Environmental Geotechnics—A Review

Sudhakar M. Rao*

A. Sridharan*

Introduction

Environmental geotechnics may be viewed as the role of geotechnical engineering in the protection of environment. Hazards to the environment may arise from natural causes or human activities (Morgenstern, 1985). Examples of natural hazards are earthquakes, floods and typhoons and a study of their causes and effects has been the concern of civil engineering profession worldwise. Hazards from human activities mainly manifest as contamination of ground and surface water resources, and of foundation clays (Morgenstern 1985, Environmental Engineering Research Council, ASCE, 1990). The sources of surface and subsurface contamination have been grouped into 4 convenient categories (Pierce et. al 1986):

—Disposal of wastes from industrial, mining and domestic activities that use the surface and subsurface as waste receptors.

—Industrial and commercial operations involving the handling of large quantities of chemical substances which may be accidentally released into the environment in significant quantities as a result of leaks and spills occurring during transport, storage and for utilization.

—Agricultural operations involving intentional application of chemicals to the land.

—Water reclamation entailing either direct or indirect artificial recharge of water with contaminated water.

Providing engineering solutions to minimize surface and subsurface contamination has become the dominant concern of governmental regulatory agencies and of geotechnical engineers particularly in North America and Europe over the past two decades. Unfortunately, the task of mitigating environmental contamination arising from various human activities has not been receiving the consideration it deserves from governmental regulatory agencies and the engineering community in India. The authors have hence attempted to review the current practices and advances in the

* Department of Civil Engineering, Indian Institute of Science, Bangalore 560 012, India.

field of geotechnical engineering with regards to protection of surface and subsurface contamination as a step towards highlighting the role of geotechnical engineering in pollution control. The role of geotechnical engineering in mitigating environmental contamination may be categorized under:

—Protection of ground and surface water resources.

—Providing engineering solutions to contaminated foundation clay problems.

Geotechnical Engineering in the Protection of Ground and Surface Water Resources

Nature of Wastes : The bulk of wastes from industrial, mining and domestic activities are constituted by 'solid wastes' and by definition include any garbage, refuse or sludge from a waste treatment plant, water supply treatment plant, air pollution control facility and other discarded materials from industrial, mining and agricultural activities (Hazardous Waste System, 1987). A hazardous waste refers to a waste which because of its quantity, concentration or physical, chemical or infectitous characteristics may pose danger to human health or environment (Hazardous Waste System, 1987). Non-hazardous wastes are mainly the municipal wastes while the hazardous wastes arise from industrial and mining activities.

Impact of wastes on ground water quality

Precipitation that infiltrates the solid wastes disposed on land can mix with liquids already present in the waste and leach compounds from the solid waste. The result is a liquid known as leachate containing dissolved inorganic and organic solutes. The leachate can move down under gravity into the subsurface and impact the ground water thereby causing its contamination.

Ground water naturally contains a number of dissolved inorganic constituents that may be grouped under major, secondary, minor and trace constituents. The major constituents, constitute the bulk of the mineral matter contributing to the total dissolved solids (TDS). The minor and trace constituents such as arsenic, barium, cadmium, chromium, fluoride, lead, mercury, selenium and silver are classified as the primary contaminants since they pose a direct health risk; likewise the major, secondary and minor constituents such as chloride, copper, iron, manganese, sulfate and zinc are classified as secondary contaminants as they affect the aesthetic quality of water by imparting taste, odour and staining fixtures. The maximum permissible concentrations of primary contaminants in drinking water vary from 0.002 ppm to 10 ppm, while, the maximum contaminant levels for the

secondary contaminants are higher and range from 0.05 ppm to 250 ppm (Freeze and Cherry 1979, Fetter 1990).

Table 1 presents the hazardous chemicals that may be present in municipal, mining and various industrial waste streams (Lining of Waste Impoundment and Disposal Facilities 1983, Barnhart 1978, Moore and Luoma 1990). Comparing the data in Table 1, it is seen that the municipal waste leachate contains 2 - 2000 times and the mining and industrial waste leachates 20 - 10^6 times higher contaminant concentrations than the maximum permissible levels in drinking water. It hence becomes the task of the geotechnical engineer to provide safe disposal of wastes that allows permissible contamination of the surface and ground water resources.

Current Methodologies for Land Disposal of Solid Wastes

Land disposal of solid wastes is usually achieved by one of the three methods; the landfill, waste piles or surface impoundments (Pierce et. al, 1986). In a landfill, municipal or hazardous wastes are buried in layers beneath the ground surface and covered with a suitable soil material. Waste piles are produced by piling solid wastes on the ground surface; pile slopes may or may not be compacted as they are formed. Wastes that are deposited in spoil piles usually have relatively low moisture contents, such as piled overburden from mining operations or materials that dewater quickly, such as waste gypsum from phosphate industry. Surface impoundments are often used for the disposal of such slurried wastes as red muds from aluminium mining operations and uranium tailings. Generally, surface impoundments consist of an open basin of the waste material surrounded by containment berms.

