Module 5

ADVANCED SOIL 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 (κ) implies the ability of a material to perform as an insulator. This property is not measured but computed by Eq. 5.1.

$$\kappa = C \text{ x } (d/A) \tag{5.1}$$

C is the capacitance in Farad, d is the length of specimen and A is the cross sectional area of specimen. κ 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 κ and electrical conductivity (σ_{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 κ 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 κ variation with frequency increases considerably. For pure water, κ value is close to 80. Such a wide variation in κ 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 (Shah and Singh 2004, 2005; Sreedeep et al. 2004). 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. Rhoades and Schilfgaarde (1976) have used an electrical conductivity probe for determining soil salinity based on the principle of Wenner four electrode method (Halvorson et al., 1977). Arulanandan (1991), Rao et al. (2007) have used an impedance analyzer to measure dielectric constant *k* of various soils. Fam and Santamarina (1997) have measured dielectric permittivity of soils with a coaxial terminator probe integrated with a network analyzer. Lee et al. (2002) have measured capacitance of the saturated contaminated sands using impedance analyzer in the frequency range of 75 kHz to 12 MHz. A descriptive methodology for electrical resistivity box and probe reported by Sreedeep et al. (2004) is discussed below.

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 insures 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 ρ_{ERB} offered by the medium can be determined by Eqs. 5.2 and 5.3, respectively.

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

$$\rho_{ERB} = a.R_{ERB} \tag{5.3}$$

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 ρ_{ERP} using an appropriate parameter b that depends on the geometry of the probe, as discussed above for ERB.

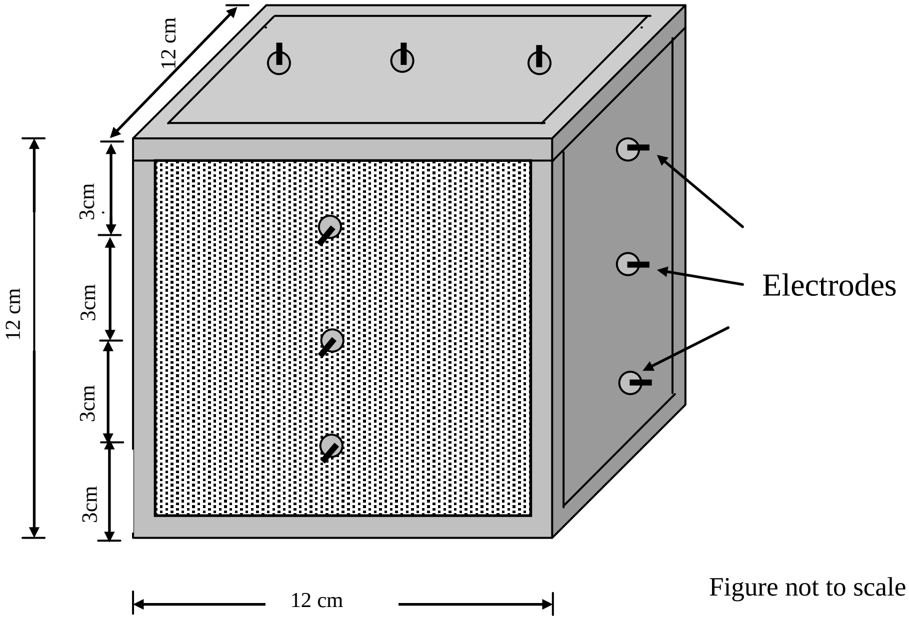

Fig. 5.1 A conceptual electrical resistivity box (Sreedeep et al. 2004)

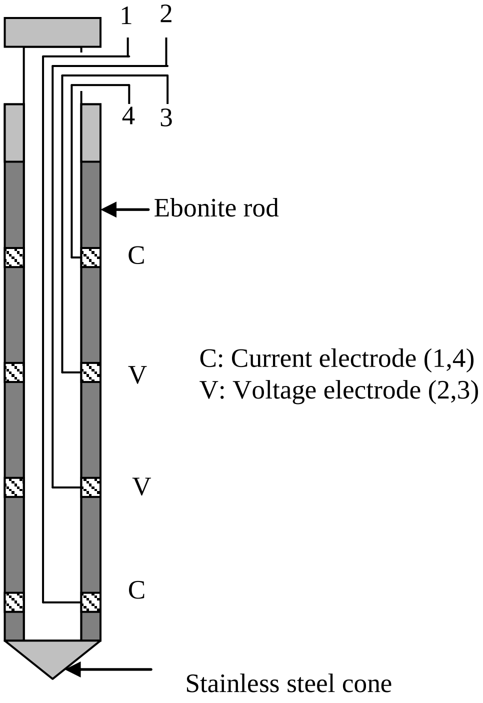

Fig. 5.2 A conceptual electrical resistivity probe (Sreedeep et al. 2004)

