Module 3
WASTE CONTAINMENT SYSTEM

3.1 Evolution of waste containment facilities 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.
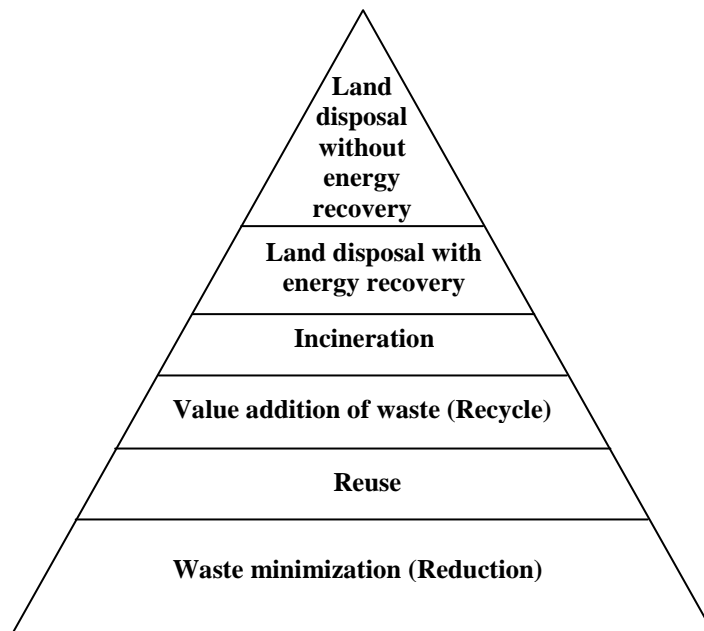

Fig. 3.1 Waste management hierarchy (Modified from Munier 2004)

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 handling and management of 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.
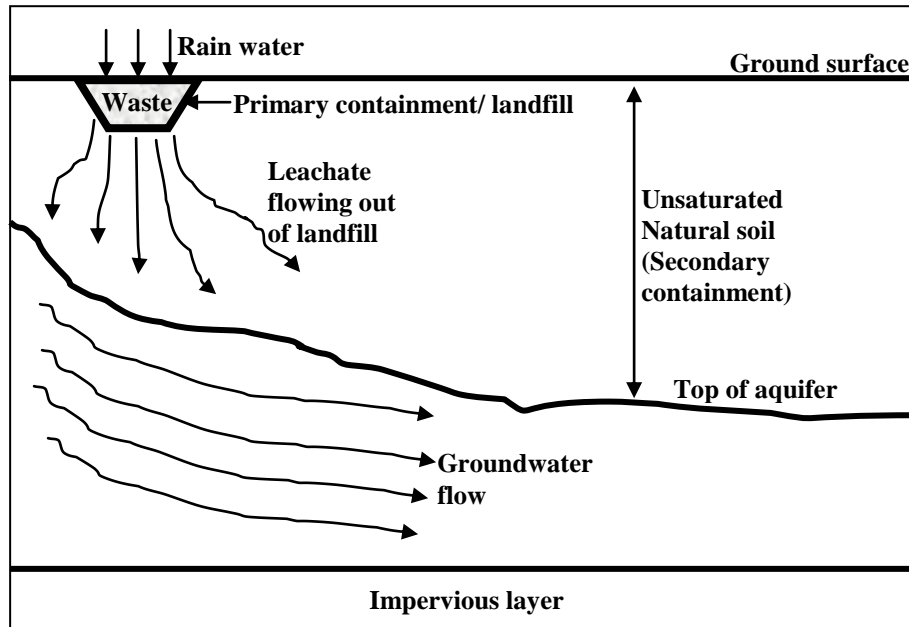
Fig. 3.2 A conceptual waste disposal facility on a global scale

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 groundwater. 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. In this course, 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.

