CHAPTER 2 - LITERATURE REVIEW

2.1. General

Consolidation is a process in which a saturated soil mass experiences a reduction in volume under external loading, caused by the expulsion of pore water. The concept of consolidation in saturated soil was introduced by Terzaghi in the 1920s, who explained it as a consequence of a change in effective stress. Over time, many researchers have contributed to the development of consolidation theories using various techniques. This chapter provides an overview of the consolidation theories proposed by several researchers and presents a comprehensive review of electrokinetics and its applications in the development of the electrokinetic consolidation technique.

2.2 Consolidation theory

Consolidation is the phenomenon of volume reduction of soil mass restrained laterally under the axial loading due to the expulsion of pore water. The stress carried by the soil skeleton is effective stress (σ') which is defined as the difference of total stress (σ) and pore pressure (u) as mentioned in equation 2.1.

The equation involved for effective stress calculation is:

$$\sigma' = \sigma - u \tag*{(Eq. 2.1)}$$

In short, consolidation phenomenon can also be stated as gradual transfer of stress from the pore water to saturated soil skeleton. A soil skeleton is compressible which tends to decrease in its volume when loaded axially. The stages involved during the consolidation process which are responsible for volume change are (a) compression of soil particles, (b) compression of pore water within the voids of soil, and (c) release of water from voids. The first two stages are unusual and can be ignored, but the third cause is responsible for consolidation i.e., dissipation of water from a fully saturated soil. The coarser soils with high permeability allow the dissipation of water quickly, but with finer soil where permeability can be extremely low, will allow pore water dissipation very slowly.

The volume decrease on axial load application is time dependent and classified into two phases. Firstly, primary consolidation is the volume decrease caused by the low permeability of the soil layer. Secondly, secondary consolidation is the creep deformation occurring due to axial loading after the primary consolidation. The equations related to this phenomenon are mentioned in equation 2.2 and 2.3.

Terzaghi proposed one-dimensional consolidation equation of clay layer that is subjected to a uniform load as follows -

$$\frac{\partial u}{\partial t} = \mathrm{c}_v \frac{\partial^2 u}{\partial z^2} \qquad \text{(Eq. 2.2)}$$

Defining c_v as coefficient of consolidation as follows-

$$\mathrm{c}_v = \frac{k_v}{\Upsilon_w m_v} \qquad \text{(Eq. 2.3)}$$

Here, u is the excess pore water pressure at fixed time t, at a given location; z is the vertical height of that location; k_v is the coefficient of permeability of the sample; m_v = coefficient of volume compressibility of the clay; Υ_w = unit weight of water.

Initial condition and boundary conditions based on Terzaghi's one-dimensional consolidation theory are-

At Initial condition (for t = 0)

u (z, 0) = $\Delta\sigma_v$ except for z = 0 and z = 2H

At boundary condition based on height of sample,

At the top, z = 0; u (0, t) = 0

At the bottom, z = 2H location, then: u (2H, t) = 0 for two-way drainage condition.

The phenomenon of consolidation is shown in Figure 2.1.

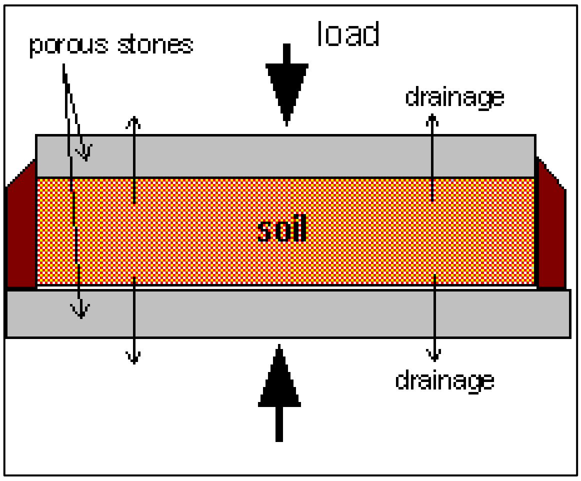


Figure 2.1 Two-way drainage consolidation (google: http://environment.uwe.ac.uk/geocal/soilmech/stresses/drainage.htm)

Another consolidation related important equations are mentioned as equation 2.4 and 2.5.

Time factor (T_v) is a dimensionless number given as:

$$T_v = \frac{c_v t}{H^2} \qquad \text{(Eq. 2.4)}$$

Where, H represents the maximum drainage path length.

