A MINI PROJECT REPORT ON

"A STUDY ON MEASURING METHODOLOGIES AND FACTORS INFLUENCING PERMEABILITY OF SOILS"

Submitted in Partial Fulfillment of the Requirement for the Award of the Degree of

MASTER OF TECHNOLOGY
In

CIVIL ENGINEERING
(*With specialization in Geotechnical Engineering)*

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Submitted By:

MADHURJA SARMA

Roll No: PG/C/23/07

ASTU Regd. No.: 361709118

Under the guidance of

Prof. Malaya Chetia

Department of Civil Engineering,

Assam Engineering College,

Jalukbari, Guwahati-781013

CERTIFICATE OF SUPERVISION

This is to certify that the work presented in this report entitled **— A Study On Measuring Methodologies And Factors Influencing Permeability Of Soils** is carried out by Madhurjya Sarma, Roll No: PG/C/23/07, a student of M.Tech 3rd semester, Department of Civil Engineering, Assam Engineering College, under my guidance and supervision and submitted in the partial fulfillment of the requirement for the award of the Degree of Master of Technology in Civil Engineering with specialization in Geotechnical Engineering under Assam Science and Technology University.

Date:

Place

MRS. MALAYA CHETIA

Professor, Department of Civil Engineering,

Assam Engineering College, Jalukbari,

Guwahati-781013

CERTIFICATE FROM HEAD OF THE DEPARTMENT

This is to certify that the work presented in this report entitled **— A Study On Measuring Methodologies And Factors Influencing Permeability Of Soils** is carried out by Madhurjya Sarma, Roll No: PG/C/23/07, a student of M.Tech 3rd semester, Department of Civil Engineering, Assam Engineering College, under my guidance and supervision and submitted in the partial fulfillment of the requirement for the award of the Degree of Master of Technology in Civil Engineering with specialization in Geotechnical Engineering under Assam Science and Technology University.

Date :

Place :

DR. JAYANTA PATHAK

(Professor and Head of Department)

Department of Civil Engineering

Assam Engineering College

Guwahati – 781013

DECLARATION

I hereby declare that the mini project "**A Study On Measuring Methodologies And Factors Influencing Permeability Of Soils**" in partial fulfillment of the requirement for the award of the degree of " MASTER OF TECHNOLOGY" in Civil Engineering (With specialization in Geotechnical Engineering), submitted in the Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13 under Assam Science & Technology University, is a real record of the work carried out in the said college for six months under the supervision of Prof. Malaya Chetia, Associate Professor, Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13.

Do hereby declare that this project report is solemnly done by me and is my effort and that no part of it has been plagiarized without citation.

Date :

Place: MADHURJYA SARMA

This is to certify that the above statement made by the candidate is correct to the best of my knowledge

Date:

Mrs.Malaya Chetia
Professor,
Department of Civil Engineering,
Assam Engineering College,
Jalukbari, Guwahati-781013

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Date:

Place:

Madhurjya Sarma

M. Tech, 3rd Semester,

Geotechnical Engineering, Department of

Civil Engineering, Assam Engineering College

Jalukbari, Guwahati-13

.

ABSTRACT

Permeability is a fundamental soil property that significantly influences the behavior of soils in geotechnical and environmental engineering applications. This study examines the methodologies used to measure soil permeability and the factors affecting it, with a focus on enhancing the reliability and accuracy of permeability assessments. The research delves into experimental techniques, including laboratory tests such as rigid-wall and flexible-wall permeameters, as well as in-situ methods like field permeability tests. Each method's principles, advantages, and limitations are evaluated to provide a comprehensive understanding of their applicability to different soil types and field conditions.

The study also looks into the degree of saturation, compaction, temperature, pore fluid properties, soil texture, structure, and other elements that affect soil permeability. In order to determine their importance in simulating field conditions during testing, the effects of external variables such as applied stress, anisotropy, and boundary conditions are also investigated.

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CHAPTER 1

Introduction

1.1 Permeability

The property of a porous material which permits the passage of water through its interconnecting voids is called permeability. A material having continuous voids is called permeable. Gravels are highly permeable while lay is the least permeable. Soil permeability is a measure of how quickly water passes through soil. Water passing into or through a soil will impact the soil properties. Therefore, it is important to determine the permeability rate for all structures located on, in and under the soil.

Since soil consists of discrete particles, the void spaces between the particles are interconnected. The water flows through these voids when there is a gradient or potential difference available. Usually, water flows from higher potential to lower potential. The flow of water through soil may be either laminar or turbulent. However, in most practical cases the flow of water through soil is laminar. There is some resistance to the flow of water through the soil. The resistance is more when the pores in the soil in the soil matrix are smaller in size, and the flow path is irregular. On the other hand, resistance is low in case of soil having greater void space and

Flow channels are of regular orientation.

The process of water passing through the voids in the soil matrix is called seepage. The study of seepage of water is important for the following problems.

- Determination of rate of a saturated compressible soil layer.
- Calculation of seepage through the body of different engineering structures.
- Calculation of uplift pressure under hydraulic structures and their safety against piping.
- Ground water flow towards wells and drainage of soil.
- Leachate transmission at waste disposal sites.

Darcy, a French Engineer, in 1856 experimentally demonstrated the flow of liquids through a porous media. Darcy demonstrated that for laminar flow condition in a saturated soil , the rate of flow is directly proportional to the hydraulic gradient.

$$Q = kiA$$

Where, Q = discharge per unit time

A = Total cross-sectional area of soil mass

i = hydraulic gradient

K = Coefficient of permeability or hydraulic conductivity.

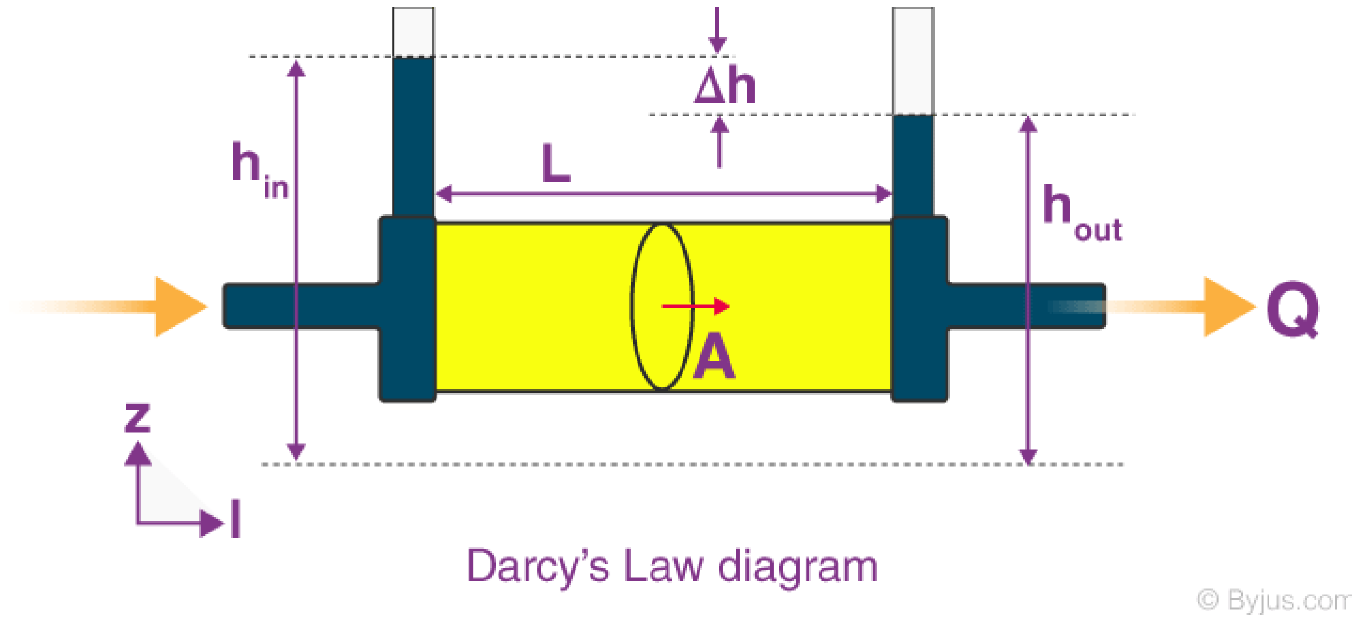

Figure 1: Flow of water through soil.