3.2 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 in the previous paragraph 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. Liners are tailor made soil layer 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. This module essentially deals with the role of geoenvironmental engineers in deciding and designing engineered containment landfills.
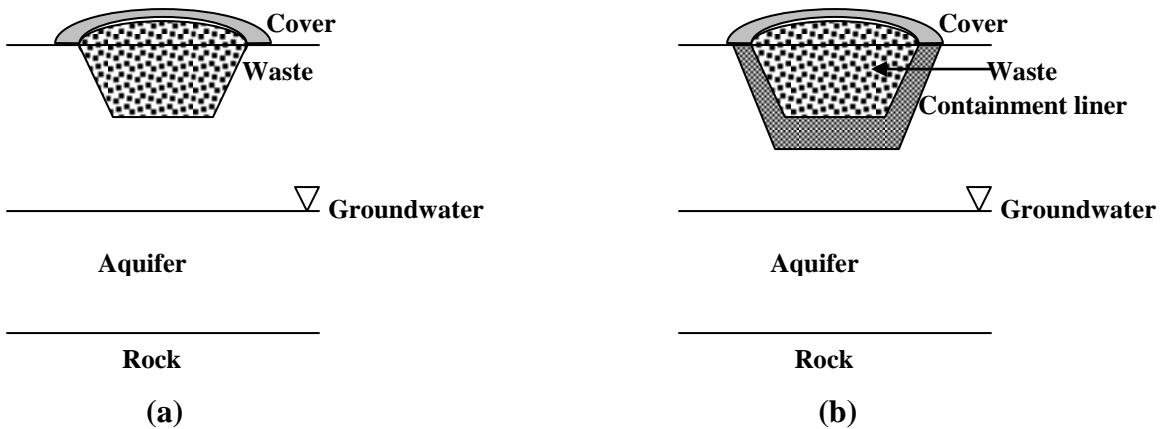

Fig. 3.3 Conceptual depiction of types of landfill (a) Natural attenuation (b) Containment

3.2.1 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 neighbourhood. 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

a) Data collection

b) Locational criterion

c) 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 refer 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.

Flood plain: Not to construct municipal waste containment within 100 year flood plain. For hazardous waste containment this requirement is 500 year flood plain.

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 carrier 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.

3.2.2 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 siting is done based on subsurface and burrow 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 near by 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 only used 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. A weight scale check list is used to recognize the relative importance of different factors or environment.

(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. 3.4 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.
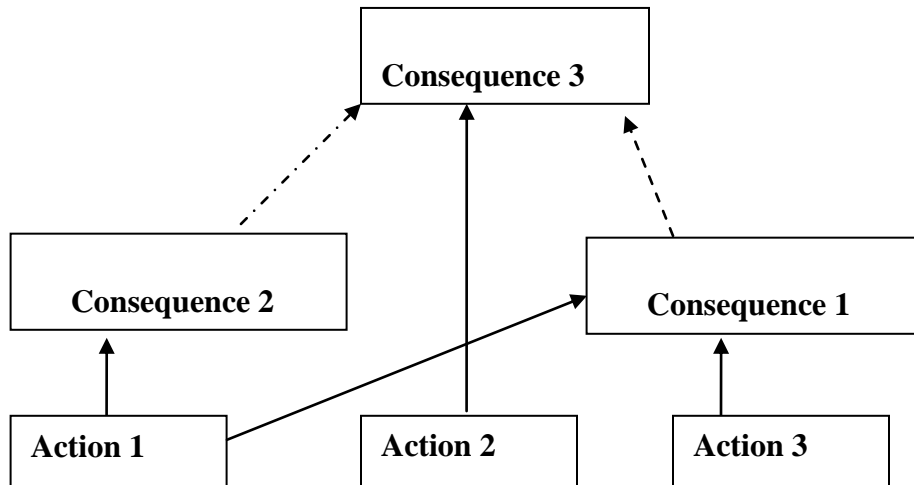

Fig 3.4 Network analysis block diagram (Munier 2004)

(c) Overlays

In this method, thematic transparent maps are developed for flora, fauna, geology, population, rivers, slopes, roads, agricultural land etc. These maps are placed on a glass table, one on top of the other, forming layers of information about the zone .When an intense electric lamp is placed beneath the glass table,

light reaching the top layer indicate the area that is feasible for a project under study. The physical limitation in the application of this method is that no more than 10 overlays can be used. These days GIS (geographic information system) is an effective quantitative method to combine the overlays.

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.

(c) Hatzichristos and Giaoutzi (2006) demonstrated the use of fuzzy set approach integrated with geographical information system (GIS) for landfill siting. The fuzzy set is considered effective to take decisions on those criteria that are not discrete and which overlap with one another. It is opined that the fuzzy set approach integrated with GIS platform is most relevant for applications where the decision criteria are not discrete and the boundaries between regions are fuzzy or overlapping.

