{1+e}$ Dry unit weight

The submerged unit weight, γ', is sometimes useful when the soil is saturated, and is given by

$$\gamma' = \gamma_{sat} - \gamma_w$$

2. Specific Gravity (Gs)

The specific gravity of a substance is defined as the ratio of its mass in air to the mass of an equal volume of water at reference temperature, 4 °C. The specific gravity of a mass of soil (including air, water and solids) is termed as bulk specific gravity G_m. It is expressed as

Another frequently used quantity is the Specific Gravity, G, which is defined by:

$$Gs = \frac{Density\,of\,Material}{Density\,of\,Water} = \frac{\rho_s}{\rho_w}$$

$$Gs = \frac{Unit\,Weight\,of\,Material}{Unit\,Weight\,of\,Water} = \frac{\gamma_s}{\gamma_w}$$

For all the common soil forming minerals $2.5 < Gs < 2.8$

We can use G_s to calculate the density or unit weight of the solid particles

$$\rho_s = G_s\,\rho_w \text{ or } \gamma_s = G_s\,\gamma_w$$

And hence the volume of the solid particles if the mass or weight is known

$$V_s = \frac{M_s}{G_s \rho_w} = \frac{W_s}{G_s \gamma_w}$$

Example No. 1:

If a soil sample has a wet mass of 100 gm and after 24 hrs of oven drying; the mass became 80 gm, find the water content of the sample.

Solution:

$$\omega = \frac{M_w}{M_s} \times 100 = \frac{M - Ms}{Ms} = \frac{100 - 80}{80} = 0.25 = 25.0\%$$

Example No. 2:

Find the void ratio, porosity, degree of saturation, total density of soil sample has volume of 100 cm^3 and mass of 200 gm. The volume of the solids is 60 cm^3 and the volume of water filled voids is 20 cm^3.

Solution:

$$\rho_t = \frac{mass}{volume} = \frac{M}{V} = \frac{200}{100} = 2.0 gm/cm^3$$

$$n = \frac{V_v}{V} \times 100\% = \frac{V - V_s}{V} = \frac{100 - 60}{100} = \frac{40}{100} = 0.40 = 40.0\%$$

$$e = \frac{V_v}{V_s} = \frac{100 - 60}{60} = \frac{40}{60} = 0.667$$

$$S = \frac{V_w}{V_v} \times 100\% = \frac{20}{40} = \frac{1}{2} = 0.50 = 50.0\%$$

Example No. 3:

A soil has a voids ratio of 0.7. Calculate the dry and saturated unit weight of the material. Assume that the solid material occupies 1.0 m3and Gs = 2.65. what would be the distribution by volume and weight of the sample?

Solution:

Phase	**Volume** (m^3)	**Dry Weight** (kN)	**Saturated Weight** (kN)
Voids	0.7	0	$0.7 \times 9.81 = 6.87$
Solids	1.0	$2.65 \times 9.81 = 26.0$	26.0

- Dry unit weight $\gamma_{dry} = \dfrac{26.0 kN}{1.7 m^3} = 15.3 kN/m^3$
- Saturated un it weight $\gamma_{sat} = \dfrac{(26.0 + 6.87)}{1.7} = 19.3 kN/m^3$

If the soil were fully saturated the moisture content would be

- Moisture content $w=\frac{6.87}{26.0}=0.264=26.4\%$

Alternatively, the unit weights may be calculated from the expressions given below:

$\gamma_{dry}=\frac{G_s\gamma_w}{1+e}$ and $\gamma_{sat}=\frac{(G_s+e)\gamma_w}{1+e}$

Example No. 4:

The mass of a moist soil sample collected from the field is (465.00 gm), and its oven dry mass is (405.76 gm). The specific gravity of the soil solids was determined in the laboratory to be (2.68). If the void ratio of the soil in the natural state is (0.83), find:

1. The moist density of the soil in the field (kg/m3).
2. The dry density of the soil in the field (kg/m3).
3. The mass of water in (kg), to be added per cubic meter of soil in the field for saturation.

$$\omega = \frac{M_W}{M_S}=\frac{465.00-405.76}{405.76} = 14.6\%$$

$$\rho = \frac{Gs * \rho_w\ (1+\omega)}{1+e} = \frac{(2.68)(1000)(1.146)}{1.83} = 1678.3kg/m^3$$

$$\rho_d = \frac{Gs\ \rho_w}{1+e} = \frac{(2.68)(1000)}{1.83} = 1468.48\ kg/m^2$$

$$\rho_{sat} = \frac{(Gs+se)\rho_w}{1+e} = \frac{(2.68+0.83)(1000)}{1.83} = 1918\ kg/m^3$$

Mass of water to be added =1918-1678.3= 239.7 kg/m^3

PHYSICAL PROPERTIES OF ROCKS

6.1 INTRODUCTION:

Rock mass is generally a three-phase system. It consists of solid particles, liquid and gas. For all practical purposes, the liquid may be considered to be water (although in some cases, the water may contain some dissolved salts) and the gas as air. The phase system may be expressed in SI units either in terms of mass-volume or weight-volume relationships. The inter relationships of the different phases are important since they help to define the condition or the physical make-up of the rock.

6.1.1 Volumetric Relations:

- **The void ratio,** $e = \frac{Volume\ of\ voids}{Volume\ of\ solids} = \frac{V_v}{V_s}$
- **The porosity, n=** $\frac{Volume\ of\ voids}{Total\ volume\ of\ sample} \times 100$

$$n = \frac{V_v}{V} \quad or\ n = \frac{V_v}{V} \times 100$$

- **The degree of saturation, S,** $S = \frac{Volume\ of\ water}{Volume\ of\ voids} \times 100 = \frac{V_w}{V_v} \times 100$

6.1.2 Mass or weight Relations:

Water Content, *w*:

$$water\ content, w\% = \frac{Mass\ of water}{Mass\ of\ solids} \times 100 = \frac{M_w}{M_s} \times 100$$

$$= \frac{Mwet - Mdry}{Mdry} \times 100$$

6.1.3 Weight-Volume Relationship:

Specific Gravity:

$$G_s = \frac{\gamma_s}{\gamma_w} = \frac{\frac{W_s}{V_s}}{\frac{W_w}{V_w}} \ @certain\ temperature$$

6.1.4 Interrelationships of Different Parameters

Relationship between e and n:

$$void\ ratio = e = \frac{Volume\ of\ voids}{Volume\ of\ solids} = \frac{V_v}{V_s}$$

$$e = \frac{n}{1-n}$$

Then,

$$n = e(1-n)$$

$$n = e - en$$

$$n(1+e) = e$$

$$n = \frac{e}{1+e}$$

Relationship Between e, Gs , ρ_{dry} or γ_{dry} :

$$\rho_{dry} = \frac{G_s}{1+e}\rho_{water}$$

Or,

$$\gamma_{dry} = \frac{G_s}{1+e}\gamma_{water}$$

Relationship Between e, Gs , w and S:

$$Gs \times w = S \times e$$

Example 1

A sample of wet rock has a mass of 126 kg. The following data were obtained from laboratory tests on the sample: Wet density, ρ_t = 2.1 g/cm^3, Gs = 2.7, water content, *w*, 15%. *Determine:*

(1) dry density, ρ_d, (2) void ratio, (3) porosity, and (4) degree of saturation.

Solution:

1. $water\ content, w\% = \frac{weight\ of water}{weight\ of\ solids} \times 100$

$$15 = \frac{126-Md}{Md} \times 100$$

$$Md = 109.56\ kg$$

$dry\ density = \frac{wet\ density}{1+watercontent}$

= 2.1/ (1+0.15) =1.83 gm/cm^3

2. $dry\ density = \rho_{dry} = \frac{G_s}{1+e}\rho_{water}$

Void ratio=0.4754

3. $n = \frac{e}{1+e} = 0.322 = 32.2\%$

4. $Gs \times w = S \times e$

$S = 0.852 = 85.2\%$

Example 2:

If the wet weight of a rock has a volume of (0.22m3) equal to(312 kg) and the water content was(12%) and the specific gravity was(2.72).

Calculate:

1. Wet density,
2. Weight of water in the sample,
3. Dry density,
4. Void ratio, e and
5. Porosity, n.

Solution:

1. $\rho_{wet} = wet\ density = \frac{M\ wet}{V} = \frac{M\ t}{V} = \frac{312\ kg}{0.22\ m3} = 1418.2\frac{kg}{m3}$
2. $w\% = \frac{M_{wet}-M_{dry}}{M_{dry}} \rightarrow \frac{12}{100} = \frac{312-M_{dry}}{M_{dry}} \rightarrow M_{dry} = 278.57\ kg$

   $M_{water} = M_w = amount\ of\ water = 312 - 278.57 = 33.43\ kg$

   Hence, the weight of water=33.43 $\times 10 = 334.3\ N$
3. $\rho_{dry} = dry\ density = \frac{M\ dry}{V} = \frac{278.57\ kg}{0.22\ m3} = 1266.23\frac{kg}{m3} = 1.266\ gm/cm3$
4. $\rho_{dry} = \frac{G_s}{1+e} \times \rho_{water} \longrightarrow e = \left(\frac{2.72}{1.266} \times 1\right) - 1 = 1.148$
5. $n = \frac{e}{1+e} = \frac{1.148}{1+1.148} = 0.5344\ \ or\ 53.44\%$

Example 3:

A rock sample has 76 mm height and 38 mm diameter. This sample was tested under standard laboratory condition and it was found that it contains 10cm3 as voids. The mass of the sample was 165 gm and 155 gm in wet and dry case, respectively. Calculate porosity, void ratio, water content as well as dry and wet unit weight.

Solution:

1. $porosity(n) = \frac{V_v}{V} \times 100\ , volume\ of\ cylinder = \frac{\pi D^2}{4} \times h\ or = \pi r^2 \times h\ ,$

$where:$

$D: Diameter\ of\ the\ cylinder$

$r: radius\ of\ the\ cylinder$

$h: height\ of\ the\ cylinder$

$volume = \pi(1.9)^2 \times 7.6 = 86.193\ cm3$

$\therefore n = \frac{10}{86.193} \times 100 = 11.6\%$

2. $Void\ ratio, e = \frac{n}{1-n} = \frac{0.116}{1-0.116} = 0.104$

3. $water\ content, w\% = \frac{M_{wet}-M_{dry}}{M_{dry}} \times 100$

$w\ , \% = \frac{165-155}{155} \times 100 = 6.4\%$

4. $\rho_{wet} = wet\ density = \frac{Wet\ \ Mass}{Volume} = \frac{165\ gm}{86.193\ cm3} = 1.914 \frac{gm}{cm3}$

$in\ the\ case\ of\ wet\ unit\ weight = \gamma_{wet} = wet\ unit\ weight = \frac{W\ wet}{Volume}$

$$\gamma_{wet} = \frac{1.914\left(gm \times \frac{1kg}{1000\ gm} \times 10 \frac{m}{sec^2}\right) N \times \frac{1kN}{1000N}}{cm^3 \times \frac{1m^3}{10^6 cm^3}}$$

$$= \frac{1.914 \times 10\ kN}{m^3} = 19.14 \frac{kN}{m3}$$

$\gamma = unit\ weight = density \times acceleration = \rho\left(\frac{kg}{m3}\right) \times \frac{m}{sec2}$

5. $\rho_{dry} = dry\ density = \frac{Dry\ \ Mass}{Volume} = \frac{155\ gm}{86.193\ cm3} = 1.798 \frac{gm}{cm3}$

$$\gamma_{dry} = \frac{1.798\left(gm\times\frac{1kg}{1000\,gm}\times 10\frac{m}{sec^2}\right)N\times\frac{1kN}{1000N}}{cm^3\times\frac{1m^3}{10^6 cm^3}} = 17.98\,\frac{kN}{m3}$$

Example 4:

A rock sample of cylindrical shape with dimensions of (38^{mm}) diameter and (76^{mm}) length, wet mass and water content and degree of saturation are equal to (160 gm, 20% and 70%) respectively. Find the void ratio, porosity and specific gravity of the sample.

Solution:

$V = volume = \pi(1.9)^2 \times 7.6 = 86.193\ cm^3$

$\rho_{wet} = wet\ density = \frac{M\ wet}{V} = \frac{160\ gm}{86.193\ m3} = 1.856\ gm/cm^3$

$\rho_{dry} = \frac{\rho_{wet}}{1+w\%} = \frac{1.856}{1+0.2} = 1.5469 gm/cm^3$

$Se = G_S w \ldots\ldots\ldots\ldots (1)$

$0.7e = 0.2G_S$

$\rho_{dry} = \frac{G_S}{1+e} \times \rho_{water}\ \ldots\ldots\ldots\ldots\ldots (2)$ by substituting (1) in (2), we get :

$\therefore 1.5469 = \frac{3.5e}{1+e}$

$e = 0.792$

$G_S = 2.772$

MECHANICAL PROPERTIES OF ROCKS (Chapter 8)

8.1 Engineering Properties of Rocks:

The performance of soil and rock under the action of load, water, temperature and tectonics of the earth crust depends upon physical properties and mechanical strength of these materials.

Rocks in their natural state are fractured, inhomogeneous, anisotropic and discontinuous. The construction design in rocks requires the knowledge of the resulting deformation, which can be achieved by knowing their mechanical strength properties.

8.2 Strength of rocks

The strength of rocks (and any earth material) is defined as the ability of rocks to resist the external applied load. This may be compressive stresses; tension stresses and shear stresses.

A. Compressive strength

The stresses are result from compression forces causing contraction (reduction) in the volume of the rocks. There are two types of these stresses.

- ❖ Confined (Triaxial) compressive strength (out of the scope of the course)
- ❖ Unconfined (uniaxial) compressive strength

It is the most frequently used strength of the rocks in which a load on the rock acts in one direction only as shown in the following figure.