Leachates from landfills, waste piles and surface impoundments are often a potential source of ground water contamination. Numerous investigations in North America and Europe have shown that in non-arid regions, infiltration of water through refuse causes water table mounding within or below the landfill. Water table mounding causes downward movement of leachate and outward flow from the landfill. Downward flow of leachate may threaten ground water resources. Outward flow usually causes leachate springs at the periphery of the landfills or seepage into streams and other surface bodies (Fetter, 1990). The volume of leachate that is produced is a function of the amount of water percolating through the waste. Land disposal of solid wastes in humid areas is more likely to produce large volume of leachate than land disposal in arid zones.

Contaminant Migration

Contaminants that can migrate from impoundment sites include inorganic and organic solutes in aqueous solutions and organic fluids. The contaminants may originally enter the impoundment as solids and subsequently become leached by water and other fluids. The leachate can move

TABLE 1

Some hazardous chemicals in Municipal, Mining and Industrial Waste Streams (in milligrams/litre)

Source	As	Cd	Cr	Cu	Pb	Hg	Se	Zn
Municipal wastes	<0.01	0.01	0.05	<10	<5	<0.2	<0.001	0.1-100
Mining and metallurgy (copper mining & smelting)	10-1000 (0.05)	0.5-13 (0.01)	✕ (0.05)	✕ (0.1)	✕ (0.05)	(0.002)	✕ (0.01)	✕ (5)
Paints and dyes		✕	✕	45-27000	24-3000	✕	✕	95-18000
Electroplating and metal finishing			✕	✕				✕
Chemical manufacturing			✕	✕		✕		
Batteries		✕	✕	✕				
Petroleum and coal	0-60	0-11	1-56500	1-530	0-1900	0-26		1-3000
Pulp and paper industry sludges		2-32	20-180	60-330	30-1300	✕	✕	154-4000
Leather tanning waste		2	13-53		130-180			160-700

Source : Barnhart (1978), Lining of waste impoundment and disposal facilities (1983), Moore and Luoma (1990), X indicates presence of conta-minant in the waste stream and the ranges have not been provided as they were unavailable. Values in parantheses specify maximum permissible limits in potable water.

downward from the impoundment site into the water table and cause ground water contamination. When leachate from a landfill mixes with ground water, it forms a plume that spreads in the direction of flowing ground water. Consequently the contaminant migration can be visualized to consist of two processes:

—Migration from impoundment site to ground water.

—Movement of solutes contained in ground water.

The recognized mechanisms that affect the transport of chemical solutes contained in ground water include

—transport as a result of bulk motion of the fluid phase (advection).

—dispersive transport caused by velocity variations about the mean velocity.

—movement of contaminants owing to chemical concentration gradients (diffusion).

—solute attenuation.

Freeze and Cherry (1979), Folkes (1982), Rowe (1988) and Fetter (1990) provide elaborate mathematical modelling and the physical concepts involved in transport of solutes by ground water.

Pollution Control Barriers

Soils are often used in parts of containment systems in waste disposal practice to inhibit the flow of liquid contaminants into the environment. Because of their low hydraulic conductivity, in-situ and recompacted clayey soils are used as "impervious" liners for landfills and waste storage impoundments. Additionally, the clay soils owing to their charged surface characteristics can interact with the contaminants in the leachate (on permeation) and retain them, thereby reducing the contaminant load polluting the ground water.

Soil remains as an adequate barrier material for many applications and in most cases a soil liner system will be cost effective; however, for certain conditions (presence of chemicals that can lead to large increase in soil permeability or unfavourable site conditions) an alternative or supplemental material to natural soil may be necessary. To satisfy this need, synthetic liners or flexible membrane liners (FMLS) are used. Properly selected, installed and maintained synthetic materials can minimize discharge quantities from a waste facility. In order to minimize the amount of leachate infiltrating the ground water, modern landfills are also being provided with a leachate collection system that drains out the leachate from the landfill (into a storage tank), before it can percolate through the engineered barriers.

If the waste extends below the water table, then it is necessary to keep the ground water from flowing through it. This is usually achieved by installing a low permeability vertical barrier around the waste body.

Based on the above considerations, barriers will usually fall within one of the following categories (*i*) natural clayey deposits, (*ii*) compacted clayey linears, (*iii*) cut-off walls and permeable surrounds, (*iv*) synthetic liners and (*v*) leachate collection systems (Rowe 1988, Fetter 1990).

Natural clayey deposits-Natural clay deposits can provide an almost ideal barrier in many situations and are used for disposal of municipal wastes, construction debris and even sometimes hazardous industrial wastes (Fetter, 1990). Naturally occurring depressions or excavated pits are used for the disposal of solid wastes. The underlying clay acts as an important medium for the retention of contaminants (transported by the leachate) by processes such as ion-exchange, adsorption, precipitation and bio-degradation. Nevertheless leachate migration from the disposal site does occur and it is important to be able to estimate the rate of movement and potential impact on underlying ground water resources. Landfills in natural clay deposits are termed as natural attenuation landfills and should be preferably placed well above the water table to promote maximum contaminant attenuation in the unsaturated zone. Leachate generation may be reduced by capping the landfill with 2' - 3' of compacted soil (Fetter, 1990).

Compacted clay liners-form part (or all of the barrier system in a lined landfill (Figure 1). They can be comprised of naturally occurring clay soils, mixes of clay soils or mixes of processed clay minerals with soils. The compacted clay liners are usually 0.3 to 1.2 m thick with coefficient of permeability $< 10^{-7}$ cm/sec. The recompacted clay liners with recompacted side walls are installed to minimize the amount of seepage from the excavation. A well constructed clay cap is essential in reducing the amount of leachate that must be handled in a lined landfill (Fetter, 1990).

Cut-off walls and permeable surrounds

These ground water flow control measures are commonly used to limit contaminant migration from existing sites that have not been adequately designed. They may also be used to control migration from new sites where it may be desirable to isolate ground water in a shallow aquifer beneath the landfill (D'Appolania 1980, Rowe 1988, Fetter 1990).

In the case shown in Figure 2, the ground water table is high enough, to cause flow through the burried waste. Slurry trench cut-off walls can be installed around the waste site (Figure 2) comprising of a slurry type mixture of soil, bentonite and water. The slurry wall locally lowers the ground water table and also reduces the flow into the aquifer changing the contaminant flow beneath the landfill from an advection controlled system (quicker
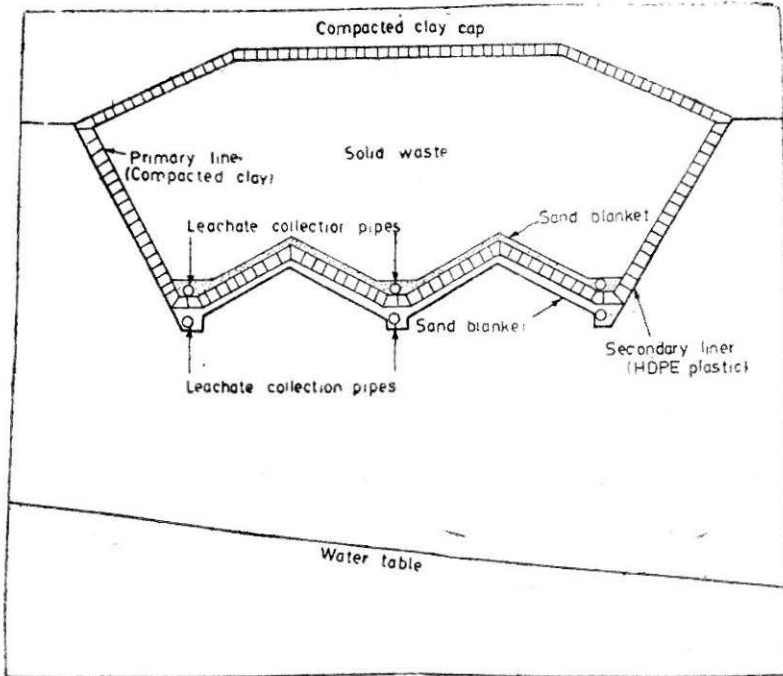
FIGURE 1 Double Lined Landfill with Leachate Collection System (Fetter, 1990)

transport) to a diffusion controlled system (slow transport), thereby substantially reducing the impact of contaminants on off site ground water quality.

As an alternative to the cut-off walls to alter the ground water flow pattern, the 'pervious surround concept' has been proposed (Matich and Tao, 1984). This involves surrounding the waste pit with a multilayered pervious envelope with less pervious material (example, clay soil) adjacent to the waste and more permeable material (example, sand or gravel) outside of this, as shown schematically in Figure 3. In this way, water flow is directed around the outside of the pit rather than through the pit, and contaminant migration would be predominantly by a slow diffusion process from the waste pit through the less permeable material. The pollutants escaping the waste pit would contaminate the water flowing through the pervious layer where it is transported by advective-dispersive process.

Synthetic liners

Synthetic liners are usually relatively thin (0.25 to 2.5 mm) and are used independently or in conjunction with compacted clay barriers in lined landfills that store hazardous wastes (Koerner 1986) (Figure 1). The major type of synthetic liner materials are plastics (example, polyvinyl chloride
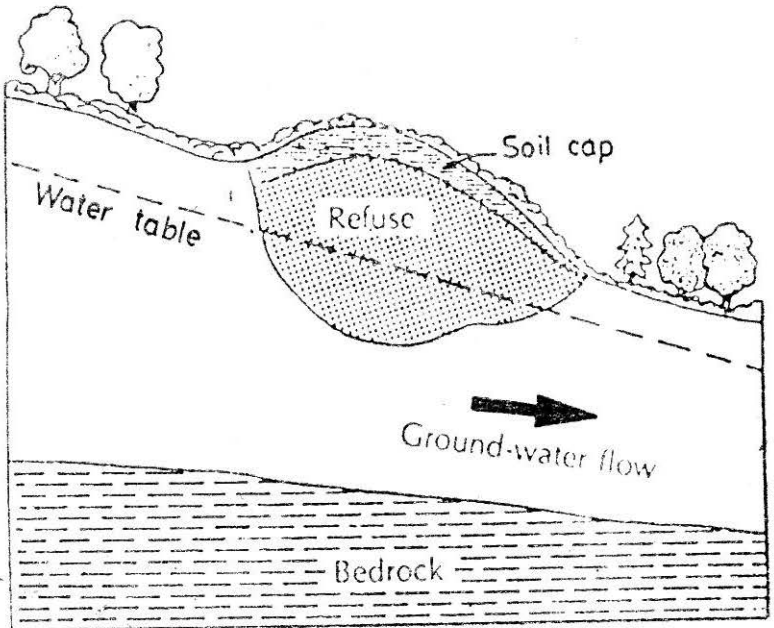
A No control measures
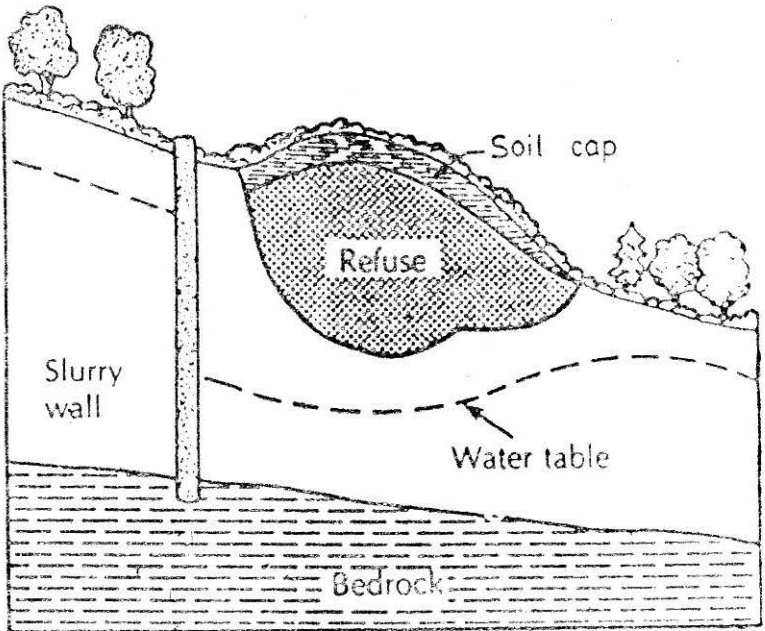
B Upgradient slurry wall to lower water table

FIGURE 2 Use of Slurry Walls to Lower Ground Water Table and Isolate Buried Waste
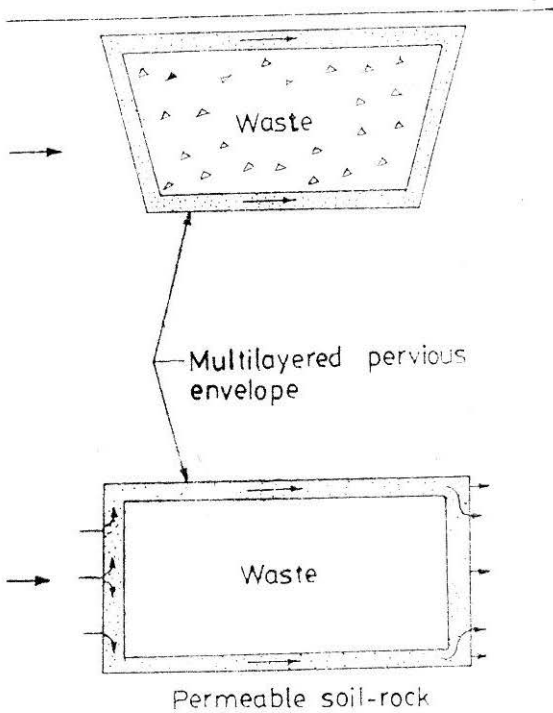   (Fetter, 1990)

FIGURE 3 Schematic Diagram of Pervious Surround Concept (Rowe, 1988).

PVC, low density polyethylene LDPE, high density polyethylene HDPE) and rubbers (example, butyl rubber, neoprene) (Koerner, 1986). Ideally the synthetic liner materials are voidless continuums and fluid passage occurs by diffusion under vapor pressure differentials, osmosis due to chemical gradients and absorption due to polymer solubility (Kays 1977, Folkes 1982). Field permeability however includes leakages through pin holes, punctures, tears, poor seams and otherwise degraded or damaged sections of the material arising from chemical incompatibility between the waste and the membrane. Kays (1977) has estimated the apparent hydraulic conductivities for properly installed membrane liners to range from 5×10^{-12} to 5×10^{-14} m/s for heads of about 6m.

Chemical compatibility of the synthetic liner to waste is determined by immersion tests (Koerner, 1986). Here candidate liner samples are exposed to the actual leachate or to a synthesized one, in either complete immersion, one-sided immersion (tub tests) or pouch encapsulation. The samples are removed at periodic intervals (usually upto 120 clays) and tested for changes in weight, thickness, strength, elongation or modulus. The liner which shows the least amount of property change is recommended.

Leachate Collection Systems—Serves several functions (Rowe, 1988).

—by lowering the height of the leachate mounding, leachate seeps and consequent contamination of surface waters can be minimized.

—by reducing the head in the leachate, the hydraulic gradient through the underlying barrier and hence the velocity of flow through the landfill can be reduced to acceptable levels.

—by removing contaminants from the landfill, the mass of contaminant available for transport into the hydrogeological system will be reduced.

The leachate collection system in a lined landfill (Figure 1) consists of a blanket of sand or gravel, with perforated drainage pipes, lying on the liner. The base of the liner is sloped towards the drain tiles. Leachate drains through the leachate collection system to a holding tank or sewer and is ultimately removed and treated. Clay-lined systems can be designed to collect about 70 to 90 percent of the leachate produced. The remainder of the leachate will seep through the liner. A double liner and secondary-leachate collection system installed beneath the primary liner (Figure 1) can be constructed to capture the leakage through the primary liner (Fetter, 1990).

Of the two types of liners commonly used in waste disposal facilities, namely soil and synthetic liners, there seems to be a greater emphasis in literature on the performance of soil liners, indicative of the extensive use of clay soils as pollution control barriers. The laboratory results have highlighted the role of remoulding water content, the method of compaction, the degree of saturation, the permeameter type, the hydraulic gradient, the direction of flow and the choice of permeant type on the permeability of compacted clay specimens. Table 2 summarizes the influence of various parameters on the permeability behavior of laboratory compacted specimens. Available data (in Table 2) show that with the exception of permeant effect, all other parameters cause < 10 fold variations in permeability of laboratory compacted clay which is not considered significant in engineering measurements. Research has indeed shown that the issue of test variables are far less important than the problem of obtaining and testing a specimen in the laboratory that duplicates all macro- and micro-fabric features existing in the clay liner in the field.

In response to the observed differences between the laboratory and field permeability values, waste disposal facilities utilizing compacted clay liners in United States of America are now required to demonstrate the field permeability of field compacted samples (Sai and Anderson, 1990). Daniel (1984) recommends that field permeability tests be conducted on small test sections, on the first lift or two of the clay liner or on the completed liner. Day and Daniel (1985). Chapuis (1990), Sai and Anderson (1990) detail procedures to conduct field permeability test for clay liners.

TABLE 2

Influence of various parameters on the permeability of laboratory compacted clays

Parameter	Effect on permeability coefficient (k)
1. Compaction conditions	
— moisture content	specimens compacted dry of optimum may have 2 to 3 times higher k than samples compacted wet of optimum, at the same compactive effort.
— method of compaction	at wet of optimum, statically compacted specimens may have 2 to 6 folds higher k than kneading compacted samples
— degree of saturation	at S_r value of 85% or more, presence of air-bubbles lead to variation in k by 2 to 5 times
2. Permeameter type	no discernable effect on k
3. Hydraulic gradient	large hydraulic gradients (40-200) cause migration of particles and blocking of pores resulting in a 2 to 5 fold decrease in k
4. Direction of flow	permeability insensitive to direction of flow for samples compacted dry and wet of optimum respectively
5. Permeant type	(10 to 200 fold variations (typically <10) in k may result if permeant with a chemistry that is widely different from the waste leachate is used.

Inspite of the shortcomings of the laboratory testing procedures (to estimate field permeability), laboratory permeability tests are considered useful for preliminary design and for general guidance during the final design, example, in comparing several possible materials for use in constructing the liner; the most important use of laboratory permeability tests would however be to rapidly evaluate the impact of the waste chemical on the permeability of the compacted clay since chemical reaction between the contained fluid and liner materials may cause a liner to break down or become significantly more permeable which would result in serious ground water contamination problems. Rao and Sridharan (1987) have reviewed the changes in permeability of-lay soils upon on interaction with chemicals and the findings are presented. Additional available literature has also been included (example, Mitchell and Madsen, 1987).

Effect of chemicals on permeability of clays

Based on the available work, the effect of various chemical contaminants on clay permeability characteristics may be grouped under:

—Influence of inorganics

   acids

   alkalis

   salt solutions

—Influence of organics

   water immiscible organics

   water miscible organics.

The influence of inorganic and organic permeants on the-clay permeabilities are summarized in Table 3.

Design considerations for a compacted clay liner

(1) Relying solely on laboratory test of results to predict the permeability of a full scale clay liner is undesirable as the laboratory results may significantly underestimate the permeability of the clay liner in the field. Laboratory permeability tests employing similar water contents, compactive effort and cold size as in the field could be useful in preliminary design, regarding choice of soil material for liner construction.

(2) Field permeability tests are likely to yield more reliable estimates of the permeability of the compacted clay liner.

(3) Compactive efforts employed in the field should ensure that large clods of clay are properly hydrated and adequately broken down. More importantly the clay liner shouldnot be allowed to dry out, during or after construction. To prevent desiccation it may be necessary to cover the liner with soil or some other protective material.

(4) A knowledge of the chemistry of the stored waste is essential so that the chemistry of the leachate generated can be predicted with reasonable confidence.

Determining the impact of either the actual or laboratory prepared waste leachate on the permeability of clay to be used in liner construction is essential. Laboratory permeability tests are well suited for this purpose.

The use of a synthetic flexible membrane liner in conjunction with a compacted clay liner may be desirable in circumstances where the chemical wastes have detrimental effects on the integrity of clay liners.

Thus, if adequate care is taken in the construction of a compacted clay liner they can be successfully utilized as pollution control barriers inwaste disposal facilities.

TABLE 3

Influence of inorganic and organic contaminants on permeability of clay soils

Permeant	Clay type	Variation in soil permeability
1	2	3
Inorganic contaminants		K_f/K_w
Acids		
7% HNO_3	Bentonite	5.6—7.7
3.65% HCl	Bentonite	10.2
7% HNO_3	Kaolinite	
3.65% HCl	Kaolinite	3.5
Synthetic tailings solution pH=2.0	CL and CH clays (clay mineralogy not provided)	0.2 to 0.003
Alkalis		
4% HaOH	Bentonite	0.3
NaOH solution pH=13	Magnesium-Montmorillonite	0.07
Salt solutions		
0.001 N NaCl replaced by 0.1N NaCl solution	Montmorillonite	1.25
0.6N NaCl solution replaced 0.1 N NaCl solution	Illite-silt mixture	0.3
215 ppm Lead-Zinc solution (pH=2.5)	Montmorillonite	15-200
	Kaolinite	2—9
Municipal Landfill leachate solution	Glacial till (predominant clays illite and kaolinite)	No change

k_f = final permeability coefficient on permeation of the contaminant

k_w = permeability coefficient with water.

Organics

Non-polar organics

Pure Heptane Pure Xylene	Compacted, kaolinite, smectite	10^2 to 10^3 increase with rigid wall permeameters

(Contd.)

TABLE 3 *(Contd.)*

1	2	3
Dilute Heptane (53 mg/L)	Compacted natural soil (illite-smectite)	None with rigid wall permeameter
Pure Heptane	Comapacted kaolinite	10^2 decrease with flexible wall permeameter
Polar Organics		
Pure Methanol	Compacted kaolinite, illite,	10^3 increase with rigid wall permeameter
60%—80% Methanol	Compacted kaolinite	None with rigid wall permeameter
Pure Methanol	Compacted kaolinite	None with flexible wall permeameter
Pure Ethanol	Compacted natural soil (illite-smectite)	10 fold increase with rigid wall permeameter
Pure Acetone	Compacted kaolinite	2-10 fold increase with rigid wall permeameter

Geotechnical engineering in contaminated foundation clay problem

It was earlier indicated that a major source of environmental contamination is industrial and commercial operations involving the handling of large quantities of chemical substances which may be accidentally released into the subsurface in significant quantities as a result of leaks and spills occurring during transport, storage and utilization activities. Contamination of sub-surface from spilled chemicals has resulted in some expensive foundation failures. Lukas et al (1972) gave a detailed account of the foundation failures of three industrial buildings as a result of chemical reaction between the subsoil and accidental chemical spillages, which were acidic in two of the cases and basic in the other. They attributed the large settlements recorded in each case to soil losses as a result of dissolution of either the lime stone in glacial till or to the high silica sand subsoils in the chemical contaminants. They also recorded substantial reductions in SPT blow-counts in borings made after the chemical contamination compated with the original borings.

Sridharan et. al (1981) have discussed a case history of extensive cracking

damage to light industrial buildings in a fertilizer factory as a result of heaving of the foundation soils on phosphoric acid contamination resulting from leakage of the industrial effluents into the subsoils. The foundation soil in the factory premise comprises of the residually formed 'red soil' that predominantly contains kaolinite mineral bonded by iron oxide coatings and exhibit a low swelling potential and marginal swelling pressure. Chemical analysis of data showed that at locations where large distress to the super-structures had occurred, the pH of the foundation soil was quite low (pH = 2-3) apparently brought about by the spilled phosphoric acid. Free swell tests conducted with the contaminated subsoils showed it to occupy unusually large sediment volumes in water ($\approx$ 6 cm^3/g as opposed to sediment volumes of 1-3 cm^3/g observed for the uncontaminated soil specimens), Laboratory oedometer tests with the contaminated sub-soil specimens showed that very slow swelling (0.1 % height of the soil specimen per 24 hours) occurs on percolating phosphoric acid through the soil specimen. The low pH of the contaminated sub-soil, the large sediment volume in the free-swell test, the slow tendency to swell on percolation of phosphoric acid in laboratory oedometer tests lead to the following hypothesis for heaving of soil on acid contamination. The acid percolating into the sub-soil acts to destroy the iron oxide coatings on the soil particles thereby releasing the soil particles held by cementation bonding. Simultaneously, the low pH imparted to the soil particles by the percolating acid, favors them to adopt a flocculated particle arrangement. The release of cemented soil particles and the mobilization of a flocculated particle arrangement on acid percolation manifests as heave of the sub-soil mass causing distress to the structures founded on them.

A similar case of accidental spillage of highly concentrated caustic soda solution into the subsoils as a result of spillages and seepage through cracked drains in an industrial establishment in Ghana that caused considerable structural damage to light industrial buildings in the factory in addition to localized subsidence of the affected area has been reported by Kumapley and Isahola (1985). The pH of the uncontaminated soil was 6.5 while that of the contaminated sub-soils were as high as 10-11. Deterioration in soil strength as a result of chemical reactions in soil was considered as a possible cause of structural distress. Laboratory investigations indeed showed general decrease in undrained soil strength with increasing caustic soda concentrations. Caustic soda imparts a negative charge to the soil particles (manifested as the high pH of the soil-water system) and acts as a dispersing agent; the consequent decrease in inter-particle attractive forces is considered responsible for the loss of undrained strength. Kumapley and Isahola (1985) state that the extent of deterioration in strength will also be a function of the level of ground water table and its range of fluctuation, since the ground water will not only influence the concentration of the contaminant available for reaction with the soil, but would also aid the removal of some of the products of the chemical reaction, by way of leaching.

The above case histories highlight the need for geotechnical engineers to take measures to prevent possible long-term effects of chemical contamination of foundation clays resulting from careless storage, handling and disposal of industrial chemicals and effluents. Over more than two decades the author/s have been conducting research on the physico-chemical factors governing the engineering behavior of clay soils. The role of physico-chemical factors in influencing the engineering behavior of clay soils has recently been elucidated by one of the authors (Sridharan, 1990).

Conclusions

The major sources of surface and sub-surface contamination are land disposal of industrial, mining and agricultural wastes and accidental leakage or spillage of chemicals during industrial operations. Land disposal of wastes is achieved through landfills, waste piles or surface impoundments. Leachates generated in the waste disposal facilities contain inorganic and organic chemicals that can move down under gravity and contaminate the ground water resources. The migration of waste leachates across compacted clay barriers in waste impoundment sites is essentially a process of flow through porous medium and is governed by Darcy's law. The factors affecting the movement of contaminants in ground water are advection, dispersion, diffusion and attenuation. Natural clayey deposits, compacted clay liners, synthetic liners, cut off walls and permeable surrounds and leachate collection systems are employed individually or in combinations, to minimize movement of contaminants from waste disposal facilities.

Laboratory test results have been found to underestimate (10-1000 times) the actual permeability of compacted clay liners in the field. Differences in clod sizes used in the laboratory testing and that existing in the field and the difficulty in obtaining a laboratory sample which contains a representative distribution of macro-features existing in the field, contribute to the incapability of laboratory samples exhibiting field permeabilities. Laboratory permeability tests are mainly considered useful in rapidly evaluating the impact of waste chemicals on the permeability of compacted clay liners.

