CHAPTER 1- INTRODUCTION

1.1. Background

`To have a better understanding of the flow properties and deformation rate of soils, different configurations of consolidation tests have been performed in the past. The critical parameters evaluated are compression index (c_c), coefficient of volume change (m_v), preconsolidation pressure (p_c), recompression index (c_r), coefficient of consolidation (c_v), and coefficient of secondary consolidation (c_α). Amongst all the testing techniques one of them is one-dimensional consolidation technique. The incremental loading (IL) consolidation test is well known and mostly performed in the laboratory to determine the compressibility characteristics. This technique takes about two weeks to complete with a load increment duration of 24 hours (Sridharan et al. 1999) The major drawback of this testing technique is the test duration.

Later on, with the advancement, another technique the constant rate of strain (CRS) consolidation test was introduced and discussed in the literature. It provides numerous continuous data points and gives a more reliable value of consolidation parameters (Pu et al., 2013).

Over the course of numerous years, the phenomenon of the CRS consolidation technique has yet to gain widespread acceptance. Notably, the technique poses a significant challenge in terms of selecting an appropriate strain rate, given its variation across different soil types. In the past, many researchers have studied modified versions of consolidation tests with different sizes, shapes, loading intensities, load increment ratios, different strain rates and materials to evaluate the consolidation parameters (Sample and Shackelford, 2012; Karim, 2014; Raheena et al., 2019)

In soft soils, consolidation is a persistent problem due to its low permeability for the reduction of pore water pressure (PWP). These soils exhibit complex composition and structural characteristics (tetrahedral or octahedral laminated structures). There is a need to develop a convenient method that facilitates a faster rate of pore water pressure dissipation and can measure the magnitude and time rate of consolidation of soft clays. Initially, Reuss in 1809 had observed the rapid movement of water from the anode (positive electrode) front to the cathode (negative electrode) front through the application of direct current (DC) in a saturated porous medium (Huweg, 2013; Zhuang et al., 2014; Malekzadeh et al., 2016; Manda et al., 2019; Kherad et al., 2020). But in the case of electrokinetic consolidation, no such standard code of practice is available to carry out the test. The present research is to develop a laboratory-based one-dimensional consolidation apparatus that works on the phenomena of the combination of both electrokinetic and surcharge loading effects and to conduct a series of experiments under various DC voltages and loadings.

To demonstrate such a combined effect, a modified consolidation cell as per the standard protocols mentioned in ASTM code with a D/H ratio equivalent to 2.5 is planned to fabricate and later on, electrokinetic phenomenon coupled with a constant load, and constant rate of strain tests are planned to perform on geomaterials to study the compressibility characteristics of the soil named as, Electrokinetic Constant Load (EKCL) and Electrokinetic Constant Rate of Strain (EKCRS) consolidation.

1.2. Consolidation techniques

From the point of view of a geotechnical engineer, an estimate of the magnitude and rate of settlement is required for a proper foundation design for engineered structures. In the case of buildings and bridges, it is important to determine the differential and total settlement of the soil whereas, in highway embankments to prevent uneven surface and distress in pavements. In the past, soil samples were subjected to load increments that results in deformation in the sample and facilitated the calculation of settlement. The method takes approximately two-week time to complete and requires good data interpretation. Later on, another laboratory-based technique, the constant-rate of-strain (CRS) consolidation, was developed. Because of the difficulty in executing both mechanical consolidation techniques IL and CRS in soft clays, the newly emerged voltage-coupled surcharge loading consolidation system i.e., Electrokinetic Consolidation has gained importance in finding the compressibility characteristics of soft clays or problematic soils.

1.2.1. Incremental Loading (IL) technique

In 1910, Frontard carried out the first consolidation test using a soil sample (2 in thick by 14 in diameter) placed in a metal container with a perforated top and bottom to allow drainage. The incremental loading was applied using a piston and the soil was allowed to reach equilibrium. These tests were performed in a highly humid environment to prevent the drying of the sample. Later on, this experimental work was carried out by Karl Terzaghi in 1919 to develop the theory of consolidation (Terzaghi, 1943). Many other researchers also contributed towards the testing method to solve the problems related to unrealistic assumptions made in the theory that led to the improvement of the consolidation apparatus. The incremental loading consolidation technique is used to find the compression characteristics of cohesive soils. In this technique, a stiff metal confining ring with a sharp edge is used to extract the soil sample from a large block of soil and then carved properly to obtain a smooth surface and to maintain the sample with a diameter/height ratio of 3 or more. Porous stone combined with a filter paper is placed at the bottom and top of the sample to allow drainage. A rigid cap is placed over the top porous stone for loading. Later on, the whole arrangement is kept under the loading frame. The load increment is applied in the ratio between 0.5 to 1.0 but is mostly preferred near 1.0. Upon loading, compression phenomenon occurs in the soil that is measured from time to time using a dial gauge, and similarly applied for other loading stages and the process is repeated.