(d) Chang et al. (2008) have presented a fuzzy multi-criteria decision analysis along with a geospatial analysis for the selection of landfill sites. The study developed a spatial decision support system (SDSS) for landfill site selection in a fast-growing urban region. Thematic maps in Geographical information system (GIS) are used in conjunction with environmental, biophysical, ecological, and socioeconomic variables leading to support the fuzzy multi-criteria decision-making (FMCDM). It differs from the conventional methods of integrating GIS with multi-criteria decision making for landfill site selection because the approach follows two sequential steps rather than a full-integrated scheme. The purpose of GIS was to perform an initial screening process to eliminate unsuitable land followed by utilization of FMCDM method to identify the most suitable site using the information provided by the regional experts with reference to different chosen criteria.

3.3 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.

3.4 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

3.4.1 Waste Characterization:

Waste characterization is important to understand the following:

1. Physical and chemical tests are preformed to evaluate whether waste is hazardous or non-hazardous.

2. Whether waste can be landfilled 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.

3.4.2 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_4, CO_2, NH_3 and H_2S 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

a) Refuse composition

b) 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. 3.5. All the contaminants present in the leachate do not exhibit peak at the same time and may not be of same shape.
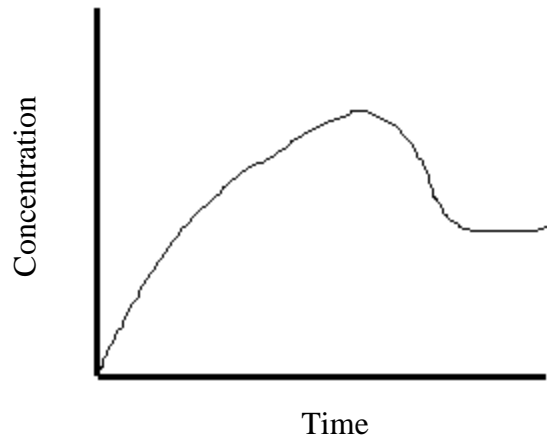
Fig. 3.5 Variation of leachate quality (concentration) with elapsed time

c) Temperature: Temperature affects bacterial growth and chemical reactions, there by affecting leachate quality.

d) Available moisture influences biodegradable and subsequent leaching of wastes.

e) 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

a) Amount of precipitation received.

b) Ground water interaction when the landfill base is below groundwater table.

c) 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.

d) 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 (Lv) is given by Eq. 3.1.

$$L_v = P + S - E - AW \qquad\qquad 3.1$$

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 in 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.

$$L'_V = P - ET - R - S \qquad\qquad 3.2$$

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

$$R = C_r \, I \, A \qquad\qquad 3.3$$

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: (i) it does not account permeability of cover layer (ii) 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. Some of the freely downloadable software such as hydrologic evaluation of landfill performance (HELP) model by US Environmental Protection Agency (USEPA) is a handy tool for performing water balance studies.

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, carbondioxide, 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 there by reducing greenhouse gas effect.

3.4.3 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 is receives. For example, comparison of a typical MSW landfill and hazardous landfill is shown in Fig. 3.6.
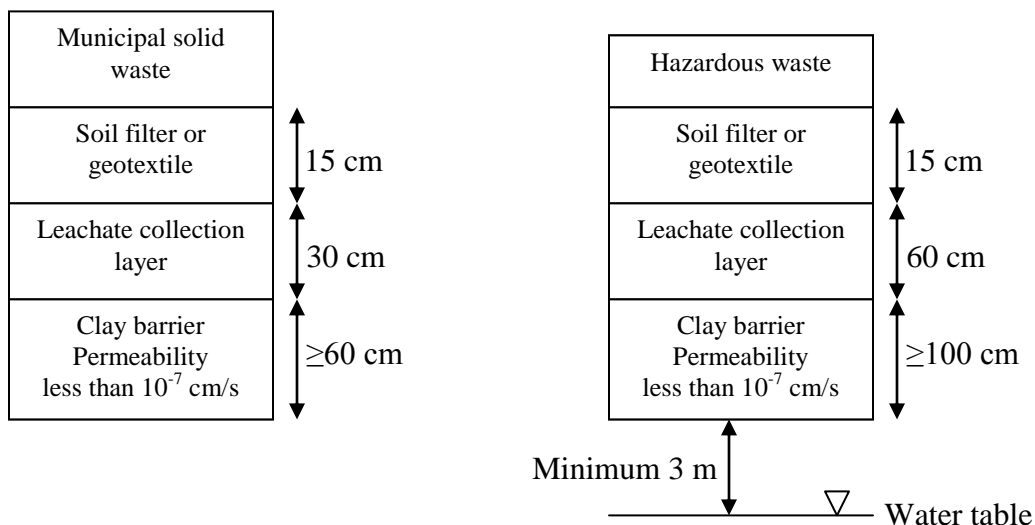