Degree of consolidation, U_z at a given time t and depth z is given as

$$U_z = \frac{excess\ pore\ water\ pressure\ dissipated}{initial\ excess\ pore\ water\ pressure} = \frac{u_i - u}{u_i} \qquad \text{(Eq. 2.5)}$$

2.3. Laboratory-based consolidation tests

In a laboratory, the usual way to execute one-dimensional consolidation test comprises of laterally confined fully saturated soil specimen in a fixed metal ring with axial loading. Based on the loading procedure, different types of one-dimensional consolidation testing methods are mentioned in the past literature (Head, 1983) Amongst all methods, the two most common methods used to determine one-dimensional consolidation characteristics are the Incremental Loading (IL) consolidation test and the Constant Rate of Strain (CRS) consolidation test which are briefly explained below in Figure 2.2

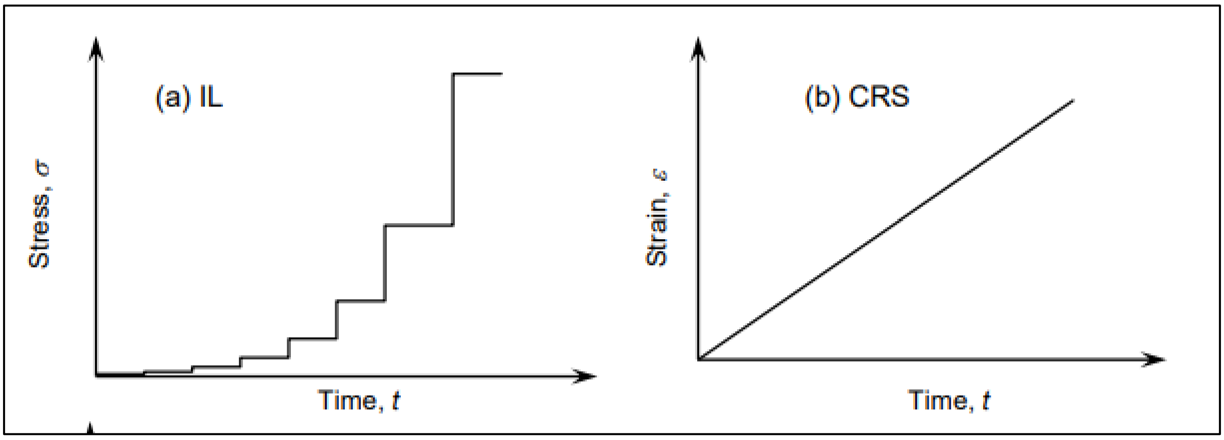


Figure 2.2 (a) Incremental loading consolidation (IL) and (b) constant rate of strain (CRS) consolidation curve (Head, 1983)

2.3.1 Incremental loading (IL) consolidation Test

In past decades, a conventional oedometer test is used to perform a one-dimensional consolidation test and to obtain compression characteristics of cohesive soils. The test is performed on a laterally confined soil specimen placed in a fixed metal ring with applied load increment ratios of unity with each increment left on for 24 hours. On load increment application, immediate deformation readings are noted with time to obtain the time-deformation curve. Based on the results obtained, the permeability (k) and coefficient of consolidation (c_v) are calculated.

In this technique, it is difficult to differentiate the primary and secondary consolidation phenomenon to create the compressive curve. Standard testing procedures adopted are well established and have also been provided in the ASTM D2435-11 (2011). Other testing standards available to determine the consolidation characteristics are IS 2720-15; BS 1377-05; AASHTO T216; ASTM D4546 and ASTM D3877. These standards specify the testing procedure, data collection, and calculation method.

2.3.1.1 Apparatus for IL Test

To perform a one-dimensional consolidation test, an oedometer is required which includes the consolidation cell and a loading unit.

2.3.1.2 Consolidation cell

In the present scenario, there are two commercially available models and schematic diagrams of consolidation cells are shown in Figure 2.3 Consolidation cell assembly; (a) Fixed ring consolidometer parts and assembly and (b) Floating ring consolidometer parts and assembly (Moozhikkal et al, 2019) The most important component of consolidation cell is the consolidation ring/oedometer in which the sample is housed. This consolidation ring is made up of non-corrosive material like stainless steel or brass with a well-polished inner surface to reduce the effect of friction. This consolidation ring should be stiff enough to prevent lateral deformation due to axial loading. To reduce the contact friction between the periphery of the soil sample and the inner surface of consolidation ring, the inner surface should be properly smeared with silicon grease. As per ASTM D2435-11 (2011), a minimum specimen diameter to height (D/H) ratio equivalent to 2.5 is recommended. The minimum allowable diameter and height recommended are 50 and 12 mm.