If a soil of length L and cross-sectional area A, is subjected to differential head of water h_{in} -h_{out}, the hydraulic gradient i will be equal to $\frac{hi-h0}{L}$ and we have $q = k\frac{hi-ho}{L}A$.

1.2 Factors affecting permeability

I. Particle Size: Permeability varies approximately as the square of the grain size. When a soil mass contains coarse grained particles, it contains large volume of voids and those voids are interconnected. So, high amounts of water may flow through these interconnected voids easily. Hence such soils have higher value of permeability. While soil mass with fine grains have poorly connected void structure consequently we observe lower value of permeability.

II. Specific Surface Area of Particles: Specific surface area of soil particles also effects the permeability. Higher the specific surface area lower will be the permeability.

III. Void Ratio: In general, Permeability increases with void ratio. But it is not applicable to all types of soils. For example, Clay has high void ratio than any other types of soil but permeability for clays is very low. This is due to, the flow path through voids in case of clays is extremely small such that water cannot permit through this path easily.

IV. Soil Structure: Structure of any two similar soil masses at same void ratio need not be same. It varies according to the level of compaction applied. If a soil contains flocculated structure, the particles are in random orientation and permeability is more in this case.

If the soil contains dispersed structure, the particles are in face-to-face orientation hence, permeability is very low. The permeability of stratified soil deposits also varies according to the flow direction. If the flow is parallel, permeability is more. If it is perpendicular, permeability is less.

V. Degree of Saturation: Partially saturated soil contains air voids which are formed due to entrapped air or gas released from the percolating fluid or water. This air will block the flow path thereby reducing the permeability. Fully saturated soil is more permeable than partially saturated soil.

VI. Absorbed Water: Adsorbed water is the water layer formed around the soil particle especially in the case of fine-grained soils. This reduces the size of the void space by about 10%. Hence, permeability reduces.

VII. Temperature: Temperature also affects the permeability in soils. From equation (1), permeability is inversely proportional to the viscosity of the fluid. It is known that viscosity varies inversely to the temperature. Hence, Permeability is directly related to temperature.

CHAPTER 2

LITERATURE REVIEW

2.1 Review of available literature.

Putera Agung, Budi Damianto and Sony Pramusandi (2013) this paper took samples from dry side ,wet side and on OMC (optimum moisture content). They developed methods for in situ measurement of hydraulic Conductivity (K) and modified procedure for laboratory measurement of K .Their study used a solution of 0.005 $CaSO_4$ and flown solution trough the sample. Experiments are conducted on samples with diameter 3” and thickness 1.0 cm; and diameter 10” and thickness 8.0 cm, respectively. All test samples are conducted in the laboratory using a constituted flexible – wall permeameter. The samples are saturated through a solution of 0.005 $CaSO_4$ and the saturation process is stopped when the pore volume of flow larger than or equals 2.0 and after that the solution of $CaSO_4$ is replaced by leachate .It was found that the hydraulic conductivity values decrease after solution standard of 0.005 N CaSO4 substituted by leachate. The size of sample in falling head test strongly influences hydraulic conductivity values on the dry; OMC; and wet conditions. The size of representative sample for measurement of hydraulic conductivity of compacted soil liner depends on the method and quality of construction. Poorly compacted soil requires larger representative size sample and well compacted soil requires smaller size representative sample.

Craig H. Benson et al. (1994) suggested about selecting the number of sample and their sizes as part of controlling the quality of compacted clay liners. It has been found that inadequate construction control may yield liners with high hydraulic conductivity even if acceptable soil is used for liners. The sample size is typically specified prior to construction and in some instances is adjusted during construction based on evaluation of the data being collected. A hydraulic-conductivity-based statistical method has been presented to select the sampling size for quality-control measurements (e.g., Atterberg limits, particle-size distribution, and compaction conditions) performed during construction of compacted soil liners.

Anderson C (2011) aimed at investigating and evaluating alternative short duration testing methods and equipment for the measurement of the permeability of fine grained soils. To meet this aim two individual schemes are proposed within the research. The first is to add to the understanding and assess the feasibility of an existing method of short duration permeability testing, known as the Accelerated Permeability (AP). The second is to develop a novel apparatus to allow a reduction in the duration of the falling head permeability test using elevated gravitational acceleration produced in a laboratory centrifuge. From the findings of this research, the following recommendations and comments can be made for the use of the AP test and the RAP test as alternatives to the BS test.

Amr F. Elhakim(2016) compared the values of coefficient of permeability obtained from pumping test conducted at the site with the value deduced from empirical calculation from one penetration test at the same location. The falling head test measures the permeability at specific depths yielding a detailed permeability profile versus depth. Conversely, the pumping test provides an average permeability for the soil stratum. The research stated that the coefficient of permeability can also be measured from grain size distribution, void ratios, and particle shape by means of the correlations. However, the formulae-based values are over estimated and hence there is no generalized method for estimating soil permeability for all soil types. It is important to calibrate such empirical method using actual field measurements especially for important projects.

Pariva Dobriyal et al. (2012) tried to compile knowledge on methods for estimating soil moisture at the landscape level, compare and evaluate them based on common parameters, and identify the most useful method for forested landscapes in developing countries. This research work found that the direct methods are accurate but destructive, slow, and time-consuming. Indirect methods, such as Time Domain Reflectometry and Ground Penetrating Radar, are instantaneously obtained and accurate.

Kashif Ali Solangi et al. (2024) explored soil hydraulic conductivity in loam and clay soils using two methods: constant head and falling head. The constant head method measured K_{sat} using a soil column, with soil texture predominantly sandy loam. The falling head method showed greater accuracy, particularly in concurrent analysis of three samples. The study suggests the laboratory method for determining K_{sat} is cost-effective and simple. In this experiment, water is tested with constant pressure and directed through a soil sample with specified dimensions, allowing for the measurement of the flow rate. When soil particles are sieved through different meshes i.e. 10,20 and 40 different porosity is obtained and the average porosity was 39.30%. In this study, Ksat showed fluctuations is determining the different meshes. It was observed that hydraulic conductivity values increased in average to coarse-textured soil layers and decreased in fine-textured soil layers. Soil texture and structure significantly influenced both saturated hydraulic conductivity and porosity.

Soonkie Nam et al. (2021) compared laboratory tests and in situ tests for determining hydraulic conductivity of natural soil deposits. Laboratory tests used constant head permeability and oedometer tests, while in situ tests used the auger hole method and Guelph permeameter. The results showed that in situ tests better represent field conditions, attributed to factors like sample disturbance, soil anisotropy, and sample size. Soil samples were collected from holes drilled vertically down to 3 m from the riverbanks' top and slope surfaces using a hand auger. These samples were analysed for water content, void ratio, grain size distribution, specific gravity, and Atterberg limits. e results showed that the hydraulic conductivity of saturated clay soil (CL) ranges from 10-9 to 10-5 m/s, while silty soils (ML and MH) show similar ranges. The differences between soil types and test methods were smaller than those between test methods. The auger hole method (AH) had the highest hydraulic conductivity values, followed by the Guelph permeameter test (GP). The consolidation test (CON) revealed that horizontal k was up to 20 times larger than vertical k. The differences were attributed to heterogeneous soil conditions in the field, such as roots, cracks, and structured soils. The variability between laboratory and in situ tests can be attributed to anisotropy, sample size and disturbance, and test method.

Jae-Myung Lee and Charles D. Shackelford (2005) evaluated hydraulic conductivity of two geosynthetic clay liners (GCLs) with different bentonite qualities. The GCL with higher quality bentonite (GCL-HQB) has a higher sodium montmorillonite content, higher plasticity index, and higher cation exchange capacity compared to the GCL with lower quality bentonite (GCL-LQB). The hydraulic conductivity is lower when permeated with water, but higher when permeated with CaCl2 solutions. This suggests that the GCL with higher quality bentonite is more susceptible to chemical attack. The permeant liquids consist of tap water that is processed by passage through three Barnstead® ion exchange columns in series, and chemical solutions containing 5, 10, 20, 50, 100, and 500 mM CaCl2. The study focuses on the hydraulic conductivity of two GCLs with nominal diameters of 102 mm using falling-head procedure and flexible wall permeameters as described in ASTM D5084. The specimens were initially exposed to the permeant liquid for at least 48 hours, without backpressure, to measure pH, EC, and solute concentrations. The thickness of the specimens was measured before, during, and after the hydraulic conductivity tests.