In this technique, it is difficult to understand the primary and secondary consolidation phenomenon to create the compressive curve. Standard testing procedures have also been provided in ASTM International (2003). The other testing standards followed in case of IL consolidation to determine the consolidation characteristics are IS code IS 2720:15 (1986); BS 1377:5 (1990); AASHTO T216; ASTM D4546 and ASTM D3877.

Over time, the IL consolidation technique has evolved to incorporate an automated approach using electronic data acquisition systems. This enhancement has effectively addressed its primary limitation of generating a restricted number of stress-strain data points due to discrete loading intervals. Consequently, the need for extensive manual labour to perform data analysis has been significantly reduced.

However, some rapid methods of consolidation testing methods were developed for the early completion of the consolidation process in clays. Sridharan et al. (1999) have reported a rectangular hyperbola method to identify the percent consolidation reached to determine the coefficient of consolidation. Raheena and Robinson (2018) proposed an accelerated consolidation testing procedure based on the standard $\sqrt{t}$ curve-fitting procedure for identifying the degree of consolidation equal to 90%.

1.2.2. Constant Rates of Strain (CRS) Consolidation

The concept of the CRS technique was first introduced in 1959 by Hamilton and Crawford. It developed as a rapid means of determining the pre-consolidation pressure and replacing it with other traditional oedometer methods. Later on, a CRS theory was developed by Smith and Wahls in 1969. Wissa has developed a fully analytic solution to reduce the CRS data in 1971. This technique is too flexible from the design point of view as it can be customized to different sizes of soil sample.

The sample formation for this technique is similar to the technique used in incremental loading and the drainage allowed is one-way. In this technique, the soil specimen is placed in a fixed ring consolidometer. The base of the sample is prevented from any type of leaks and O-rings are placed at the place of cell pressure acting. A certain amount of backpressure is applied to the specimen to control the variation of pore pressure and effective stresses. Loading is applied through a constant rate of strain device driven by a gear arrangement. The magnitude of the load applied is measured by an external load cell. A pressure transducer is introduced in the sample in the vicinity of the base stone to measure the magnitude of excess pore pressure generated. This pore pressure aids in the computation of hydraulic conductivity. LVDTs are also attached to measure the deformation during the loading. A standard testing procedure has been provided to determine the one-dimensional consolidation parameters of saturated cohesive soils in ASTM D4186/D4186M.

The advantage of this method is the reduced time and manpower requirements for testing and data interpretation, due to the automated computer control system to record data at different intervals with high accuracy as well as easy application of backpressure for sample saturation. However, a disadvantage of this method is that secondary consolidation cannot be obtained due to no values for the rate of secondary compression (c_α) of soil.

1.2.3. Electroosmotic dewatering and consolidation

Electro-osmosis is a known method of improving soft clays using a DC voltage gradient applied to the clays. Electro-osmotic flow depends on the nature of the soil, water content, pH, zeta potential of soil and on ionic type concentration in the pore-water. Due to the applied electric potential, the electrolysis of water occurs at the electrodes. The drainage by the electroosmosis method can overcome the conventional water discharge method (preloading) during the initial stage of DC voltage application but the later stage drainage speed is slow. So, a kind of combined method of electroosmosis-surcharge load consolidometer, that can carry out electric osmose simultaneously and load the fixed laboratory testing ring are combined use in recent years, obtained than simple electric-osmosis consolidation. In recent years, many people prefer the electro-osmosis method with the traditional drainage consolidation method due to its ability for rapid consolidation of soils; electro-osmosis has generated much interest in geotechnical engineering. In the past, numerous large-scale and small-scale consolidation studies were performed to study the effect of constant electric gradient application in soft/problematic soils. Thus, the application of a constant electric gradient accelerates the rate of consolidation and helps in the early determination of compressibility characteristics.