At the beginning of the experiment initially, the soil specimen is confined in the consolidation ring and then sandwiched between two porous stones and filter paper to allow free drainage at the boundaries. Other components are the perforated loading pad placed over the above arrangement to permit the water flow from the soil specimen. Later, the whole assembly is placed with the outer chamber tightened with fasteners and filled with water to saturate the specimen for 24 hours.

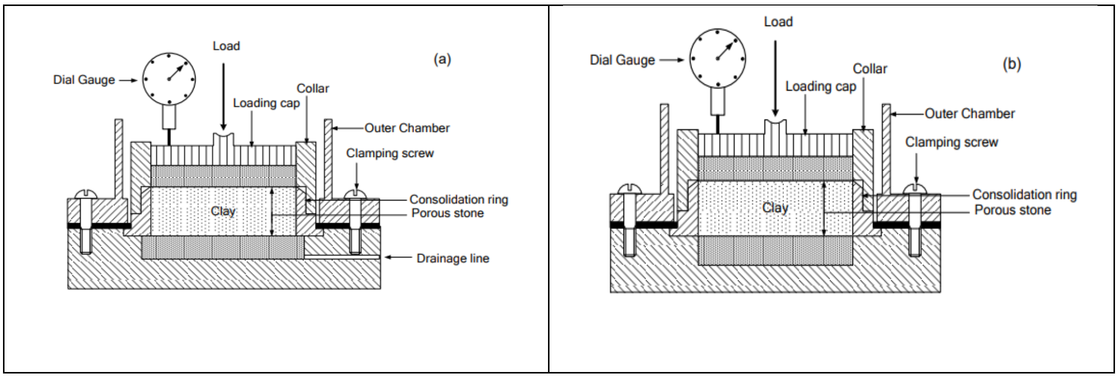


Figure 2.3 Consolidation cell assembly; (a) Fixed ring consolidometer parts and assembly and (b) Floating ring consolidometer parts and assembly (Moozhikkal et al, 2019)

With modifications in the past, a modified consolidation cell was developed by Rowe and Barden in 1966. Based on the researchers, it was named as Rowe cell or hydraulic consolidation cell with an additional provision of back pressure arrangement as can be seen in figure 2.4

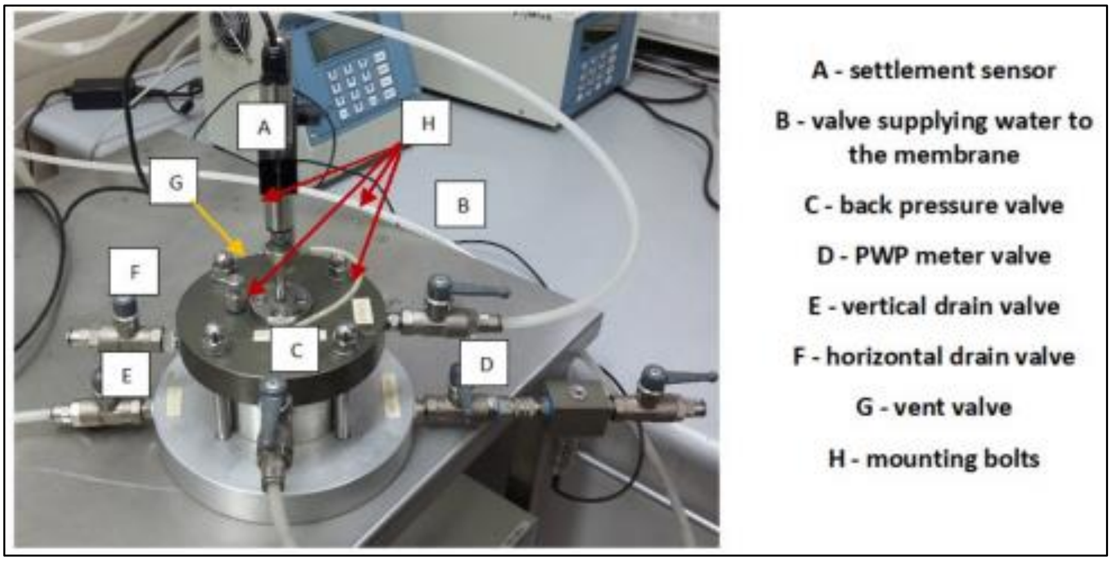
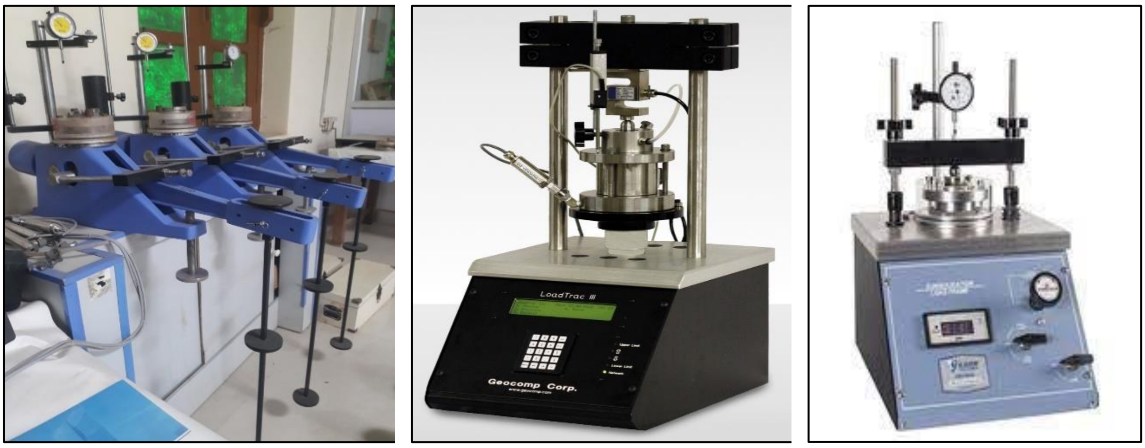