The model predicts soil permeability values for water, plasticity index, water saturation, and relative dielectric constant. It complies with experimental values and has a good adherence to experimental data. However, it has an error of 6.4 times for predicted soil permeability values. The model captures variation in experimental results, but more than 10% are outside the confidence interval.

The tests were conducted at an average hydraulic gradient of 200, with the average effective stresses at the bottom, middle, and top being 14.7 kPa s2.1 psid, 23.5 kPa s3.4 psid, and 32.3 kPa s4.7 psid, respectively. The hydraulic conductivity of GCLs is affected more by average effective stress than the magnitude of hydraulic gradient. For tests involving water as the permeant liquid, the tests were continued beyond the durations required for ASTM D5084 termination criteria. However, conformance to ASTM D5084 termination criteria was used for comparison with hydraulic conductivity values based on tests performed using CaCl2 solutions as permeant liquids. Equilibrium in EC and solute concentrations between the influent and effluent was established before termination, but pH equilibrium was not considered as a termination criterion in this study. Tests using lower CaCl2 concentrations required extensive test durations, and tests with water as the permeant liquid were not duplicated due to limited permeameter availability. The GCL with higher quality bentonite (GCL-HQB) has a higher sodium montmorillonite content, higher plasticity index, and higher cation exchange capacity compared to the GCL with lower bentonite quality. The hydraulic conductivity of GCL-HQB is lower than GCL-LQB but increases with CaCl2 concentration. The GCL with higher bentonite quality is more susceptible to chemical attack upon permeation with CaCl2 solutions. The elapsed time required to achieve chemical equilibrium is longer for GCL-HQB specimens permeated with CaCl2 solutions, while shorter test durations are required for GCL-HQB specimens. The quality of bentonite affects both hydraulic conductivity and time and PVF required for chemical equilibrium.

Sandro Lemos Machado (2016) presented a model to predict soil permeability based on soil water permeability values using various organic fluids and soil types. The model uses Nutting's equation and considers fluid and solid particle interactions. The model complies well with experimental values, with an error of 6.4 times for predicted soil permeability values. However, over 10% of the results are outside the confidence interval. The study used compacted and undisturbed soil samples with varying compaction energies, and tested their water content, air-dried (AD), and oven-dried (OD) before and after tests For the compacted samples, the compaction mold was adapted to be used as part of a rigid wall permeameter. For undisturbed samples two kinds of permeameters were used: a flexible wall and a rigid wall permeameter. This work used experimental soil permeability data obtained for different fluids (water, gasoline, commercial gasoline with 24% ethanol by volume, ethanol, diesel and carbon tetrachloride) in a variety of soils, from non-cohesive sediments without the presence of fines to swelling soils (residual soils from shale and fine sandstone) to derive a model to predict soil permeability of organic fluids based on soil and fluid properties.

Jianquan Ma et al. (2023) investigated the impact of sample preparation methods on remoulded loess permeability and microstructure. 40 falling-head permeability tests were conducted using two methods, five different dry density and initial water content conditions. Results show that pre-wetting samples have inferior homogeneity compared to transfer wetting, with higher permeability coefficients due to pore structure changes. Microscopic structural analysis reveals larger pores and aggregates in pre-wetting samples. The impact is more significant when dry density is low, but less pronounced when higher. The study reveals that increasing dry density reduces the permeability coefficient of pre-wetting samples, with varying trends among samples. Low compaction and loose particle structures show a continuous decrease with increased seepage time, while larger samples show a small, stable coefficient. The permeability coefficient exhibits two types of changes over seepage time: decrease for lower dry density and increase for higher dry density. The effect is most pronounced at lower dry density. This study examined the impact of sample preparation methods on the permeability of remoulded loess through falling-head permeability tests. The results showed that the preparation method, initial moisture content, and dry density significantly influence the permeability of remoulded loess. Prewetting samples showed poorer homogeneity and higher permeability coefficients compared to transfer wetting samples. Monitoring total dissolved solids revealed that soluble salts leach out with the infiltrating fluid, impacting soil structure and permeability. The pre-wetting method had larger pores and an obvious aggregate structure, affecting permeability. The impact of the sampling method was minimal when dry density was high.

Brivaldo Gomes de Almeida et al. (2024) aimed to validate a single piece of equipment for determining hydraulic conductivity of saturated soil (Ksat) in laboratory settings. The double permeameter (DP) was tested on undisturbed soil samples from three soil profiles with different textures. The DP's efficacy was assessed using the coefficient of variation (CV) for the two methods, sample size, and applied hydraulic head. The results showed that the DP could be used as an alternative permeameter for Ksat tests, particularly with samples of sandy texture and larger volumes. The study collected structured soil samples using volumetric cylinders to maintain soil structure and ensure integrity in Ksat trials. Two volumes were tested, one with a height and internal diameter of 5 cm and the other with a height and internal diameter of 250 cm3. The samples were packaged and transported to the Soil Physics Laboratory for Ksat determination tests. Other attributes like soil bulk density and total porosity were also determined. Unstructured samples were used for characterization tests, such as the "f" factor and granulometric analysis, which were collected via auger and converted to air-dry fine earth in the laboratory. Based on NBR 13292 of the Brazilian Association of Technical Standards (ABNT), LAFIS at UFRPE created the double permeameter (DP) utilized in this study as a substitute permeameter for laboratory Ksat determination testing. The DP is composed of a threaded nipple, a cylindrical nylon billet container, and four screws with butterfly nuts to secure and guide the lids. Because the DP has a containment plate, rubber seals, and a sealing rubber, liquid can only pass via the test piece's pores. Both hydraulic constant and falling modes can be used with the DP without causing any disruption to the sample cylinder. The laboratory tests for determining Ksat values using a double permeameter showed no disturbance to soil structure, no influence of hydraulic head on Ksat values, and larger samples (100 cm3) were more accurate. The double permeameter can be used within methodological limits, based on soil properties and equipment availability. The results suggest it can be used within these limits.

Morbidelli et al. (2017) compared the saturated hydraulic conductivity (Ks) estimates of three classical devices: the double ring infiltrometer (DRI), the Guelph version of the constant-head well permeameter (GUELPH-CHP), and the CSIRO version of the tension permeameter (CSIRO-TP). The results show that the DRI overestimates Ks, the GUELPH-CHP has conflicting estimates, and the CSIRO-TP has average Ks values with significant errors. The reasons for these discrepancies are not fully understood, prompting future work to better characterize uncertainty and field scale variability**.**

Indra P. Acharya et al. (2021) presented a comparative study of existing predictive models for predicting the coefficient of permeability of granular soils. It examines the application of these models to natural sands. The study found that there is no unique relationship for predicting coefficients of permeability values for all soil types. The expressions provided by Kozeny-Carman, Taylor, and Chapuis are rational and scientific, but they need to be determined specifically to the soil. The study highlights the need for proper determination of coefficients and parameters in these equations. For Ganga sand, the Hazan equation yields precise permeability estimates; however, none of the predictive models can accurately depict Ennore sand. Accurate permeability fluctuation with void ratio is provided by Taylor's equation and Casagrande's empirical relation. The proper permeability coefficients for both sands cannot be predicted by the relations of Kozeny-Carman and Chapuis. As long as the multiplication and power coefficients are determined through experimentation, Chapuis' equation can be applied to make accurate predictions. These factors, however, are not applicable to every form of sand. Permeability coefficients for all soil types cannot be predicted using a single equation with well-defined parameters, according to the study.

Hongjun Lei et al. (2016) found that the clayey soil's permeability is influenced by its stress-strain condition, which also affects seepage and consolidation characteristics. Variations in soil permeability in shear processes have not been taken into account in previous research. In order to investigate changes in hydraulic conductivity in clayey soil, new triaxial seepage equipment was created. The impact of the stress-strain state on hydraulic conductivity was examined through tests conducted under various confining pressures. For clayey soil hydraulic conductivity under conditions of large shear deformation, a mathematical model was put out. The impact of mesostructure and void ratio on soil hydraulic conductivity is precisely calibrated by the model.

CHAPTER 3

Existing Methodology

3.1 Direct Permeability Testing Techniques

From Darcy's relationship for the coefficient of permeability it can be seen that the calculation, requires of a number of variables, namely, the length of sample, the cross-sectional area of the sample perpendicular to flow, the head loss across the sample the rate of flow of permeant through the sample. There are two different applied flow conditions commonly used.

I. Falling head technique in which the head loss declines with time due to a fall in influent permeant level at a measured rate in a tube or chamber of known cross-sectional area allowing the computation of rate of flow and identification of head difference.

II. Constant-head technique in which a head difference is applied across the sample at a known and constant magnitude and the corresponding rate of flow is measured.

3.1.1 Falling Head Permeability Test.

The falling head permeability test is a common laboratory testing method used to determine the permeability of fine-grained soils with intermediate and low permeability such as silts and clays. The falling head permeability test involves flow of water through a relatively short soil sample connected to a standpipe which provides the water head and also allows measuring the volume of water passing through the sample. Before starting the flow measurements, the soil sample is saturated, and the standpipes are filled with de-aired water to a given level. The test then starts by allowing water to flow through the sample until the water in the standpipe reaches a given lower limit. The time required for the water in the standpipe to drop from the upper to the lower level is recorded.

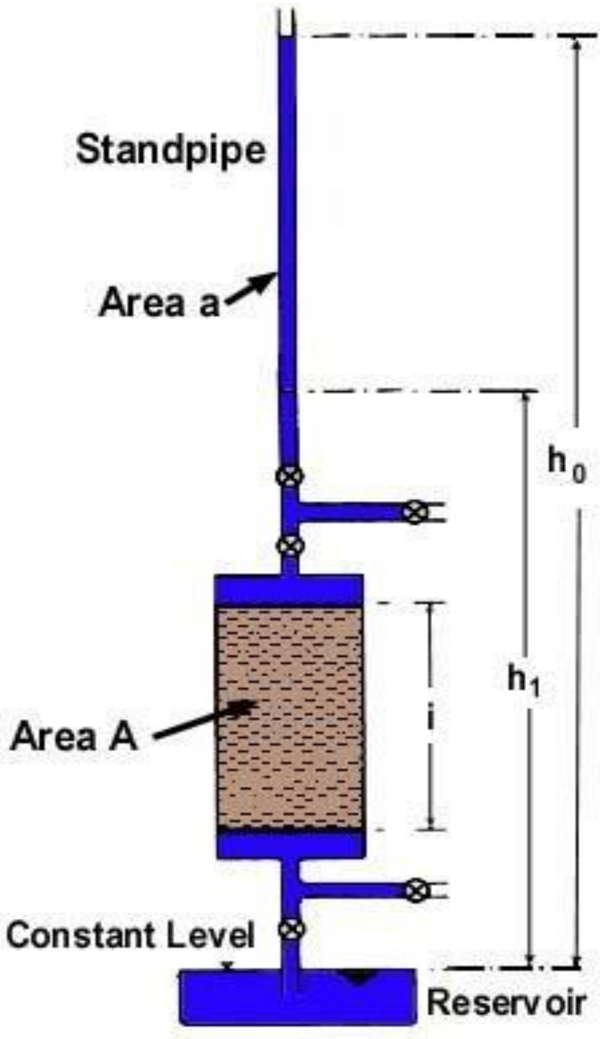

Figure 2: Falling head permeability setup

3.1.2 Constant Head Permeability Test.

The constant head permeability test is a common laboratory testing method used to determine the permeability of granular soils like sands and gravels containing little or no silt. he constant head permeability test involves flow of water through a column of cylindrical soil sample under the constant pressure difference. The test is carried out in the permeability cell, or permeameter, which can vary in size depending on the grain size of the tested material. The soil sample has a cylindrical form with its diameter being large enough in order to be representative of the tested soil.

The testing apparatus is equipped with a adjustable constant head reservoir and an outlet reservoir which allows maintaining a constant head during the test. Water used for testing is de-aired water at constant temperature. Before starting the flow measurements, however, the soil sample is saturated.

During the test, the amount of water flowing through the soil column is measured for given time intervals.

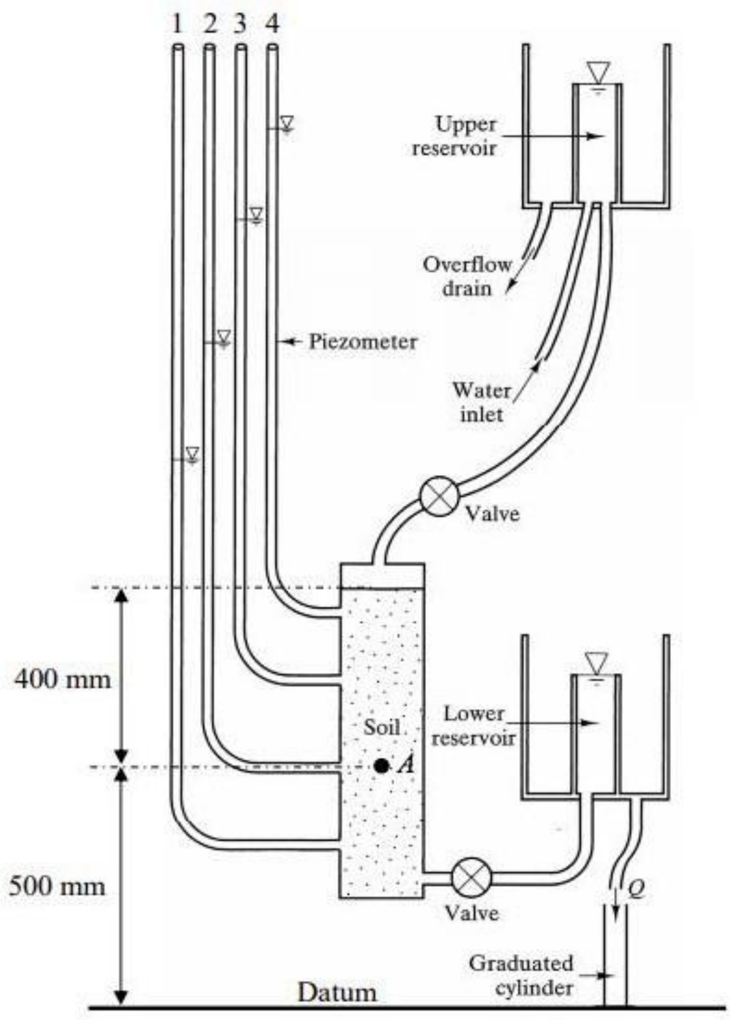

Figure 3: Constant head permeability test.

Table 1 : Advantages and disadvantages associated with the use of various common flow conditions

Type of flow	Advantages	disadvantages
Constant Head Test	Simplicity in both set-up and analysis	Long test duration
	Steady State flow is reached	Relatively large gradients are generally employed leading to seepage induced consolidation
	Can calculate head loses through permeation system	
Falling Head Test	Simplicity	Long test duration
	Low Cost	Steady state flow is not reached
	Common use and standardized commercially available equipment	Cannot calculate head losses in the permeation system

3.2 Indirect Testing Techniques

A variety of empirical relationships are available for the determination of permeability values The relationships are the Hazen, Kozeny-Carmen, and Taylor relationships, respectively. As was previously mentioned, there has been extensive research on the reliability and correctness of permeability measurements, and the general agreement is that these equations are not reliable indicators of the permeability of fine-grained materials. This could be the result of errors or challenges in measuring or estimating some of the necessary parameters in these equations. Direct permeability assessment is typically easier and less expensive than precisely measuring the parameters needed for indirect permeability estimation. As a result, most of the variables in each of these formulas

3.2.1 Hazen Equation

Few purely empirical correlations had been proposed before the creation of mathematically based rational models. According to one of the first attempts based on grain size distribution by Hazen (1911), Darcy's equals for homogeneous sand (< 5) with loose dimensions between 0.1 and 3 mm

$$k= CD_{10}^{2} ,$$

where k = Coefficient of permeability (cm/sec) ; D_{10} =effective diameter (cm)

C=Constant approximately equal to 100.

3.2.2 Kozeny-Carmen Equation

Attempts have been made to correlate the permeability with the specific surface of the soil particles . One such relationship given by Kozeny (1907)

$$k = 1/(K_k N S^2) \times n^3/(1-n^3)$$

where k = Coefficient of permeability (cm/sec) ; n = porosity; S= specific surface of particles (cm2/cm3); N= viscosity (g sec/cm2) ; K_k= Constant.