1.3. Motivation of the study

Soft clays exist as natural clays, as dredges from sea beds, and as recent deposits like dredged material in reclaimed lands. These dredged soils named soft clays comprises of dominant clayey fractions and alter the consolidation behaviour of the dredges. These soft clays are generally possess low bearing capacity and undergo excessive settlements when subjected to structural loads. Thus, these vast amounts of dredges require knowledge of the consolidation characteristics for the accurate design of the dykes or other structures placed on these dredged sediments. Therefore, it is very critical to have a realistic understanding of the consolidation behaviour of these environmentally challenging sediments, thus, it is challenging and complex to evaluate the consolidation process in soft clays. Due to this, it is difficult to test the compressibility and permeability of these types of soils at low effective stresses with conventional consolidometers. It was reported that the conventional oedometer test based on one-dimensional consolidation theory does not apply to very soft clays having high water content, high void ratio and low permeability. The fine soil particles of these soft clays having high water content tend to settle down in flocs and therefore the compression of particles restricts at very low effective stresses applied in the traditional consolidometer. One of the other reasons is due to the very low specific gravity and buoyant weight of soft soils, self-weight consolidation starts from very low effective stresses which causes the conventional oedometer test to be ineffective. For overcoming such difficulties, an alternative method, the constant rate of strain consolidation test (CRS) is proposed to determine the consolidation constants for soft clays. The consolidation phenomena in soft clays with CRS tests were analysed by using the consolidation constants obtained by measuring the axial load, the axial displacement and pore pressure at the base of the specimen during the CRS-consolidation process based on consolidation theory in which the thickness of clay specimen is variable. Ultimately, it is found that field monitoring and laboratory testing of soft clays have led to significant improvement in their behaviour prediction with the aid of the most applicable testing system for the soft clays i.e., the CRS testing method.

To overcome the limitations such as low performance, and poor carrier stack preload reinforcement effect while following the conventional consolidation methods on soft clays in recent years, many people prefer the electro-osmosis method with the traditional drainage consolidation method that is applied to joint reinforcement of soft clay foundation and achieved good results.

However, no consolidation study was performed in the laboratory using oedometer with a fixed D/H ratio ranging between 2.5 to 4. Therefore, there is a need for improvement in the existing consolidometer that is completely suitable for all kinds of soil samples to accelerate the consolidation process, provides a feature of continuous monitoring of experimental data in real-time, saves time in acquiring the consolidation parameters and aims to improve the dissipation of excess pressure in early stages of the consolidation so that the process of consolidation is winded up within a shorter duration of time.

The main objective of the study is to compare the test results of EK consolidation with conventional IL and CRS; thus, developing a system and method for faster determination of the compressibility and consolidation characteristics of fine-grained soils will be recommended.

1.4. Research Objectives

The first aim of the study is to explore the mechanical consolidation (IL and CRS) technique performed on four different geomaterials i.e., Marine soil; black cotton soil; red mud and Varanasi local soil with an experimental framework considering the compressibility characteristics. This experimental programme involves CRS consolidation performed with a modified oedometer, and IL test performed with a conventional and modified oedometer, later the consolidation parameters were performed for the validation of the test setup. Later, the results of CRS and EKCRS consolidation are compared with incremental loading consolidation.

1.5. Organization of the Thesis

This thesis consists of seven chapters followed by references at the end.

Chapter 1 provides a brief introduction to existing consolidation techniques and the challenges involved in studying the consolidation tests in soft clays. Also, it briefs the importance of the electrokinetic approach in the consolidation testing of soft clays. This chapter ends with highlighting the research objectives and organization of the present thesis.

Chapter 2 discusses the review of literature on various one-dimensional consolidation (IL, CL and CRS) techniques and research progress in the line of electroosmotic consolidation with the use of electric gradient while determining the consolidation parameters.

The details of the material and methodology adopted with different-sized oedometers are discussed in Chapter 3. This chapter discusses the outline of the experimental programme adopted on various geomaterials while determining the consolidation parameters using the indigenously developed experimental devices of consolidation testing.

Chapter 4 briefs the design and fabrication equipment devices developed for the consolidation testing. This chapter will also discuss the schematic diagrams related to the modified consolidation ring, indigenously developed CRS, EKCL and EKCRS experimental components.

Chapter 5 presents the consolidation test results based on the application of one-dimensional mechanical consolidation techniques performed on four different soils with different sizes i.e., conventional, and modified oedometers. Later, the findings of consolidation parameters obtained from conventional and modified IL tests were compared and validated with modified oedometer CRS consolidation.

Chapter 6 presents the comparative study performed in two phases with the comparison of mechanical and coupled electrokinetic consolidation tests on a modified oedometer.

i. IL, CL and EKCL consolidation
ii. CRS and EKCRS consolidation

Later the results were analyzed for the consolidation parameters.

Chapter 7 presents a summary of the thesis with major conclusions drawn from the study and suggests the scope of future research.