Fig. 3.6 A typical engineered landfill provision

Major role of soil in engineered landfill

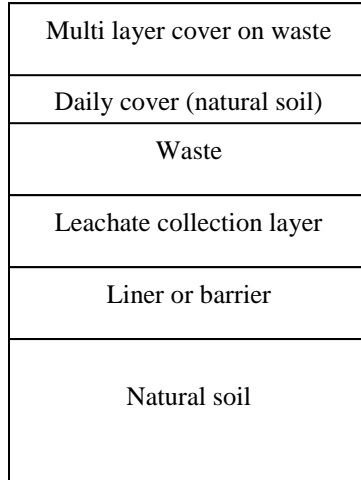As indicated in Fig. 3.7, the major role of soil in an engineered landfill can be summarized as follows:

Multi layer cover on waste
Daily cover (natural soil)
Waste
Leachate collection layer
Liner or barrier
Natural soil

Fig. 3.7 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 geosythetics, 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.

3.4.3.1 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. A typical eg; is geosynthetic clay liner popularly known as GCL. 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 Sreedeep 2012 a, b). UCS of not less than 200 kPa is desirable for liner material to bear 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 leading to enhanced 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.

3.4.3.2 Design philosophy of compacted liner

For the design of compacted liner it is important to understand the governing mechanism of contaminant transport through soil. Knowing the governing mechanism, the appropriate governing differential equation is formulated. The solution of governing equation is used to predict the concentration of contaminant with respect to space and time. Such predictions are used to evaluate whether the thickness of compacted liner (with a specific set of properties) would be able to protect the groundwater aquifer from pollution for the period of design life (which may be as high as 100 years). If not, then the thickness or the material of liner is modified to meet the requirements. To start with, the governing mechanisms of contaminant transport are discussed below:

1) Advection: It is the movement of contaminant along with the flowing water. Seepage velocity (v_s) become important. Movement of contaminant with velocity equal to ground water is termed as plug flow.

Mass flux of contaminant transported by advection is $f = n. v_s. C = v. C$ (3.4)

Mass flux is defined as the amount of mass transported across a given cross section in unit time. n is the porosity and C is the concentration.

Total mass flux due to advection $m_a = A * \int_0^t f . d\tau$ (3.5)

$$= A * \int_0^t n.v_s . C . d\tau$$

m_a is the mass of contaminant transported from landfill by advection. A is the cross section area through which contaminant passes. For non-reactive contaminant, contaminant moves with a velocity equal to flow velocity. If velocity is negligible, contaminant movement by advection is minimal.

2) Diffusion: It is the process of solute transport from a region of higher concentration to a region of lower concentration. The process is termed as molecular diffusion, D_m, when the solute migrates in pure water. However, diffusion in the porous media is restricted only to pore space and can be

expressed by Fick's first and second laws (Rowe et al. 1988), which corresponds to steady (Eq. 3.6) and transient diffusion (Eq. 3.7), respectively.

$$F_d = -nD_e\left(\frac{\partial C}{\partial z}\right) \qquad (3.6)$$

where, $D_e = \tau D_m$ and $\tau = \left(\dfrac{L}{L_e}\right)^2$

$$\frac{\partial C}{\partial t} = nD_e\frac{\partial^2 C}{\partial z^2} \qquad (3.7)$$

where F_d is the mass flux due to diffusion of solute per unit area per unit time, D_e is the effective diffusion coefficient, D_m is the molecular diffusion coefficient, τ is the tortuosity coefficient, $\dfrac{\partial C}{\partial z}$ is termed as concentration gradient, L is the straight line distance of the flow path, L_e is the actual distance traveled by the solute through the pore space and z is the distance of solute travel.

Total mass flux due to steady state diffusion $m_d = A * \int_0^t (-n.D_e.\frac{\partial C}{\partial z}).d\tau \qquad (3.8)$

Advective-dispersive transport:

Mechanical dispersion (D_{md}) occurs when the flow velocity is high or when there is sudden variation in flow velocity or due to non-homogeneity in porous media. Dispersion and diffusion process are normally lumped together and known as hydrodynamic dispersion coefficient (D).

$$D = (D_e + D_{md}) \qquad (3.9)$$

For low permeable soils like clays, D_e dominates and for high permeable soils like sands D_{md} dominates. D_{md} is represented as a linear function of velocity as represented by Eq. 3.10.

$$D_{md} = \alpha.v \qquad (3.10)$$

α is known as dispersivity (in m). It is scale dependent and changes with the extent of problem domain.