3.3 Rigid-Wall and Flexible-Wall Permeameter

Rigid-Wall and Flexible-Wall Permeameters are laboratory instruments used to determine the permeability of soils, which is a measure of the ease with which water flows through soil pores. These devices are critical in geotechnical engineering for evaluating soil behavior in applications like drainage, slope stability, and foundation design.

3.3.1 Rigid-Wall Permeameter

The rigid-wall permeameter has a fixed and non-deformable wall that holds the soil sample in place. It is typically used for granular soils, such as sands and gravels, that are not significantly affected by confinement during testing. The soil sample is placed in a rigid mold, ensuring a

constant cross-sectional area. This is primarily used for constant-head or falling-head permeability tests.

The flow of water through the sample is measured under controlled head or pressure differences.

Table 2: Advantages and disadvantages of Rigid-Wall Parameter.

Advantages	Disadvantages
• Simple and quick to use.	• Suitable for soils where changes in volume or deformation are minimal during testing (e.g., coarse-grained soils)
• Suitable for soils where changes in volume or deformation are minimal during testing (e.g., coarse-grained soils)	• Suitable for soils where changes in volume or deformation are minimal during testing (e.g., coarse-grained soils)

3.3.2 Flexible-Wall Permeameter

The flexible wall permeameter surrounds the soil sample with a flexible membrane and allows for the application of confining stress. It is widely used for both cohesive and cohesionless soils, especially when field stresses need to be simulated. The soil sample is encased in a latex membrane, and confining pressure is applied using water or air in a surrounding chamber. Conducts both constant-head and falling-head tests, with the capability to simulate anisotropic stress conditions. The test can replicate field stress and flow conditions more accurately.

Table 3: Advantages and disadvantages of Flexible-Wall Permeability.

Advantages	Disadvantages
• Suitable for fine-grained soils and conditions where deformation or volume change is significant.	• More complex and time-consuming than rigid-wall tests.
• Allows for the simulation of in-situ stress states, making it versatile and realistic.	• Requires careful preparation to avoid leakage around the membrane.

3.4 Oedometer Test

The most popular test for determining a soil's one-dimensional consolidation is the oedometer test. A time-deformation curve is plotted after a constant vertical load is applied to the sample, as described in the American Society for Testing and Materials (ASTM) standard [16]. The primary consolidation under each loading is identified following a series of oedometer tests in which the constant load is gradually increased for each test.

The outcomes are displayed in a log (p') curve for the void ratio e, where p' is the effective vertical stress.

An equation that can be used to calculate hydraulic conductivity from the oedometer was proposed by Terzaghi test. The hydraulic conductivity by the consolidation test k_{CON} can be calculated from the

Equation : $k_{CON} = c_v m_v g_w$

where c_v = coefficient of consolidation,

m_v = coefficient of volume change, and

g_w = unit weight of water.

3.5 In situ Methods of Measuring Permeability

Because permeability depends on both the macrostructure (such as stratification) and microstructure (such as the arrangement of soil grains), field testing are necessary. In situations where obtaining a representative sample is challenging, it could also be necessary. The field techniques for determining permeability are described below.

3.5.1 Pumping Out Test

Pumping water out of a main well and monitoring the drawdown surface of the initial horizontal water table from at least two observation wells constitutes a field permeability test. The flow amount and levels in the observation wells are recorded once a steady condition of flow has been achieved.

Before getting into the details of the pumping-out test, it is important to know about aquifers. An aquifer is a permeable formation that allows a significant quantity of water to move through it under field conditions. Broadly there are two types of aquifers based on the position of water strata within the soil, namely confined aquifer and unconfined aquifer.

The phrase "drawdown curve" is the next one to comprehend. A well must be drilled into the soil layer in order to conduct the pumping-out test. At first, the well's water table would stay horizontal. However, the aquifer is exhausted, and the water table is lowered as water is pumped out of the well, creating a circular depression. The "cone of depression" or "drawdown curve" are terms used to describe this.

In pumping out tests, drawdown corresponding to a steady discharge is observed at a number of observation wells. To establish this steady condition, pumping must be carried out at a uniform rate for an adequate time.

Assumptions in Pumping Out Test are as follows:

- Flow is laminar and Darcy's law is valid.
- Flow is horizontal and uniform at all points in the vertical section.
- The aquifer is homogeneous with uniform permeability.
- Well penetrates the entire thickness of the aquifer
- The natural groundwater regime affecting the aquifer remains constant with time.

There are two separate formulas to find out permeability for unconfined and confined aquifers. Illustrations and formulas for both conditions are mentioned below.

I. Unconfined Aquifers

II. Confined Aquifers

Below given is the illustration used to derive the formula for permeability in an unconfined aquifer. The formula is derived using Darcy's law.

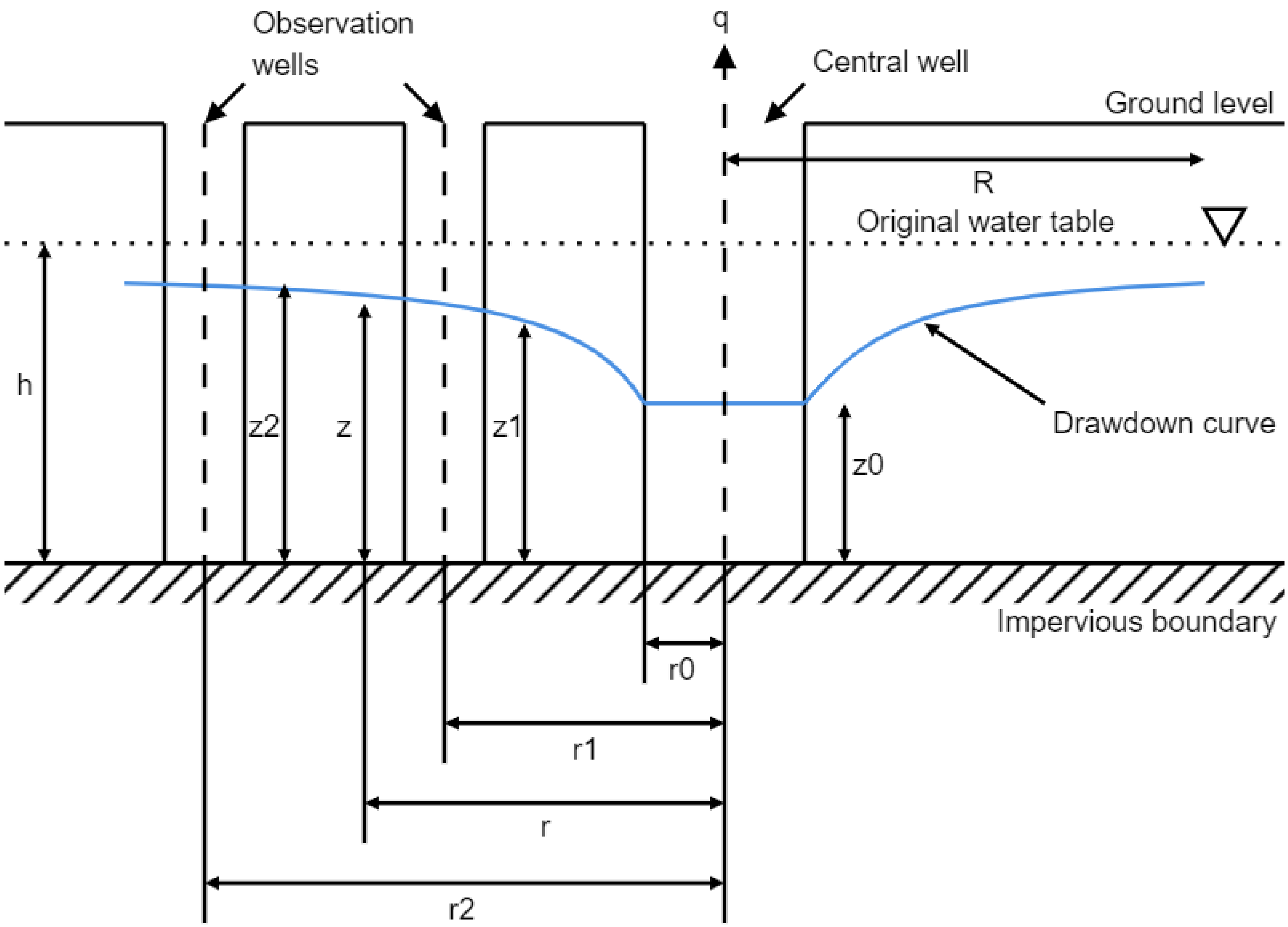

Figure 4: Pumping Out Test: Unconfined Aquifer.

$$k = \left(\frac{q}{1.36\left(z_2^2 - z_1^2\right)}\right) * \log\left(\frac{r_2}{r_1}\right)$$

From finding z1, z2, and r1, r2, from field observations, k can be evaluated for unconfined aquifer.