Case histories in literature highlight the detrimental effects of contamination of foundation clay in terms of distress to the structures founded on them.

REFERENCES

BARNHART, B.J. (1978). The disposal of hazardous wastes, *Environmental Science and Technology*, 12, 1132-1136.

CHAPUIS, R.P. (1990). *Sand-bentonite liners : field control methods, Can. Geotech J.* 27, 216-223.

DANIEL, D.E. (1984). Predicting hydraulic conductivity of clay liners, *J. Geotech Engg. ASCE*, 110, 285-300.

D 'APPOLONIA (1980). Soil-bentonite slurry trench cutoffs, *J. Geotech. Engg. ASCE*, 106, 399-417.

DAY, S.R. and DANIEL, D.E. (1985). Hydraulic conductivity of two prototype clay liners, *J. Geotech. Engg. ASCE*, 111, 957-970.

Environmental Engineering Research Council ASCE (1990). Ground water protection and reclamation, *J. Env Engg ASCE*, 116, 654-662

FETTER, C.W. (1990). *Applied Hydrogeology*, II edition, CBS Publishers, New Delhi.

FOLKES, D.J. (1982). Control of contaminant migration by the use of liners; Fifth Canadian Colloquium, *Can. Geotech. J.* 19, 320-344.

FREEZE, R.A. and CHERRY, J.A. (1979), *Ground Water*, Prentice Hall Inc., New Jersey.

Hazardous Waste System (1987). *U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response Report*, Washington D.C.

KAYS, W.B. (1977). *Construction of Linings for Reservoirs, Tanks and Pollution Facilities*, John Wiley, New York.

KOERNER, R.M. (1986). Use of flexible membrane liners for industrial and hazardous waste disposal, *Hazardous and Industrial Solid Wastes Testing and Disposal : Sixth volume ASTM STP* 933, D. Lovenzen, R.A. Conway, L.P. Jackson. A. Hamza, C.L. Perket and W.J. Lacy (eds.), ASTM Philadelphia, 195-207.

KUMAPLEY, N.K. and ISHOLA, A. (1985). The effect of chemical contamination on soil strength, *Proc. XI ICSMFE Vol.* 3, San Francisco, A.A. Balkema, Rotterdam, 1199-1201.

Lining of waste impoundment and disposal facilities (1989). *U.S. Environmental Protection Agency Report SW*-870, Washington D.C.

LUKAS, R.G. and GNAEDINGER, R.J. Jr. (1972). Settlement due to chemical attack of soils, *Proc. ASCE Speciality Conf. on the Performance of Earth and Earth-Supported Structures* Lafayette, Indiana, 1087-1104.

MATICH, M.A.J. and TAO, W.F. (1984). A new concept of waste disposal, *Proc. of the Consulting Engineers of Ontario—Can. Geotech. Society, Seminar on Design and Construction of Municipal and Industrial Waste Disposal Facilities*, Toronto, 43-60.

MITCHELL, J.K. and MADSEN, F.T. (1987). Chemical effects on clay hydraulic conductivity, *Proc. ASCE Speciality Conf. Geotech. Practice for Waste Disposal*-87, R.D. Woods (ed.), ASCE, New York, 87-116.

MOORE, J.N., and LUOMA, S.N. (1990). Hazardous wastes from large scale metal extraction, *Environmental Science and Technology* 24, 1278-1285.

MORGENSTERN, N.R. (1985). Geotechnical aspects of environmental control, *Proc. XI ICSMFE* 1, San Francisco, 155-185.

PIERCE, J.J., SALLFORS, G. and MURRAY, L. (1986). Overburden pressures exerted on clay liners, *J. Env. Eng. ASCE* 112, 280-291.

RAO, S.M. and SRIDHARAN, A. (1987). The performance of clay liners on chemical permeation, *Proc. Indian Geotech. Conf.* 1, Bangalore, 405-48.

ROWF, R.K. (1988). Contaminant migration through ground water —the role of modelling in the design of barriers : Eleventh Canadian Geotech. Colloquium, *Can. Geotech. J.* 25, 778-798.

SAI, J.O. and ANDERSON, D.C. (1990). Field hydraulic conductivity tests for compacted soil liners, *ASTM Geotech. Testing Journal* 13, 215-225.

SRIDHARAN, A. (1990). Engineering behaviour of soils—A fundamental approach : 13th IGS Annual Lecture, *Indian Geotechnical Journal* 21, 1-136.

SRIDHARAN, A. NAGARAJ T.S. and SIVAPULLIAH, P.V. (1981). Heaving of soil due to acid contamination 10th *Int. Conf. on Soil Mech and Foundation Engineering*, Stockholm, Vol. 6., 383-386.