Total mass flux due to advective-dispersive transport is then given by

$$m_d = A * \int_0^t (\mathrm{n.\,v_s.\,C} - n.D.\frac{\partial C}{\partial z}).d\tau \qquad (3.11)$$

Sorption

Sorption process, as discussed in chapter 2, is an important contaminant retention mechanism that slow down or remove the contaminant from flowing pore water there by delaying its presence in groundwater. Therefore, for reactive contaminants, sorption plays an important role in deciding its fate (presence of contaminant with respect to space and time). Sorption is governed by physico–chemical properties of both solute and soil. Many soils can preferentially adsorb some type of contaminants to others.

When water containing dissolved contaminants (reactive) comes in contact with soil, the total mass of the contaminant will partition between solution and the soil. Concentration of contaminant sorbed on to the soil solids is given by

$C_s = (C_i – C_e).(V/M_s)$ \qquad (3.12)

Where C_i is the initial concentration of contaminant in pore water, C_e is the concentration of contaminant in pore water at equilibrium sorption reaction, C_s is the concentration of contaminant sorbed on soil mass, V is the volume of pore water which has interacted with M_s mass of soil. V/M_s is known as liquid to solid ratio.

For water flowing at a sufficiently low pace, the sorption reaction reaches equilibrium. The equilibrium sorption reaction is mathematically defined by using sorption isotherms. These isotherms define the equilibrium relationship between sorbed concentration on soil and equilibrium concentration present in solution.

$C_s = f(C_e)$ \qquad (3.13)

The simplest case of sorption can be modelled using linear isotherm represented by Eq. 3.14.

$C_s = K_d. C_e$ \qquad (3.14)

K_d is the partition coefficient representing the amount of sorption on soil. Such linear isotherms are good approximations for low concentration range. For higher range of concentration, sorption is non-linear. Two commonly used non-linear

isotherms are Langmuir isotherm and Freundlich isotherm as represented by Eqs. 3.15 and 3.16, respectively.

$$C_s = \frac{S_m b C_e}{1 + b C_e} \tag{3.15}$$

$$C_s = K_f C_e^n \tag{3.16}$$

Where S_m is the maximum capacity of sorption at all available sorption site (mono layer), b is a constant representing rate of sorption, K_f and n are empirical constants. Once the sorption isotherm are defined for a particular contaminant-soil system, then the solute sorbed on soil for any concentration of solution can be determined.

Sorption characteristics of contaminant-soil system are determined by batch test procedure (ASTM D 4646). The liquid to solid ratio and required pH for the batch sorption test is decided. Based on the expected range in the field, the range of concentration of solution is finalized. The soil is mixed with solution in the chosen liquid to solid ratio and shaken for 16 hrs using a mechanical shaker. The solution is then filtered and analyzed for equilibrium concentration (C_e). Knowing the initial concentration, the sorbed mass (C_s) can be determined based on Eq. 3.12. Plot the results of C_s vs. C_e and use appropriate sorption isotherm to define the trend mathematically.

Governing differential equation for contaminant transport

By considering conservation of mass within small soil volume and summing up the process explained above, the governing differential equation for contaminant transport (Fetter 1992) can be expressed as

$$n \frac{\partial C}{\partial t} = -\frac{\partial f}{\partial z} - \rho \frac{\partial S}{\partial t} - n\lambda C \tag{3.17}$$

f is the mass flux due to advective-dispersive transport = $n.v_s.C - n.D.\frac{\partial C}{\partial z}$, S is the sorbed concentration of contaminant and equal to C_s (Eq. 3.13), n is the porosity, C is the concentration of pore water at time t and distance z, D is the

hydrodynamic dispersion coefficient, ρ is the dry density of soil, λ represent first order decay reaction such as radioactive decay.