Figure 2.4 Labelled Rowe cell (Adamczyk and Pomykała, 2022)

2.3.1.3 Loading unit

A loading unit is a suitable device used for the application of axial loads or total stresses to the soil specimen. The device can maintain the specified loads for a long duration with a tolerance of 0.5% of the applied load. This device provides suitable arrangements to mount the piston and displacement transducer and permits quick application of an applied load increment without any impact. This lever loading unit consists of a mechanical loading arrangement which distributes the applied axial load in a 1:10 ratio with the lever arm. This type of loading unit is very simple and inexpensive to use. However, this method is a mechanical loading system, but it has a certain limitation in that even a slight vibration can cause disturbance to the sample and the applied stress level to the arrangement is restricted.

To overcome the limitations associated with conventional loading units, pneumatic and fully automated consolidation apparatuses were developed with fewer footprints. In a pneumatic consolidation assembly, the loading is applied with a pneumatic cylinder. For automatic consolidation assembly, the loading is applied with the servo-controlled mechanism. The different types of loading arrangements found for consolidation practices are shown in Figure 2.5.



(a) **(b)** **(c)**

Figure 2.5 (a) Conventional loading arrangement, (b) Automatic consolidation loading arrangement (https://www.utest.com) and (c) Pneumatic consolidation loading arrangement (https://www.globalgilson.com).

2.3.1.4 Determination of Coefficient of Consolidation (c_v)

With the initiation of the IL consolidation test, the soil settlement data are continuously monitored with time to obtain the coefficient of consolidation (c_v) and the coefficient of secondary compression (c_α). The available standard methods widely used for analyzing the settlement data include the Time Fitting Method proposed by Casagrande and Fadum

(1940), and the Square root of Time Fitting Method introduced by Taylor (1948).A review of these methods can be found in the literature (Duncan, 1993; Leonards, 1962; Olson, 1986; Shukla et al., 2009; Raheena and Robinson, 2018). In addition, the Inflection point method is also discussed (Cour, 1971; Mesri et al., 1999; Robinson, 1997; Shukla et al., 2009; Raheena and Robinson, 2021).

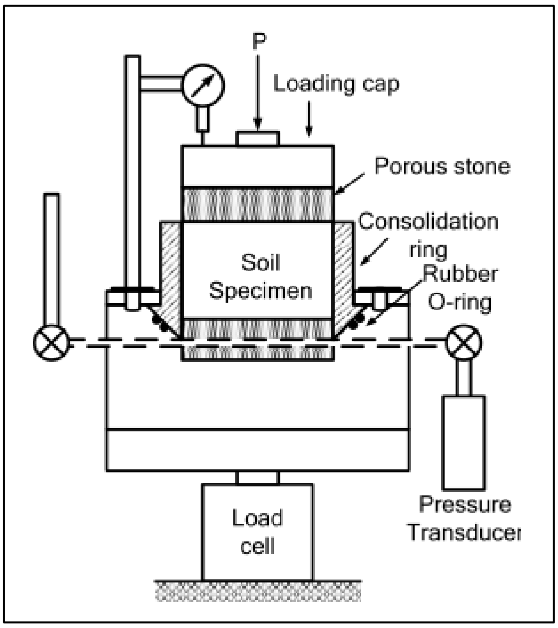
2.3.2 Constant rate of strain consolidation

Hamilton and Crawford were the first to introduce the constant rate strain consolidation method in 1959 (Kassim and Clarke, 1999; Adams, 2011; Fantaziu and Muat, 2014; Prashant and Vikash, 2015; Henniche and Belkacemi, 2018; Maleksaeedi et al., 2018). This phenomenon is a strain-controlled method in which the saturated soil specimen is allowed to deform vertically at the constant strain rate $\left[\delta\left(\frac{\Delta H}{\Delta t}\right) = constant\right]$ with drainage permitted at top of the specimen and an excess pore water pressure is developed at the base with continuous data recording with data acquisition system (DAQ). Based on this, several theories and experimental procedures were developed.

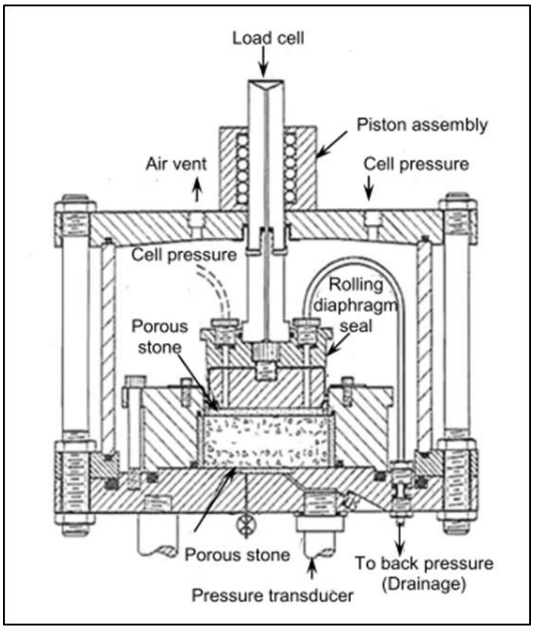
2.3.2.1 Apparatus for CRS Test

For the CRS test, a metal consolidometer with restrained lateral movement of soil specimen is attached with a rigid base. A pair of filter paper and saturated porous stones is placed at top and bottom of the specimen with a pore pressure arrangement at the base plate. The top loading plate is attached to the top porous stone for the piston to distribute the axial load uniformly on constant strain rate application. Pore pressure and deformation are measured with a pore water pressure (PWP) sensor and LVDT at their respective locations. Based on this concept, different CRS consolidometers were developed by many researchers for the CRS consolidation test.

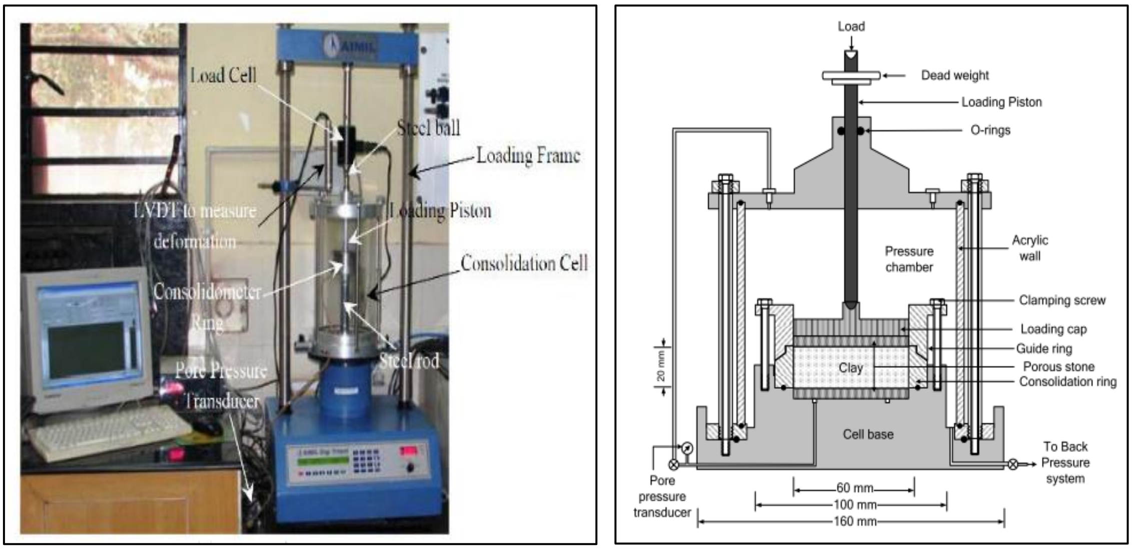
Hamilton and Crawford developed an arrangement to perform the CRS consolidation test. With further advancement, Smith and Wahls (1969) developed a fixed ring CRS consolidation apparatus with a provision of pore water pressure at the base of the specimen and the schematic diagram of this CRS test as shown in Figure 2.6 (a) and (b). Later many other models were proposed to understand the concept with modifications. In the last decades, Prashant and Vikash (2014) and Moozhikkal et al., (2019) also customised the triaxial cell with modified fixed rind ring consolidation with and without back pressure arrangement suitable connections made at the bottom for the CRS test as shown in Figure 2.6 (c) and (d). ASTM D4186-12 provides a standard provision for CRS tests considering the past apparatuses. The CRS consolidation cell comprises of back pressure arrangement saturated condition of the sample throughout the test as can be seen in Figure 2.6. The commercially available CRS setup in the market is quite expensive. Therefore, little alterations in conventional one-dimensional consolidation cells can be useful for teaching and experimental purposes.



(a.) Smith and Wahls (1969)



(b.) Wissa (1971)



(c.) Prashant and Vikash (2014) **(d.) Moozhikkal and Robinson (2018)**

Figure 2.6 Different CRS consolidometer assembly

2.3.2.2 Maximum allowable ratio of excess pore pressure and applied pressure (u_a/σ_v)

In the present study, the pore-water pressure ratio (PPR) is the prime concern for the suitability of the CRS technique. This PPR is expressed as a ratio of excess pore water pressure to applied total vertical stress. From the literature, some of the suggested PPR data have been identified based on the reported values of allowable PPR. (Smith and Wahls, 1969; Wissa, 1971; Sallfors, 1975; Sheahan and Watters, 1997; Gorman et al., 1978; Lee et al., 1993; González, 2000) have also reported PPR values in their work. ASTM D4186-89 and ASTM D4186/D4186M-12 recommend the PPR in the range of 0.03-0.30 and 0.03-0.15 respectively.

2.4 Electrokinetic Phenomenon

Electrokinetic treatment was first discovered by Reuss in 1809 (Malekzadeh et al., 2016). It is the phenomenon of water flow across the porous medium under the influence of an external electric gradient (Mitchell and Soga, 2005) This treatment leads to a change in physical, chemical, and hydrological changes in the soil due to the application of DC. These changes occur in soft clays or problematic soils due to the presence of negatively charged clay particles and ions present in the pore fluid which get attracted to the oppositely charged electrodes and tend to drag them with their surrounding water. The net negative charge of clay particles is balanced by positively charged ions present in pore water. Therefore, in clayey soils, the application of DC is responsible for the flow of water and aids in the early consolidation of the soil. This method was first employed by L. Casagrande in 1939 for stabilizing a long railroad cutting in Germany. Later on, a theory was developed by Esrig in 1968 (Karim, 2014; Fu et al., 2018).

The main aim of electrokinetic treatment is to stabilize, remediate or consolidate the existing problematic soils before construction. From the geotechnical point of view, it is useful in improving excessive foundation deformations, increasing friction pile capacity, stabilization and strengthening of soft clays, controlling pore water pressures at excavation sites, consolidation of marine sediments, and dredged sediments for land reclamations and dewatering (Jeyakanthan et al., 2011; Jeyakanthan and Gnanendran, 2013; Annamalai et al., 2014; Kaniraj, 2014; Flora et al., 2016; Gargano et al., 2020a)

2.4.1 Principle of Electrokinetics

For fine-grained soils, this technology involves the use of a relatively low electrical current density, of the order of several A/m^2 of soil cross-sectional area, to transport and remove the contaminant species from soils. The application of a low-level electrical current is responsible for the soil water-electrolyte system to undergo physicochemical and hydrological changes leading to contaminant transport and removal. This applied electric current to soil leads to several complex transport processes and electrolytic reactions at the electrodes.

Reactions occurred at the electrode are mentioned in equation 2.6 and 2.7 respectively:

Anode: $2\ H_2O \rightarrow O_2\,(g) + 4\ H^+ + 4\ e^-$ (Eq. 2.6)

Cathode: $4\ H_2O + 4\ e^- \rightarrow 2\ H_2\ (g) + 4\ OH^-$ (Eq. 2.7)

2.4.2 Diffuse Double Layer (DDL)

To understand the behaviour of clayey soils, concepts of Stern–Gouy double layer theory were Figure 2.7. In clays, the surface of a clay particle is negatively charged which attracts positive ions and creates a double layer of ion concentrations on the surrounding particle. Thus, the layer closest to the surface is termed as Stern layer which comprises a thin layer of tightly packed positive ions strongly attracted to the negative surface charge of the clay particle and are not detachable under normal circumstances (Mitchell and Soga, 2005; Guo, 2017). After the Stern layer, another layer consists of the positive particle in high concentration attracted to negative charges but not strongly attached. This layer mainly contributes to electrokinetic flow and termed a Diffuse Double Layer (DDL).

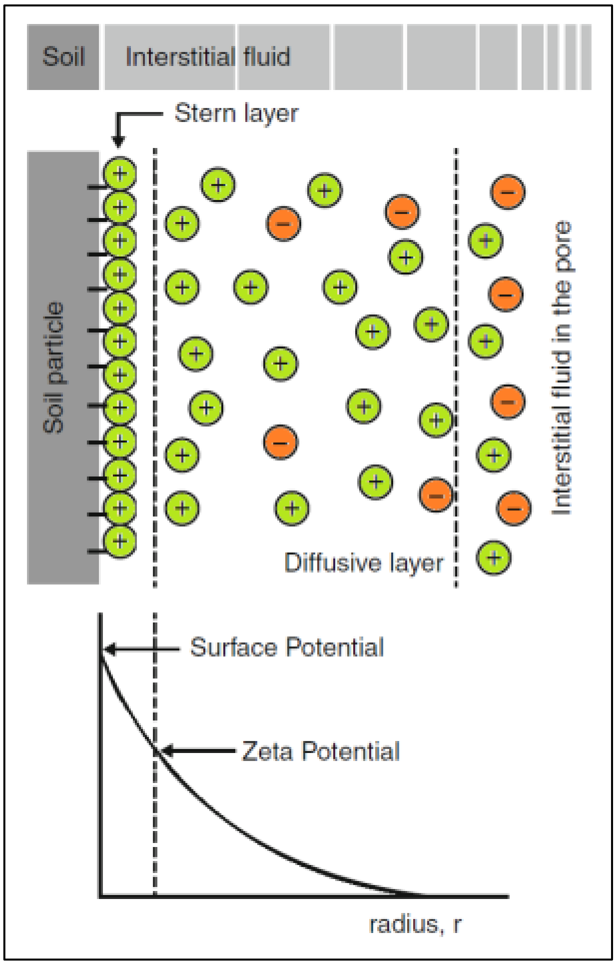


Figure 2.7 DDL phenomenon (Martin, 2019)

The formula for Diffused double-layer thickness (κ) is expressed below in equation 2.8;

$$\kappa = \sqrt{\frac{2c_o e^2 F^2}{\epsilon_o K_m RT}} \qquad \text{(Eq. 2.8)}$$

where, c_o represents molar concentration of electrolyte, e represents valence; F represents Faraday constant; ϵ_o represents vacuum permittivity; K_m represents the relative permittivity; R represents the gas constant, and T represents absolute temperature.

2.4.3 Electrokinetic Consolidation

Electrokinetic consolidation is a widely used alternate ground improvement technique being adopted in soft soils due to highly negatively charged clay surfaces. This section discusses the related theories, factors affecting electrokinetics, and numerous laboratory test set-up mentioned in past studies.

2.4.4 Soft soils

Soft soils are a major challenge for the geotechnical engineer in the development of construction, building, and infrastructure. This soil possesses stability and settlement problems which increase its treatment time and cost. Some major problems of soft soils are:

(i) high compressibility,

(ii) low shear strength,

(iii) decreased permeability,

(iv) low bearing capacity,

(v) low shear strength,

(vi) high potential for swelling and shrinkage,

(vii) high maintenance and construction costs, and

(viii) slow rate consolidation which leads to long-term settlement.

To overcome these issues, the Electrokinetic technique can be adopted to study the influence of constant electric gradient application on soil specimens which improves the soil structure and problems associated with it.

2.4.5 Theory of electrokinetics

Casagrande (1949) used the electro-osmosis technique as a dewatering tool to stabilize slopes and excavation. This technique helps in the removal of pore water pressure which results in consolidation.

This consolidation leads to the generation of a hydraulic head due to the electro-osmosis action. Therefore, the expulsion of pore water pressure is due to the cumulative effect of the hydraulic and electro-osmotic gradient. The equation generated for flow induced by electric gradient can be given as mentioned in equation 2.9:

$$q_e = k_e i_e A \qquad \text{(Eq. 2.9)}$$

Where, q_e = flow induced by electric gradient; k_e= electro-osmotic permeability; i_e = constant voltage gradient, and A = cross-sectional area.

The equation mentioned by Darcy’s law for hydraulic flow can be given as mentioned in equation 2.10:

$$q_h = k_h i_h A \qquad \text{(Eq. 2.10)}$$

Where, q_e= flow induced by hydraulic gradient; k_e= hydraulic permeability; i_e= hydraulic gradient and A=cross-sectional area.

At equilibrium condition mentioned in equation 2.11 and 2.12:

$$k_h i_h = k_e i_e \qquad \text{(Eq. 2.11)}$$

$$k_h \frac{h}{l} = k_e \frac{E}{l} \qquad \text{(Eq. 2.12)}$$

Here, $h =$ hydraulic head difference; $E =$electric gradient difference; $l =$length of soil specimen as mentioned in equation 2.13;

$$h = \frac{k_e}{k_h} E \qquad \text{(Eq. 2.13)}$$

Casagrande was successful in predicting the relationship for the electro-osmotic head. But no theories were presented to understand the variation in excess pore water pressure with time. Esrig (1968) first presented the first theoretical model for one-dimensional electro-osmotic consolidation.

The assumptions associated with the theory are:

i. Homogenous and fully saturated soil structure.
ii. Uniform physicochemical properties do change with time.
iii. No movement of soil particles under electrophoresis.
iv. Electro-osmotic permeability is assumed to be constant with time.
v. The voltage applied is effective in the movement of ions.
vi. No alteration in the electric field throughout the soil mass.
vii. Superimposition of electric and hydraulic gradients results in the movement of fluids.

With the advancement in research, different coupled consolidation-related numerical and analytical studies were performed and mentioned in Table 2.1. These studies deal with coupling electrokinetic technique with vacuum loading, surcharge loading or considering the consolidation in one-dimensional or two-dimensional study

Table 2.1. Review of the development of coupled consolidation theories and models

Authors	Important feature
Esrig (1968)	A one-dimensional (1-D) consolidation analytical model was developed to study the excess pore-water pressure and electro-osmotic consolidation, permeable cathode and an impermeable anode due to a uniform electric field.
Wan and Mitchell (1976)	The coupled phenomenon of electro-osmotic consolidation with surcharge preloading for the 1-D model.
Su and Wang (2004)	Analytical solution of excess pore-water pressure in soils proposed in a hypothetical two-dimensional (2-D) electric field in a horizontal plane for different boundary conditions.
Rittirong et al., (2008)	Two-dimensional (2-D) finite difference model for consolidation to analyze the subsurface ground settlement and undrained shear strength with the change of excess pore-water pressure and water discharge.
Liaki et al. (2008)	An axisymmetric model for consolidation was developed to analyze the average excess pore pressure and radial average degree of consolidation under the combined action of the load and electro-osmosis.
Tamagnini et al., (2010)	A developed numerical model for electro-osmosis processes to study the gas generation and transport under unsaturated conditions.
Cang et al. (2011)	A two-dimensional (2-D) consolidation analytical model was proposed in the vertical plane to account for the combined effect of preloading and electro-osmotic consolidation of clayey soils.
Wu and Hu (2012)	Developed a physical model for electro-osmotic consolidation, coupling pore pressure parameter, displacement and electric field.
Wu and Hu (2013)	The axisymmetric model was developed for coupled horizontal and vertical seepage conditions and proposed an analytical solution to study the pore-water pressure distribution in a radial direction without considering the equal strain hypothesis.
Hu and Wu (2014)	A Time-dependent three-dimensional (3-D) finite element model was developed and a simulation of the mechanical and hydraulic behaviour of soil was performed.

Table 2.1. Continued.

Yuan and Hicks, (2014)	Compared the efficacy of evaporation and electro-osmotic consolidation with the Finite Kinematics approach and extended to unsaturated soil states.
Yuan and Hicks, (2016)	Large strains numerical simulation of electro-osmosis consolidation in multi-dimensional domains was performed. The modified Cam Clay model was exercised to describe the elastoplastic behaviour of clay.
Wu et al. (2017)	A one-dimensional (1-D) consolidation analytical model was developed to study the excess pore water pressure and degree of consolidation based on non-linear variations of soil compressibility, and hydraulic and electro-osmosis conductivities through laboratory experiments.
Gargano et al. (2019)	Developed 1-D finite difference numerical code Lassec 1 to understand the coupled mechanism of mechanical and electroosmotic consolidation.
Zhang and Hu (2022)	A multi-field numerical model was created that takes into account the variation in soil pH and non-linear soil parameters.

2.4.6 Factors affecting the electrokinetic treatment process

Electrokinetic phenomenon depends on soil type, water content, pH, temperature, soil salinity and the changes in physical and chemical properties of the soil. Some other factors like the amount of current and voltage applied, soil resistance, type of electrodes, treatment time and cost are the factors which govern the designing of the system.

2.4.6.1 Soil Type

The electrokinetic phenomenon is effective in fine soils consisting of high organic content. These kinds of soils consist of high surface area and low permeability (Jayasekera and Hall, 2007; