

## 1. Scope Of Geoenvironmental Engineering

- ❖ Any project that deals with the interrelationship among environment, ground surface and subsurface (soil, rock and groundwater) falls under the purview of geoenvironmental engineering (Fang and Daniels 2006).
- ❖ Scope is vast and requires the knowledge of different branches of engineering and science put together to solve the multi-disciplinary problems.
- ❖ Engineer should work in an open domain of knowledge and should be willing to use any concepts of engineering and science to effectively solve the problem at hand.
- ❖ Most challenging aspect is to identify the unconventional nature of the problem, which may have its bearing on multiple factors, e.g. an underground pipe leakage may not be due to the faulty construction of the pipe but caused due to the highly corrosive soil surrounding it. Corrosiveness may be attributed to single or multiple manmade factors, which need to be clearly identified for the holistic solution of the problem.
- ❖ The conventional approach of assessing the material strength of the pipe alone will not solve the problem at hand.
- ❖ For achieving the "Green Environment". Despite a lot of effort, it is very difficult to cut off the harmful effects of pollutants disposed off into the geoenvironment.
- ❖ The damage has already been done to the subsurface and ground water resources, which is precious.
- ❖ An effective waste containment system is one of the solutions to this problem. However, such a project has different socio-economic and technical perspectives.
- ❖ Realization of such projects require the contribution of
  - a) environmentalist,
  - b) remote sensing experts,
  - c) decision makers,
  - d) common public during its planning stage,
  - e) hydrologists,
  - f) geotechnical engineers for its execution stage and
  - g) several experts for management and monitoring of the project
- ❖ The totality of the problem can be visualized under the umbrella of geoenvironmental engineering.
- ❖ the real challenge for a geoenvironmental engineer is how well he can integrate the multi-disciplinary knowledge for achieving an efficient waste containment.
- ❖ In most parts of the world, damage has already been done to the geoenvironment and groundwater reserves due to indiscriminate disposal of industrial and other hazardous wastes.
- ❖ Owing to excessive demand, it becomes important to remediate and revive the already polluted geoenvironment and groundwater.
- ❖ Geoenvironmental engineer has a great role to play for deciding the scheme of such remediation practice, requiring lot of concepts from soil physics, soil chemistry, soil biology, multi-phase flow, material science and mathematical modeling, need to be taken for planning and execution of an efficient remediation strategy.
- ❖ Therefore, it is essential for the geoenvironmental engineer to think out of the box, to an extent that the knowledge can help him visualize the problem better and suggest efficient solution. Else, the solution to such problems becomes a trial and error process or rather, learn from mistakes and rectify. Since such projects are cost intensive one cannot afford to take too much of chances.
- ❖ Another important issue is the reuse and recycling of waste materials, which reduces the burden on our environment manifold, e.g. example is exploring the possibility of mass utilization of fly ash for geotechnical applications.
- ❖ For using the waste meaningfully, there are issues like short term and long term impact of such process, which is a governing factor for deciding its selection as a viable material.
- ❖ Geoenvironmental engineering is to simplify the process of understanding the behavior and resort to reliable predictions and estimations. This would require a thorough knowledge on material science and chemistry and the reaction it undergoes with time. This is indeed a tough task, but needless to say, such challenges make this subject quite interesting.

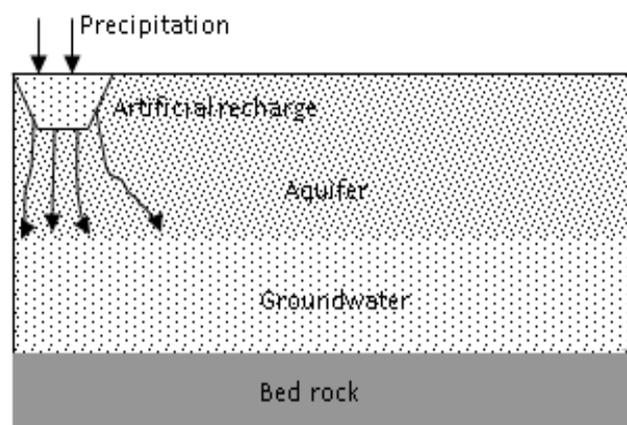
- ❖ Examples (i) frequent occurrence of landslides, and flood protection works.
- ❖ Geoenvironmental engineering is more research oriented and new concepts and methodologies are still being developed.

## **2. Multiphase Behavior of Soil**

- ❖ Classical soil mechanics assumes soil media to be completely water or air saturated, which is a typical example of a two phase media consisting of soil solids and water/air. The assumption of two phases considerably simplifies the mathematical quantification of the complex phenomena that take place in porous media.
- ❖ Of late, geotechnical and geoenvironmental engineering problems require the concept of three or multiphase behaviour of soil for realistic solution of several field situations. e.g. a partially saturated soil is a three phase porous media consisting of air, water and soil. The three phases result in transient and complex behaviour of unsaturated soil.
- ❖ Such cases are encountered while designing waste containment facility where flow characteristics of unsaturated soil need to be determined. When it comes to soil-water-contaminant interaction there are multi-phase interactions involved.
- ❖ The migration of non-aqueous phase liquid (denoted as NAPL) through porous media is a typical example. Fluidized bed, debris flow, slurry flow, gas permeation through unsaturated soil media are some problems where multiphase behaviour becomes important.
- ❖ Such studies are handy while designing remediation scheme for contaminated soil and groundwater, which are very important issues for the geoenvironmental engineer to solve.

## **3) Role Of Soil In Geoenvironmental Applications**

- ❖ All civil engineering structures are ultimately founded on soil and hence its stability depends on the geotechnical properties of soil.
- ❖ Conventional geotechnology is more concerned about rendering soil as an efficient load bearing stratum and designing foundations that can transfer load efficiently to subsurface.
- ❖ Apart from this, soil is directly related to a number of environmental problems, where the approach should be a bit different.
- ❖ Consider the case of groundwater recharge as shown in Fig. 1.1.
- ❖ The infiltration and permeation property of homogenous or layered soil mass above water table decides the rate of recharge.
- ❖ In this case, a geotechnical engineer has to work closely with hydrogeologists for deciding different schemes of artificial groundwater recharge.



**Fig. 1.1 Artificial groundwater recharge**

- ❖ Consider the case of waste dumped on ground surface.
- ❖ During precipitation, water interacts with these wastes and flow out as leachate. When the leachate flows down, soil act as buffer in retaining or delaying several harmful contaminants from reaching groundwater.
- ❖ Such a buffering action obviously depends on the texture and constituents of soil mass.
- ❖ While designing a waste containment facility, the role of soil in such projects is enormous. A coarse grained soil with filter property is required for leachate collection where as a fine grained soil is required for minimizing flow of leachate.
- ❖ These are two entirely different functions expected from soil in the same project. The cap provided for waste dumps also necessitate the use of specific type of soils with the required properties.
- ❖ Special type of high swelling soils is used as backfills for storing high level radioactive waste in deep geological repositories. Another important geoenvironmental problem, namely, carbon sequestration uses the geological storage capacity for disposal of anthropogenic CO<sub>2</sub> to mitigate the global warming.
- ❖ Therefore, soil plays a very vital role in geoenvironmental projects and the property by which it becomes important is problem-specific.

#### **4) Importance of Soil Physics, Soil Chemistry, Hydrogeology and Biological Process**

- ❖ Soil physics is the study of the physical properties and physical processes occurring in soil and its relation to agriculture, engineering and environment.
- ❖ It deals with physical, physico-chemical and physico-biological relationship among solid, liquid and gaseous phase of soil as they are affected by temperature, pressure and other forms of energy.
- ❖ The concepts of soil physics is used for determining the transport of water, solute and heat (matter and energy) through porous media, which is important to solve the problems related to subsurface hydrology, groundwater pollution, water retention characteristics of soil, improving crop production, rainfall induced landslides etc. Soil physics is mostly quantitative and mathematical in nature and requires the knowledge of soil physical properties.
- ❖ The emergence of discipline "soil chemistry" began when J. T. Way (father of soil chemistry) realized that soil could retain cations such as NH<sup>4+</sup>, K<sup>+</sup> in exchange for equivalent amounts of Ca<sup>+2</sup> (Thomas 1977).
- ❖ Knowledge of soil chemistry is important to understand interactions between soil solids, precipitates and pore water, including ion exchange, adsorption, weathering, buffering, soil colloidal behaviour, acidic and basic soils, salinity etc.
- ❖ Understanding subsurface for geoenvironmental problems requires extensive knowledge of hydrogeology. Hydrogeologic parameters influence a lot on how a waste containment facility performs over its design life.
- ❖ In biological processes occurring in soils some type of microorganisms such as Pseudomonas aeruginosa is used for remediation of hydrocarbon contaminated site. It is very essential to understand the rate of such reaction and the impact of such remediation.

#### **5) Sources And Type Of Ground Contamination**

- ❖ Solid, liquid and gaseous waste forms contaminates subsurface and groundwater due to indiscriminate disposal. Solid wastes come from municipal, domestic and industrial sources.
- ❖ Municipal wastes amounts to around 50 percent of the total wastes produced. Household, hospital, agricultural wastes forms part of municipal wastes. Returning these wastes to soil is considered to be a low cost option.
- ❖ Abandoned e-waste, batteries, vehicles, furniture, debris from construction industry is considered as solid waste and is produced from both urban and rural areas.
- ❖ Large scale industrial development produces huge quantities of hazardous waste and the sources are iron and steel industries, packaging factories, paints, dyes, chemicals, glass factories, fertilizer and pesticide industries, mine excavation waste etc. Coal mining, radioactive fuel mining, petroleum mining and thermal power plants generate hazardous solid waste that requires effective management.

- ❖ The main source and type of hazardous liquid waste include industrial waste water contained in surface impoundments, lagoons or pits. It is also produced from municipal solid refuse and sludge that are disposed on land.
- ❖ If not handled properly sewage becomes an important source of liquid waste that has undesirable effect on environment. Petroleum exploration leaves waste brine solution which needs to be managed to prevent groundwater pollution. Liquid waste emerges due to mining operation which is hazardous.
  - ❖ Some of the gaseous waste includes NO<sub>x</sub>, CO, SO<sub>2</sub>, volatile hydrocarbons etc. Chemical reaction may take place in air producing secondary pollutants. SO<sub>2</sub> combines with oxygen to produce SO<sub>3</sub>, which in turn combines with suspended water droplets to produce H<sub>2</sub>SO<sub>4</sub> and fall on ground as acid rain. Natural breakdown of uranium in the geoenvironment emits cancer causing radon gas into atmosphere.

### **6) Impact Of Contamination On Geoenvironment**

- ❖ In most of the cases, wastes are disposed off indiscriminately in low-lying areas without taking adequate engineering measures to effectively contain it.
  - ❖ This results in a highly unhygienic and unhealthy environment leading to breeding of pests, mosquitoes and several harmful microorganisms.
  - ❖ During precipitation, or groundwater coming in contact with these wastes generates contaminated water called leachate that can travel far field and pollute the surface and groundwater resources.
  - ❖ Many of the harmful heavy metals can also travel along with the leachate if it is not contained properly.
  - ❖ One of the complexities of contamination impact is its long term effects without a chance for realization. Most of the impacts are realized much later from rigorous studies, and by the time the damage would have been done.
  - ❖ Hence, remediation becomes a tedious and cost-intensive affair. This makes geoenvironmental engineering a challenging and much needed subject. There is a need to focus on research that would help to predict and minimize the long term impact of indiscriminate and mismanaged waste contamination.

### **Case Histories On Geoenvironmental Problems**

#### **(i) Use of readily available local soil instead of expensive commercial soil (like bentonite) for waste management**

- ❖ Engineered waste management scheme necessitates the construction of highly impermeable barrier so that waste disposed on it does not find its way to ground water resources.
- ❖ Mostly these barriers are made of high plastic clays which are commercially available.
- ❖ This would considerably increase the cost of such geoenvironmental projects.
  - ❖ Exploring the possibility of using local soils for such applications, therefore, becomes an important geoenvironmental problem. Any success in this direction would add to the economy of the project. This in turn would result in sustainable development of such very important project. e.g.
  - ❖ Taha and Kabir (2005) have explored the possibility of using tropical residual soil for waste management, which is readily available over a considerable part of peninsular Malaysia.
  - ❖ Hydraulic conductivity is used as the criterion for evaluation of soil suitability for the said application.
  - ❖ The soil was compacted at different water content and compaction effort and then permeated with de-aired tap water. The results of hydraulic conductivity test indicates that the required flow of less than 10<sup>-9</sup> cm/s can be achieved by using a broad range of water content and compaction effort.
  - ❖ The soil has minimum shrinkage potential and adequate strength to support the load of waste overburden.
  - ❖ These properties discussed would fall under the purview of geotechnical engineering. But the evaluation of soil suitability is not complete without understanding its chemical reactivity.
  - ❖ In this study, cation exchange capacity (CEC) of soil is used as an indicator of chemical reactivity. It is desirable that the pollutants released from the waste disposal site should be effectively attenuated by the liners. This means that the soil should have high chemical reactivity. A soil with high CEC indicates high reactivity and hence high attenuation capacity of pollutants.

Knowledge of **soil-water interaction** and **soil-water-contaminant** interaction is very important for solving several problems encountered in geoenvironmental engineering projects.

## 2.1 Soil Mineralogy Characterization And Its Significance In Determining Soil Behaviour

- ❖ Soil is formed by the process of weathering of rocks which has great variability in its chemical composition.
- ❖ Therefore, it is expected that soil properties are also bound to the chemical variability of its constituents.
- ❖ Soil contains almost all type of elements, the most important being oxygen, silicon, hydrogen, aluminum, calcium, sodium, potassium, magnesium and carbon (99 percent of solid mass of soil).
- ❖ Atoms of these elements form different crystalline arrangement to yield the common minerals with which soil is made up of.
- ❖ Soil in general is made up of minerals (solids), liquid (water containing dissolved solids and gases), organic compounds (soluble and immiscible), and gases (air or other gases).

### 2.1.1 Formation Of Soil Minerals

- ❖ Based on their origin, minerals are classified into two classes: primary and secondary minerals (Berkowitz et al. 2008).
- ❖ Primary minerals are those which are not altered chemically since the time of formation and deposition. This group includes quartz ( $\text{SiO}_2$ ), feldspar ( $(\text{Na,K})\text{AlSi}_3\text{O}_8$  aluminosilicates containing varying amounts of sodium, potassium), micas (muscovite, chlorite), amphibole (hornblende: magnesium iron silicates) etc.
- ❖ Secondary minerals are formed by the decomposition and chemical alteration of primary minerals. Some of these minerals include kaolinite, smectite, vermiculite, gibbsite, calcite, gypsum etc.
- ❖ These secondary minerals are mostly layered aluminosilicates, which are made up of silicon/oxygen tetrahedral sheets and aluminum/oxygen octahedral sheets.
- ❖ Primary minerals are non-clay minerals with low surface area (silica minerals) and with low reactivity (Berkowitz et al. 2008). These minerals mainly affect the physical transport of liquid and vapours.
- ❖ Secondary minerals are clay minerals with high surface area and high reactivity that affect the chemical transport of liquid and vapours (Low 1961).
- ❖ Silica minerals are classified as tectosilicates formed by  $\text{SiO}_4$  units in frame like structure.
- ❖ Quartz, which is one of the most abundant minerals comprises up to 95 percent of sand fraction and consists of silica minerals.
- ❖ The amount of silica mineral is dependent upon parent material and degree of weathering.
- ❖ Quartz is rounded or angular due to physical attrition. The dense packing of crystal structure and high activation energy required to alter Si-O-Si bond induce very high stability of quartz. Therefore, the uncertainty associated with these materials is minimal. In the subsurface, quartz is present in chemically precipitated forms associated with carbonates or carbonate-cemented sandstones.
- ❖ Clay minerals, which can be visualized as natural nano materials are of great importance to geotechnical and geoenvironmental engineers due to the more complex behaviour it exhibits. Therefore, emphasis is given more on understanding clay mineral formation and its important characteristics. Basic units of clay minerals include silica tetrahedral unit and octahedral unit depicted in Fig. 2.1.

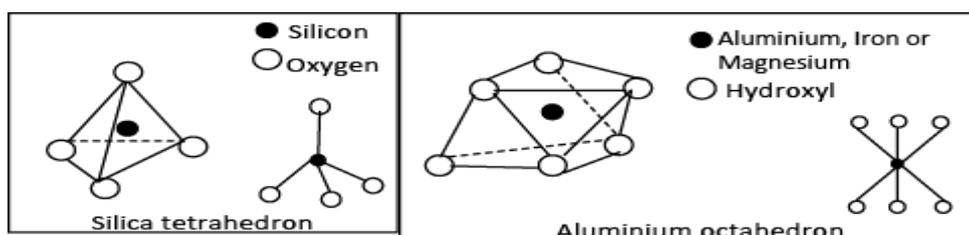


Fig. 2.1 Basic units of clay minerals (modified from Mitchell and Soga 2005)

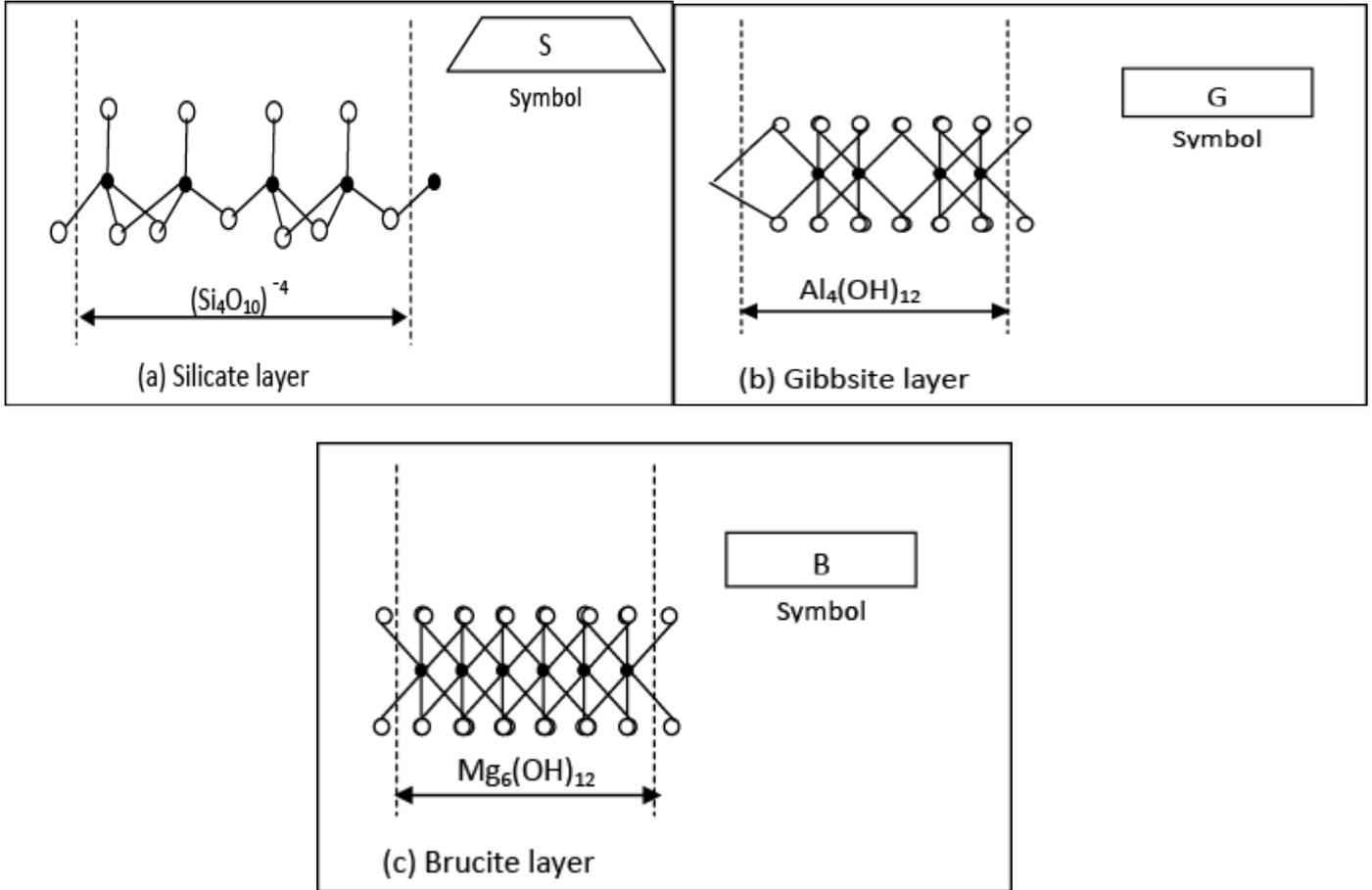


Fig. 2.2 Basic layer of mineral formation (modified from Mitchell and Soga 2005)

- ❖ It can be noted from the Fig. 2.1 that metallic positive ion is surrounded by non-metallic outer ions.
- ❖ Fig. 2.2 shows the formation of basic layer from basic units indicated in Fig. 2.1. There are 3 layers formed such as (a) silicate layer, (b) gibbsite layer and (c) brucite layer.
- ❖ Gibbsite layer is otherwise termed as dioctahedral structure in which two-third of central portion is occupied by  $Al^{+3}$ .
- ❖ Similarly, brucite layer is termed as trioctahedral structure in which entire central portion is occupied by  $Mg^{+2}$ .
- ❖ These basic layers stack together to form basic clay mineral structure. Accordingly, there is two and three layer configuration as indicated in Fig. 2.3. More than hundreds of these fundamental layer join together to form a single clay mineral.

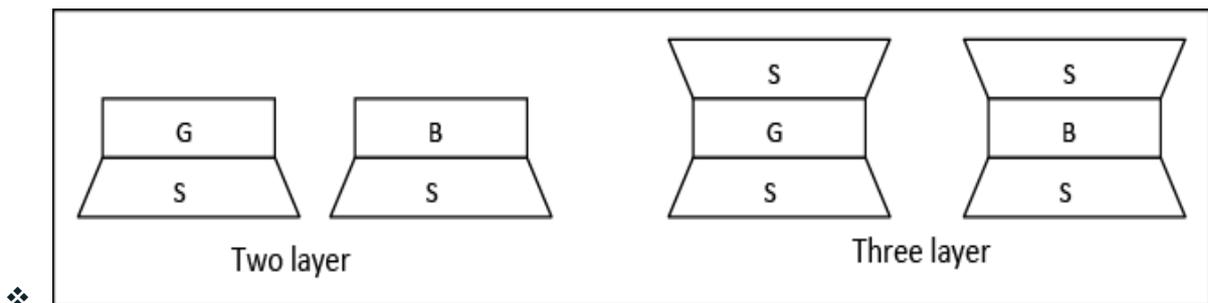
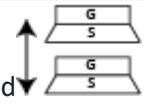
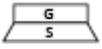
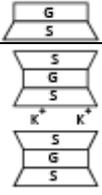
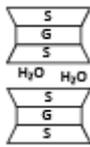
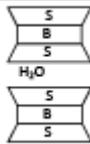


Fig. 2.3 Fundamental layers of clay minerals (modified from Mitchell and Soga 2005)

Some of the important and common clay minerals are described below in Table 2.1.

**Table 2.1 Summary of important clay minerals**

Mineral	Origin	Symbol	Bond	Shape	Remark
Kaolinite	Orthoclase Feldspar (Granite rocks)		Strong hydrogen bond	Flaky and platy	Approximately 100 layers in a regular structure $d = 7.2 \text{ \AA}$
Halloysite (Kaolinite group)	Feldspar Tropical soil	 H <sub>2</sub> O	Less strong bond	Tubular or rod like structure	At 60°C it loses water and alters soil properties
Illite	Degradation of mica under marine condition Feldspar		K <sup>+</sup> provides bond between adjacent layers	Thin and small flaky material	Bond is weaker than kaolinite $d = 10 \text{ \AA}$ High stability
Montmorillonite (Smectite group)	Weathering of plagioclase		H <sub>2</sub> O molecules push apart mineral structure causing swelling Presence of cations	Very small platy or flaky particle	Exhibits high shrinkage and swelling Weak bond $d > 10 \text{ \AA}$
Vermiculite	Weathering of biotite and chlorite		Presence of H <sub>2</sub> O and Mg <sup>+2</sup> predominantly Mg <sup>+2</sup>	Platy or flaky particle	Shrinkage and swelling less than montmorillonite

- ❖ Kaolinite formation is favoured when there is abundance of alumina and silica is scarce.
- ❖ The favourable condition for kaolinite formation is low electrolyte content, low pH and removal of ions that flocculate silica (such as Mg, Ca and Fe) by leaching. Therefore, there is higher probability of kaolinite formation in those regions with heavy rainfall that facilitate leaching of above cations.
- ❖ Similarly halloysite is formed due to the leaching of feldspar by H<sub>2</sub>SO<sub>4</sub> produced by the oxidation of pyrite. Halloysite formations mostly occur in high-rain volcanic areas.
- ❖ Smectite group of mineral formation are favoured by high silica availability, high pH, high electrolyte content, presence of more Mg<sup>+2</sup> and Ca<sup>+2</sup> than Na<sup>+</sup> and K<sup>+</sup>. The formation is supported by less rainfall and leaching, and where evaporation is high (such as in arid regions).
- ❖ For illite formation, potassium is essential in addition to the favourable conditions of smectite.

**Important Properties Of Clay Minerals**

**High Surface Area**

- ❖ Specific surface area (SSA) is defined as the surface area of soil particles per unit mass (or volume) of dry soil. Its unit is in m<sup>2</sup>/g or m<sup>2</sup>/m<sup>3</sup>.
- ❖ Clay minerals are characterized by high specific surface area (SSA) as listed in Table 2.2.
- ❖ High specific surface area is associated with high soil-water-contaminant interaction, which indicates high reactivity.

- ❖ The reactivity increases in the order Kaolinite < Illite < Montmorillonite.
- ❖ For the purpose of comparison, SSA of silt and sand has also been added in the table. There is a broad range of SSA values of soils, the maximum being for montmorillonite and minimum for sand. As particle size increases SSA decreases.

**Table 2.2 Typical values of SSA for soils (modified from Mitchell and Soga 2005)**

Soil	SSA (m <sup>2</sup> /g)
Kaolinite	10-30
Illite	50-100
Montmorillonite	200-800
Vermiculite	20-400
Silt	0.04-1
Sand	0.001-0.04

- ❖ For smectite type minerals such as montmorillonite, the primary external surface area amounts to 50 to 120 m<sup>2</sup>/g. SSA inclusive of both primary and secondary surface area (interlayer surface area exposed due to expanding lattice) and termed as total surface area would be close to 800 m<sup>2</sup>/g.
- ❖ For kaolinite type minerals there is possibility of external surface area where in the interlayer surface area does not contribute much. There are different methods available for determination of external or total specific surface area of soils (Cerato and Lutenegeger 2002, Arnepalli et al. 2008).

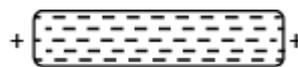
**Plasticity And Cohesion**

Clay attracts dipolar water towards its surface by adsorption. This induces plasticity in clay. Therefore, plasticity increases with SSA. Water in clays exhibits negative pressure due to which two particles are held close to each other. Due to this, apparent cohesion is developed in clays.

**Surface Charge And Adsorption**

Reasons for clay surface charge (i) Isomorphous substitution (Mitchell and Soga 2005):

- ❖ During the formation of mineral, the normally found cation is replaced by another due to its abundant availability, e.g. when Al<sup>+3</sup> replace Si<sup>+4</sup> there is a shortage of one positive charge, which appears as negative charge on clay surface. Such substitution is therefore the major reason for net negative charge on clay particle surface.
- ❖ Dissociation of hydroxyl ions or broken bonds at the edges is also responsible for unsatisfied negative or positive charge.
- ❖ Positive charge can occur on the edges of kaolinite plates due to acceptance of H<sup>+</sup> in the acid pH range (Berkowitz et al. 2008). It can be negatively charged under high pH environment.
- ❖ Absence of cations from the crystal lattice also contributes to charge formation.
- ❖ In general, clay particle surface are negatively charged and its edges are positively charged.



Typical charged clay surface

- ❖ Due to the surface charge, it would adsorb or attract cations (+ve charged) and dipolar molecules like water towards it. As a result, a layer of adsorbed water exists adjacent to clay surface.

**Exchangeable Cations And Cation Exchange Capacity**

- ❖ Due to negative charge, clay surface attracts cations towards it to make the charge neutral. These cations can be replaced by easily available ions present in the pore solution, and are termed as exchangeable ions.
- ❖ The total quantity of exchangeable cations is termed as cation exchange capacity, expressed in milliequivalents per 100 g of dry clay.

- ❖ Cation exchange capacity (CEC) is defined as the unbalanced negative charge existing on the clay surface.
- ❖ Kaolinite exhibits very low cation exchange capacity (CEC) as compared to montmorillonite.
- ❖ Determination of CEC is done after removing all excess soluble salts from the soil. The adsorbed cations are then replaced by a known cation species and the quantity of known cation required to saturate the exchange sites is determined analytically.

### Flocculation And Dispersion

- ❖ When two clay particles come closer to each other it experiences (a) interparticle attraction due to weak van-der-Waal's force (b) repulsion due to -ve charge.
- ❖ When particles are sufficiently close, attraction becomes dominant active force and hence there is an edge to face configuration for clay particles as shown in Fig. 2.4a. Such a configuration is termed as flocculant structure.
- ❖ When the separation between clay particles increase, repulsion becomes predominant and hence the clay particles follows face to face configuration called dispersed structure (Fig. 2.4b).
- ❖ A lot of micro and macro level behaviour of clays are associated with these arrangement of clay particles (Mitchell and Soga 2005).

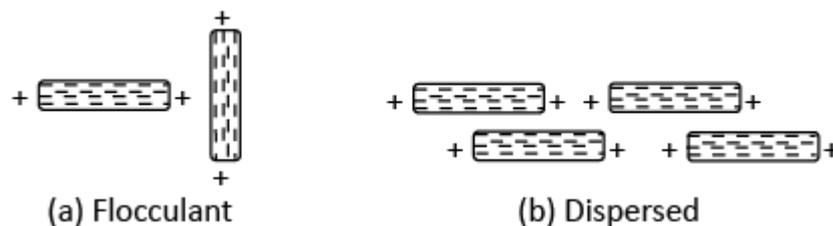


Fig. 2.4 Different arrangement of clay particle

### Swelling and shrinkage

- ❖ Some clay minerals when exposed to moisture are subjected to excessive swelling and during drying undergo excessive shrinkage.
- ❖ A lot of engineering properties of soil is affected by this behaviour and the stability of structures founded on such soils become detrimental.
- ❖ The swelling of clay minerals decreases in the order montmorillonite > illite > kaolinite.

### Minerals Other Than Silica And Clay

- ❖ Other than silica and clay, subsurface contains a variety of minerals such as oxides and carbonates that governs the reactivity of soil and its interaction with the environment.
- ❖ Some of the abundant metal oxide minerals present are iron oxides (hematite, magnetite, goethite etc.) and aluminium oxides (gibbsite, boehmite).
- ❖ Other oxide minerals (such as manganese oxide, titanium oxide) are far less than Fe and Al oxides, but because of small size and large surface area, they would affect very significantly the geochemical properties of subsurface.
- ❖ These oxides are mostly present in residual soils of tropical regions.
- ❖ Other major components include soluble calcium carbonate and calcium sulphate, which has relatively high surface area. In most soils, quartz is the most abundant mineral, with small amount of feldspar and mica present. Carbonate minerals such as calcite and dolomite are found in some soils in the form of bulky particles, precipitates etc. Sulphate minerals mainly gypsum are found in semiarid and arid regions.

The soil-water and soil-water-contaminant interaction and hence reactivity is greatly influenced by the mineralogy.

### Soil-Water-Contaminant Interaction

- ❖ Under normal conditions, water molecules are strongly adsorbed on soil particle surface.
- ❖ Unbalanced force fields are generated at the interface of soil-water which increases soil-water interaction.
- ❖ When particles are finer, magnitude of these forces are larger than weight of these particles.
- ❖ This is mainly attributed to low weight and high surface area of fine particles.

### Forces Between Soil Solids

- ❖ There are essentially two type of bonding: (1) Electrostatic or primary valence bond and (2) Secondary valence bond.
- ❖ Atoms bonding to atoms forming molecules are termed as primary valence bond. These are intra-molecular bonds.
- ❖ When atoms in one molecule bond to atoms in another molecule (intermolecular bond), secondary valence bonds are formed. What is more important in terms of soil solids is the secondary valence bonds.
- ❖ van der Waals force and hydrogen bonds are the two important secondary valence forces.
- ❖ Secondary valence force existing between molecules is attributed to electrical moments in the individual molecules.
- ❖ When the centre of action of positive charge coincide with negative charge, there is no dipole or electric moment for the system and is termed as non-polar. However, for a neutral molecule there can be cases where the centre of action of positive and negative charge does not coincide, resulting in an electric or dipole moment. The system is then termed as polar.
- ❖ For example: water is dipole. Also, unsymmetrical distribution of electrons in silicate crystals makes it polar.
- ❖ Non-polar molecules can become polar when placed in an electric field due to slight displacement of electrons and nuclei. This is induced effect and the extent to which this effect occurs in molecule determines its polarisability.
- ❖ van der Waals force is the force of attraction between all atoms and molecules of matter. This force comes into effect when the particles are sufficiently close to each other.
- ❖ Hydrogen bond is formed when a hydrogen atom is strongly attracted by two other atoms,
- ❖ for example: water molecules. This bond is stronger than van der Waals force of attraction and cannot be broken under stresses that are normally experienced in soil mechanics.
- ❖ These secondary valence bonds play a vital role in understanding soil-water interactions. Essentially, the forces dealt in soil mechanics may be grouped as gravitational forces and surface forces.
- ❖ From classical soil mechanics perspective, gravitational forces which are proportional to mass are more important.
- ❖ In geoenvironmental engineering surface forces are important. Surface forces are classified as attractive and repulsive forces. Attractive forces include (a) Van der Waals London forces (b) hydrogen bond (c) cation linkage (d) dipole cation linkage (e) water dipole linkage and (f) ionic bond.
- ❖ van der Waals London force is the most important in soils and becomes active when soil particles are sufficiently close to each other.
- ❖ For example, fine soil particles adhere to each other when dry. Cation linkage acts between two negatively charged particles as in the case of illite mineral structure.

### Soil-Water Interaction

- ❖ Water present in pore spaces of soil is termed as soil water or pore water. The quantity of water present in the pores will significantly influence its physical, chemical and engineering properties.
- ❖ It can be classified as (a) free water or gravitational water and (b) held water or environmental water.

- ❖ As the name suggests, free water flows freely under gravity under some hydraulic gradient and are free from the surface forces exerted by the soil particle. This water can be removed by laboratory oven drying procedure.
- ❖ Environmental water is held under the influence of surface forces such as electrochemical forces or other physical forces.
- ❖ Both type of water are important in geoenvironmental engineering. There are many cases like seepage and infiltration problems whose solution necessitates the knowledge of free water.
- ❖ However, these concepts are discussed in detail in classical soil mechanics text books.
- ❖ The mechanism of soil-held water interaction is complex and influenced by soil type, mineralogy, current and past environmental conditions, stress history etc.
- ❖ Held water can be further subdivided into structural water, adsorbed water and capillary water. Structural water is present within the crystal structure of mineral. This water is not very important as far engineering property of soil is concerned. For finding solution to several problems in geoenvironmental engineering, it is essential to understand in detail adsorbed water and capillary water.

### **Different Soil-Water-Contaminant Interaction Mechanisms**

- ❖ The contaminant that can pose serious threat to humans persist in short or long interval of time.
- ❖ These contaminants can be naturally occurring ones such as arsenic, fluoride, traces of mercury or anthropogenic substances such as chlorinated organics, dissolved heavy metals etc.
- ❖ The major role of a geoenvironmental engineer is to predict the fate of contaminants in the subsurface and minimize its migration towards groundwater.
- ❖ Fate prediction is very essential to understand the presence of contaminants in groundwater sources or subsurface for long term (50 to 200 years).
- ❖ This would essentially depend on different interaction mechanisms between contaminant and soil solids and also between contaminant and dissolved solutes present in pore water.
- ❖ This knowledge is required to assess the risk or threat posed by these contaminants to humans and other organisms. Fate of contaminant in geoenvironment is decided by retention and transport of contaminants.
- ❖ The important mechanisms governing these factors are as follows (Yong 2001):

#### **(A) Chemical Mass Transfer And Attenuation**

- (a) Sorption- contaminant partitioning
- (b) Dissolution/ precipitation- addition or removal of contaminants
- (c) Acid-base reaction- proton transfer
- (d) Redox reaction- electron transfer
- (e) Hydrolysis/ substitution/ complexation/ speciation- ligand-cation complexes.

#### **(B) Mass Transport**

- (a) Advection- fluid flow
- (b) Diffusion- molecular migration(c) Dispersion- mixing

#### **(C) Other Factors**

- (a) Biological transformations
- (b) Radioactive decay
- An adequate knowledge of these mechanisms is required to predict the fate of contaminant.

- When the contaminated pore fluid passes through the soil mass, it is bound to undergo weak or strong reactions.
- Sorption process in which the contaminants clings on to the soil solids is one of the predominant reactions. Such reactions does not ensure permanent removal of contaminants from the pore fluid, rather attenuation takes place.
- Attenuation is the reduction in contaminant concentration during fluid transport due to retardation, retention and dilution. The extent of interaction between the contaminants and soil fraction determines reversible or irreversible nature of contaminant partitioning.
- The term retention is used for strong sorption of contaminants on the soil particles such that the concentration of pore fluid decreases with time.
- The amount of contaminant concentration reaching a particular target is considerably less than the source concentration. Chemical mass transfer and irreversible sorption removes the contaminants from the moving pore fluid.
- This is a very important aspect for a contaminant barrier system, where in the contaminants reaching ground water is minimized.
- Retardation is mainly governed by reversible sorption and hence release of contaminant would eventually occur. This will ensure the delivery of the entire contaminant load to the final target (example ground water), but with much delay.
- In nature, the effect of contaminated pore fluid is reduced when it interacts with fresh water (especially during precipitation). This process of dilution also delays the contaminant migration. However, the process of dilution is mostly independent of soil interaction.
- The process of retention and retardation is depicted in Fig. 2.5. From the figure, it can be noted that for retention process, the area under the curves (concentration) goes on reducing. For retardation, the area remains constant (mass conservation), however the concentration of a particular contaminant reduces.

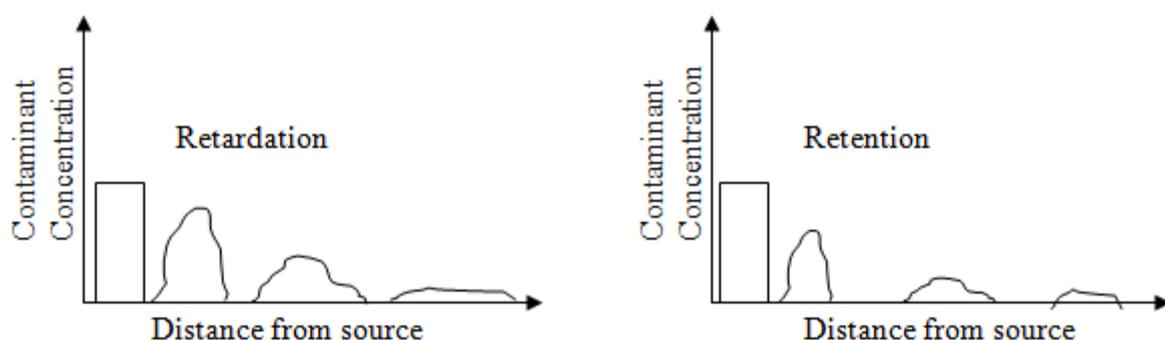


Fig. 2.5 Attenuation Process Due To Soil-Contaminant Interaction

For an effective waste management, retention process is more ideal than retardation. For proper prediction of contaminant fate, it is very essential to know whether the contaminant is retained or retarded.

The important reactions determining attenuation are discussed as follows:

### 1) Hydrolysis

Hydrolysis is the reaction of  $H^+$  and  $OH^-$  ions of water with the solutes and elements present in the pore water. Such a reaction would continue only if the reaction products are removed from the system. Water is amphiprotic in nature (Yong 2001), which means it can act as acid or base. According to Bronsted-Lowry concept an acid is a proton donor and base is a proton acceptor. According to Lewis, acid is an electron acceptor and base is an electron donor. As discussed earlier, soil minerals have ionized cations and anions (metal ions) attached to it that results in a particular pH level in soil-water system. Hydrolysis reaction of metal ions can be represented as



The reaction increases with decrease in pH, redox potential and organic content and increases with temperature. Hydrolysis can be an important reaction in the process of biodegradation

### 2) Oxidation-Reduction (Redox) Reaction

Oxidation-reduction (redox) reaction involves transfer of electrons between the reactants. In general, transfer of electrons is followed by the proton transfer also. Soil pore water provides medium for oxidation-reduction reaction which can be biotic and/or abiotic. Microorganisms present in the soil utilize oxidation-reduction (redox) reactions as a means to derive energy required for its growth. Hence, these microorganisms act as catalysts for reactions (redox) involving molecular oxygen, soil organic matter and organic chemicals. For inorganic solutes, redox reaction results in the decrease or increase in the oxidation state of the atom. This is important because some ions have multiple oxidation states and hence would influence the soil-contaminant interaction. It is found that biotic redox reactions are more significant than abiotic redox reaction.

### 3) Complexation

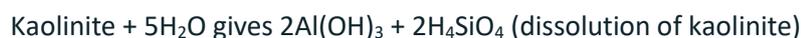
Complexation is the reaction between metallic cations and anions called ligands. The inorganic ligands such as  $Cl^-$ ,  $B^-$ ,  $F^-$ ,  $SO_4^{2-}$ ,  $PO_4^{3-}$ ,  $CO_3^{2-}$  and organic ligands such as amino acids take part in complexation reaction. For example,



Complexation can also occur in series, such that complex formed from one reaction can react with another ligand.

### 4) Precipitation and dissolution

The process of precipitation and dissolution is an important mass transfer mechanism in the subsurface, where in dissolution increases and precipitation decreases the concentration of contaminants in pore water. Water is a good solvent for a variety of solids, liquids and gases. Dissolution is the process of complete solubility of an element in groundwater. Some natural minerals also undergo dissolution. For example,



Precipitation is reverse process of dissolution where in dissolved element comes out of the solution due to the reaction with dissolved species. Due to precipitation, the concentration of the element reduces in pore water. For example, Lead gets precipitated from pore water due to its reaction with sulfides, carbonates or chlorides. Iron, zinc and copper precipitates due to hydrolysis reaction, and chromium, arsenic precipitates due to redox reaction.

### 5) Exsolution And Volatilization

This process involves mass transfer between gaseous and liquid or solid phase. Similar to precipitation this process removes mass from pore fluid to gaseous phase. This process is mostly governed by the vapour pressure (pressure of gaseous phase) with respect to liquid or solid at a particular temperature. There are a lot of volatile contaminants disposed into subsurface that finds its way to atmosphere. A thorough knowledge on the exsolution and volatilization is required to understand the mass transfer mechanism of these organic contaminants.

### **6) Radioactive Decay**

In this process, unstable isotopes decay to form new ones with release of heat and particles from element nucleus. The process is known as  $\alpha$  or  $\beta$  decay depending on whether the element loses  $\alpha$  particle (helium) or a  $\beta$  particle (electron). The process of decay is irreversible and daughter isotope increases in quantity. The disposal of radioactive waste generated from nuclear installations, mining etc. to subsurface will considerably increase the heat. Moreover, the radioactive isotope such as uranium, plutonium, cesium etc gets transported to far field and would pollute the groundwater. Preventing such harmful pollution and reducing the ill effect of overheating of subsurface is a challenging geoenvironmental problem.

### **7) Sorption And Partitioning**

When contaminant laden pore water flow past the soil surface, mass transfer of these contaminants takes place on to the solids. The process is referred to as sorption or partitioning. The amount of partitioning depends on the soil surface (sorbent) and the reactivity of contaminant (sorbate). This is one of the predominant mechanisms governing the fate of contaminant once it is released into the geoenvironment. The term sorption refers to the adsorption of dissolved ions, molecules or compounds on to the soil surface. The mechanism of sorption includes physical and chemical sorption as well as precipitation reaction. These reactions are governed by surface properties of soil, chemistry of contaminant and pore water, redox potential and pH of the environment. Physical adsorption refers to the attraction of contaminant on to the soil surface mainly due to the surface charge (electrostatic force of attraction). Physical sorption is weak bonding and can be reversed easily by washing with extracting solution. Chemical sorption is strong force of attraction due to the formation of bonds such as covalent bond. High adsorption energy is associated with chemical sorption and it can be either exothermic or endothermic reaction.

### **8) Biological Transformation**

Biological transformation is the degradation or assimilation of contaminants (mostly organic) by microorganisms present in the soil. Transformations from biotic processes occur under aerobic or anaerobic conditions. The transformation products obtained from each will be different. The biotic transformation processes under aerobic conditions are oxidation reaction. The various processes include hydroxylation, epoxidation, and substitution of OH groups on molecules (Yong 2001). Anaerobic biotic transformation processes are mostly reduction reaction, which include hydrogenolysis,  $H^+$  substitution for  $Cl^-$  on molecules, and dihaloelimination (Yong 2001).

**Evolution Of Waste Containment And Disposal Practices**

- ❖ Increased events of environmental pollution and its realization have led to the evolution of planned and engineered waste management facilities.
- ❖ The waste management essentially comprises of collection, transport, disposal and/or incineration of wastes.
- ❖ A sustainable waste management is founded on 3 R's, namely Reduce, Reuse and Recycle so that the quantity of waste to be disposed on land is considerably reduced.
- ❖ For better clarity, the waste management hierarchy is presented in Fig. 3.1.
- ❖ The major focus is to reduce the quantity of waste production by efficient process control, try to reuse the by-products or waste products from a process, and try to recycle the left out waste products by value added transformation.



**Fig. 3.1 Waste management hierarchy (Modified from Munier 2004)**

- ❖ Some of the major challenges faced in the implementation of an efficient waste management scheme are the non-awareness of public and the need for systematic functioning of various divisions like collection, transportation, disposal and site management.
- ❖ The concept of waste management started in 1800 century. However, the need for an integrated solid waste management program (ISWMP) has been realized in late 1980s.
- ❖ The main aim of ISWMP is to optimize all aspects of solid waste management to achieve maximum environmental benefits cost-effectively. It essentially consists of :-

1. Waste source identification and characterization.
2. Efficient waste collection
3. Reduction of volume and toxicity of waste to be discarded.
4. Land disposal and/or incineration.
5. Optimization of first four steps to reduce cost and environmental impact.

❖ The wastes which are produced include non-hazardous municipal solid waste, construction and demolition waste, partially hazardous medical wastes, agricultural waste, highly hazardous industrial and nuclear waste. The philosophy of handling hazardous and non-hazardous waste varies a lot.

❖ When the wastes are disposed on to the land, the percolating rainwater interacts with it and produces liquid known as leachate (contaminated liquid that comes out of the waste matrix).

❖ In the due course of time, the leachate percolates through the soil and reaches the groundwater and moves along with it as shown in Fig. 3.2.

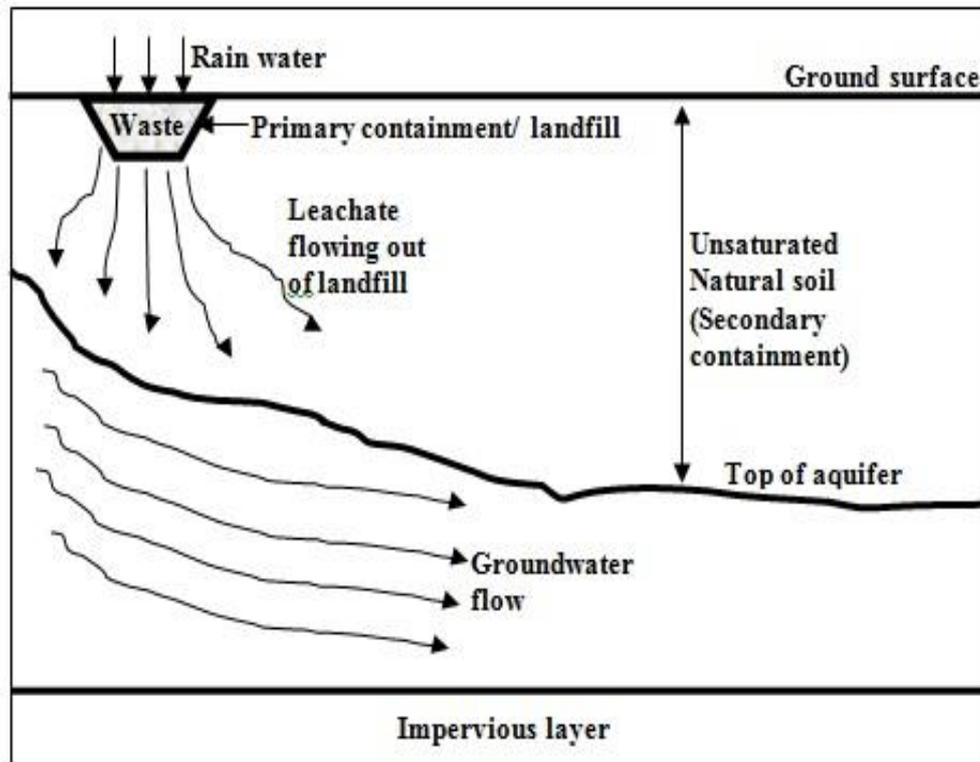


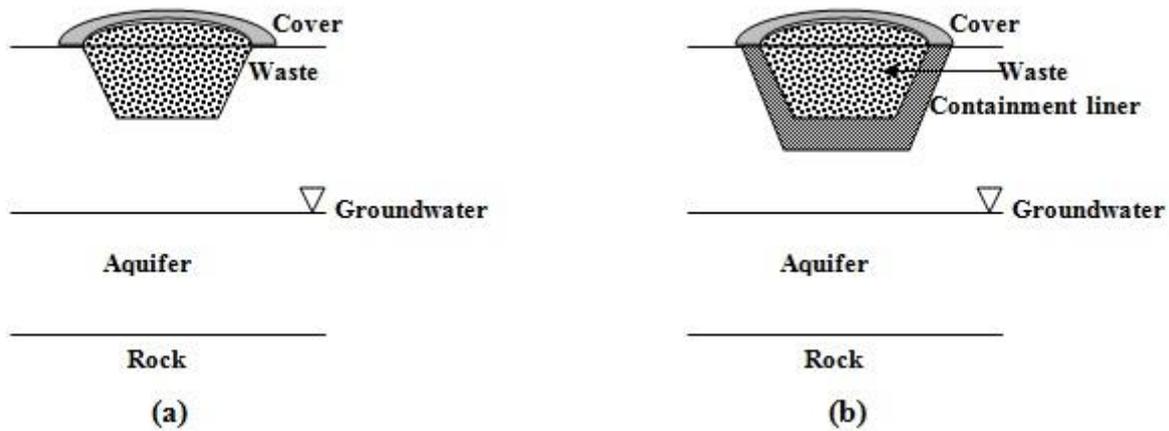
Fig. 3.2 A conceptual waste disposal facility on a global scale

- ❖ In the past, it was presumed that leachate generated from waste dumped directly on natural soil is completely attenuated (purified) by the subsurface before it reaches or interacts with ground water.
- ❖ In the figure, subsurface is the unsaturated natural soil which provides an indirect containment of harmful contaminants leaching out.
- ❖ In view of the above, all forms of non-engineered land disposal such as gravel pits were acceptable.
- ❖ Since, 1950 onwards there were considerable increase in the ground water pollution. The cause for such pollution was traced back to such indiscriminate casual waste disposals.
- ❖ This gave way to the development of engineered waste disposal facilities known as landfills.
- ❖ The properties of soils used for the construction of landfills and the natural soil beneath the landfill become very important. So, major emphasis is laid on understanding the concepts of landfill and the role of soil in minimizing the harmful pollution of geoenvironment and ground water.

### 3.1 Landfills

- ❖ There are two types of landfills namely natural attenuation landfill and containment landfill as depicted in Fig. 3.3.
- ❖ Natural attenuation landfill is similar to what has been discussed earlier where there is no provision below the wastes to minimize the migration of harmful contaminants. The unsaturated subsurface below the wastes naturally attenuate harmful contaminants before it reaches ground water. It is presumed that the contaminants reaching ground water will be well within the permissible limit, even though in most of the cases it would not be. For the same reason, these types of landfills are not preferred in spite of its simplicity.
- ❖ In the containment landfill, there is an engineered layer of soil known as liner on which the waste is disposed or dumped. Soil liners are constructed with some desirable properties meeting the regulations set by the pollution control board.

- ❖ The design of these liners is done in such a way that the contaminants leaching out seeps at a very low pace and gets attenuated.
- ❖ The concentration of contaminants reaching the ground water within the prescribed design life is expected to be well within the permissible limit. This type of landfill is mandatory for containing hazardous wastes such as industrial and nuclear wastes. All the working elements of such landfills are properly designed.



**Fig. 3.3 Conceptual depiction of types of landfill (a) Natural attenuation (b) Containment**

**3.2 Engineered Landfills**

- ❖ The first and foremost task in the planning of engineered landfills is its site selection.
- ❖ There are several socio-economic concerns which need to be satisfied before a site can be decided for waste disposal.
- ❖ The major concern is social since nobody likes wastes to be dumped in their neighborhood. This would necessitate mass education and awareness program on the pros and cons of the waste management project.
- ❖ Apart from public acceptance the other factors which are important in site selection are locational, geotechnical and hydrogeological criteria.
- ❖ Another important aspect in landfill site selection is establishing search radius, which is the maximum distance of waste hauling (transport). Waste hauling is one of the costliest items in landfill operations.
- ❖ Three important steps of landfill site selection are
  1. Data collection
  2. Locational criterion
  3. Obtaining public reaction and acceptance

**a) Data collection:** The data pertained to landfill site selection are summarized as follows:

**i) Topographic maps:** This include information on contour, natural surface, water drainage, location of streams, wetlands etc. Ideally landfills should be avoided on land contributing to groundwater recharge. The surface flow should be in such a way that water flow away from the landfill site. In case the flow is towards the landfill then adequate measure has to be taken to prevent excessive water seeping into the landfill.

**ii) Soil Maps:** Gives information on the type of soil available at a particular place. This information is important before going for an in depth subsurface investigation. A high permeable soil strata is normally avoided for landfills.

**iii) Land Use Maps:** These maps are very important as it gives the land value and its importance. There will be some zoning restriction for some lands laid down by the government, which can be assessed based on land use maps. For example, landfills should be located away from the flood plain.

**iv) Transportation:** The data on transportation would include the present network and the futuristic development. It is very essential that the landfill site is easily accessible and waste hauling is optimal. At the same time, the site should be away from important facilities like airport. It is essential to consider road and rail network details before site selection.

**V) Waste Type And Volume:** The primary question is whether the waste is hazardous or not.

- ❖ The philosophy of waste containment changes depending on whether it is municipal or industrial waste. Stringent specifications need to be followed for industrial waste and in no case the waste can be dumped in open pits.
- ❖ Around 50% of the total waste comes from domestic municipal sources. A waste generation rate of 0.9-1.8 kg/person/day is a reasonable estimate for determining municipal waste volume. The population and its growth during the active life of landfill need to be computed.
- ❖ Waste volume per year = population per year x waste generation rate.

❖ The landfill volume is the sum of daily, intermittent and final cover volume and waste volume. Waste: daily cover ratio of 4:1 is needed if soil is used as the cover.

**B) Locational Criterion:** Following are some of the important points to be followed while deciding location for waste containment.

**Lake Or Pond:** Away by 300m. The distance can be reduced for engineered waste containment. Surface water need to be monitored continuously for pollution in future.

**River:** Away by 100 m.

**Highway and public park:** Away by 300 m.

**Airport:** Away by 3 km to avoid bird menace.

**Water supply well:** Away by 400 m.

Crowded habitat, wetland, unstable area to be avoided.

The geology of the place should be suitable with no faults and folds. Maximum horizontal acceleration for the site caused by earthquake should not exceed 0.1g in 250 years.

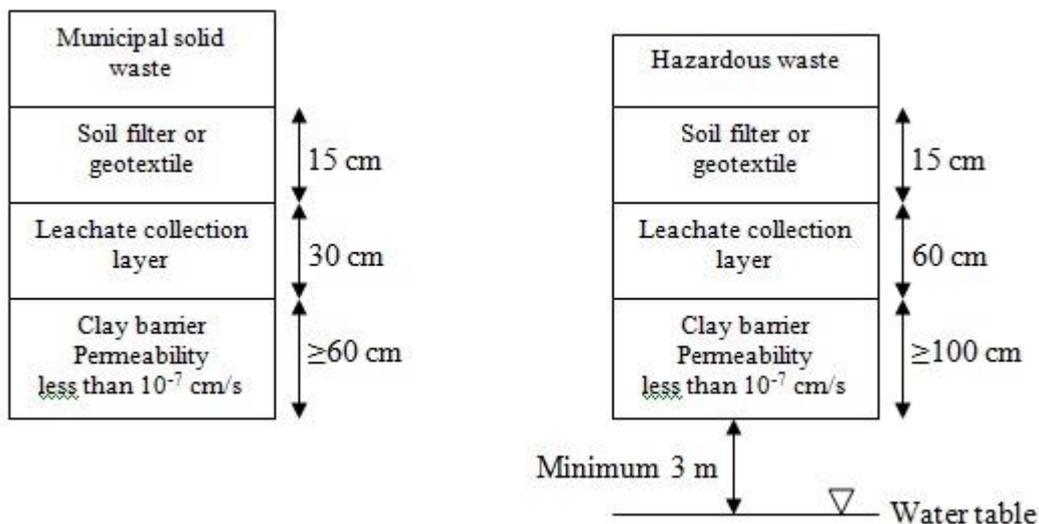
**C) Preliminary Assessment Of Public Reaction:**

- ❖ Public education on the short term and long term advantages of the facility should be carried out extensively.
- ❖ Not in my backyard (NIMBY) sentiment can prevent the execution of landfill.
- ❖ Some of the major concerns are noise, odour, increase in traffic volume, reduction in property value, fear of groundwater contamination etc.
- ❖ The public needs to be assured that the above mentioned concerns would be tackled efficiently. This is one of the challenging issues for geoenvironmental engineers and municipal authorities in the planning and execution of such projects.

**3. 3 Engineered Containment Landfills**

❖ The engineered landfill includes designed man made barrier layers for minimizing the migration of harmful contaminants from the place of disposal to the groundwater.

❖ The provisions in engineered landfill depends upon the type of waste received. For example, comparison of a typical MSW landfill and hazardous landfill is shown in Fig. 3.4

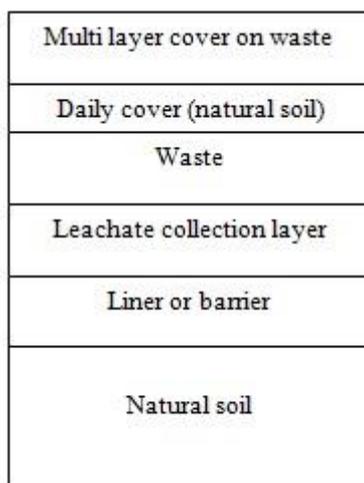


**Fig. 3.4 A typical engineered landfill provision**

**Major Role Of Soil In Engineered Landfill**

- ❖ As indicated in Fig. 3.5, the major role of soil in an engineered landfill can be summarized as follows:
  1. Compacted liner or barrier which minimize the migration of contaminant to groundwater and hence it is the most integral and important part of a landfill. The reduction in migration is due to low permeability and contaminant retention capacity of the clayey soil used in liners.
  2. Leachate collection system provided below the waste to collect the leachate and effectively drain to a collection source for further treatment.
  3. After the service life of the landfill, an integrated multi layer cover system is provided on top of the waste to isolate it from the environment and minimize the generation of post closure leachate.
  4. Natural soil is used as daily cover material for waste during the operational phase of landfill.

5. The unsaturated natural soil below the liner act as an additional buffer layer in reducing the migration of contaminants to groundwater.
6. In addition, suitable geosynthetics, geotextiles, geomembrane, geonets etc. are used individually or in combination with soil to act as liner, drainage layer, filtration layer or separation layer. The use of geosynthetic helps to reduce the thickness of liner layer.



**Fig. 3.5 Role of soil in an engineered landfill**

1. Compacted liner or barrier which minimize the migration of contaminant to groundwater and hence it is the most integral and important part of a landfill. The reduction in migration is due to low permeability and contaminant retention capacity of the clayey soil used in liners.
2. Leachate collection system provided below the waste to collect the leachate and effectively drain to a collection source for further treatment.
3. After the service life of the landfill, an integrated multi layer cover system is provided on top of the waste to isolate it from the environment and minimize the generation of post closure leachate.
4. Natural soil is used as daily cover material for waste during the operational phase of landfill.
5. The unsaturated natural soil below the liner act as an additional buffer layer in reducing the migration of contaminants to groundwater.
6. In addition, suitable geosynthetics, geotextiles, geomembrane, geonets etc. are used individually or in combination with soil to act as liner, drainage layer, filtration layer or separation layer. The use of geosynthetic helps to reduce the thickness of liner layer.

**3.4 Compacted liner**

- ❖ Soil used for compacted liners include natural clays, glacial till, residual soil, shale, mud, bentonite etc.
- ❖ Natural or locally available soils with high clay content are preferred to commercial soil like bentonite due to cost effectiveness. In the absence of suitable natural soil, swelling clays like bentonite is mixed with locally available soil, fly ash, sand etc. to achieve the desired performance of liners.
- ❖ In recent years, geosynthetic materials have been used along with clays to enhance the performance of liners due to its low permeability.
- ❖ These are factory manufactured hydraulic and gas barriers typically consisting of bentonite clay or other low permeability clay materials sandwiched between synthetic materials such as geomembranes or geotextiles or both, which are held together by needling or chemical adhesives. The thickness of GCLs is much less than that of compacted clay liners.
- ❖ The main advantage in using geosynthetic materials are their ready availability, small volume consumption, better performance, durability, low cost and homogeneity as compared to soils. The simplest compacted liner is that of compacted clay liner (CCL), which is widely used as hydraulic barriers for water and waste containment.
- ❖ Other configurations of liners include single, multiple and composite layers and are used depending on the importance of the project and vulnerability of waste.
- ❖ The thickness of liner varies from 60 cm for an ordinary solid waste facility to approximately 300 cm for highly hazardous waste. It is reported that even for a homogenous liner, a thickness of less than 60 cm would result in a sharp increase of leakage through the liner (Kmet et. al., 1981).

- ❖ As the liner thickness is increased, the flow through the liner is significantly decreased. The trend of decreasing flow is observed until a thickness of 1.2 m to 1.8 m is reached. Beyond this, the decrease in flow with further increase in thickness is minimal (Benson et. al., 1999).
- ❖ As such, it is recommended that a minimum liner thickness of 1.2 m to 1.8 m be used to provide an effective flow barrier. This factor of safety is required to account construction errors and to compensate the difficulty of ensuring quality control for such a large aerial extent of liner.
- ❖ It is very important to assess the suitability of geomaterial for compacted liner construction. One of the universally accepted criteria to be satisfied by compacted liner is that the permeability (k) should be  $10^{-9}$  m/sec. Therefore, this requirement becomes the primary criterion for deciding the suitability of geomaterial as compacted liner.
- ❖ There are different other criteria available in the literature for assessing the suitability of material for liner construction based on soil properties such as unconfined compressive strength (UCS), index properties etc (Younus and Sreedeeep 2012 a, b). UCS not less than 200 kPa is desirable for liner material to account for the overburden placed above.
- ❖ In some cases plasticity characteristics are used for initial assessment of geomaterials. Clay with liquid limit less than 90%, plasticity index (PI) between 6% and 65% and clay content greater than 10% is found suitable for liners.
- ❖ However, these guidelines are qualitative and need to be ascertained with the permeability characteristics of compacted liner material.
- ❖ Daniel and Benson (1990) recommend that the soil liner materials should contain at least 30% of fines, where as other state regulatory agencies recommend at least 50% fines.
- ❖ Compaction is one of the most important factors that govern permeability of liners. Most of the liners are compacted with footed rollers, which are fully or partially penetrating the soil layer.
- ❖ The dry unit weight of compaction in the field should be 96-98 % of maximum dry unit weight established in the lab. Water content of the soil is normally 0 to 4% of OMC on wet of optimum. A broader range of compaction water content resulting in target permeability is desirable from workability point of view.
- ❖ Sufficient care is required to guard against desiccation of the compacted liner due to the loss of water content. Desiccation results in cracks and preferential pathways for liquid, thereby enhancing the permeability.
- ❖ The problem of desiccation can be alleviated by covering the liner by natural soil, using clayey sand with low shrinkage, specify the range of compaction water content and dry unit weight that ensures both low permeability and low shrinkage.

### **3.5 Methods For Landfill Site Selection**

- ❖ There are different qualitative and quantitative methods available for landfill site selection by assessing the extent of environmental impact caused by the project.
- ❖ Essentially the decision on landfill site is done based on subsurface and borrow source investigation.
- ❖ The subsurface investigation includes the assessment of hydrogeology of a place to understand permeability, strength, compressibility, contaminant interaction, presence of faults and folds, seismic hazard investigation etc.
- ❖ Borrow source investigation reveals the quality of material available near to the probable landfill site and its utility in landfill construction. If soil nearby is suitable, it would considerably reduce the cost of the project by minimizing transportation and material expenditure. Some of the qualitative and quantitative methods for landfill site selection are briefly discussed below.

**Qualitative Methods** for landfill site selection are used only for preliminary evaluation as discussed below:

**(A) Check List:** It is a simple list consisting of different criteria that are important for knowing potential impact due to a project on the environment. It includes factors related to environment, social and ecosystem considering its beneficial or adverse impact. For instance:

1. Population likely to be affected by project.
2. Soil, air, water.
3. Flora and fauna
4. Land use etc.

A descriptive check list gives list of impacts during the various stages of project which can be used as criteria for understanding environmental impact.

**(B) Network Analysis:** In this method, cause and effect relationship is detected by analyzing different areas likely to be affected by the project. A block diagram shown in Fig. 3.6 is used to show the connectivity between action and consequence. The connectivity is shown by solid arrow for direct consequence and broken for indirect consequence. It provides an effective and visual way to illustrate positive or adverse impacts of a project.

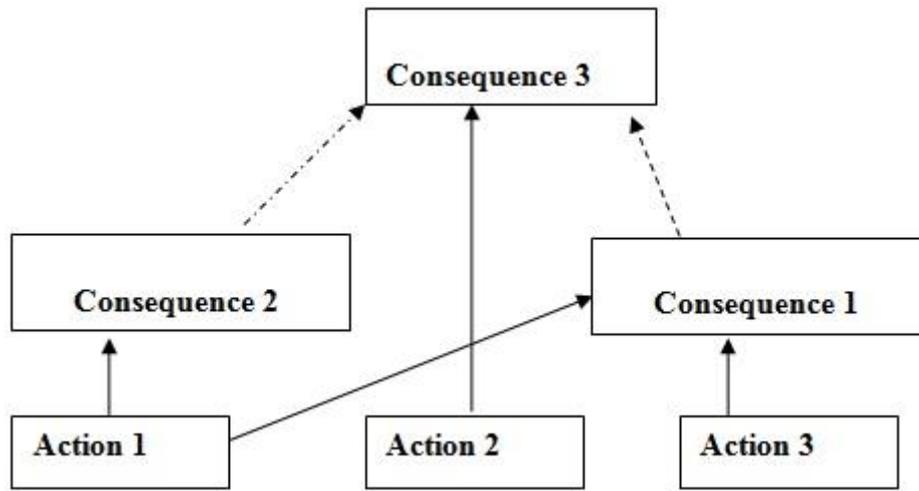


Fig 3.6 Network analysis block diagram (Munier, 2004)

Some of the **Quantitative Methods** for landfill site selection include the following:-

**(a) Matrix Method**

- ❖ This method relates activities of a project and its impact on the environment.
- ❖ An example problem of site selection for landfill is presented in Table 3.1. The table corresponds to the assessment of one of the alternative (Site 1). As listed in the table, an importance value is assigned to different environmental parameters.
- ❖ Further, the impact of different activities (denoted as A, B, C, D in table) on these environmental parameters is defined by assigning magnitude of impact, which can be negative or positive. A, B, C, D corresponds to activities like disposal of solid waste, reclamation, transportation etc.

Table 3.1 Details of matrix method

SITE-1					
Environmental Parameters	Importance Value	A	B	C	D
Air Quality	100				
Water Quality	95				
Health	90			3	
Land Use	85				
Human Settlement	80		-5		

- ❖ A matrix is formed by assigning importance values to the environmental parameters selected for the problem. Further a value is assigned in the matrix which shows the magnitude of impact (positive or negative depending upon the sign of magnitude) due to the activity on the environment. Importance values are multiplied with magnitude of impact and summation is done for rows as well as for columns. Best site is then decided based on the maximum summation value of row, column or both.

**(B) Multi-Criteria Analysis**

- ❖ In this method, best possible optimal criteria are selected for evaluation of sites.
- ❖ A total score of 1000 is apportioned among the assessment criteria based on their importance .
- ❖ There is no hard and fast rule for total score. A site sensitivity index (SSI) is developed for different attribute qualities on a scale of 0 to 1. Based on SSI, score for each parameter of various sites is computed.
- ❖ Ranking is done for the individual site alternatives based on summation of the score.

**3.6 Subsurface Investigation For Waste Management**

- ❖ Subsurface investigation for waste management is required for deciding the site for landfills and also for delineating the extent of contamination.
- ❖ Several hydrogeological parameters required for landfill site selection are obtained from subsurface investigation conducted for different potential sites.

- ❖ The methodology for subsurface investigation remains similar to any other geotechnical investigation (for example, open pit, bore holes).
- ❖ In addition, several geophysical methods such as electrical resistivity imaging, seismic refraction, ground penetration radar, etc. are used for defining the zone of contamination, establishing the depth of aquifer, and also to reduce the number of bore holes.

### **3.7 Design Of Landfills**

- ❖ An engineered landfill essentially consists of a barrier layer or liner which is a low permeable zone to prevent the leaching of waste from the landfill.
- ❖ Above the liner, a drainage layer is placed which collects the leachate from the waste for treatment. Such a layer also minimizes the head causing flow in liner due to the timely removal of leachate from the landfill.
- ❖ The third important layer is the cover to the landfill, which is a multi-layered system to cut off the harmful effect of waste on the atmosphere. The various aspects required for planning and design of landfill are as follows:
  1. Waste Characterization
  2. Assessment of leachate and gas generation
  3. Landfill elements to be provided
  4. Liner and cover materials
  5. Landfill design approach

#### **3.7.1 Waste Characterization:**

Waste characterization is important to understand the following:

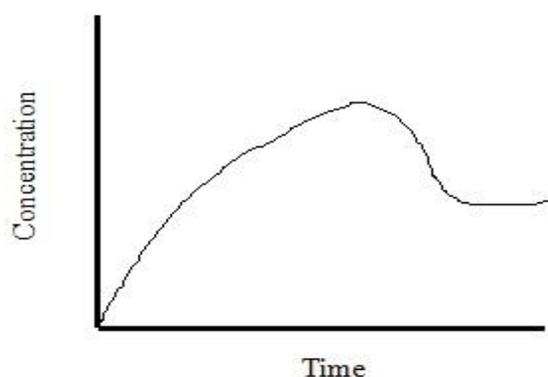
1. Physical and chemical tests are performed to evaluate whether waste is hazardous or non-hazardous.
2. Whether waste can be landfill directly or necessitate processing (reduction, recycling etc.) before disposal.
3. Approximate rate of waste volume generated.
4. Assessment of leachate quantity.
5. Assessment of leachate quality for judging liner compatibility, treatment plant design, ground water monitoring program design.
6. Safety precautions to be followed during landfill operations.
7. Identify waste reduction alternatives.

#### **3.7.2 Assessment Of Leachate And Gas Generation**

- ❖ Leachates are produced when water or other liquids percolates and interacts with waste.
- ❖ The information on quality and quantity of leachate and gas generated during active life and after closure are important for realistic and efficient design of a landfill. Leachate contains a lot of dissolved and suspended materials.
- ❖ Gases produced include CH<sub>4</sub>, CO<sub>2</sub>, NH<sub>3</sub> and H<sub>2</sub>S due to anaerobic decomposition of waste. These gases either escape to atmosphere or dissolve in water leading to further reactions.
- ❖ Contaminated liquids of high concentration are formed due to chemical reaction taking place within the waste. The percolating water increases the quantity of leachate but would help to dilute the concentration.

#### **Factors Influencing Leachate Quality**

- ❖ Refuse composition
- ❖ Elapsed time: Leachate quality (concentration) increases and reaches peak during the working period of landfill and then start decreasing with time as shown in Fig. 3.7. All the contaminants present in the leachate do not exhibit peak at the same time and may not be of same shape.



**Fig. 3.7 Variation of leachate quality (concentration) with elapsed time**

- ❖ Temperature: Temperature affects bacterial growth and chemical reactions, there by affecting leachate quality.
- ❖ Available moisture influences biodegradable and subsequent leaching of wastes.

- ❖ Available oxygen influences leachate quality due to the fact that chemicals released due to aerobic decomposition is different from anaerobic decomposition. Anaerobic condition would arise due to landfill cover or covering due to fresh waste.

**Factors Influencing Leachate Quantity**

- Amount of precipitation received.
- Ground water interaction when the landfill base is below groundwater table.
- Moisture content of waste increases biodegradation and increases leachate production. Such a scenario is mostly applicable in the case of municipal solid waste and due to sludge that are disposed.
- Final cover reduces leachate quantity due to low percolation through compacted covers. Also vegetation in the top soil of final cover reduces infiltration by increased evapotranspiration.

**Estimation Of Leachate Quantity**

- ❖ The quantity of leachate is directly dependent on precipitation received. Pre-closure and post-closure leachate generation from a landfill vary significantly.
- ❖ Pre-closure leachate generation rate is required for designing leachate collection pipes in the landfill, fixing the size of leachate collection tank and treatment plant.
- ❖ Post-closure leachate generation rate is required to plan the management of leachate and cost incurred for it. Leachate quantity considerably reduces after closure and construction of covers.

Leachate volume ( $L_v$ ) is given by Eq. 3.1.

$$L_v = P + S - E - AW \quad \text{-----} \quad 3.1$$

Where P is the precipitation volume, S is the volume of pore liquid squeezed from the waste, E is the volume lost by evaporation and AW is the volume of liquid lost through absorption in waste.

**Pore Squeeze Leachate Volume (S)**

- ❖ When sludge is disposed, liquid within the pores gets squeezed due to self-weight of sludge and weight of waste dump and cover soil.
- ❖ Such an action is similar to the consolidation process occurring in a saturated soil. Primary consolidation of waste accounts for the majority of pore squeeze leachate. The primary consolidation properties of sludge are used to predict leachate generation rate.
- ❖ Loss due to evaporation depends on ambient temperature, wind velocity difference in vapour pressure etc.
- ❖ Leachate absorbed in waste (AW) is depended on field capacity (FC) of waste. FC is the maximum moisture content that waste can retain against gravitational force without producing down ward flow. When the moisture content is within FC, the waste has the capacity to retain water without causing downward flow.

**Post Closure Leachate Generation Rate**

- ❖ Only water that can infiltrate through the final cover of the landfill percolates through the waste and generates post closure leachate.
- ❖ Water balance method expressed by Eq. 3.2 is a popular method for estimating post closure leachate generation.

$$L'_v = P - ET - R - S \quad \text{-----} \quad 3.2$$

Where  $L'_v$  is the volume of post closure leachate, P is the volume of precipitation, ET is the volume lost through evapotranspiration, R is the volume of runoff and S is the volume of moisture stored in soil and waste. Potential ET is obtained based on appropriate empirical equation.

$$R = C_r I A \quad \text{-----} \quad 3.3$$

Where  $C_r$  is the run off coefficient, I is the rainfall intensity and A is the area of landfill surface.

- ❖ Soil moisture storage (S): A portion of infiltrating water is stored by soil and only a part of this is used for vegetation. Soil moisture storage capacity is the difference between field capacity and wilting point.
- ❖ Wilting point is the moisture content at which plants cannot draw moisture and starts wilting. Normally, moisture content corresponding to 1500 kPa matric suction is taken as wilting point.
- ❖ Water balance method if not done properly results in large errors especially when used for long term leachate generations rate. The disadvantages of water balance method are:
  - it does not account permeability of cover layer
  - evapotranspiration is sometimes wrongly calculated due to over prediction of root length in vegetation layer. In reality root would not have penetrated entire thickness of vegetation layer.

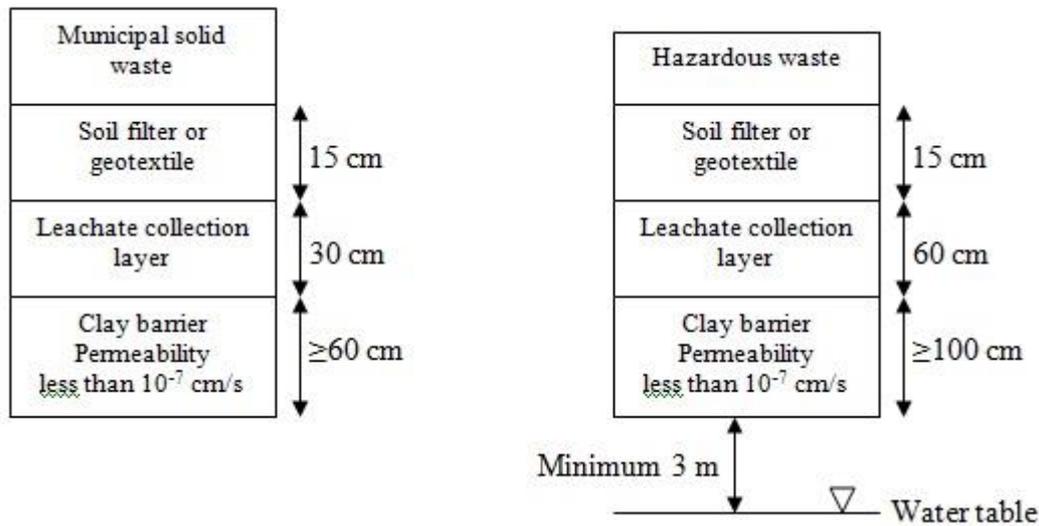
**3.7.3 Gas Generation Rate**

- ❖ Gas generation rate is mostly valid for municipal solid waste (MSW) landfill where organic matter decomposition results in the production of gases.
- ❖ Gas production in MSW landfill occurs due to anaerobic degradation resulting from hydrolysis and fermentation (attributed to bacterial activities), acetogenesis and dehydrogenation, and methanogenesis.

- ❖ Hydrogen gas is produced due to the oxidation of soluble products to organic acids.
  - ❖ Some of the other gases produced from MSW are methane, carbon dioxide, hydrogen sulphide and nitrogen.
  - ❖ Gas production reaches a stable rate and then decreases as biological activity in MSW landfill start decreasing.
- The assessment of time dependent percentage production of methane from a MSW landfill is important for recovering methane as an energy source, and thereby reducing greenhouse gas effect.

**3.7.4 Engineered Containment Landfills**

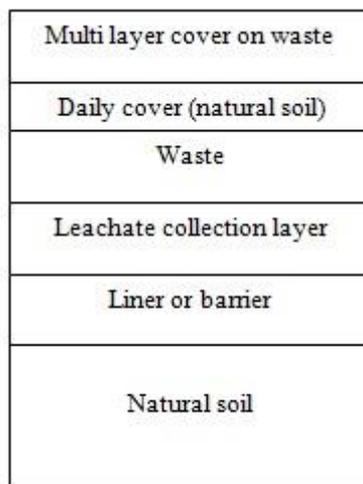
- ❖ The engineered landfill includes designed man made barrier layers for minimizing the migration of harmful contaminants from the place of disposal to the groundwater.
- ❖ The provisions in engineered landfill depends upon the type of waste is receives. For example, comparison of a typical MSW landfill and hazardous landfill is shown in Fig. 3.8.



**Fig. 3.8 A typical engineered landfill provision**

**Major Role Of Soil In Engineered Landfill**

As indicated in Fig. 3.9, the major role of soil in an engineered landfill can be summarized as follows:



**Fig. 3.9 Role of soil in an engineered landfill**

1. Compacted liner or barrier which minimize the migration of contaminant to groundwater and hence it is the most integral and important part of a landfill. The reduction in migration is due to low permeability and contaminant retention capacity of the clayey soil used in liners.
2. Leachate collection system provided below the waste to collect the leachate and effectively drain to a collection source for further treatment.
3. After the service life of the landfill, an integrated multi layer cover system is provided on top of the waste to isolate it from the environment and minimize the generation of post closure leachate.
4. Natural soil is used as daily cover material for waste during the operational phase of landfill.

5. The unsaturated natural soil below the liner act as an additional buffer layer in reducing the migration of contaminants to groundwater.
6. In addition, suitable geosynthetics, geotextiles, geomembrane, geonets etc. are used individually or in combination with soil to act as liner, drainage layer, filtration layer or separation layer. The use of geosynthetic helps to reduce the thickness of liner layer.

Contaminated Site Characterization/ Assessment

4.1 Site characterization or contaminated site assessment (CSA) is important for:

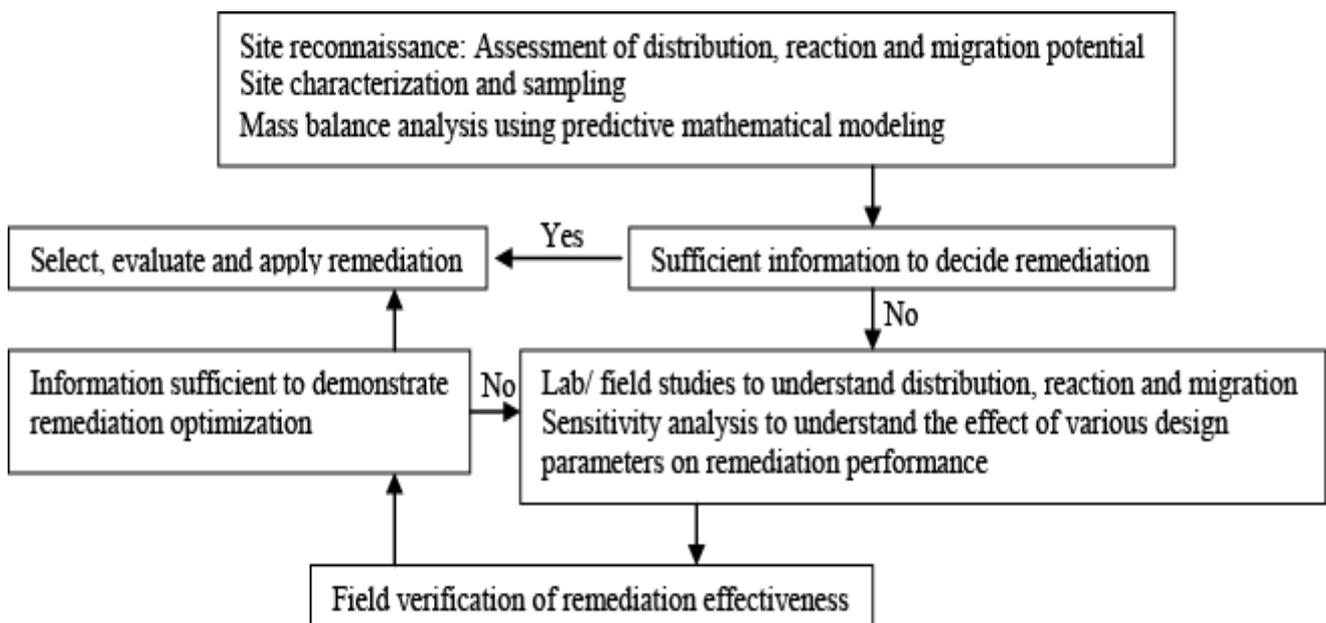
- Determining concentration and spatial distribution of harmful pollutants under consideration.
- Determining the extent of site remediation (zonation) based on which the suitable remediation technique is selected.
- For assessing environmental and human health risk due to contamination.

More specifically, CSA is required to answer the following questions:

- What is the source of contaminants?
- What is the type and physical form of contaminants?
- Spatial and depth wise extent of contamination
- Whether the contaminants are stationary or movable?
- If they are movable, then identify the significant pathways.
- Identify the potential receptors of contaminants.

4.2 Selection And Planning Of Remediation Methods

Fig. 4.1 (United States Environmental Protection Agency (EPA or sometimes USEPA) 1991) presents a flowchart on various processes involved in the planning of site remediation.



**Fig. 4.1 Processes involved in deciding contaminated site remediation**

It can be noted from Fig. 4.1 that the most important step for making a decision on site remediation is collection of data.

Table 4.1 summarizes the essential data to be collected as part of site reconnaissance and site characterization.

Table 4.1 Summary of data required for planning contaminated site remediation

Data	Details	Method of acquisition
1) Site history and land use pattern	a) Population density within 3 km from the contaminated site b) Proximity to important geographical features like airport, railways, river etc. c) Ownership of the land d) Extent of contamination	Field
2) Geologic and hydrologic	a) Topography b) Soil profile up to bed rock c) Information on aquifer d) Groundwater depth and flow direction	Field
3) Geotechnical	a) Soil sampling and classification b) Permeability of soil c) Chemical characteristics of soil d) Soil strength	Field Lab Field Lab
4) Waste	a) Water quality b) Identifying the type of contamination c) Concentration of contaminants d) Spatial extent of contamination e) Depth of contamination f) Contaminant retention characteristics g) Contaminant transport characteristics h) Hazard assessment and zonation	Field/ Lab Field/ Lab Lab Field/ Lab Field/ Lab Lab Lab Lab

### 4.3 Risk Assessment Of Contaminated Site

Risk assessment or hazard assessment is required to decide the extent of contaminant remediation required for a particular site. The factors influencing risk assessment are:

#### Toxicity

A material is deemed toxic when it produces detrimental effects on biological tissues or associated process when organisms are exposed to concentration above some prescribed level.

- ❖ Acute toxicity is the effect that occurs immediately after exposure where as chronic toxicity deals with long term effects.
- ❖ It is expressed as mass unit of toxicant dose per unit mass of receiving organism. It must be noted that concentration is an important factor while deciding toxicity.
- ❖ Only when a contaminant crosses a particular concentration, it becomes toxic. If the concentration is within the prescribed limit then no remediation need to be performed.
- ❖ Only those site which have toxic level of contaminant concentration needs remediation. For example, toxic contamination level leading to cancer becomes the basis for some of the site clean-up programs.

#### Reactivity

It is the tendency to interact chemically with other substances. These interactions become hazardous when it results in explosive reaction with water and/or other substances and generate toxic gases.

#### ❖ Corrosivity

Corrosive contaminants degrade materials such as cells and tissues and remove matter.

- ❖ It is defined as the ability of contaminant to deteriorate the biological matter.
- ❖ Strong acids, bases, oxidants, dehydrating agents are corrosive.  $\text{pH} < 2$  or  $\text{pH} > 12.5$  is considered as highly corrosive. Substances that corrode steel at a rate of 6.35 mm/year is also considered hazardous.

- ❖ **Ignitability**  
It is the ease with which substance can burn.
- ❖ The temperature at which the mixture of chemicals, vapour and air ignite is called the flash point of chemical substances.
- ❖ Contaminants are classified as hazardous if it is easily ignitable or its flash point is low.
- ❖ Based on the above four factors the risk associated with a particular site is determined by specifying maximum acceptable risk using risk estimation equations (Reddi and Inyang 2000).
- ❖ Risk assessment provides a numerical quantification of the probability of harm from hazardous or toxic contamination.
- ❖ Risk management uses this input of risk assessment in deciding how much regulation and corrective measure need to be taken.
- ❖ The corrective action is mostly the practice of remediation of the contaminated site.
- ❖ The maximum possible concentration that could lead to the maximum acceptable risk is back calculated. If the level of concentration at a particular site is greater than the maximum possible concentration, then it requires remediation.
- ❖ This approach would clearly indicate the extent of remediation required for the contaminated site.
- ❖ Appropriate remediation scheme is then selected to bring the concentration level much less than the maximum possible concentration.

#### **4.4 Remediation Methods For Soil And Groundwater**

- ❖ Based on the toxic level of contaminants and the risk it pose to the environment, a suitable remediation method is selected.
- ❖ It must be noted that the remediation does not aim for entire decontamination. The major focus is to bring the contamination level well below the regulatory toxic limit.
- ❖ This is done by removing the toxic contaminants and/or immobilizing the contaminant that prevents its movement through subsurface geoenvironment.
- ❖ The remediation methods are broadly classified as physico-chemical, biological, electrical, thermal and combination of these methods.

##### **4.4.1 Physico-Chemical Methods**

#### **Removal And Treatment Of Contaminated Soil**

- ❖ One of the simplest physical methods for remediation is by removing the contaminated soil and replacing it with clean soil.
- ❖ Essentially it is a dig, dump and replace procedure. Such a method is practically possible only if the spatial extent and depth of the contaminated region is small.
- ❖ The dug out contaminated soil can be either disposed off in an engineered landfill or subjected to simple washing as shown in Fig. 4.2.

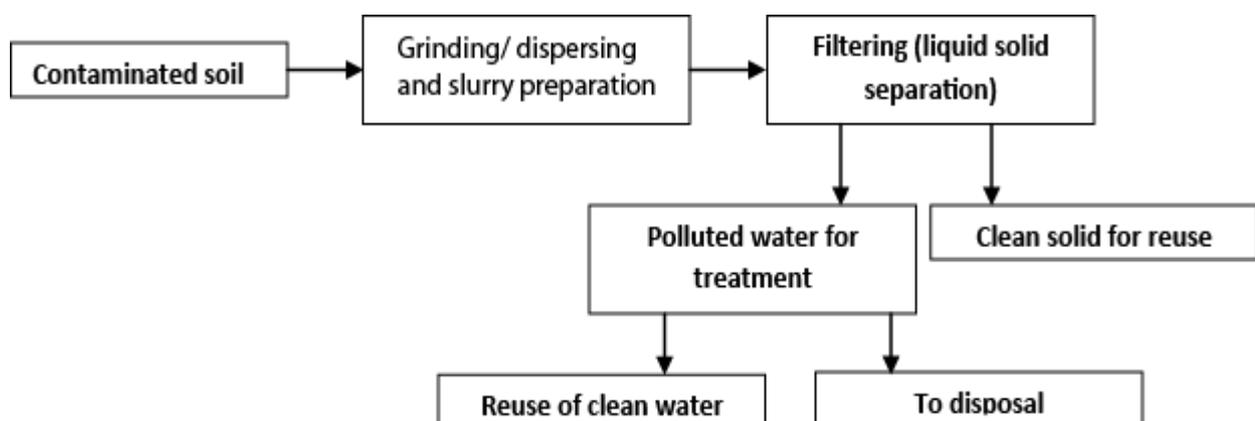


Fig. 4.2 Soil washing for granular soils contaminated with inorganic pollutant

- ❖ However, washing procedure is mostly suitable for granular soils with less clay content and contaminated with inorganic pollutants.
- ❖ For clay dominated soils, a chemical dispersion agent need to be added to deflocculate and then chemical washing is employed to break the retention of contaminants with the clay surface.
- ❖ Incineration is suggested for soils contaminated with organic pollutants.
- ❖ In case, it is necessary to remove organic pollutants then certain solvents or surfactants are used as washing agents.
- ❖ The method is directly applied in situ where solvent, surfactant solution or water mixed with additives is used to wash the contaminants from the saturated zone by injection and recovery system. The additives are used to enhance contaminant release and mobility resulting in increased recovery and hence decreased soil contamination.

### Vacuum Extraction

- ❖ This method is one of the most widely used in situ treatment technologies.
- ❖ The method is cost-effective but time consuming and ineffective in water saturated soil.
- ❖ The technique, as depicted in Fig. 4.3, is useful for extracting contaminated groundwater and soil vapour from a limited subsurface depth.
- ❖ The contaminated water is then subjected to standard chemical and biological treatment techniques.
- ❖ Vacuum technique is also useful when soil-water is contaminated with volatile organic compound (VOC).
- ❖ The method is then termed as “air sparging”. Sometimes biodegradation is clubbed with air sparging for enhanced removal of VOC. Such a technique is then termed as biosparging.

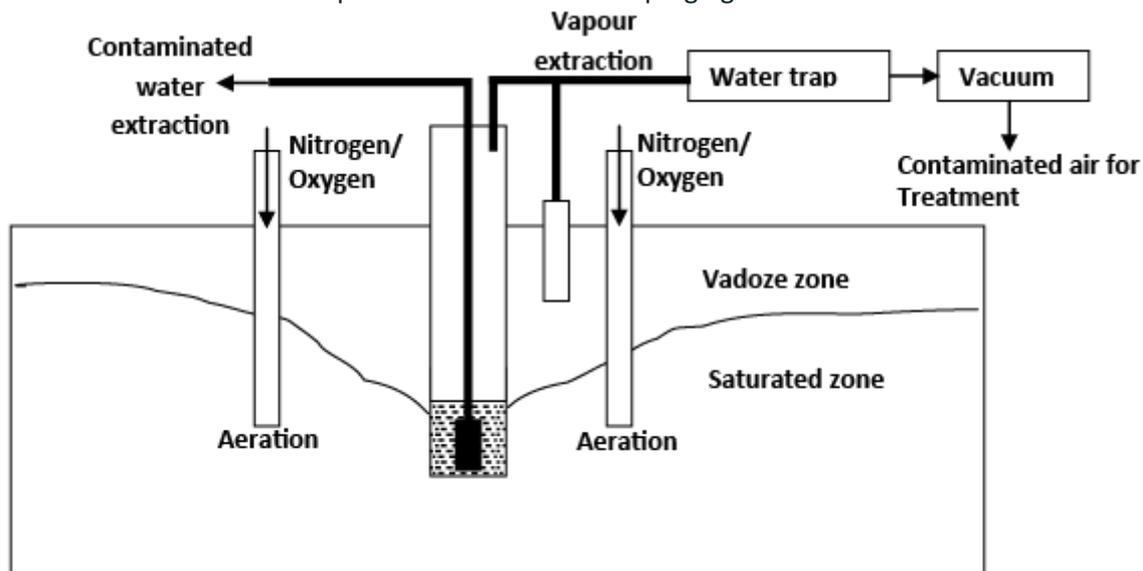


Fig. 4.3 A schematic diagram for vacuum extraction procedure (Reddi and Inyang, 2000)

- ❖ The vacuum extraction probe is always placed in the vadoze zone. The success of the method depends on the volatilization of VOC from water into air present in voids.
- ❖ An injecting medium is used to extract soil-water and/ or soil-air. When oxygen is used instead of nitrogen as the injecting medium, it enhances aerobic biodegradation.
- ❖ Soil structure influences a lot on the passage of extracted water and vapour and hence on the success of vacuum extraction technique.
- ❖ It is not only important that the injecting medium is delivered efficiently but also the extracted product reaches the exit with less hindrance.
- ❖ Granular soils provide better passage whereas the presence of clay and organic matter impedes the transmission of both fluid and vapour.
- ❖ Organic matter provides high retention leading to less volatilization. High density and water content also minimize transmissivity. Apart from soil, the VOC properties such as solubility, sorption, vapour pressure, concentration etc. also influence the extraction process.

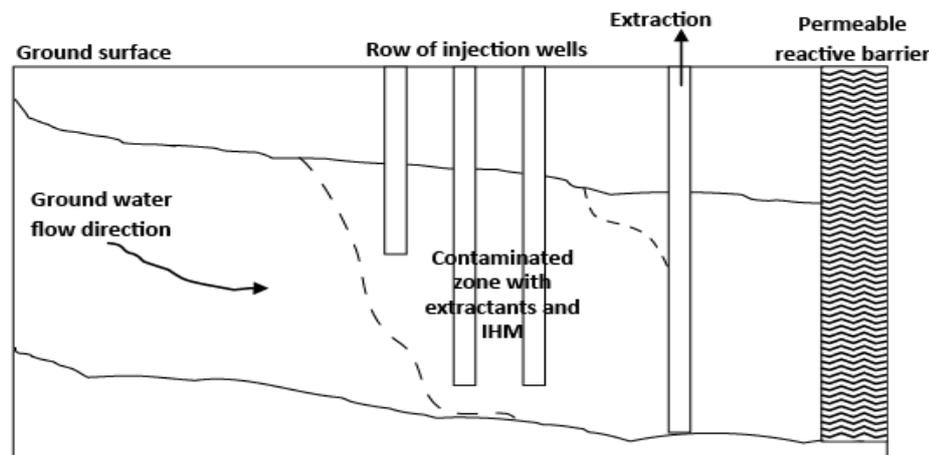
### Solidification And Stabilization

- ❖ This is the process of immobilizing toxic contaminants so that it does not have any effect temporally and spatially.

- ❖ Stabilization-solidification (SS) is performed in single step or in two steps.
- ❖ In single step, the polluted soil is mixed with a special binder so that polluted soil is fixed and rendered insoluble.
- ❖ In two step process, the polluted soil is first made insoluble and non-reactive and in the second step it is solidified.
- ❖ SS process is mostly justified for highly toxic pollutants. In-situ SS process is mostly influenced by the transmissivity characteristics of the soil, viscosity and setting time of the binder. Well compacted soil, high clay and organic content do not favour in-situ SS.
- ❖ In ex-situ methods, polluted soil is first grinded, dispersed, and then mixed with binder material. The resultant SS material need to be disposed in a well contained landfill. It is essential that the resultant SS product does not undergo leaching.
- ❖ The common binders used in practice include cement, lime, fly ash, clays, zeolites, pozzolonic products etc. Organic binders include bitumen, polyethylene, epoxy and resins. These organic binders are used for soil contaminated with organic pollutants.

#### Chemical Decontamination

- ❖ This method is mostly applicable for those soils which have high sorbed concentration of inorganic heavy metals (IHM).
- ❖ The first process in this method is to understand the nature of bonding between the pollutant and the soil surface. A suitable extractant need to be selected for selective sequential extraction (SSE) of IHM from the soil mass. The extractants include electrolytes, weak acids, complexing agents, oxidizing and reducing agents, strong acids etc. The use of these extractants in single or in combination will depend upon the concentration of IHM and nature of the soil mass.
- ❖ In-situ application (as depicted in Fig. 4.4) of extractants would remove IHM from the soil surface and enter into the pore water. The pore water is pumped and treated (pump and treat method) on the ground. While treating the pumped water, both extractants and IHM are removed.



**Fig. 4.4 A schematic diagram for in-situ chemical decontamination**

- ❖ Another method is to allow the contaminated pore water to flow through a permeable reactive barrier (PRB).
- ❖ Hence the placement of the barrier is determined by the direction of flow of ground water. The material packed in the barrier will retain IHM by exchange (sorption), complexation or precipitation reaction. The transmission and the reaction time determine the thickness of the reactive barrier to be provided.
- ❖ The material to be provided in the barrier is influenced by the knowledge of IHM to be removed. This is mainly due to the fact that the above mentioned reaction occurs differently when IHM is present as single or as multiple species.
- ❖ The successful use of PRB or treatment wall (TW) depends upon its location such that majority of the contaminated groundwater flows through it.
- ❖ It is essential to have a good knowledge on the hydrogeological conditions where such barriers need to be placed.
- ❖ In some cases, sheet pile walls are used to confine the flow towards the permeable barrier.

- ❖ Some of the materials used in such PRBs are exchange resins, activated carbon, zeolites, various biota, ferric oxides, ferrous hydroxide etc.
- ❖ Hydraulic conductivity of the PRB should be greater than or equal to the surrounding soil for proper permeation to occur.
- ❖ Further, reaction kinetics and permeability of the barrier would determine the thickness of the wall to be provided such that enough residence time is achieved for the removal reaction to occur.

#### **4.4.2 Biological Methods**

- ❖ Remediation by biological treatment is mostly applicable for soil contaminated with organic pollutants and the process is termed as bioremediation.
- ❖ In this method, certain soil microorganisms are used to metabolize organic chemical compounds. In the process these microorganisms degrade the contaminant.
- ❖ If naturally occurring microorganisms such as bacteria, virus or fungi is not capable of producing enzymes required for bioremediation, then genetically engineered microorganisms would be required.
- ❖ At the same time, it should be ensured that such microorganisms do not produce any undesirable effect on the geoenvironment (such as toxins).
- ❖ The process of bioremediation is dependent on reactions such as microbial degradation, hydrolysis, aerobic and anaerobic transformation, redox reaction, volatilization etc.

#### **4.4.3 Electro-Kinetic Methods**

- ❖ Electro-kinetic methods are popular field method for decontaminating a particular site by using electrical principles. The procedure is more effective for granular type of soils.
- ❖ Two metal electrodes are inserted into the soil mass which acts as anode and cathode. An electric field is established across these electrodes that produces electronic conduction as well as charge transfer between electrodes and solids in the soil-water system.
- ❖ This is achieved by applying a low intensity direct current across electrode pairs which are positioned on each side of the contaminated soil. The electric current results in electrosmosis and ion migration resulting in the movement of contaminants from one electrode to the other.
- ❖ Contaminants in the soil water or those which are desorbed from the soil surface are transported to the electrodes depending upon their charges.
- ❖ Contaminants are then collected by a recovery system or deposited at the electrodes.
- ❖ Sometimes, surfactants and complexing agents are used to facilitate the process of contaminant movement.
- ❖ This method is commercially used for the removal of heavy metals from the soil such as uranium, mercury etc.

#### **4.4.4 Thermal Methods**

- ❖ Thermal methods include both high temperature (>500°C) and low temperature (<500°C) methods and are mostly useful for contaminants with high volatilization potential (Evangelou 1998).
- ❖ High temperature processes include incineration, electric pyrolysis, and in-situ vitrification.
- ❖ Low temperature treatments include low temperature incineration, thermal aeration, infrared furnace treatment, thermal stripping.
- ❖ High temperature treatment involves complete destruction of contaminants through oxidation. Low temperature treatment increases the rate of phase transfer of contaminants from liquid to gaseous phase thereby causing contaminant separation from the soil.
- ❖ Radio frequency (RF) heating is used for in situ thermal decontamination of soil having volatile and semi-volatile organic contaminants.
- ❖ Steam stripping or thermal stripping is another process useful for soils contaminated with volatile and semi-volatile organic contaminants. It is an in situ process in which hot air, water or steam is injected into the ground resulting in increased volatilization of contaminants. Sometimes vacuum is applied to extract air or steam back to the surface for further treatment.
- ❖ The effectiveness of this method is increased by the use of chemical agents that are capable of increasing the volatility of the contaminants. High cost and its ineffectiveness with some contaminants (with low volatilization potential) make thermal method less attractive. Also, in some cases incineration process produces more toxic gases.

## Advanced Site Characterization

Many a times solution to geoenvironmental problems necessitates advanced characterization of soil. These characterization results serve as inputs for mathematical modelling, parameterization of certain soil related functions, verification or validation of some phenomenon, field investigation, physical modelling of soil behaviour, indirect estimation of properties etc. While the list of such advanced soil characterization is exhaustive due to the recent developments in electronics and instrumentation, only some of the important and common advanced characterizations for geoenvironmental problem are discussed in the following.

### 5.1 Soil Contaminant Analysis

A wide variety of instruments are available for analyzing the concentration of organic and inorganic contaminants present in the soil. In most of these methods, the contaminant present in the soil need to be first brought into solution form by using suitable methods. The contaminated soil is washed using water or suitable extractants in single, multiple or sequential steps (ASTM D 3974; Reddy and Chintamreddy 2001; Dean 2003; Maturi et al. 2008). Another process for extracting soil contaminants into solution form is by acid digestion method (Method 3050B, EPA). The contaminant in solution form is then analyzed using the appropriate method for contaminant analysis such as atomic absorption spectrometer (AAS), inductively coupled plasma mass spectrometer (ICP MS), ion chromatograph, gas chromatograph, flame photometer, UV visible spectrophotometer. The choice of contaminant analysis methodology would depend upon the type of contaminant and whether single or multiple contaminants need to be analysed. The accuracy of all these methods would depend upon the precise calibration performed by the user. In the process of calibration, instrument parameter is correlated to the contaminant concentration using standard contaminant solution of known concentration. Further, for a solution of unknown concentration, instrument parameter is measured and the concentration determined using the calibration equation.

### 5.2 Electrical Property Of Soil

The knowledge of soil electrical property of soil system (solid, liquid and gaseous phase) is required for several applications in engineering and geosciences. Electrical properties of soil system have multiple phases due to the following reason (Fang and Daniels 2006): (a) Soil and water has inherent electrical characteristics, (b) electrical energy is related to thermal and magnetic properties and difficult to separate (c) electro-chemical interaction in soil-water system is sensitive to surrounding environment. The important factors influencing soil electrical properties are particle size distribution, compaction, water content, mineral structure, mineral surface condition, characteristics of pore fluid and ion exchange reaction. The direction of electric current is the direction of flow of ions. The zone of electric field depends on the magnitude of electric charge and soil-water system. The electrical property of soil is defined in terms of electrical resistivity, conductivity, capacitance and dielectric property. Resistivity and conductivity quantifies the flow of electric current through a medium. Electrical resistivity is the most common method for defining electrical property of soil-water system. There are a lot of literature that describe the use of resistivity or conductivity for indirectly assessing water content, extent of soil contamination or salinity, unit weight, porosity, frost depth, buried objects etc. (Fang and Daniels 2006). Capacitance is the charge storage capacity of a material. Dielectric property defined in terms of dielectric constant ( $\kappa$ ) implies the ability of a material to perform as an insulator. This property is not measured but computed by Eq. 5.1.

$$\kappa = C \times (d/A) \quad 5.1$$

C is the capacitance in Farad, d is the length of specimen and A is the cross sectional area of specimen.  $\kappa$  is an important property that has been used extensively for indirect correlation with different soil properties.

When the soil is fully dry the electrical resistivity is very high because there is little interaction between the electrical charge (or energy) and ions present in the soil. When the soil is wet, resistivity decreases and electrical conductivity increases due to the formation of water film around soil surface. Such a film act as a bridge between electrical charge and ions present in the soil. Flow of electricity through soil can be due to direct current (DC) or due to alternating current (AC) of particular frequency. The effect produced by both on soil is different. To assess the effect of flow of alternating current in soils, it is necessary to determine  $\kappa$  and electrical conductivity ( $\sigma_{ec}$ ) of the soil corresponding to the frequency of the current (Smith-Ross 1933). This is because these characteristics are dependent on the frequency of AC. The density, water content of soil and frequency of AC are the important parameters affecting electrical properties of soil under AC. The  $\kappa$  value for dry soil and minerals varies between 2.8 to 2.6 for a frequency variation from 100 to 10000 kHz. As moisture content increases, the  $\kappa$  variation with frequency increases considerably. For pure water,  $\kappa$  is close to 80. Such a wide variation in  $\kappa$  values is used for indirectly determining volumetric water content of soils.

### **5.2.1 Uses Of Electrical Properties Of Soil**

Electrical properties of subsurface are used extensively for oil and mineral exploration, subsurface exploration, to delineate contaminated land etc. Soil electrical properties are used for in situ soil mapping and monitoring when the studied soil property is dependent on the mobile electrical charges in the soil. It is used for characterizing soil morphology, develop accurate soil maps for agricultural purposes, identify the extent of soil pollution, forensic and environmental applications (Anatoly and Larisa 2002). The important soil properties studied are soil salinity, texture, stone content, groundwater depth, and horizon sequence in soil profiles (Larisa 1999). Some of the geophysical methods measure soil electrical properties such as electrical conductivity, resistivity and electrical potential from soil surface to a particular depth without soil disturbance. These electrical properties are then correlated to the appropriate soil parameters such as salinity, water content, density, porosity, degree of saturation, permeability, swelling potential, liquefaction potential etc. by using some empirical equation. However, the success of such methods depends upon detailed knowledge of subsurface electrical properties and systematic procedure for data interpretation, which is still an open area of research.

### **5.2.2 Measurement Of Electrical Properties Of Soil**

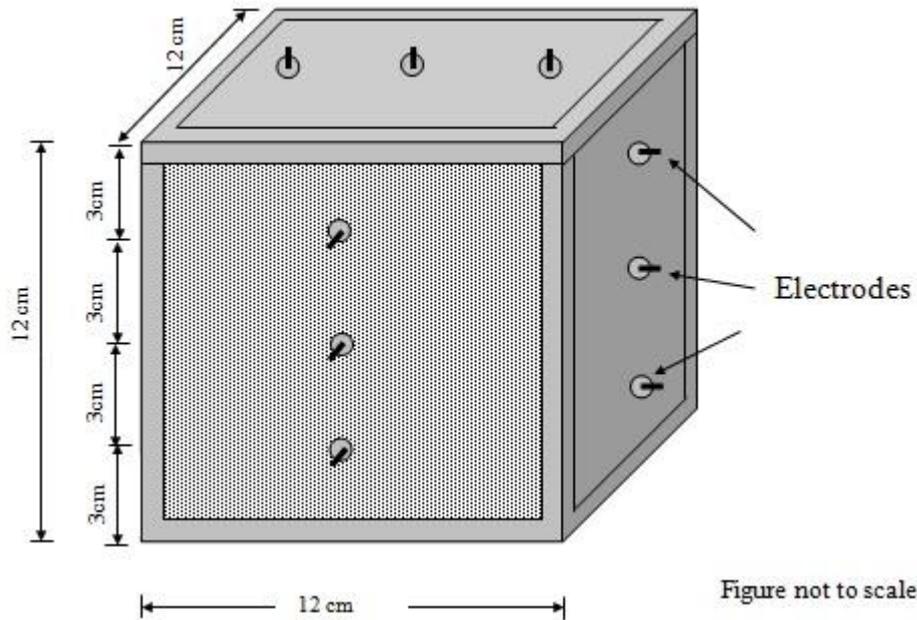
There are different types of probe and box arrangement for measuring electrical property of compacted soil in the lab or in situ soil. Electrical resistivity box (ERB) consists of a perspex cubical box, 100 mm in dimension and 10 mm thick, as depicted in Fig. 5.1, which works on the principle of two-electrode method (Abu-Hassanein 1994). ERB can be used for measuring electrical resistivity of disturbed and undisturbed soil samples in all the three dimensions and can also be used for layered soil deposits. Each face of the ERB is provided with three brass screw electrodes of length 12.5 mm and diameter 2.5 mm, which can be screwed into the compacted soil sample. This arrangement ensures proper contact of the electrode with the soil. A known AC voltage  $V$  is applied between the two electrodes mounted on the opposite faces of the box and the current  $I$  passing through the medium is measured using a digital multimeter. Hence, the resistance  $R_{ERB}$  and electrical resistivity  $\rho_{ERB}$  offered by the medium can be determined by Eqs. 5.2 and 5.3, respectively.

$$R_{ERB} = V/I \quad 5.2$$

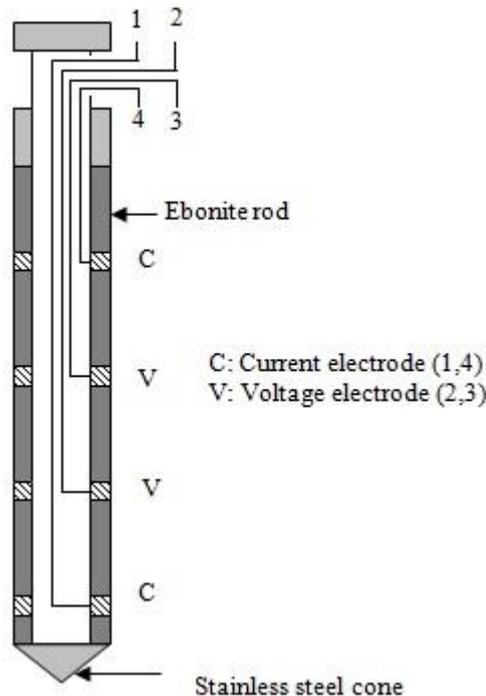
$$\rho_{ERB} = a \cdot R_{ERB} \quad 5.3$$

$a$ , is a constant that depends on the geometry of the box, which can be determined by measuring resistance of the standard KCl and NaCl solutions of known electrical resistivity. Electrical resistivity probe (ERP) is more appropriate for measuring the soil electrical resistivity in situ. As depicted in Fig. 5.2, four annular copper rings, which act as electrodes are mounted on an ebonite rod of 16 mm outer diameter, at a center-to-center spacing of 25 mm. The two outer electrodes are the current electrodes while the inner electrodes are used for

measuring the voltage. For sufficient insertion and ensuring perfect contact of the ERP with the soil mass, a 100 mm long and 15 mm diameter hole is created in soil with the help of a dummy rod. AC of intensity  $I$  is applied to the outer electrodes and the potential drop  $V$  across the two inner electrodes is measured. Soil resistance ( $R_{ERP}$ ) can be obtained, which can be correlated to the resistivity  $\rho_{ERP}$  using an appropriate parameter  $b$  that depends on the geometry of the probe, as discussed above for ERB.



**Fig. 5.1 A conceptual electrical resistivity box (Sreedeeep et al. 2004)**



**Fig. 5.2 A conceptual electrical resistivity probe (Sreedeeep et al. 2004)**

Thermal property of soil are of great importance in several engineering projects where heat transfer takes place through the soil. These projects include underground power cables, high level nuclear waste repository, hot water or gas pipes and cold gas pipelines in unfrozen ground, agriculture, meteorology and geology. The thermal properties of soil include thermal conductivity ( $K= 1/\rho$ ),  $\rho$  is the thermal resistivity, thermal diffusivity (D), and heat capacity (C). K is defined as the amount of heat passing in unit time through a unit cross-sectional area of the soil under a unit temperature gradient applied in the direction of heat flow. Considering a prismatic element of soil having a cross-sectional area A at right angles to the heat flow q, then K is defined as

$$K = \frac{q}{A(T_2 - T_1)l} \quad 5.4$$

Where, l is the length of the element,  $T_1$  and  $T_2$  are temperature where  $T_2 > T_1$ .

The heat capacity C per unit volume of soil is the heat energy required to raise the temperature of unit volume of soil by 1 C. It is the product of the mass specific heat c (cal/g °C) and the density  $\rho_m$  (g/cc). Thermal diffusivity is the ratio of thermal conductivity to specific heat. It indicates how materials or soil adjust their temperature with respect to the surroundings. A high value of the thermal diffusivity implies capability for rapid and considerable changes in temperature.

### **5.3.1 Factors Influencing Soil Thermal Resistivity (P)**

Fine grained or cohesive soil and peaty soils exhibit high thermal resistivity ( $\rho$ ) than granular soil. Sand with quartz as the principal constituent has low  $\rho$ . The type of clay minerals present in soil also influences  $\rho$ . Expansive clay minerals such as montmorillonite would cause the soil particles to be forced apart during swelling action when it comes in contact with water, thereby increasing  $\rho$ . Well-graded soils conduct heat better than poorly graded soils because the smaller grain can fit in the interstitial positions between the larger grains thus increasing the density and the mineral-to-mineral contact. The shape of the soil particles determines the surface contact area between particles which affects the ability of the soil to conduct heat.  $\rho$  increases with decreasing particle size due to reduced surface contact between adjacent particles.

The density of soil has an important influence on  $\rho$ . The presence of air with its high  $\rho$  increases the overall  $\rho$  of the soil as compared to that of its solid components. Therefore, a well compacted soil will have low  $\rho$  due to low total void volume and better contact between the solid grains. When water is added to the soil, it tends to distribute itself in a thin film around solid grain of the soil. This water film provides a path for the heat and hence bridges the air gaps between the solid particles. Additional water, over and above that required for film formation, serves to fill voids which were initially occupied with air. Since  $\rho$  of air is much higher than water, inclusion of water in soil would considerably decrease  $\rho$  of soil. The moisture content also has an indirect influence on  $\rho$  since higher density can be achieved by adding water to the soil. The  $\rho$  of soil is also influenced by temperature, because each of the constituents has temperature dependent thermal properties. The  $\rho$  of all crystalline minerals increase with increasing temperature, however, the  $\rho$  of water and gases exhibit the inverse effect.

### **5.3.2 Measurement Of Soil Thermal Resistivity (P)**

$\rho$  measurement of soil could be categorized as steady state and transient state methods. For steady-state method, a known thermal gradient is established in soil specimen with definite shape and length and  $\rho$  can be determined based on recording the heat flow through the soil. In transient-state method, known time-

rate of energy is applied into soil specimen and the corresponding temperature change with time is recorded and analyzed to determine  $\rho$ . The thermal gradient across the soil sample being tested may induce appreciable moisture migration in unsaturated soils there by changing the properties it is attempting to measure. Therefore, selection of appropriate method of  $\rho$  measurement should be based on the condition of the target materials. Some of the methods employing steady state and transient measuring principle are discussed below.

### 5.3.2.1 Steady State Method

In this method, the soil sample being tested should be in steady state when the measurements are made. Attainment of such a state is time consuming after the initial temperature difference has been applied. Also, there is possibility of moisture changes by the time the steady state is reached. The methods based on steady state are described below:

#### Guarded Hot Plate Method

The most important steady state method for measuring the  $\rho$  of soils is the guarded hot plate (GHP) test as depicted in Fig. 5.3 (ASTM C 177). As shown in figure, two identical specimens are placed above and below a flat-plate main heater unit which is surrounded by an outer guard heater. The guard eliminates horizontal heat losses and causes heat from the main heater to flow vertically up or down through the test specimen. Liquid-cooled heat sinks are placed adjacent to the outer surfaces of the specimens. A certain temperature drop is obtained across each specimen of certain thickness.  $\rho$  ( $=1/K$ ) of the specimen material is calculated from Eq. 5.5.

$$K = \frac{Q L}{A \Delta T}$$

5.5

Where,  $Q$  is the heat flow through soil,  $A$  is the area of soil specimen,  $L$  is the length of heat flow, and  $\Delta T$  is the temperature drop. The GHP test is time consuming and only suitable for laboratory use.

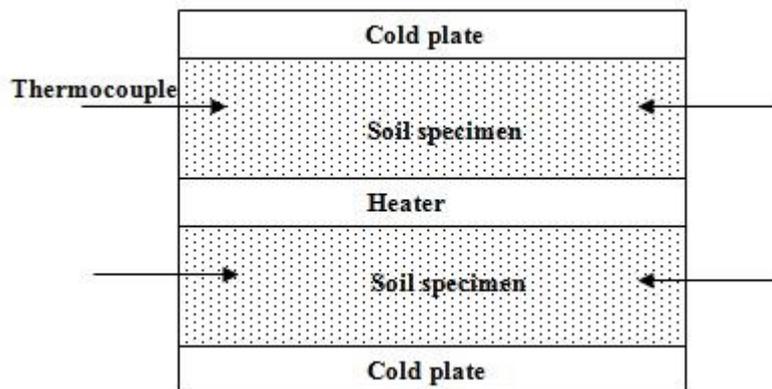


Fig. 5.3 Schematic diagram of the guarded hotplate method for determining thermal conductivity (ASTM C 177)

#### Heat Flux Meter

The  $\rho$  of soil can be determined by measuring temperatures at two points and the heat flows between these points with the help of a heat flux meter. The heat flux meter is a thin plate of suitable material with known  $\rho$ , and installed with thermal couples on both side. The temperature difference (gradient) between both sides multiplied by the  $\rho$  of the plate gives the heat flux per unit area across the plate. This method is described in detail in ASTM C 518. The heat flux meter also requires long measuring time. The contact

between the plate and the specimen need to be perfect to eliminate the influence of contact thermal resistance. Therefore, a contact pressure needs to be applied, which may alter the soil state (density or volumetric water content).

### **5.3.2.2 Transient State Method**

In transient method, temperature of the soil varies with time. Such methods are less time intensive and can be easily performed than the steady state methods. Thermal probe and point-source method based on transient state are discussed below.

#### **Thermal Probe Method**

The thermal probe or needle is a rapid and convenient method for measuring  $\rho$  of soils in situ or in the laboratory. The theory of the probe method is based on the theory of the line heat source placed in a semi-infinite, homogeneous and isotropic medium. This method is described in detail in ASTM D 5334.

The apparatus for thermal probe method shall consist of the following:

1. Thermal needle probe: A device that creates a linear source and incorporates a temperature measurement element (thermocouple or thermostat) to measure variation of temperature at a point along the line.
2. Constant current source: A device to produce a constant current.
3. Thermal read out unit: A device to produce a digital read out of temperature in  $^{\circ}\text{C}$ .
4. Voltage-Ohm-Meter (VOM) - A device to read voltage and current to the nearest 0.01 V and ampere.
5. Stopwatch measuring time to the nearest 0.1 s for a minimum of 15 min.
6. Equipment capable of drilling a straight vertical hole having a diameter as close as possible to that of the probe and to depth at least equal to the length of the probe.

This method can be utilized on both undisturbed and remolded sample. For undisturbed sample, thermal probe shall be pushed into the pre-drilled hole on dense specimens or directly inserted into soft ones. The length of the soil sample should be large enough to accommodate the probe length. During the measurement, a steady current is applied while the temperature is recorded as a function of time. Temperature is then plotted as a function of time on semi-log graph. A straight line is drawn through points that exhibit linear trend (pseudo steady state portion).  $K$  can be expressed in terms of the slope of this line:

$$T = \frac{q}{4\pi K} \ln t + c \quad (5.6)$$

(Jackson and Taylor, 1965)

slope =  $\frac{q}{4\pi K}$  Where  $q$ =heat flow rate ( $q = i^2 \cdot r'$ ),  $t$  is the time,  $T$  is the temperature,  $K$  is the thermal conductivity of soil,  $I$  is the current applied,  $r'$  is the resistance per unit length of probe.

#### **Point-Source Method**

This method eliminates the disadvantages of thermal probe due to large-sized samples in which controlling water content becomes difficult, thermal resistance produced between the soil sample and the probe inserted and movement of water occurring due to high temperature. This method is comprised of recording the voltage variations of the thermistor and variable resistor in the measuring circuit over a period of time. The variations in temperature and heat production with time for the thermistor are calculated from the measured

voltage values. Then, the thermal diffusivity of sample is determined by inverse analysis based on the Eqs. 5.6 and 5.10 (Chu 2009).

$$D = \frac{K}{\gamma c}$$

5.7

Where, K is thermal conductivity, D is thermal diffusivity, c is specific heat, T is temperature and  $\gamma$  is density of soil.

## **5.4 Water Content And Permeability Measurements**

### **5.4.1 Volumetric water content sensors**

Determination of gravimetric water content,  $w$ , is simple and employs direct methods such as oven drying, sand bath method, alcohol method, infrared lamp method and calcium carbide method (IS 2720 part II: 1973). However, gravimetric water content does not provide instant measurement of water content and cannot be monitored continuously. Such requirements are common in geoenvironmental projects where water content has to be monitored continuously. This can be done by measuring volumetric water content ( $\theta$ ), which is defined as the ratio of volume of water to the total volume of soil.  $\theta$  is one of the vital parameters correlated to different soil properties such as compaction state, permeability, seepage, soil suction, volume change etc. Its determination is mainly based on indirect techniques such as electrical resistivity, capacitance and dielectric property of the soil mass (Topp et al., 1980). The fundamental approach of  $\theta$  measurement is that electrical properties such as capacitance, dielectric constant, resistivity is strongly related to the soil water content. A calibration equation is developed between any of the electrical property and known volumetric water content of the soil. The same calibration equation can be used to monitor the variation of  $\theta$  by measuring electrical properties. There are different resistivity, capacitance, dielectric, probes available in the market such as time domain reflectometry (TDR), frequency domain reflectometry (FDR), theta probes for insitu measurement of  $\theta$ .

### **5.4.2 Guelph Permeameter**

This is a handy instrument for measuring insitu permeability of natural and compacted soil for hydrogeological investigations at shallow depth. As depicted in Fig. 5.4, Guelph permeameter consist of a reservoir which stores and releases water into a hole (termed as well) under constant head. The constant head is maintained with the help of Marriot bubble principle. There are two reservoirs, one outer tube and smaller inner tube. For high permeable soil, bigger outer reservoir is used and for low permeable soil smaller inner reservoir is used. The scale attached to the inner reservoir is used to measure rate of fall of water in the reservoir. When air tip is raised, water flows out of the reservoir into the bore hole (or well). Water height in the well is established based on the height of air inlet tube tip. This height (constant head causing flow) can be set and read using well height indicator connected with the head scale.

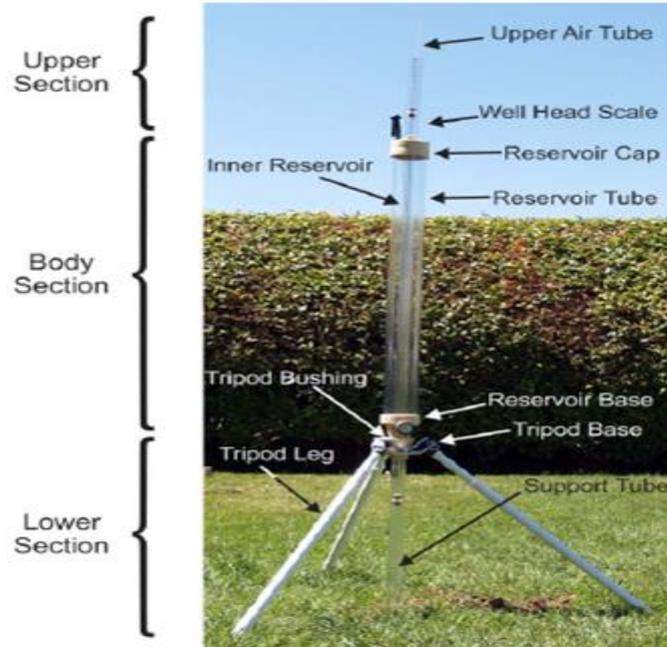


Fig. 5.4 Guelph permeameter

### 5.4.3 Tension Infiltrometer (Ti)

Tension Infiltrometer (TI) as depicted in Fig. 5.5 is a handy instrument for measuring infiltration characteristics and permeability of nearly saturated soil. It consists of three major components namely, reservoir assembly, infiltrometer foot assembly and Mariot bubbler assembly. In tension infiltrometer, water is allowed to infiltrate the under lying soil at a slower rate than the infiltration rate that would have been established when water is ponded on the soil surface. This is accomplished by maintaining a small negative pressure (maximum tension of 20 cm) maintained with the help of Mariot bubbler on the water as it moves out of the infiltrometer disc into the soil. Water can only flow out of the infiltrometer disc at the base and infiltrate into the soil. The amount of infiltration is measured based on the fall of water level in the reservoir. Saturated permeability is determined indirectly based on the infiltration characteristics (Zhang 1997).

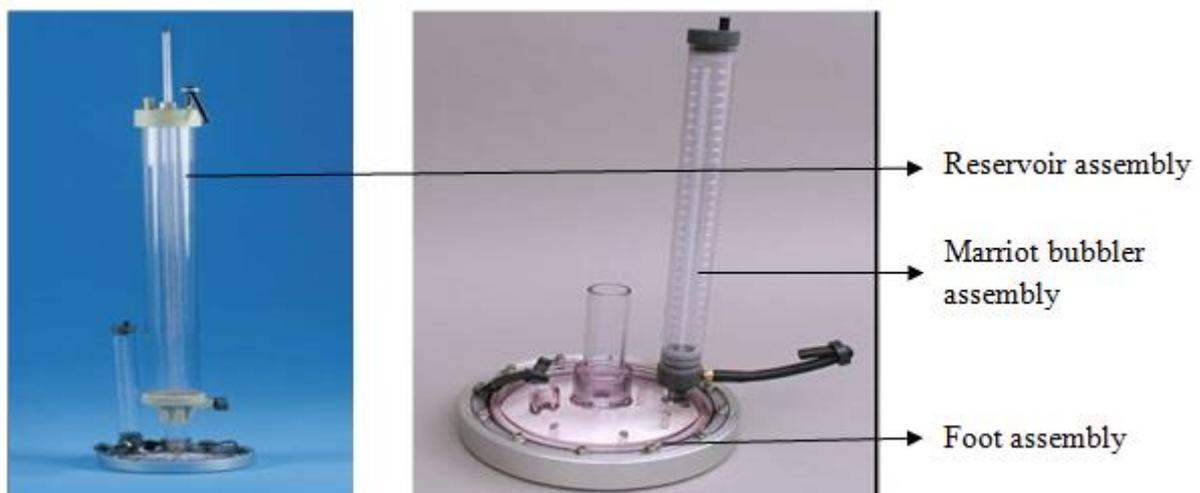
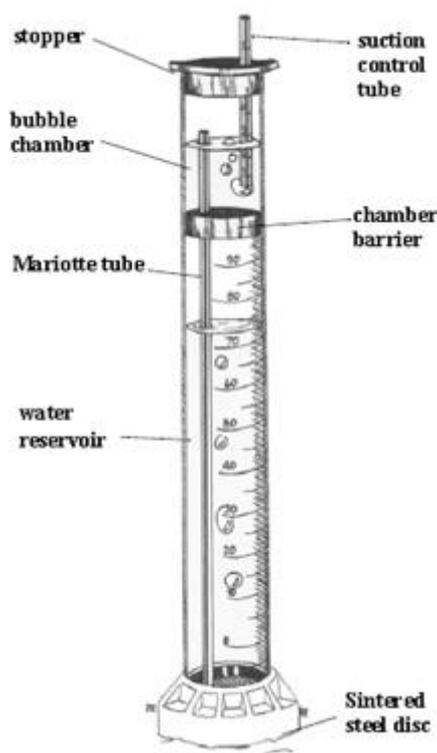


Fig. 5.5 Tension Infiltrometer (Ref. 31)

Mini disc infiltrometer as shown in Fig. 5.6 is similar to the working of tension infiltrometer but with a lower range of suction applied to the infiltrometer disc. Since the infiltrometer is small in dimension (total length of the infiltrometer is 32.7 cm), it can be used for measuring infiltration and near saturation permeability in lab and field. The upper and lower chambers of the infiltrometer are both filled with water. The top chamber controls the suction head. The lower chamber contains the volume of water that infiltrates into the soil. The minidisk infiltrometer is tension infiltrometer and it can measure the hydraulic conductivity in the unsaturated medium (close to near saturation) for adjustable suction ranging from 0.5 cm to 7 cm. At time zero, the infiltrometer is placed on the soil surface. The volume of water that infiltrate into the ground has been recorded as a function of time, based on which infiltration and permeability characteristics is determined.



**Fig. 5.6 Minidisk Infiltrometer**

**5.5 Ground Penetrating Radar For Site Evaluation**

Ground penetrating radar (GPR) is a non destructive and non intrusive geophysical method to measure electrical properties at various depth of subsurface. It works by generation, transmission, propagation, reflection and reception of discrete pulses of high frequency (1 MHz to 1 GHz) electromagnetic energy. The depth of imaging would depend on the frequency of electromagnetic wave. A lower frequency is essential for imaging larger depth where as shallow imaging requires higher frequency. The fundamental issue with its application is the efficiency in processing the electrical data to interpret subsurface information accurately. As the electromagnetic wave propagates downwards it experiences materials of differing electrical properties, which alter its velocity. If velocity changes are abrupt with respect to the dominant radar wavelength, some energy is reflected back to the surface. The reflected signal is detected by the receiving antenna. In systems with a single antenna, it switches rapidly from transmission to reception. The time between transmission, reflection and reception is referred to as two-way travel time (TWT) and is measured in nanoseconds. Reflector TWT is a function of its depth, the antenna spacing (in systems with two antennae), and the average radar-wave velocity in the overlying material. GPR is used to detect the underground buried objects such as

pipes, beams, tunnels, buried walls, salinity, water content, ground contamination, depth of ground water table, and properties of ground water and so on. GPR applicability in certain type of soils such as clay is a subject of debate due to the high attenuation of electromagnetic waves. A lot of research is still required for exploring the full utility of GPR for efficient subsurface investigation.