Substituting for f, assuming the simplest linear sorption isotherm ($\frac{\partial S}{\partial t} = K_d \frac{\partial C}{\partial t}$) and neglecting first order decay Eq. 3.17 can be represented as

$$\mathrm{n}\frac{\partial C}{\partial t} = nD\frac{\partial^2 C}{\partial z^2} - nv_s\frac{\partial C}{\partial z} - \rho K_d\frac{\partial C}{\partial t} \tag{3.18}$$

$$\left(1+\frac{\rho K_d}{n}\right)\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v_s\frac{\partial C}{\partial z} \tag{3.19}$$

$\left(1+\dfrac{\rho K_d}{n}\right)$ is termed as retardation coefficient "R" when linear sorption is assumed for contaminant-soil interaction. This assumption is valid for low concentration range of contaminant.

When the contaminant is reactive with the soil, the velocity of its travel may be less than the seepage velocity due to the retention process. To take this into account, relative ionic velocity (v_s/v_{ion}) is represented as

$$v_s/v_{ion} = \left(1+\frac{\rho K_d}{n}\right)$$

v_{ion} is the average velocity of reactive (non-conservative) contaminant species. For a non-reactive (conservative) contaminant, K_d will be negligible and hence v_s is equal to v_{ion}.   Eq. 3.19 is valid only for saturated soil where porosity is equal to volumetric water content (θ). For unsaturated soil n is replaced by θ.

Determination of hydrodynamic dispersion and retardation coefficient

A simple soil column test set up can be used to determine hydrodynamic dispersion and retardation coefficient simultaneously in the laboratory. A detailed description of these test procedures are discussed in the literature (Rowe et al. 1988). The soil sample is packed in the soil column with the compaction state expected in the field. The soil sample is saturated with water and the required contaminant solution of particular concentration is transferred on top of the

compacted soil. Depending upon the test facilities, the flow of contaminant solution can be under constant head or under constant flow rate. Constant flow rate is possible only for high permeable soil. The contaminant solution after flowing through the soil is collected as effluent from the bottom of the column. The effluent is collected at regular intervals of time, filtered and analyzed for concentration. This measured concentration is designated as C_t (concentration at time t). Concentration variation of effluent can be related to time or pore volume. Once the test is over, the soil is sliced and the concentration sorbed on soil mass is determined. This will give the concentration variation with depth. Therefore, measured C_t can be obtained as a function of time, pore volume or depth. The solution to the governing differential equation (Eq. 3.19) can be best fitted to the experimental data to obtain the values of R and D. Analytical solution for Eq. 3.19 for simple boundary conditions given below is represented by Eqs. 3.20 and 3.21 for non-reactive and reactive contaminants, respectively. The solution is applicable for barrier which is assumed to be infinitely deep and subject to a constant source concentration.

Initial condition C (z, 0) = 0   z >0
Boundary conditions C (0, t) = C_o (initial concentration)   t ≥ 0

$$C (\infty, t) = 0 \; t \geq 0$$

$$\frac{C_t}{C_0} = \frac{1}{2}\left[erfc\left(\frac{z - v_s t}{2\sqrt{Dt}}\right) + \exp\frac{v_s z}{D} erfc\left(\frac{z + v_s t}{2\sqrt{Dt}}\right)\right] \tag{3.20}$$

$$\frac{C_t}{C_0} = \frac{1}{2}\left[erfc\left(\frac{z - v_s t}{2\sqrt{Dt/R}}\right) + \exp\frac{v_s z}{D} erfc\left(\frac{z + v_s t}{2\sqrt{Dt/R}}\right)\right] \tag{3.21}$$

For a given liner, it is essential to check whether the provided thickness is sufficient or not. For this purpose, the parameters governing contaminant transport such as v_s, D and R is obtained as discussed above for the liner material and model contaminant used. v_s is obtained by determining discharge velocity and knowing the compaction state. Numerical or analytical modelling is performed to determine the fate of model contaminant (position of contaminant with respect to space and time). For 1-D modelling as discussed above, space refers to depth. Based on the numerical modelling, it is checked whether the liner

of given thickness and properties will be able to contain the contaminant for the given design life. It is expected that the concentration of contaminant reaching groundwater aquifer should not exceed the safe drinking water standards for the specified design or operational life. In case, it exceeds then the thickness or the material need to be reconsidered till it becomes safe. In certain cases, groundwater table is assumed at the bottom of the liner as worst case scenario. This means that the role of natural soil below liner is not considered. In the above modelling, the deterioration of liner material with aging is not considered. The modelling is done with a gross assumption that the material properties remain same with age.