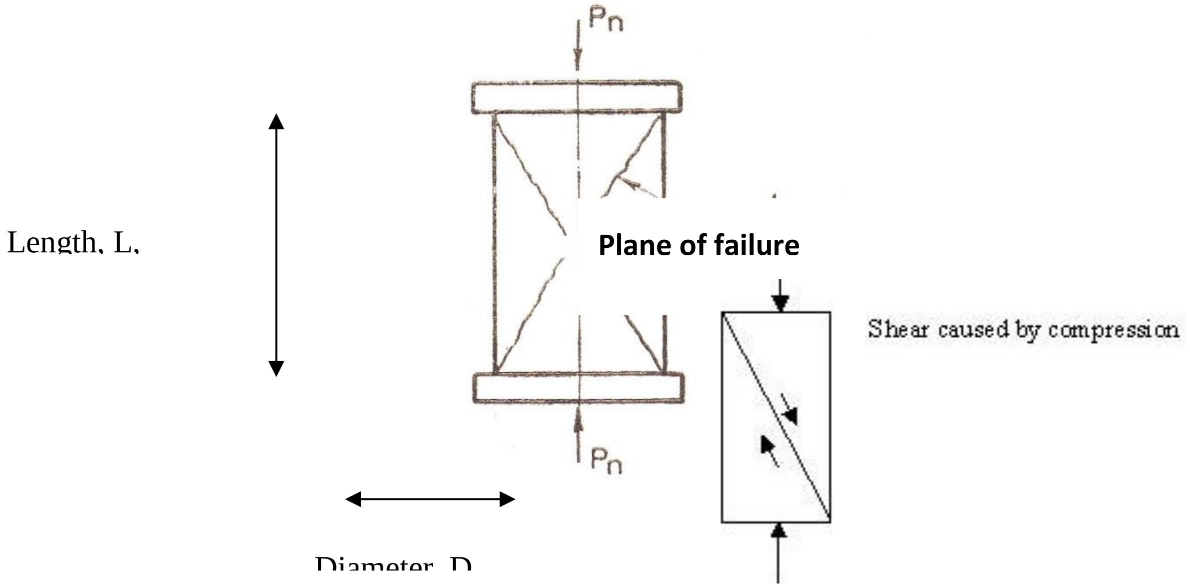


Figure (8.1): Illustration of load application to rock sample

The resulting forces and stress are obtained as:

$$\boldsymbol{\sigma_n = P_n / A}$$

Where:

$\sigma_n = axial\ or\ normal\ stress\ in = \dfrac{Forec}{area}\ \dfrac{F}{L^2}\ such\ as\ \dfrac{kg}{m^2}\ \ or\ \dfrac{kN}{m^2}$

$P_n = Compression\ force\ (axial)$

$A = cross\ sectional\ \ area$

Table 8.1: uniaxial compressive strength of some common rocks

Rock	UC Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Poisson's Ratio	Strain at Failure (%)	Point Load Index $I_{s(50)}$ (MPa)	Fracture Mode I Toughness
Igneous							
Granite	100 – 300	7 – 25	30 – 70	0.17	0.25	5 – 15	0.11 – 0.41
Dolerite	100 – 350	7 – 30	30 – 100	0.10 – 0.20	0.30		>0.41
Gabbro	150 – 250	7 – 30	40 – 100	0.20 – 0.35	0.30	6 – 15	>0.41
Rhyolite	80 – 160	5 – 10	10 – 50	0.2 – 0.4			
Andesite	100 – 300	5 – 15	10 – 70	0.2		10 – 15	
Basalt	100 – 350	10 – 30	40 – 80	0.1 – 0.2	0.35	9 – 15	>0.41
Sedimentary							
Conglomerate	30 – 230	3 – 10	10 – 90	0.10 – 0.15	0.16		
Sandstone	20 – 170	4 – 25	15 – 50	0.14	0.20	1 – 8	0.027 – 0.041
Shale	5 – 100	2 – 10	5 – 30	0.10			0.027 – 0.041
Mudstone	10 – 100	5 – 30	5 – 70	0.15	0.15	0.1 – 6	
Dolomite	20 – 120	6 – 15	30 – 70	0.15	0.17		
Limestone	30 – 250	6 – 25	20 – 70	0.30		3 – 7	0.027 – 0.041
Metamorphic							
Gneiss	100 – 250	7 – 20	30 – 80	0.24	0.12	5 – 15	0.11 – 0.41
Schist	70 – 150	4 – 10	5 – 60	0.15 – 0.25		5 – 10	0.005 – 0.027
Phyllite	5 – 150	6 – 20	10 – 85	0.26			
Slate	50 – 180	7 – 20	20 – 90	0.20 – 0.30	0.35	1 – 9	0.027 – 0.041
Marble	50 – 200	7 – 20	30 – 70	0.15 – 0.30	0.40	4 – 12	0.11 – 0.41
Quartzite	150 – 300	5 – 20	50 – 90	0.17	0.20	5 – 15	>0.41

B. Tensile strength

A material can sustain the maximum tensile stress prior to failure. In general, the tensile strength of rocks is less than the compressive strength of the same rock. For example, the tensile strength of granite is less than quarter than the compressive strength. The tensile strength of a rock sample can be calculated as:

$$\sigma_{n\ tension} = P_n(tension)/A$$

C. Shear strength

It is the capacity of a rock mass to take a shear stress or the maximum resistance to deformation due to shear displacement caused by shear stresses. The shear strength of the rocks results from:

- The cementation between particles of the rock, and
- The type of packing or arrangement of these particles.

In general, the shear strength can be obtained from the following relation:

$$\boldsymbol{\tau = c + \sigma_n \tan \varphi}$$

Where:

$\tau = shear\ strength\ of\ rocks, \quad take\ a\ unit\ of\ stresses\ such\ as\ \frac{kN}{m^2}$

$c = cohesion\ of\ rocks, take\ a\ unit\ of\ stresses\ such\ as\ \frac{kN}{m^2}$

$\sigma_n = compressive\ stress\ on\ rock, unit\ of\ stresses\ such\ as\ \frac{kN}{m^2}$

$\varphi = angle\ of\ internal\ shearing\ resistance, degree$

8.3 Deformation and Elasticity of Rocks:

Deformation of the rocks means the change in the size and shape of the rock sample and mass that induced by the applied force even though the rock sample does not break or fail.

By referring to Figure (8.2), it can be seen that when uniaxial compression load is applied to a rock sample, the sample become small is the direction of load application and expand in the lateral direction. Furthermore, when the applied load is tension, the sample became longer (the load pull the sample in the direction of load application).

For both loading conditions, the original length of the sample before deformations denoted as (L), the radius of the sample (r) and the cross sectional area as (A). The change in the dimensions of the sample would be denoted as (L1), (r1) and (A1).

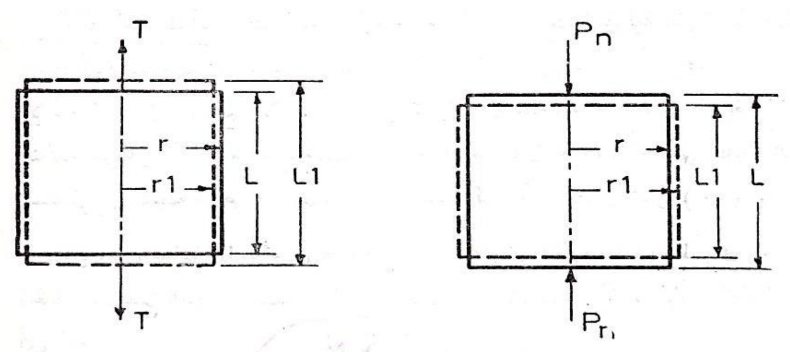


Figure (8.2): Rock sample under tensile and compression forces and the resulting deformations

As a measure of the rock deformations, the axial and lateral strains are introduced as well as the other elastic parameters should be explained.