5.3 Thermal property of soil

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 ($K= 1/\rho$), ρ 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

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

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 ρ (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

Fine grained or cohesive soil and peaty soils exhibit high ρ than granular soil. Sand with quartz as the principal constituent has low ρ. The type of clay minerals present in soil also influences ρ. 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 ρ. 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. ρ increases with decreasing particle size due to reduced surface contact between adjacent particles.

The density of soil has an important influence on ρ. The presence of air with its high ρ decreases the overall ρ of the soil as compared to that of its solid components. Therefore, a well compacted soil will have low ρ 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 gap 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 ρ of air is much higher than water, inclusion of water in soil would considerably decrease ρ of soil. The moisture content also has an indirect influence on ρ since higher density can be achieved by adding water to the soil. The ρ of soil is also influenced by temperature, because each of the constituents has temperature dependent thermal properties. The ρ of all crystalline minerals increase with increasing temperature, however, the ρ of water and gases exhibit the inverse effect.

5.3.2 Measurement of soil thermal resistivity (ρ)

Thermal resistivity (ρ) 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 ρ 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 ρ. 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 ρ measurement should be based on the condition of the 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 ρ 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. K of the specimen material is calculated from Eq. 5.5.

$$1/\rho = K = \frac{Q}{A}\frac{L}{\Delta T} \tag{5.5}$$

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

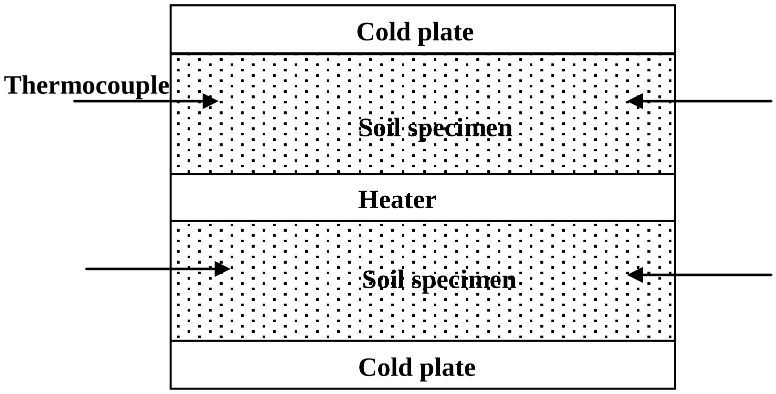

Fig. 5.3 Schematic diagram of the guarded hotplate method for determining thermal conductivity (ASTM C 177)

Heat flux meter

The ρ 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 ρ, and installed with thermal couples on both side. The temperature difference (gradient) between both sides multiplied by the ρ 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 method are discussed below.

Thermal probe method

The thermal probe or needle is a rapid and convenient method for measuring ρ 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 heat flowing from a line heat source through a medium of thermal diffusivity must conform to the following equation:

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial x^2} \tag{5.6}$$

T is the temperature at time t in x direction. For cylindrical coordinates Eq. 5.6 becomes:

$$\frac{\partial T}{\partial t} = D\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{5.7}$$

Where, r is the radial distance from the line source. Assuming heat is produced from t=0 at a constant rate q per unit length of probe, the solution of Eq. 5.7 is given by Eq. 5.8.

$$\Delta T = \frac{q}{4\pi}\frac{1}{K}\left[-Ei\left(-\frac{r^2}{4Dt}\right)\right] \tag{5.8}$$

Where, Ei (-x) is an exponential integral and K or (1/ρ) is thermal conductivity.