Determination of diffusion coefficient

For determining diffusion coefficient of the contaminant the half-cell assembly, depicted in Fig. 3.8 (Sreedeep 2006), can be employed. This is mostly applicable for unsaturated soil where the flow component (advective component) is negligible. The contaminated soil half (source) is packed along with the uncontaminated soil half (receiver) as shown in the figure. With time, the contaminant migrates only by diffusion from source to receiver. After the test duration, the soil mass is sliced and analyzed to obtain concentration variation with depth. The analytical or numerical solution for differential equation for diffusion (Eq. 3.22) (Shackelford 1991) is fitted to the experimental results to obtain D_e and R parameters.

$$\frac{\partial C_t}{\partial t} = \frac{D_e}{R} \frac{\partial^2 C_t}{\partial z^2} \qquad (3.22)$$

where C_t is the concentration at any time t, D_e is the effective diffusion coefficient, R is the retardation coefficient and z is the distance.

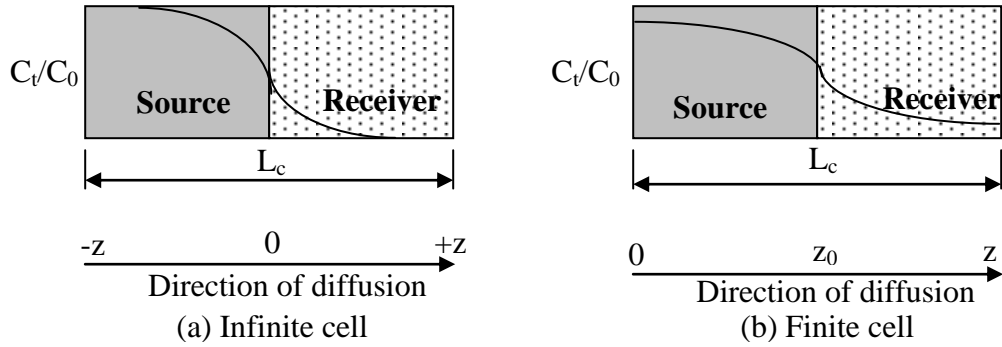(a) Infinite cell   (b) Finite cell

Fig. 3.8 Details of the half-cell

Solution of Eq. 3.22 depends on the boundary conditions, as presented below:

(i) When the concentration profile does not reach at the ends of half-cell, the soil medium can be considered to be infinite and the origin for x-axis is taken at the interface of the half-cell, as depicted in Fig. 3.8 (a). The initial and boundary conditions for this case can be stated as follows:

Initial conditions: C_t (z, t) = C_0 (for z≤0, t=0); C_t (z, t) = 0 (for z>0, t=0)

Boundary conditions: C_t (z, t) = C_0 (for z = -∞, t>0); C_t (z, t) = 0 (for z = ∞, t>0)

The solution for Eq. 3.22 corresponding to case (i) can be represented by Eq. 3.23 (Crank 1975):

$$\frac{C_t}{C_0} = \frac{1}{2} erfc\left(\frac{z}{2\sqrt{D_e t / R}}\right)$$
(3.23)

(ii) When the concentration profile reaches at the ends of half-cell, the soil medium can be considered to be finite and the origin for x-axis is taken at the end of the source half-cell, as depicted in Fig. 3.5(b). The initial and boundary conditions for this case can be stated as follows:

Initial conditions: C_t (z, t) = C_0 (for z≤0, t=0); C_t (z, t) = 0 (for z>0, t=0)

Boundary conditions: $\frac{\partial C_t}{\partial z} = 0$ (for z=0, t>0); $\frac{\partial C_t}{\partial z} = 0$ (for z=L_c, t>0)

where L_c is the total length of the cell.

The solution for Eq. 3.22 corresponding to case (ii) can be represented as follows (Carslaw and Jaeger 1959):

$$\frac{C_t}{C_0} = \frac{z_0}{L_c} + \frac{2}{\pi} \sum_{m=1}^{\infty} \frac{\exp(-D_e m^2 \pi^2 t / R_d L_c^2)}{m} . \cos\left(\frac{\pi m z}{L_c}\right) \sin\left(\frac{\pi m z_0}{L_c}\right) \qquad (3.24)$$

where z_0 is the interface between source and receiver.