1- **Axial and Lateral Strains:**
The axial and lateral strain is expressed as given below

Tension

$$\varepsilon_n = \frac{L_1 - L}{L}$$

$$\varepsilon_{rT} = \frac{r - r_1}{r}$$

Compression

$$\varepsilon_n = \frac{L - L_1}{L}$$

$$\varepsilon_{rn} = \frac{r_1 - r}{r}$$

In general, the strain= change in length/original length=dimensionless

2- **Modulus of Elasticity:** is the constant that shows the relation between the axial stress and axial strain. It is a distinguished feature for elastic material and can be calculated from the following relation:

$$Modulus\ of\ Elasticity = E = \frac{axial\ stresses}{axial\ strains} = \frac{\sigma_n}{\varepsilon_n} = dimensionless$$

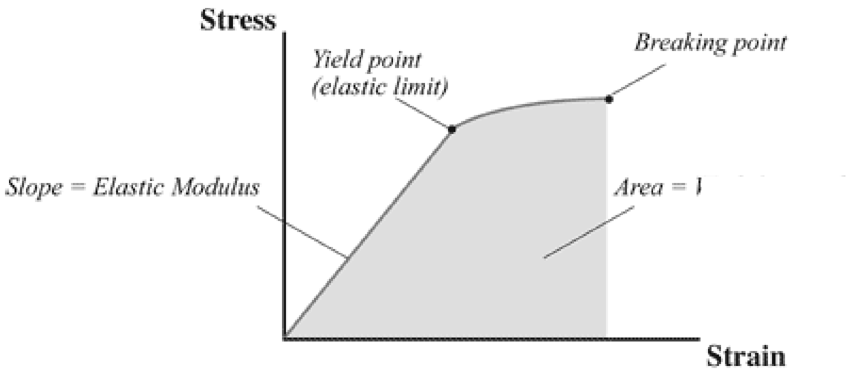


Figure (8.3): stress-strain relationship and modulus of elasticity

3- **Poisson's Ratio:** it is the ratio of lateral strain to the axial strain and is dimensionless. Its value is ranged between (0.0-0.5)

$$Poisson's\ Ratio = \upsilon = \frac{lateral\ strain}{axial\ strain} = \frac{\varepsilon_{rn}}{\varepsilon_n} \quad from\ compressive\ stress$$

Or

$$\upsilon = \frac{\varepsilon_{rt}}{\varepsilon_t} \quad from\ tensile\ stress$$

4- **Shear Modulus:** is the ratio between the shear stress and shear strain are expressed as a unit of stress.

$$Shear\ Modulus\ G = \frac{shear\ stress}{shear\ strain} = \frac{\tau}{\varepsilon_{shear}}$$

5- **Bulk Modulus:** is the ratio between the equal all round stresses to the resulted volumetric strain due to applied stresses and expressed as a unit of stress.

$$Bulk\ Modulus = K_v = \frac{\sigma_n}{\Delta V/_V} = \frac{\sigma_n}{\varepsilon_{Volumetric}} = \frac{\sigma_n}{\varepsilon_V}$$

6- **Compressibility Modulus:** is the magnitude of reduction in sample volume corresponding to the one unit of subjected compression stresses on all parts of the external surface, i.e., is the reciprocal of the Bulk Modulus:

$$compressibility\ Modulus = \frac{\varepsilon_V}{\sigma_n} = \frac{1}{K_v} = \frac{1}{Bulk\ Modulus}$$

Interrelationships of Different Parameters

We can establish relationships between the different parameters:

a- Relationship between Modulus of Elasticity and Shear Modulus in term of Poisson's Ratio:

$$\mu = Shear\ Modulus = \frac{E}{2(1+\upsilon)}$$

b- Relationship between Modulus of Elasticity and Bulk Modulus in term of Poisson's Ratio:

$$K_v = Bulk\ Modulus = \frac{E}{3(1-2v)}$$

8.4 Worked examples:

1. A rock sample with dimensions of (10 cm×10 cm ×10 cm), volume of voids was equal to 40 cm^3, 10 cm^3 of voids filled with distilled water.

   Find: porosity and degree of saturation of the sample.

2. A specimen of rock was subjected to a compressive force of (5 kN) which tends an axial deformation or strain was equal to (0.02 mm) and lateral or diametrical strain was equal to (0.002 mm).If the sample dimensions(length 76 mm and Diameter 38 mm).

   Find:

   a. Axial strain.

   b. Lateral strain.

   c. Volumetric strain.

   d. Young's Modulus.

   e. Bulk Modulus.

   f. Shear Modulus.

3. A cylindrical rock sample was saturated with water, its wet weight was equal to (653.2 kN) and the dry weight was (500.6 kN). If the cross sectional area was (37.39 cm^2) and the thickness was (0.832 cm) and the specific gravity of the solids was equal to (2.65).

   Find: water content, degree of saturation, total and dry density.

4. A cylindrical rock sample has a bulk modulus of 208000 kg/m^2 and shear modulus equals to 13000 kg/m^2. This sample was subjected to compression force of 1500 kg, which causes longitudinal deformation of 0.0006. Find (1) the modulus of elasticity (2) Poisson's ratio (3) Diameter of the sample

in mm (4) sample length if the change in length was 0.012 cm and (5) compressibility modulus.

5. A sandy sample has a dry density of 1.75 gm/cm^3 and the water content and degree of saturation was 20 and 90 % respectively. Calculate the void ratio, porosity and specific gravity. If the density of the sample was kept constant, what is the quantity of water that must be added to the sample to get fully saturated sand?

8. Earthquakes

8.1Introductions

Earthquakes are natural geologic phenomena caused by the sudden and rapid movement of a large volume of rocks and earth mass. The violent shaking and destruction caused by earthquakes are the result of rupture and slippage along fractures in Earth's crust called *faults*. Larger quakes result from the rupture of larger fault segments. The origin of an earthquake occurs at depths between 5 and 700 kilometers, at the *focus*. The point at the surface directly above the focus is called the ***epicenter*** as shown in Figure (1). During large earthquakes, a massive amount of energy is released as ***seismic waves***; a form of elastic energy that causes vibrations in the material that transmits them.

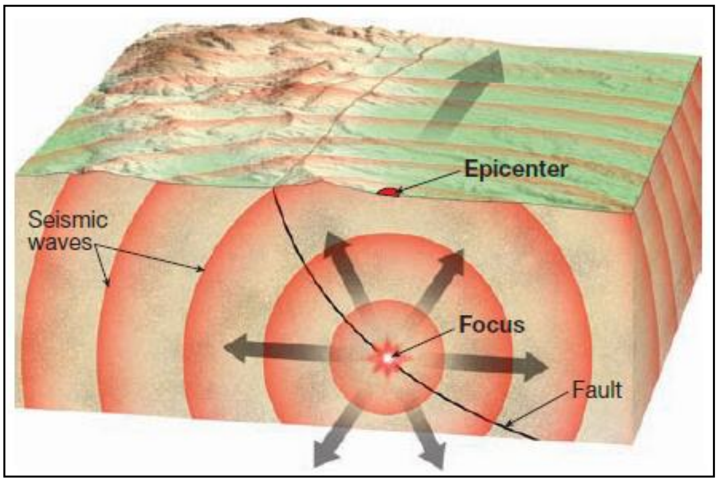


Figure (1): Earthquakes definitions

8.2 Earthquakes and Faults

Earthquakes take place along faults both new and old that occurs in places where differential stresses have ruptured Earth's crust. Some faults are large and capable of generating major earthquakes. One example is the **San Andreas Fault**, which is the transform fault boundary that separates two great sections of Earth's lithosphere: the

North American plate and the Pacific plate. Other faults are small and capable of producing only minor earthquakes.

Most of the displacement that occurs along faults can be satisfactorily explained by the *plate tectonics theory*, which states that large slabs of Earth's lithosphere are in continual slow motion. These mobile plates interact with neighboring plates, straining and deforming the rocks at their margins. Faults associated with plate boundaries are the source of most large earthquakes.

8.3 Earthquakes waves

Waves that travel through rock are called *seismic waves*. Earthquakes and explosions produce seismic waves. *Seismology* is the study of earthquakes and the nature of the Earth's interior based on evidence from seismic waves. An earthquake produces several different types of seismic waves. **Body wave's** travel through the Earth's interior. **Surface waves** then radiate from the epicenter along the Earth's surface.

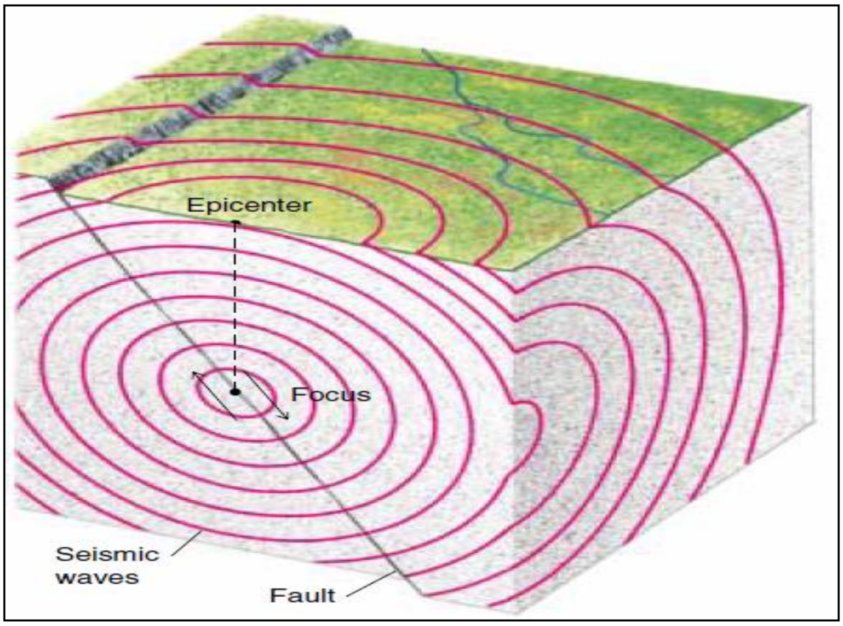


Figure (2): Earthquakes waves

8.3.1 Body waves

Two main types of *body waves* travel through the Earth's interior. A "**P**" wave (also called a compressional wave) is an elastic wave that causes alternate compression and expansion of the rock. P- Waves travel through air, liquid, and solid material. P waves travel at speeds between 4 and 7 kilometers per second in the Earth's crust and at about 8 kilometers per second in the uppermost mantle.

A second type of *body wave,* called an **"S"** wave, is a shear wave. Motions in an S-wave produces shear stress in rock and gives the wave its name. S-waves are slower than P-waves and travel at speeds between 3 and 4 kilometers per second in the crust. As a result, S-waves arrive after P-waves and are the secondary waves to reach an observer.

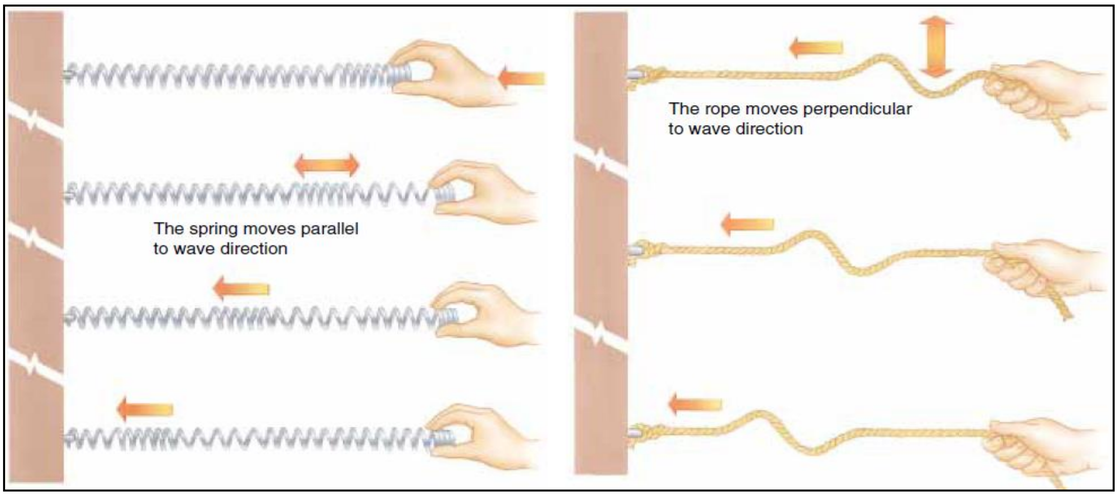


Figure (3)

Model of a P wave; a compressional wave. The wave is propagated along the spring. The particles in the spring move parallel to the direction of wave propagation.

Model of an S wave; a shear wave. The wave is propagated along the rope. The particles in the rope move perpendicular to the direction of wave propagation.

8.3.2 Surface waves

Surface waves travel more slowly than body waves. Two types of surface waves occur simultaneously in the Earth. A Rayleigh wave moves with an up-and down rolling motion like an ocean wave. Love waves produce a side-to-side vibration. Thus, during an earthquake, the Earth's surface rolls like ocean waves and writhes from side to side like a snake.

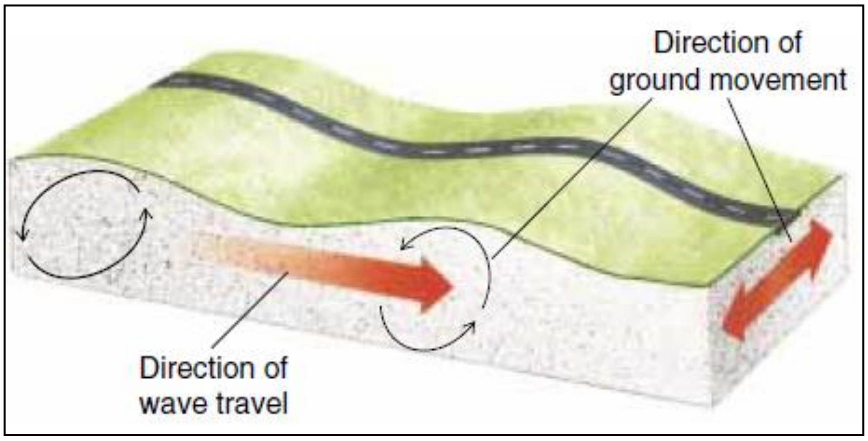


Figure (4): Surface waves

8.4 Source and Location of an earthquake

When analyzing an earthquake, the first task seismologists undertake is determining its epicenter, the point on Earth's surface directly above the focus. The method used for locating an earthquake's epicenter relies on the fact that P-waves travel faster than S-waves.

If a seismograph is located close to an earthquake epicenter, the different waves will arrive in rapid succession. On the other hand, if a seismograph is located far from the epicenter, the S-waves arrive at correspondingly later times after the P waves arrive, and the surface waves are even farther behind. Geologists use a time-travel curve to calculate the distance between an earthquake epicenter and a seismograph.

To make a time-travel curve, a number of seismic stations at different locations record the times of arrival of seismic waves from an earthquake with a known epicenter and occurrence time. Then a graph is drawn. This graph can then be used to measure the distance between a recording station and an earthquake whose epicenter is unknown.

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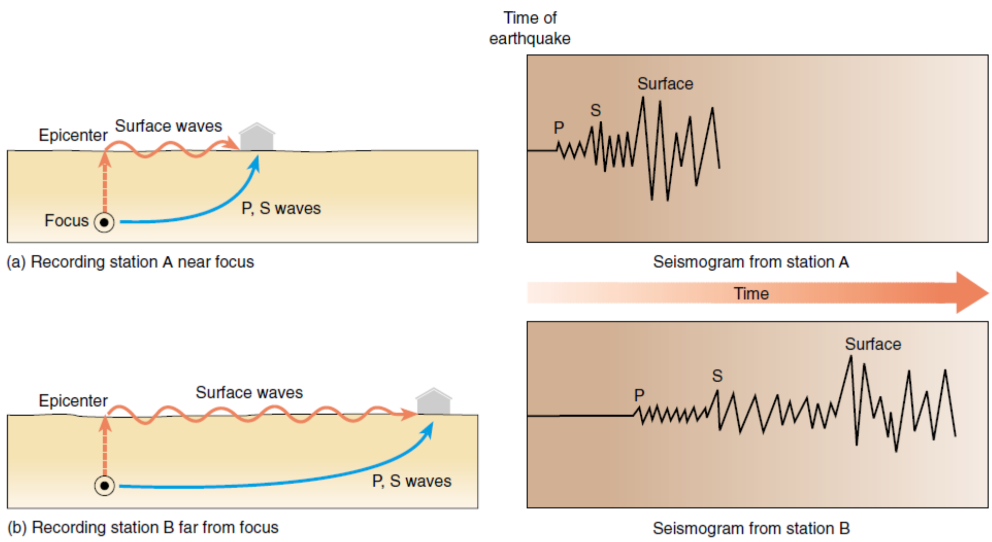


Figure (5): The time intervals between arrivals of P, S, and L waves at a recording station increase with distance from the focus of an earthquake.

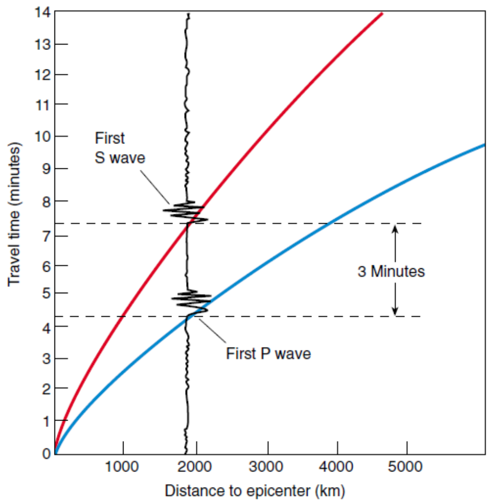


Figure (6): A time-travel curve: with this graph, the distance from a seismic station to the source of an earthquake can be calculated.

8.5 Size of An earthquake measurements

A variety of methods to determine two fundamentally different measures that describe the size of an earthquake are intensity and magnitude. The first of these to be used was intensity; a measure of the degree of earthquake shaking at a given locale based on observed effects. With the development of seismographs, it became possible to measure ground motion using instruments. This quantitative measurement, called magnitude, relies on data gleaned from seismic records to estimate the amount of energy released at an earthquake's source.

8.5.1 Modified Mercalli Intensity Scale

This intensity scale is divided into twelve levels of severity based on observed effects such as people awakening from sleep, furniture moving, plaster cracking and falling, and finally; total destruction. As in the table below, the lower numbers on the Mercalli scale (I-V) refer to what people in various locations felt during the quake, whereas the higher numbers (VI-XII) are based on observable damage to buildings and other structures.

Modified Mercalli Intensity Scale	
I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake.
IV	During the day felt indoors by many, outdoors by few. Sensation like heavy truck striking building.
V	Felt by nearly everyone, many awakened. Disturbances of trees, poles, and other tall objects sometimes noticed.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. (Fall of chimneys, factory stacks, columns, monuments, walls.)
IX	Damage considerable in specially designed structures. Buildings shifted off foundations. Ground cracked conspicuously.
X	Some well-built wooden structures destroyed. Most masonry and frame structures destroyed. Ground badly cracked.
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground.
XII	Damage total. Waves seen on ground surfaces. Objects thrown upward into air.

8.5.2 Magnitude Scales

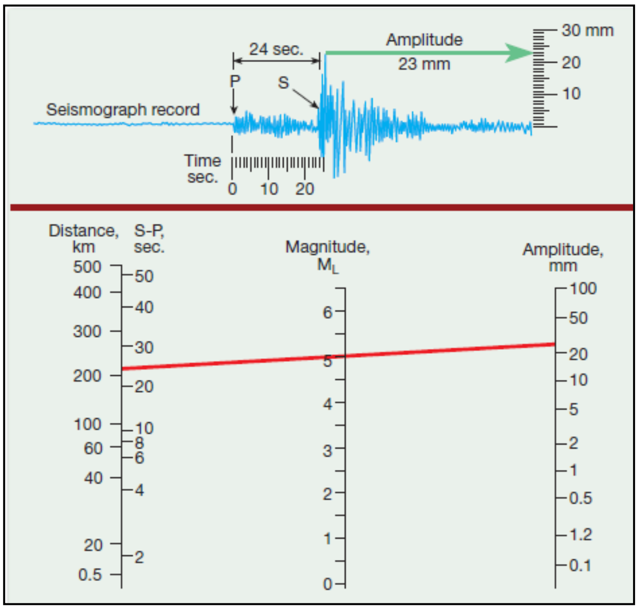
In order to compare earthquakes across the globe, a measure was needed that does not rely on parameters that vary considerably from one part of the world to another. Consequently, several magnitude scales were developed.

The first magnitude scale using seismic records is the Richter scale. As shown in the figure below, the Richter scale is based on the amplitude of the largest seismic wave (P, S, or surface wave) recorded on a seismogram. Because seismic waves weaken as the distance between the focus and the seismograph increases, Richter developed a method that accounts for the decrease in wave amplitude with increasing distance. Earthquakes vary enormously in strength, and great earthquakes produce wave amplitudes that are thousands of times larger than those generated by weak tremors.

The strength of an earthquake at source can be calculated as follows:

$$M = \log_{10}\left(\frac{A}{T}\right) + q(\Delta, h) + c$$

Where,
A = maximum amplitude of the wave (10^{-6} m),
T = wave period (sec.),
q = function correcting for the distance from the source of the quake,
Δ= angular distance from seismometer to epicenter,
h = focal depth of the quake, and
c = an empirical constant related to the station and regional characters.



The Richter scale is shown in the following Table

Richter Magnitudes	Description	Earthquake Effects	Frequency of Occurrence
Less than 2.0	Micro	Micro-earthquakes, not felt.	About 8,000 per day
2.0-2.9	Minor	Generally not felt, but recorded.	About 1,000 per day
3.0-3.9	Minor	Often felt, but rarely causes damage.	49,000 per year (est.)
4.0-4.9	Light	Noticeable shaking of indoor items, rattling noises. Significant damage unlikely.	6,200 per year (est.)
5.0-5.9	Moderate	Can cause major damage to poorly constructed buildings over small regions. At most slight damage to well-designed buildings.	800 per year
6.0-6.9	Strong	Can be destructive in areas up to about 160 kilometres (100 mi) across in populated areas.	120 per year
7.0-7.9	Major	Can cause serious damage over larger areas.	18 per year
8.0-8.9	Great	Can cause serious damage in areas several hundred miles across.	1 per year
9.0-9.9	Great	Devastating in areas several thousand miles across.	1 per 20 years
10.0+	Epic	Never recorded; see below for equivalent seismic energy yield.	Extremely rare (Unknown)

The amount of damage to man-made structures attributable to the vibrations depends on several factors, including:

(1): the intensity.

(2): the duration of the shaking.

(3): the nature of the material upon which the structure rests.

(4): the nature of building materials and the construction practices of the region.

9.1 **Geophysical Methods:**

Geophysics is the application of physics principles to the study of the earth. The earth is comprised of materials that have different physical properties. For example clay and granite have different densities, acoustic velocities, elastic moduli, electrical conductivities, magnetic susceptibilities, and dielectric constant.

Geotechnical geophysics is the application of geophysics to geotechnical engineering problems. Such investigations normally extend from a total depth of less than few meters to hundred meters depending on the site.

9.1.1 Applications of Geophysics methods:

1- Hydrocarbon exploration (coal, gas, oil).
2- Regional geological studies (over areas of hundreds of km^2).
3- Exploration/development of mineral deposits.
4- Engineering site investigations.
5- Hydrological investigations.
6- Detection of subsurface cavities.
7- Mapping of leachate and contaminant plumes.
8- Location and definition of buried metallic objects.

9.1.2 Geophysical techniques measure physical phenomena:

- **Gravity**
- **Magnetism**
- **Elastic waves**
- **Electricity**
- **Electromagnetic waves**

9.1.3 Which are sensitive to sub-surface physical properties:

- **Density**
- **Magnetic susceptibility**
- **Seismic wave velocity and density**
- **Resistivity**
- **Conductance/inductance/permitivity**

9.1.4 Active and passive Methods

Active

Transmit a signal into the subsurface and record what comes back

- **Seismic arrival – explosions**
- **Electrical current**
- **Electromagnetic waves**

Passive
Measure naturally occurring phenomena
- **Gravity field**
- **Magnetic field**
- **Seismic arrivals - earthquakes**

Table 9.1.1: Summary of Some Used Geophysical Surveying Methods for Geotechnical Investigations

Geophysical Method	Measured Parameter(s)	Physical Property or Properties	Physical Property Model (Geotechnical Application)	Typical Site Model (Geotechnical Applications
Shallow seismic refraction	Travel times of refracted seismic energy (p- or swave)	Acoustic velocity (function of elastic moduli and density)	Acoustic velocity–depth model often with interpreted layer boundaries	Geologic profile
Ground penetrating radar (GPR)	Travel times and amplitudes of reflected pulsed EM energy	Dielectric constant, magnetic permeability, conductivity and EM velocity	EM velocity/depth model with interpreted layer boundaries	Geologic profile

Geophysical Method	Measured Parameter(s)	Physical Property or Properties	Physical Property Model (Geotechnical Application)	Typical Site Model (Geotechnical Applications)
Electromagnetics (EM)	Response to natural–induced EM energy	Electrical conductivity and inductivity	Conductivity–depth model often with interpreted layer boundaries	Geologic–hydrologic profile
Electrical resistivity	Potential differences in response to induced current	Electrical resistivity	Resistivity–depth model often with interpreted layer boundaries	Geologic–hydrologic profile
Self potential (SP)	Natural electrical potential differences	Natural electric potentials	Model depicting spatial variations in natural electric potential of the subsurface	Hydrologic model (seepage through dam, levee, or fractured bedrock, etc.)
Magnetics	Spatial variations in the strength of the geomagnetic field	Magnetic susceptibility and remanent magnetization	Model depicting spatial variations in magnetic susceptibility of subsurface	Geologic profile or map (location of faults, variable depth to edrock, etc.)
Gravity	Spatial variations in the strength of gravitational field of the Earth	Bulk density	Model depicting spatial variations in the density of the subsurface often with interpreted layer boundaries	Geologic profile or map (location of voids, variable depth to bedrock, etc.)
Shallow seismic reflection	Travel times and amplitudes of reflected seismic energy (p- or swave	Density and acoustic velocity (acoustic velocity is a function of elastic moduli and density)	Acoustic velocity–depth model often with interpreted layer boundaries	Geologic profile

9.2 Methods:

9.2.1 Seismic Refraction: Typically, acoustic pulses are generated at predetermined source locations (S) along the length of the refraction seismic profile. The travel times of acoustic energy that has been critically refracted at horizons of interest (L1) is recorded at predetermined receiver locations (R1, R2, etc.). The recorded travel time information is used to generate a velocity–structure profile of the shallow subsurface along the length of the refraction profile. If external constraints are available, the velocity–structure profile can be transformed into a geologic model.

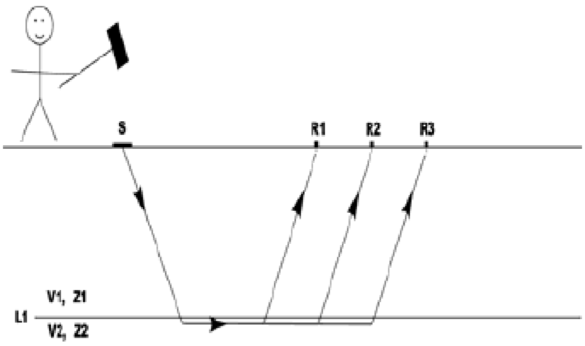


Figure (9.2.1): View of Seismic Refraction.

9.2.2Seismic Reflection: Typically, acoustic pulses are generated at predetermined source locations (S) along the length of the reflection seismic profile. The travel times and amplitudes of reflected acoustic energy is recorded at predetermined receiver locations (R1, R2, etc.). The recorded travel time–amplitude information is used to generate a reflection seismic profile. These data can be transformed into a velocity–structure profile. If external constraints are available, the velocity–structure profile can be transformed into a geologic model.

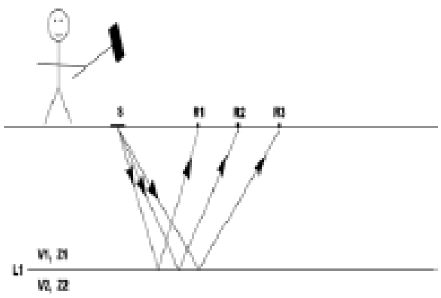


Figure (9.2.2): View of Seismic Reflection

9.2.3 Ground penetrating radar (GPR): Typically, pulsed EM energy is generated at predetermined station locations along the length of the GPR profile. The travel times and amplitudes of reflected EM energy are usually recorded by a monostatic transmitter–receiver. The recorded travel time–amplitude information is normally used to generate a GPR profile (2-D time–amplitude image). These data can be transformed into a 2-D velocity–depth model. If external constraints are available, a geologic model can be generated.

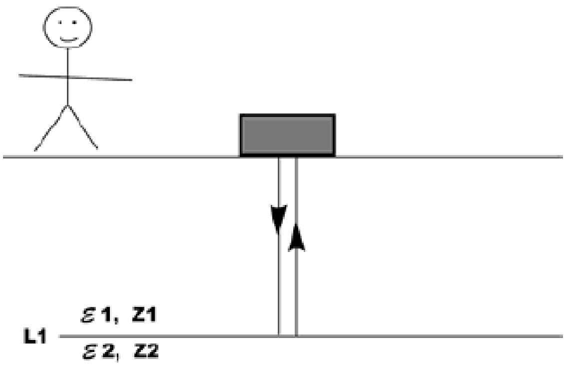


Figure (9.2.3): View of GPR.

9.2.4 Electromagnetics (EM): EM tools are used to measure the Earth's response to natural or anthropogenic EM energy. Measurements can be made in either the time or frequency domain. Some tools are used to locate metals or utilities; others are used to create conductivity–depth models of the subsurface. If external constraints are available, conductivity–depth models can be transformed into geologic models.

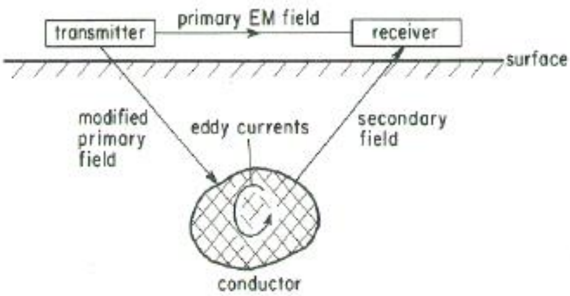


Figure (9.2.4): View of EM.

9.2.5 Electrical Resistivity: Typically, current (I) is induced between paired electrodes (C1, C2). The potential difference (ΔV) between paired voltmeter electrodes P1 and P2 is measured. Apparent resistivity (Δa) is then calculated (based on I, ΔV, electrode spacing's). If the current electrode spacing is expanded about a central location, a resistivity–depth sounding can be generated. If the array is expanded and moved along the surface, 2-D or 3-D resistivity–depth models can be created. If external constraints are available, resistivity–depth models can be transformed into geologic models.

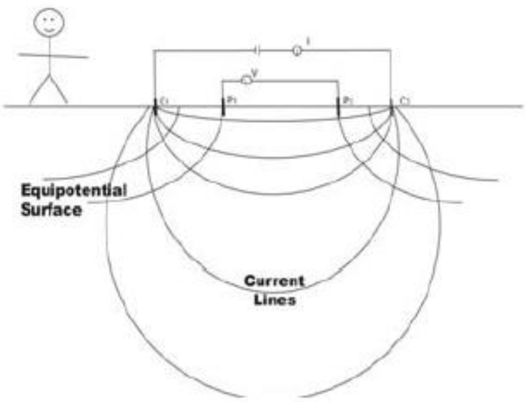


Figure (9.2.5): View of Electrical Resistivity.

9.2.6 Self Potential (SP): SP tools are used (mostly) to measure (*a*) natural potential differences arising from oxidization–reduction of metallic bodies straddling the water table and (*b*) streaming potential associated with flowing groundwater. SP data are usually interpreted in a qualitative manner, and are routinely used to locate zones of seepage in earth fill dams and levees.

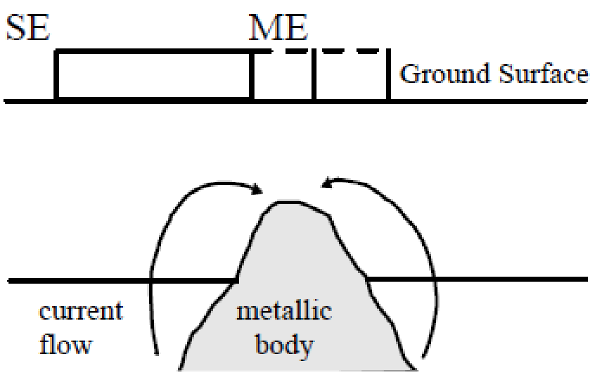


Figure (9.2.6): View of SP.

9.2.7 Magnetics: Magnetometers are designed to measure variations in the magnetic field of the Earth. These are usually caused by the presence of magnetically susceptible material of natural or human origin (typically magnetite or iron, respectively). In certain instances, magnetic data can be interpreted quantitatively, and transformed into constrained geologic models. More typically, however, magnetic data are interpreted qualitatively, and simply used to verify the presence or absence of magnetically susceptible materials.

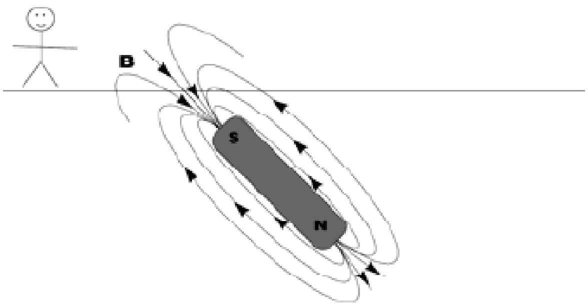


Figure (9.2.7): View of Magnetics.

9.2.8 Gravity: Gravimeters are designed to measure variations in the gravitational field of the Earth, and are typically used to generate 2-D or 3-D density–depth models of the subsurface. If external constraints are available, the density–depth models can be transformed into a geologic model.

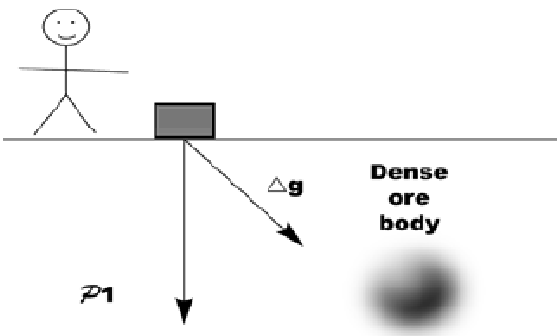


Figure (9.2.8): View of Gravity.

9.3 Limitations of Geophysics

The most significant limitation of geotechnical geophysics is its non-uniqueness. In the absence of any external constraints (ground truth or basic conceptual model), a single geophysical data set can be transformed into an infinite number of "theoretically correct" output models, but not likely geologically consistent, since geologic features are not commonly shaped.

9.4 Selection of Appropriate Geophysical Methods

The selection of the most appropriate geotechnical geophysical tool is generally a two-step approach. In Step I, potentially useful geophysical methods are identified on the basis of the nature of the engineering problem. This initial "high grading" can be done using updated reference tables and reference guides. In Step II, the most appropriate geophysical tool, or tools, is selected based on site-specific criterion such as the depth of the target, required resolution, site accessibility, and cost.