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 ^{0}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:

$$T= \frac{q}{4\pi K}\ln t + c \quad \text{(Jackson and Taylor, 1965)} \tag{5.9}$$

$$\text{slope}= \frac{q}{4\pi K}$$

Where q=heat flow rate (q= i^2.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 eliminate 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).

$$D=\frac{K}{\gamma c} \tag{5.10}$$

Where, K is Thermal conductivity, D is thermal diffusivity, c is Specific heat, T is temperature and γ 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 (θ), which is defined as the ratio of volume of water to the total volume of soil. θ is one of the vital parameter 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 θ 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 θ 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 θ. As an example, two low cost probes EC-5 and EC-TE (Decagon Devices, Inc., USA) as shown in Figs. 5.4 and 5.5 are explained below. The value of κ for water is close to 80, dry soil minerals is around 4 and for air it is 1 (Topp et al., 1980). Therefore, κ of soil medium is highly sensitive to changes in water content. κ is dependent on the capacitance property or the charge storage property of the soil mass. The probe measures the capacitance property which is converted to κ. θ is determined based on κ value.

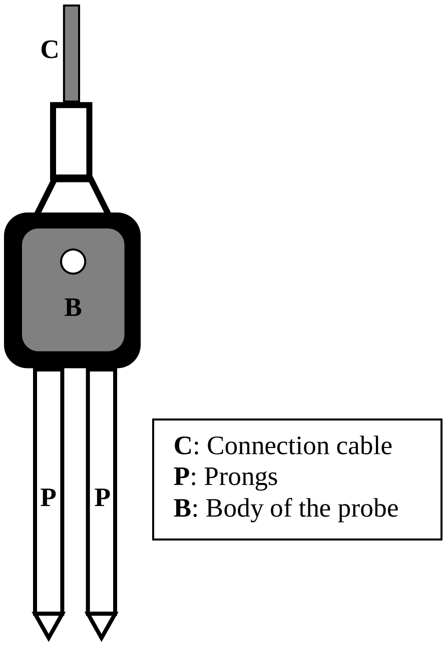

Fig 5.4 Two prong EC-5 probe details

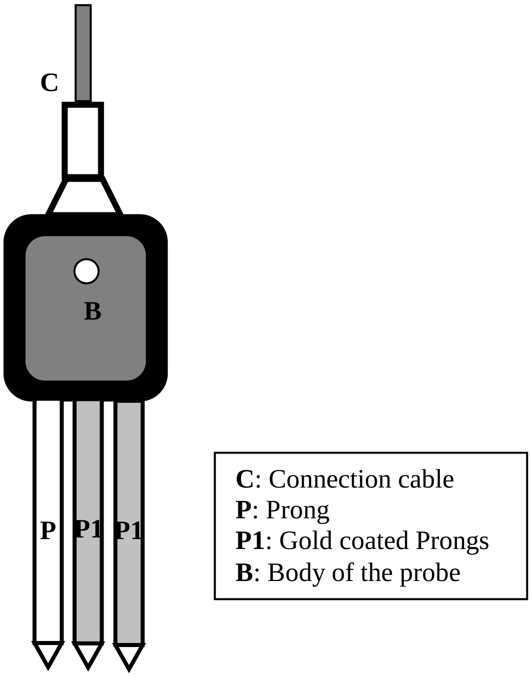

Fig. 5.5 Details of EC-TE probe

The probe comprises of an oscillator working at a particular frequency, which generates an electromagnetic (EM) field. The EM field charges the soil around the probe. This stored charge is measured using copper traces provided on the prongs and is proportional to κ and θ. It must be noted that the electromagnetic field thus produced by the probe decreases with distance from the probe surface and has little or no sensitivity at the extreme edges of the probe. The stored charge thus measured would confine to a zone of influence of 5 cm measured from the edge of the prong.

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. 5.6, 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. The determination of permeability is done by either single head or double head method by the procedure discussed in Ref. 29.

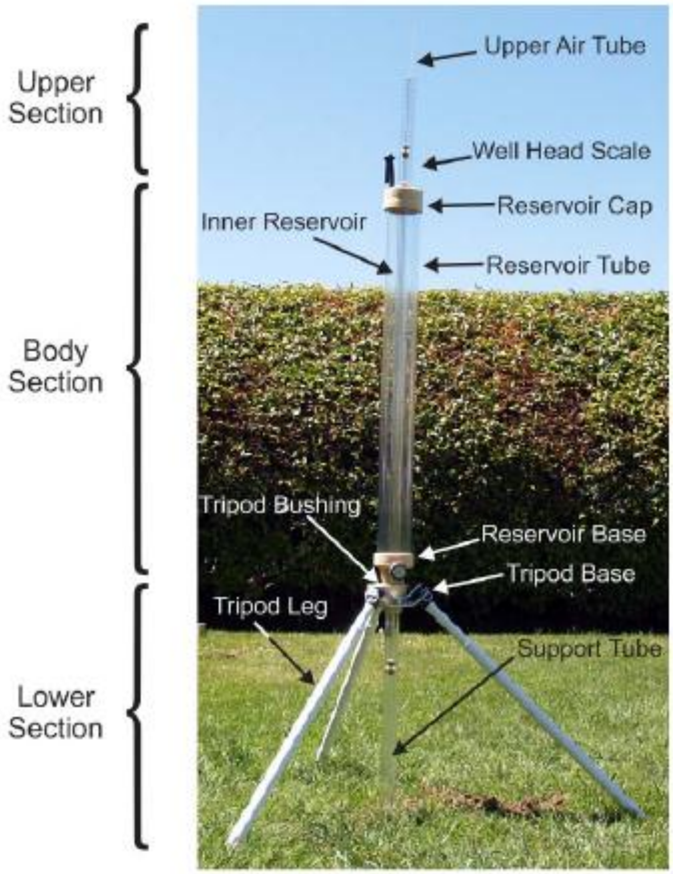

Fig. 5.6 Guelph permeameter (Ref. 31)

5.4.3 Tension Infiltrometer (TI)

Tension Infiltrometer (TI) as depicted in Fig. 5.7 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 Marriot 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 Marriot 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).

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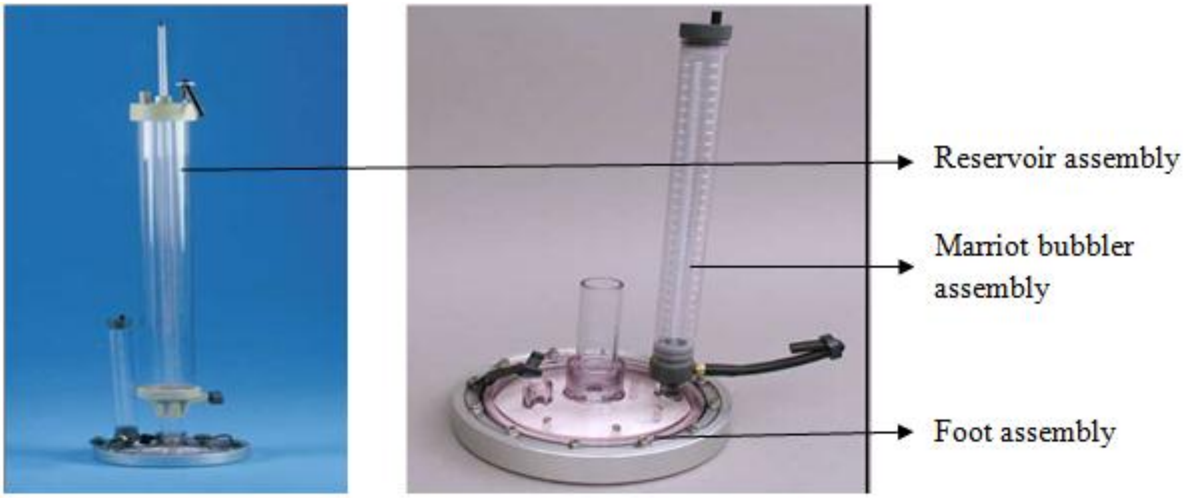

Fig. 5.7 Tension Infiltrometer (Ref. 31)

5.4.4 Minidisk infiltrometer

Mini disc infiltrometer as shown in Fig. 5.8 is similar to the working of tension infiltrometer but with a lower range of suction applied to the infiltrometer disc (Ref. 30). 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 minidisc 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.

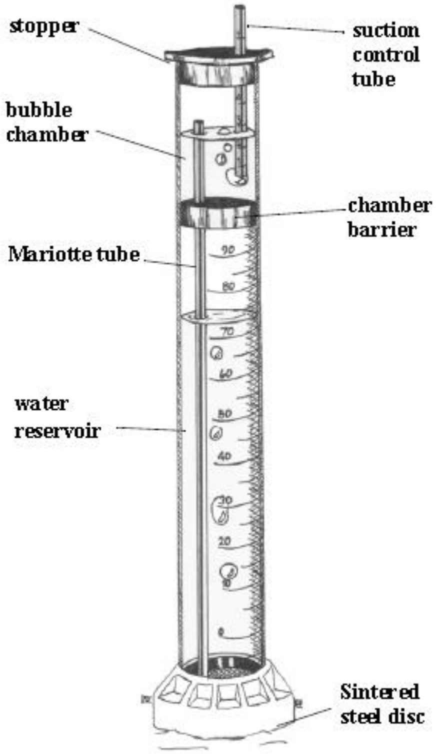

Fig. 5.8 Minidisk Infiltrometer (Ref. 32)

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. 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.

5.6 Introduction to geotechnical centrifuge modelling

A geotechnical centrifuge is used to conduct physical modeling of geotechnical problems for which gravity is the primary driving force. These studies include determination of settlement of embankments, stability of slopes and tunnels, flow and contaminant migration characteristics of soil (Cooke and Mitchell 1991; Singh and Gupta 1999). The basic principle of centrifuge modelling is that when a soil sample model of (N times smaller than its prototype) is subjected to N times the acceleration due to Earth's gravity (Ng) by centrifugation, it results in identical self-weight stresses at homologous points in the model and the prototype as depicted in Fig. 5.9 (a) (Taylor 1995). In the figure, ρ is the mass density of soil, g is the acceleration due to gravity, ω is the angular velocity of rotation in rad/sec, r_e is the effective radius represented by Eq. 5.11, where r_t is the distance from axis of rotation to the top of the soil sample. It can be clearly seen that the stress in prototype and N-g model is identical where as the geostatic stress scale down by N in a 1-g model.

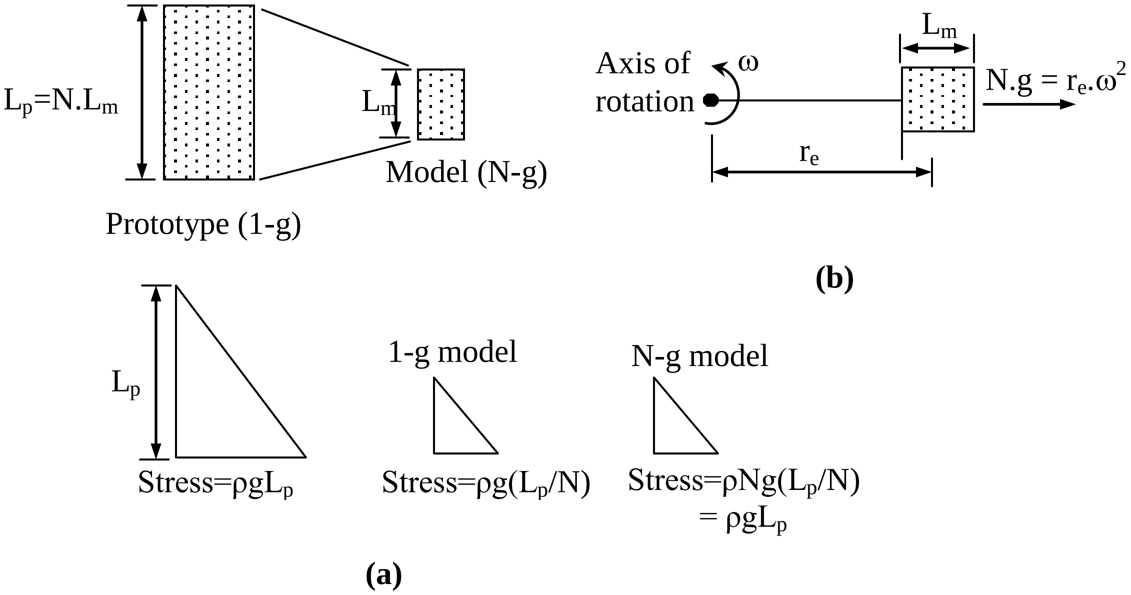

Fig. 5.9 Basic principle of the centrifuge modelling

$$r_e = r_t + \frac{L_m}{3} \tag{5.11}$$

5.6.1 Similitude in centrifuge modeling

The results of centrifuge model, which is used to understand a mechanism or process, can be extrapolated to corresponding prototype condition using suitable scaling laws. To formulate these scaling laws, three types of similitude conditions have to be considered, as discussed in the following.

Geometrical similarity

This can be achieved if there is a constant ratio of length, L, between the homologous points in the model and the prototype.

$$L_m/L_p = \lambda = 1/N \tag{5.12}$$

where subscripts m and p correspond to the model and its prototype, respectively, and λ is the scale factor.

Kinematic similarity

The model and the prototype are said to be kinematically similar if their ratio of velocity, v, and acceleration, a, are constant. Hence:

$$v_m/v_p = \beta \quad (5.13)$$

$$a_m/a_p = n \quad (5.14)$$

where β and n are constants.

Dynamic similarity

This similarity can be ensured if there is a constant ratio between the forces in the model and its prototype.

$$F_m/F_p = \chi \quad (5.15)$$

where F is the force and χ is a constant.

5.6.2 Modeling of mass in Ng model

$$\text{Mass } M = \rho.V \quad (5.16)$$

ρ is the density and V is the volume of soil mass.

$$\frac{M_m}{M_p} = \frac{\rho_m V_m}{\rho_p V_p} \quad (5.17)$$

Subscripts m and p stands for model and prototype, respectively.

If the material used in model and prototype are same, then the mass density will be same ($\rho_m = \rho_p$).

$$\frac{M_m}{M_p} = \frac{V_m}{V_p} = \left(\frac{L_m}{L_p}\right) = \frac{1}{N^3} \quad (5.18)$$

$$\text{Unit weight } \gamma = \rho.g \quad (5.19)$$

$$\frac{\gamma_m}{\gamma_p} = \frac{\rho_m g_m}{\rho_p g_p} \quad (5.20)$$

For Ng model, $\rho_m = \rho_p$ and $g_m = Ng_p$

Therefore, $\gamma_m = N\,\gamma_p$ (5.21)

5.6.3 Scale factor for body forces or geostatic forces

$$F = Mg \tag{5.22}$$

$$\frac{F_m}{F_p} = \frac{M_m g_m}{M_p g_p} = \frac{1}{N^3} \text{ for 1-g model where } g_m = g_p \tag{5.23}$$

$$\frac{F_m}{F_p} = \frac{M_m g_m}{M_p g_p} = \frac{1}{N^2} \text{ for N-g model where } g_m = Ng_p \tag{5.24}$$

5.6.4 Potential of geotechnical centrifuge for geoenvironmental project

Geotechnical centrifuge has potential application in geoenvironmental problems such as fluid and contaminant transport that is mostly governed by seepage forces. The permeability of high compacted liners is very low. Therefore, determination of permeability and contaminant transport parameters (advective-dispersive) is extremely time consuming with normal 1-g modelling. For establishing advective-dispersive contaminant transport parameters, it is essential that the contaminant solution flows through the soil column as discussed in module 3. This is time intensive even for a small soil column. Using geotechnical centrifuge for simulating seepage can considerably reduce the time required for experimentation as discussed below.

$$\text{Seepage force (SF)} = i.\,\gamma_w.V \tag{5.25}$$

$$= (v/k).W$$

V is the volume of soil mass, i is the hydraulic gradient, v is the discharge velocity, k is the hydraulic conductivity or permeability, γ_w is the unit weight of water and W is the weight of seepage water.

$$\frac{SF_m}{SF_p} = \frac{v_m}{v_p}.\frac{k_p}{k_m}.\frac{W_m}{W_p} \tag{5.26}$$

$$\frac{v_m}{v_p} = \frac{L_m}{L_p}.\frac{t_p}{t_m} = \frac{1}{N}.\frac{t_p}{t_m} \tag{5.27}$$

t is the time.

k can be represented by Eq. 5.28.

$$k = \frac{K.\rho_w.g}{\mu} \tag{5.28}$$

where ρ_w is the fluid density, μ is the dynamic viscosity of the fluid, and K is the intrinsic permeability. If the same pore fluid and the soil are used in the model and prototype, then Eq. 5.28 can be written as:

$$\frac{k_m}{k_p} = \frac{\frac{K.\rho.g_m}{\mu}}{\frac{K.\rho.g_p}{\mu}} = \frac{g_m}{g_p} = N \tag{5.29}$$

$$k_m = N.k_p \tag{5.30}$$

$$\frac{W_m}{W_p} = \frac{M_m}{M_p}.\frac{g_m}{g_p} = \frac{1}{N^2} \tag{5.31}$$

Substituting Eqs. 5.27, 5.30 and 5.31 in Eq. 5.26, and considering seepage force as a body force with scale factor represented by Eq. 5.24, we get

$$\frac{SF_m}{SF_p} = \frac{1}{N^2} = \frac{1}{N}\frac{t_p}{t_m}.\frac{1}{N}.\frac{1}{N^2} \tag{5.32}$$

$$\frac{t_m}{t_p} = \frac{1}{N^2} \tag{5.33}$$

The above derivation clearly indicates that the seepage phenomenon is accelerated at N-g due to increase in velocity of flow. The time for seepage in model is reduced by $1/N^2$. Therefore, permeability of compacted liner can be determined in short interval of time with the help of geotechnical centrifuge model and the prototype permeability can be obtained by using the scale factor derived above. The advective-dispersive transport parameters can also be established in relatively short duration due to accelerated seepage in geotechnical centrifuge.

References

1. Abu-Hassanein, Z. S. (1994) “Use of electrical resistivity measurement as a quality control tool for compacted clay liners”, M. S. Thesis, University of Wisconsin, Madison.
2. Anatoly, P. and Larisa, P. (2002) “Electrical field and soil properties”, 17th WCSS, August, Thailand, pp. 1558-1-1558-11, www.landviser.com/.../17WorldCongress%20of%20**Soil**%20Science.pdf, (website accessed on 18-11-2011).
3. Arulanandan, K. (1991) "Dielectric method for prediction of porosity of saturated soil, Journal of Geotechnical Engineering, ASCE, Vol. 117, No. 2, pp. 319-330.
4. ASTM C 177 (2010) “Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus”, Annual Book of ASTM Standard, ASTM International, West Conshohocken, USA.
5. ASTM C 518 (2010). “Standard test method for steady-state thermal transmission properties by means of the heat flow meter apparatus”, Annual Book of ASTM Standard, ASTM International, West Conshohocken, USA.
6. ASTM D 3974-81 (1994) “Standard practices for extraction of trace elements from sediments”, Annual Book of ASTM Standards, 04.08, ASTM International, West Conshohocken, PA, USA.
7. ASTM D 5334 (2000) “Determination of thermal conductivity of soil and soft rock by thermal needle probe procedure”, Annual Book of ASTM Standard, ASTM International, West Conshohocken, USA.
8. Chu, C-A. (2009) “Measurement and modeling for thermal conductivity of geomaterials”, Ph. D. Thesis submitted to Department of Civil Engineering, National Central University, Taiwan. URL: thesis.lib.ncu.edu.tw/ETD-db/ETD-search-c/getfile?URN...pdf (website visited on 6-4-2012).

9. Cooke, B. and Mitchell, R. J. (1991) “Physical modelling of a dissolved contaminant in an unsaturated sand”, Canadian Geotechnical Journal, Vol. 28, pp. 829-833.
10. Dean, J. R. (2003) “Methods for environmental trace analysis”, John Wiley and Sons Ltd., England.
11. Fam, M. A., and Santamarina, J. C. (1997) “A study of consolidation using mechanical and electromagnetic waves”, Geotechnique, Vol. 47, No.2, pp. 203-219.
12. Fang, H-Y. and Daniels, J. L. (2006) “Introductory geotechnical engineering: An environmental perspective”, Routledge, Taylor and Francis, New York, USA.
13. Halvorson, A. D., Rhoades, J. D. and Reule, C. A. (1977) “Soil-four electrode conductivity relationships for soils of the northern great plains”, Soil Science Society of America Journal, Vol. 41, pp. 966-971.
14. IS 2720, Part II, (1973) “Methods of Test for Soils: Determination of water content”, Indian Standards Institute, New Delhi, India.
15. Jackson, R. D. and Taylor, S. A. (1965) "Heat transfer. in methods of soil analysis. Part 1. Agronomy, Vol. 9 (Black C A ed.), pp. 349-356.
16. Larisa P. (1999) “Electrical properties of soils”, Ph. D. thesis submitted to the department of renewable resources, University of Wyoming, Laramie, WY.
17. Lee, J., Oh, M., Park, J., Ahn, K. H. and Kim, H. (2002) “Application of dielectric constant for estimating moisture content and contamination in sand”, Second Japan-Korea Joint Seminar on Geoenvironmental Engineering, pp. 75-82.
18. Maturi, K., Khodadoust, A. P. and Reddy, K. R. (2008) “Comparison of extractants for removal of lead, zinc and phenanthrene from a manufactured gas plant field soil”, Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management, ASCE, Vol.12, No. 4, pp.230-238.
19. Method 3050B, EPA “Acid digestion of sediments, sludges and soils”, http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/3050b.pdf (website accessed on 16-11-2011).

20. Rao, B. H., Bhat, A. M., and Singh, D. N. (2007) **“**Appli**c**ation of impedance spectroscopy for modeling flow of ac in soils”, Geomechanics and Geoengineering: An International Journal**,** Vol. 2, No. 3, pp. 197-206**.**
21. Reddy, K. R. and Chintamreddy, S. (2001) “Assessment of electrokinetic removal of heavy metals from soils by sequential extraction analysis”, Journal of Hazardous Material, Vol. 84, No. 2-3, pp. 279-296.
22. Rhoades, J. D. and Schilfgaarde, J. V. (1976) “An electrical conductivity probe for determining soil salinity”, Soil Science Society of America Journal, Vol. 40, pp. 647-650.
23. Shah, P. H. and Singh, D. N. (2004) “A simple methodology for determining electrical conductivity of soils”, Journal of ASTM International, Vol. 1, No. 5, published on line, 11 Pages.
24. Shah, P. H. and Singh, D. N. (2005) “Generalized Archie’s law for estimation of soil electrical conductivity”, Journal of ASTM International, Vol. 2, No. 5, published on line, 20 Pages.
25. Singh, D. N. and Gupta, A. K. (2000) “Permeability modeling in a small centrifuge”, Canadian Geotechnical Journal, Vol. 37, No. 5, pp. 1150-1155.
26. Smith-Ross, R. L. (1933) “Electrical properties of soils for alternating currents at radio frequencies” Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, The Royal Society, Vol. 140, No. 841, pp. 359-377, http://www.jstor.org/stable/95996 (website visited on 20-1-2012).
27. Sreedeep, S., Reshma, A. C. and Singh, D. N**.** (2004) **"**Measuring soil electrical resistivity using a resistivity box and a resistivity probe” Journal of Testing and Evaluation, ASTM, Vol. 27, No.4, pp. 411-415.
28. Taylor, R. N. (1995) “Centrifuges in modelling: principles and scale effects”, Geotechnical Centrifuge Technology, Taylor (ed.), Blackie Academic and Professional, Glasgow, pp. 19-33.
29. Topp, G. C., Davis, J. L. and Annan, A. P. (1980) “Electromagnetic determination of soil water content: Measurements in coaxial transmission lines”, Water Resour. Res. Vol. 16, pp. 574–582.

30. Zhang, R. (1997) “Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer”, Soil Science Society of America Journal, Vol. 61, pp. 1024-1030.
31. http://www.soilmoisture.com/operating.html (website visited on 4-1-2012).
32. http://www.decagon.com/products/lysimeters-and-infiltrometers/mini-disk-tension-infiltrometer/ (website visited on 4-1-2012).

Model Questions

1. Prepare a review on different methods of soil contaminant analysis and clearly list its limitations.
2. The concentration of contaminant sorbed on the soil need to be determined. What are the different single and sequential procedures for extraction of contaminants from soil?
3. Based on the available information in literature, try to device a scheme for measuring electrical and thermal property of soil.
4. What are the uses of measuring electrical property of soil?
5. What is the difference between calibration and validation procedure?
6. Discuss about the dielectric and electrical properties of soil-water-contaminant system and its important features.
7. Explain steady state and transient methods for measuring thermal properties of soil.
8. What is application of thermal property of soil?
9. What are the factors influencing thermal and electrical property of soil?
10. What are the various methods used for measuring volumetric water content of soil?
11. From the available literature, prepare the procedure for measuring permeability using Guelph permeameter, tension and minidisk infiltrometer.
12. What are the different modeling approaches in geotechnical and geoenvironmental engineering? Discuss the relative merits and demerits of each method.
13. What are the different geophysical methods for subsurface investigation/
14. Explain the principle and working of ground penetrating radar for delineating subsurface contamination.
15. Explain the philosophy of accelerated physical modeling and how the stress similitude is achieved.
16. With respect to permeability of soil, demonstrate mathematically how accelerated physical modeling is useful in studying any seepage induced phenomenon.
17. Suggest and justify a less time consuming procedure in the lab for obtaining advective-dispersive contaminant transport parameters for a compacted bentonite soil layer
18. A falling head permeability test is conducted in centrifuge. The details of falling head test is as follows: Area of stand pipe is 0.28 cm^2. Area of soil column is 80 cm^2. Length of soil column is 10 cm. There is a change in head from 90 cm to 84 cm for a time of 15 minutes. The centrifuge is rotated at 700 RPM. Effective radius is 50 cm. Determine prototype permeability, prototype length, model velocity and prototype velocity, prototype seepage velocity. (report all results in SI and time in seconds). Weight of wet soil sample is 1500 g and after oven drying the weight reduced to 1200 g. Specific gravity is 2.45. What will be the time taken in days if the same test is conducted at 1g.