Below given is the illustration used to derive the formula for permeability in a confined aquifer. The formula is derived using Darcy's law.

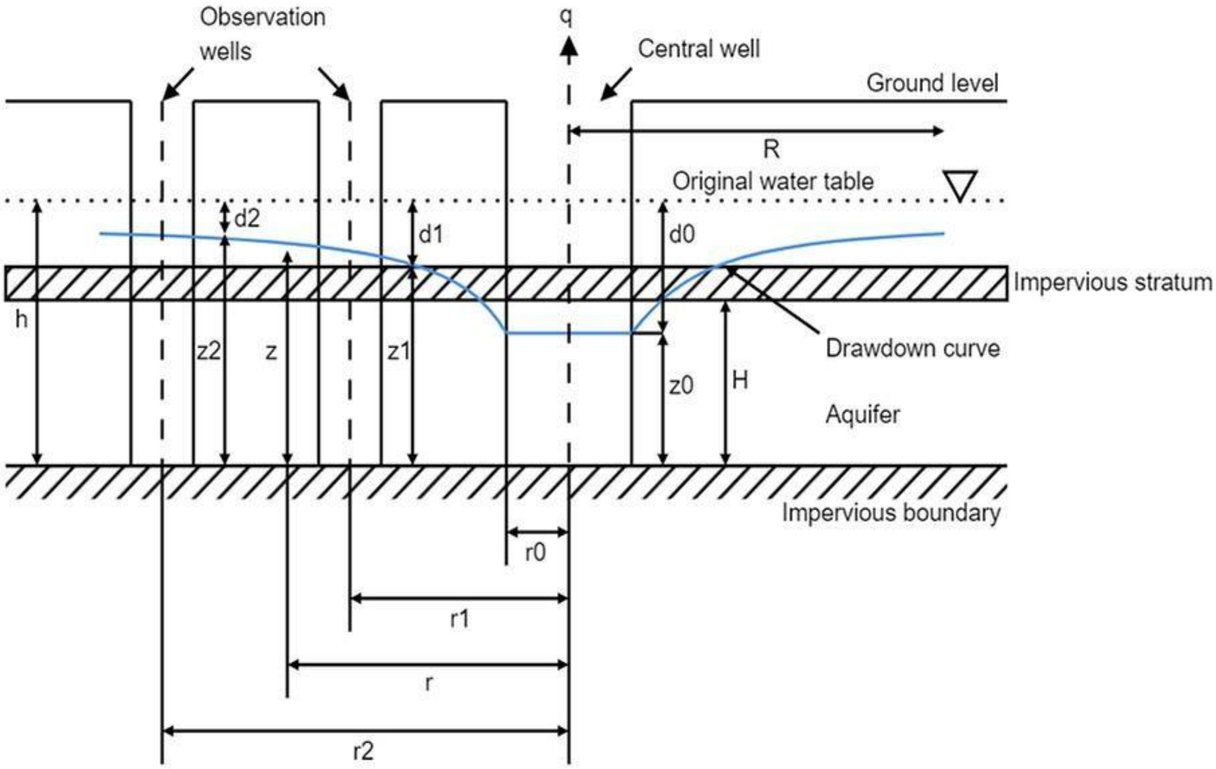

Figure 5: Pumping Out Test: Confined aquifer.

$$k = \left(\frac{q}{2.72 * H * (d_1 - d_2)} \right) * \log\left(\frac{r_2}{r_1} \right)$$

From finding d1, d2, and r1, r2, from field observations, k can be evaluated for confined aquifer.

3.5.2 Auger Hole Method

In situ tests conducted in the field are frequently chosen because of the limitations of laboratory testing, such as sample disruption and the difficulty to accurately replicate outdoor circumstances. When the water table is low, the auger hole (AH) method is an easy test that may be carried out in the field without the need for complex equipment. Diserens first proposed it, and numerous scholars later enhanced it.

The test also has the advantages of (i) identifying the soil profile during the test, (ii) collecting both disturbed and undisturbed soil samples during hole drilling, and (iii) enabling the simultaneous execution of many tests. The auger hole method requires monitoring wells to be drilled that extend below the groundwater table. Once the observation well is completed and the water table inside the well reaches equilibrium, the test starts by removing the water in the hole. Groundwater then seeps into the hole, rising until it returns to the original level, and the time required to reach equilibrium is measured.

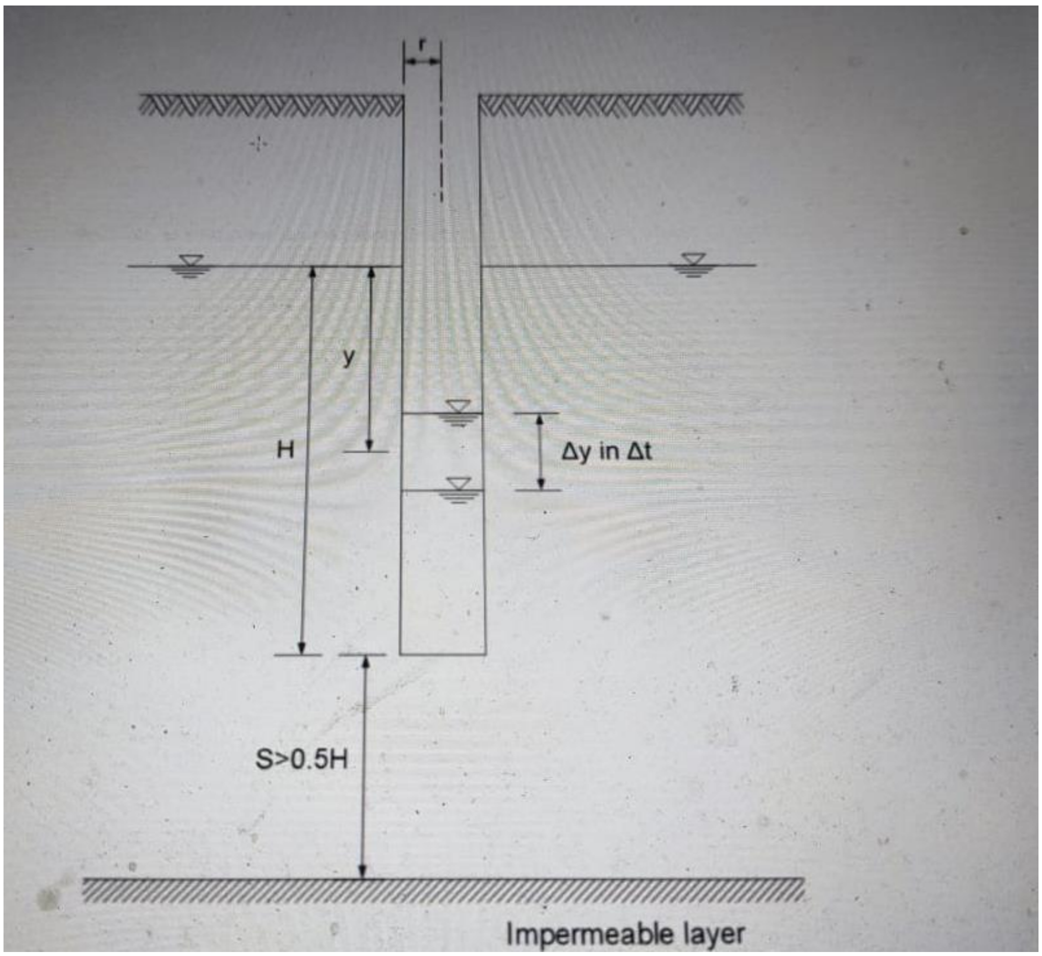

Figure 6: Schematic of the auger hole method.

Where, r = radius of the hole, H = depth of the hole below the groundwater table, y = distance between the groundwater table and the average water level in the hole for a given time Dt, Dy = water level change in the hole for a given time Dt, and S = distance from the bottom of the hole to the impermeable layer.

3.5.3 Guelph Parameter

Using a Mariotte siphon reservoir, the Guelph permeameter (GP) method is an in situ constant head test that determines the saturated hydraulic conductivity of unsaturated soils. Assuming that the surrounding soils are uniform and saturated throughout the test, the rate at which water exits a cylindrical well above the groundwater table is measured.

However, GP values are lower than the actual saturated hydraulic conductivity because of the saturation process in soils above the GWT [22]. Furthermore, smearing and compaction of well walls, as well as the initial water content of the soil, have a major impact on the outcomes [23]. Therefore, a well-preparation brush was used to complete each hole in this study.

3.5.4 Pumping In Test

The pumping test can be used for strata that are above or below the water table. The test is particularly carried out in thin formations.

The material's permeability in the immediate area of the drill hole's bottom is determined by the tests. As a result, it can be used to assess the efficacy of grouting in stratified foundations by figuring out the permeability of various strata. This approach is cost-effective and eliminates the need for complex setups that are necessary for the pump out testing.

Pumping in Tests also known as Gravity Feed in Drill Holes or Bore Holes is carried out by three ways:

I. **Constant Head Method:** The method in which the water level in the test hole is maintained constant and the permeability is computed from the data of steady state constant discharge.

II. **Falling Head Method:** The method in which the water level in the test hole is allowed to fall and the equivalent permeability is computed from the data of the rate of fall of the water level

III. **Slug Method:** The test done by instantaneous injection of a given quantity of ‘slug’ of water into a well and determining the coefficient of permeability from the fall of water level.

CHAPTER 4

4.1 Soil Characteristics Influencing the Permeability of Soils

When it comes to mineral liners and numerous other technical issues that rely on seepage, settlement, stability, or drainage, a soil's permeability is a crucial characteristic. Permeability is very varied when compared to other soil parameters. The permeability of a clean gravel would be roughly represented by the speed of light by comparative deviation in order of magnitude, if the average walking speed of a person represents the permeability of a homogeneous clay. This analogy serves to highlight the variability of soil permeability. Permeability is influenced by various soil characteristics such as effective particle size, void ratio, composition, fabric/structure, and degree of saturation, which can be complexly interrelated and difficult to independently relate to.

4.1.1 Influence of Effective Particle Size

The size and frequency of the accessible pore space for flow through any porous medium will have the most noticeable impact on the permeability. It makes sense that as particle size shrinks, so will the pore space between them, increasing the resistance to permeant flow and, ultimately, lowering permeability. The direct relationship between permeability and effective particle size, which is predicated on the logical premise that the smaller the particles, the smaller the voids and the lower the permeability, is only reasonable for granular material because the particles in granular soil (Le. silts and sands) are more equidimensional than the flat, plate-like particles found in clays.

4.1.2 Influence of Void Ratio

The void ratio, e, is a ratio of the volume of voids (gas or liquid) to the volume of solids. It is directly related to porosity, n, a better-known parameter, which is the ratio of volume of voids to the total volume of soil.

$$e = n/1-n$$

since only the numerator of the void ratio will change during soil swelling or consolidation, e is typically thought to be more useful in representing the relative portion of void volume in a given soil element. In contrast, n will cause both the numerator and the denominator to increase or decrease, respectively.

It should be mentioned that while discussing permeability and fluid flow in soils, the phrase "effective porosity," which is related, is frequently used. It is calculated by dividing the volume of soil by the amount of empty space that is accessible for fluid flow. It also accounts for immobile water that is affixed to soil particles and encroaches on the available pathways for fluid movement. The composition of the soil affects the amount of immobile water. Therefore, the composition and the void ratio/porosity both affect the effective porosity.

4.1.3 Influence of Composition

Sands and silts have a very different composition than clays. Although individual pieces of very strong, unmodified rock minerals, such quartz, can be extremely angular, sands and silts are far more equidimensional than clays and are aggregates of fragments of these minerals that lack cohesiveness. The chemical breakdown of weaker rock minerals, such feldspar, produces clays, which are typically smaller than silts and have a flat plate-like shape. The minerals in a particular clay, which have a negatively charged surface due to their chemical composition, the cations that are absorbed and drawn to the mineral (usually sodium, potassium, calcium, or hydrogen), and, in the case of clays that form naturally, organic material and ion oxides will typically be present.

4.1.4 Influence of Fabric

The arrangement of particles, particle groups, and pore spaces inside a particular soil is referred to as the fabric. Although the terms are occasionally used interchangeably, soil structure normally refers to the combined impacts of composition and fabric. Particle orientation does not significantly affect permeability for granular soils because silts and sands contain more equidimensional particles than clay particles, which have high aspect ratios. As a result, fabric changes are less severe. Fabric, on the other hand, is one of the most significant soil properties affecting the permeability of fine-grained soils because the extremes of fabric that may be felt within a clay are vast. Strong interparticle forces of attraction caused by edge-to-face contacts with a flocculated fabric typically result in a higher strength and lower compressibility than the same element of soil at the same void ratio but with a dispersed fabric that contains parallel particles that tend to repel each other.

4.1.5 Influence of Saturation

The degree of saturation is an important parameter to consider for the permeability. Since many soils are somewhat unsaturated after recompaction, particularly when compacted at a molding moisture content dry of optimal, the degree of saturation is a crucial parameter to take into account when testing the permeability of saturated soils with reference to landfill liners. The goal of permeability testing is to make sure that samples are completely saturated and free of air voids, although this is especially challenging in fine-grained soils. In fact, it is often believed that partially saturated soil samples are the cause of a discrepancy between saturated permeability results and theoretical expectations in a large portion of the examined literature.

4.2 Imposed Conditions influencing the Permeability of Soils

In addition to the soil characteristics outlined in section 4.1, there are a variety of other factors that influence the permeability of a soil. These factors are imposed during both the sampling and the permeability testing of a given soil. An understanding of the influence of these factors on permeability is crucial to limiting unwanted variables in both sample preparation and permeability testing, which would otherwise affect the permeability results obtained. Consequently, a review of the relevant literature pertaining to these factors is presented in this section.

4.2.1 Influence of the Permeant

The two main permeant factors controlling soil permeability are the dynamic viscosity and the unit weight (or density). Results from pertinent literature, however, show that this is untrue, and that permeant chemistry can significantly alter the physio-chemical events observed at particle surfaces in fine-grained materials. Permeant chemistry can alter particle bonding, which can alter the soil fabric and, in turn, alter permeability. This alters permeability by influencing not just the diffuse double layer that encroaches on the vacuum space available for fluid movement.

The work of Michaels and Lin (1954), which uses a variety of different permeants to conduct permeability tests on Kaolinite samples over a range of void ratios, demonstrates that as the polarity of the permeating fluid increases, the absolute permeability, K (i.e., the effects of viscosity and permeant fluid weight are eliminated), decreases. This is because the size and mobility of the diffuse double layer of absorbed fluid surrounding the clay particles are directly correlated with the polarity of the pore water fluid. The quantity of electro-osmotic backflow, or the movement of permeant in the opposite direction of net flow as a result of an electrical potential produced by the fluid, is likewise directly correlated with polarity.

Wilkinson's (1970) work, which compares the effects of employing distilled water against natural pore water as permeants in permeability tests, is presented by Olsen and Daniel (1981). Wilkinson (1970) discovered that studies employing distilled water reveal that the permeability declines during the course of the test, in contrast to natural pore water, which exhibits a consistent permeability over an extended length of time. According to Olsen and Daniel (1981), employing distilled water as a permeant may result in erroneous permeability readings because leaching a sample with inert distilled water may cause the diffuse double layer to expand, lowering permeability and potentially increasing particle mobility, which could lead to particle migration and further influencing permeability.

4.2.2 Influence of Hydraulic Gradient and Effective Stress

The hydraulic gradient across a mineral liner in the field is often less than unity and seldom exceeds it. However, in order to shorten testing times, higher hydraulic gradients—in certain situations surpassing l00 have been used in flexible wall laboratory permeability experiments. Numerous investigations into the impact of hydraulic gradient and the resulting effective stresses on measured permeability have been conducted.

Mitchell and Younger (1967) discovered that when the gradient is increased in samples of compacted silty clay, the permeability drops. They attributed this to particle migration in the flow direction, which clogs the flow channels. Additionally, they show that zones of increased permeability through the sample may result from particle movement.

The gradient is applied in a flexible wall test by either raising the influent/headwater pressure, lowering the effluent/tailwater pressure, or doing both at once. In order to guarantee contact between the flexible membrane and the test specimen, the rise in influent pressure is constrained by the requirement to maintain a minimal difference between confining pressure and maximum back pressure. The back pressure provided to the sample limits the amount of effluent pressure that can drop, and significant pressure drops can cause the permeant's dissolved air to be released, desaturating the sample and lowering its permeability (Shackelford, 1994).

4.2.3 Influence of Sample Size

The permeability of a relatively poor but representative in-situ soil liner can generally be significantly underestimated by two to three orders of magnitude by laboratory tests conducted on small samples, according to several studies comparing permeability results between field scale tests and laboratory tests (Daniel 1981; Day and Daniel, 1985). Larger macroscale flaws that are impossible to depict in small laboratory samples, such as regions of nonhomogeneity, inter-aggregate voids created from poorly compacted large clods, desiccation cracks, and slickensides found in a badly built liner, are generally accepted to be the cause of these variations in permeability measurement. On the other hand, other authors (Lahti et al., 1987; Reades et al., 1990) attribute the good agreement between laboratory and field permeability test results to the high quality of the liner under test, where the molding moisture water content is optimally wet and the flow-controlling pores are small enough to be represented with small samples.

According to Shackleford and Javed (1991) and Benson et al. (1994b), larger samples should be evaluated in order to get around the scale effect issue that arises during laboratory testing.

A low permeability smear zone created during sample cutting may have contributed to the trend reported by Carpenter and Stephenson (1986). The impact of these smear zones on the observed permeability increases with sample length. In order to reduce the effects of smear, Olsen and Daniel (1981) advise cutting the sample with a sharp knife as opposed to trowelling it during final trimming, including open root holes and other areas of the sample that are visible to have higher conductivity, and testing as large a sample as feasible. According to other research, smear effects can be lessened by lightly cleaning clipped ends with a wire brush.

4.2.4 Influence of Time

Dunn and Mitchell (1984) and Mitchell and Hooper (1965) both looked at the thixotropic effects of clay and how they affected permeability. The degree of thixotropy in a fine-grained soil suggests that the soil fabric may change with time, with samples tending toward a higher degree of flocculation than was first produced by compaction. Strength and permeability have been demonstrated to increase as a result of thixotropic effects. It's time for this change dependent and can happen when the sample is at rest in between permeability testing and sample compaction, keeping the moisture content constant and density.

Permeability can also be decreased by conducting permeability tests over comparatively lengthy periods of time. The findings of Allison (1947), which show that the development of organic matter in the soil can clog flow channels with extended testing, resulting in a decrease in permeability, are emphasized by Olsen and Daniel (1981). Using slightly chlorinated fresh tap water, as recommended by Mitchell (1994).

4.2.5 Influence of Temperature

Measurements of permeability are influenced by the permeant viscosity. Since a liquid's viscosity depends on its temperature, the temperature at which permeability tests are conducted will affect the permeability readings. n general, a drop in viscosity brought on by an increase in temperature will enhance permeability. According to Olsen and Daniel (1981), the observed permeability for fine-grained dirt changes by about 3% for every 1C change in temperature. Thus, it stands to reason that permeability results would be impacted by natural variations in ambient temperature.

CHAPTER 5

Conclusion

The necessity of choosing suitable testing procedures and comprehending the elements affecting soil behaviour is shown by the study on measuring methodologies and factors influencing soil permeability.

Laboratory techniques, such as rigid-wall and flexible-wall permeameters, and in-situ field methods each have specific advantages and limitations, making them suitable for different soil types and project requirements.

Replicating field conditions, such as stress states, saturation levels, and anisotropy, is crucial to the precision of permeability measurements.

Key factors such as soil texture, structure, compaction, and pore fluid properties significantly influence permeability and must be carefully accounted for during testing and analysis. Additionally, external factors like temperature, applied stress, and boundary conditions can alter the permeability of soils, emphasizing the need for meticulous test preparation and result interpretation.

This study comes to the conclusion that collecting accurate and realistic permeability data requires a thorough grasp of both methodology and impacting factors. Reducing experimental uncertainties and improving the simulation of intricate field situations should be the main goals of future studies and testing technology developments. These initiatives will improve permeability models' predictive power, which will help with a variety of geotechnical and environmental applications, such as groundwater management, slope stability, and foundation design.

REFERENCES

1. Morbidelli, R., Saltalippi, C., Flammini, A., Cifrodelli, M., Picciafuoco, T., Corradini, C., & Govindaraju, R. S. (2017). In situ measurements of soil saturated hydraulic conductivity: Assessment of reliability through rainfall-runoff experiments. *Hydrological Processes*, *31*(17), 3084–3094.

2. Statistical sample size for construction of soil liners. (1995). *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *32*(6), A280.

3. Lee, J., & Shackelford, C. D. (2004). Impact of bentonite quality on hydraulic conductivity of geosynthetic clay liners. *Journal of Geotechnical and Geoenvironmental Engineering*, *131*(1), 64–77. https://doi.org/10.1061/(asce)1090-0241(2005)131:1

4. Anderson (2011). The permeability of fine grain soils: An investigation into unconventional methods of measurement in the laboratory.

5. Machado, S. L., Da Silva Paes Cardoso, L., De Oliveira, I. B., De Faria Mariz, D., & Karimpour-Fard, M. (2016). Modeling soil permeability when percolated by different soil. *Transport in Porous Media*, *111*(3), 763–793. https://doi.org/10.1007/s11242-016-0627-9.

6. De Almeida, B. G., Da Silva Santos, E. M., Freire, F. J., De Almeida, C. D. G. C., Silva, T. H. D. S., Lima, A. L. T., & Mota, J. C. A. (2024). Validation of double constant and falling head permeameter for determination of hydraulic conductivity of soils in the laboratory. *Revista Brasileira De Geografia Física*, *17*(6), 4744–4760. https://doi.org/10.26848/rbgf.v17.6.p4744-4760

7. Putera Agung, Budi Damianto and Sony Pramusandi (2013). Hydraulic Conductivity Measurement of Compacted Clay Soil Liners for Waste Containment Structures. *Journal of Earth Sciences and Geotechnical Engineering, vol. 3, no. 4, 2013, 125-145 ISSN: 1792-9040 (print), 1792-9660 (online)* Scienpress Ltd, 2013

8. Ma, J., Qiu, Y., Gao, Y., An, Y., Duan, Z., & Li, S. (2023). Effects of sample preparation methods on permeability and microstructure of remolded loess. *Water*, *15*(19), 3469. https://doi.org/10.3390/w15193469.

9. Pariva Dobriyal, Ashi Qureshi, Ruchi Badola, Syed Ainul Hussain (2012). A review of the methods and its implications for water resource management available for estimating soil moisture.

10. Nam, S., Gutierrez, M., Diplas, P., & Petrie, J. (2021). Laboratory and in situ determination of hydraulic conductivity and their validity in transient seepage analysis. *Water*, *13*(8), 1131. https://doi.org/10.3390/w13081131.

11. Solangi, K., Abbasi, B., Solangi, F., Khaskhali, S., Siyal, A., Mehmood, H., Akram, M., Iqbal, R., Al-Ghamdi, A., & Elshikh, M. (2024). Assessment of Saturated Hydraulic Conductivity with Using Soil Particle Size Distribution: A Comparative Study of Constant Head and Falling Head Methods. *Global NEST Journal*, 1–9. https://doi.org/10.30955/gnj.005833

12. Acharya, I. P., Anubhav, N., & Basudhar, P. K. (2021). Predictive models for estimating the coefficient of permeability for sands. In *Lecture notes in civil engineering* (pp. 49–57). https://doi.org/10.1007/978-981-33-6346-5_5.

13. Lei, H., Wu, Y., Yu, Y., Zhang, B., & Lv, H. (2016). Influence of shear on permeability of clayey soil. *International Journal of Geomechanics*, *16*(5). https://doi.org/10.1061/(asce)gm.1943-5622.0000636.