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Model Questions

1. Explain the concept of 3Rs and waste management hierarchy?
2. What is the aim of integrated solid waste management program?
3. Bring out the difference between a natural attenuation landfill and an engineered landfill.
4. Explain the important details required for deciding landfill site.
5. Discuss in detail the multicriteria method for landfill site selection.
6. What is the importance of waste characterization?
7. What are the factors influencing leachate quality and quantity?
8. How to estimate leachate and gas generation rate?
9. With a neat figure, explain a conceptual liner and cover in landfill.
10. What is the major role of soil in a waste containment facility?
11. What are the requirements of compacted liner?
12. Explain in steps the design philosophy of waste containment liner system.
13. Starting from the basics, derive the differential equation for defining contaminant transport for reactive contaminant. Every phenomena governing differential equation need to be discussed in detail.
14. With neat figures, explain laboratory method for establishing a) hydrodynamic dispersion coefficient, b) retardation coefficient, c) diffusion coefficient of unsaturated soil with low water content d) partition coefficient.
15. What are the major differences between physisorption and chemisorption?
16. Explain the batch method for establishing sorption characteristics of the soil-contaminant system.
17. Explain the physical significance of sorption characteristics and its importance in contaminant transport modeling.
18. What are the different isotherms used for establishing sorption characteristics?
19. What are the different contaminant transport phenomena?
20. What is diffusion and when it is expected to dominate contaminant transport phenomena?
21. What is retardation coefficient and how it is helpful in determining ionic velocity?
22. A column test was conducted to determine dispersion coefficient. The soil used was a silty clay with specific gravity 2.7. The diameter and height of the saturated soil column is 5 cm and 7cm, respectively with a water content of 35%. Calculate the pore volume of the soil column. An advective flux equal to 0.003 kg/day/m^2 of 1000 mg/l SrCl$_2$ has flown through the soil column for 5 hrs. Determine the total pore volume and number of pore volume for 5 hrs. The longitudinal hydrodynamic dispersion coefficient is 1.267 x 10^{-9} m^2/s with a tortuosity coefficient of 0.7. The molecular diffusion coefficient of Sr^{+2} is 7.9 x 10^{-10} m^2/s. Determine the longitudinal dispersivity for the soil-contaminant system.

23. A batch test was conducted for 3 soil samples A, B, C with an initial concentration of 100 mg/l of $SrCl_2$. 5 g of each of the soil sample is mixed with 50 ml, 100 ml, and 250 ml of $SrCl_2$ and the values of C_e for A are 10, 8 and 6 mg/l, for B it is 12, 10 and 8 mg/l and for C it is 4, 3, 2 mg/l respectively. Compare the reactivity of the soil-contaminant system of the three soils and comment on the role of liquid to solid ratio on the sorption capacity of the three soil. Make any suitable assumptions.

24. Specific discharge in the field is given as 1.68×10^{-8} m/s. Bulk density of fully saturated porous medium is 1.6 g/cc with volumetric water content of 0.4. Partition coefficient of lead obtained by linear isotherm is 10 ml/g. Determine average velocity of lead. What will be the velocity of lead if it is assumed as non-reactive with porous medium?

25. A drainage pipe became blocked during a storm event by a plug of sand and silty clay as shown in figure Q3.1. When the storm ceased, water level above ground is 1 m. Permeability of sand is 2 times that of silty clay.
    a) Obtain variation of head components and total head for the length of drainage pipe
    b) Calculate pore water pressure at centre of sand and silty clay
    c) Find average hydraulic hydraulic gradient in both soil plugs.
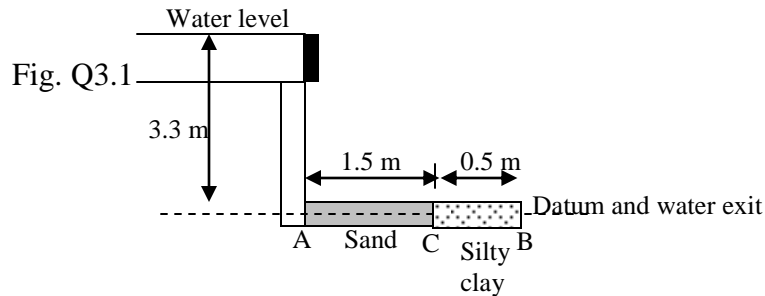
Fig. Q3.1

26. Determine the quantity of flow and seepage velocity for constant head set ups given below (Fig. Q3.2) in SI units.

Fig. Q3.2

ksat= 3×10^{-5} cm/s
saturated volumetric water content = 0.5

ksat= 3×10^{-5} cm/s
Specific gravity = 2.65; w=25 %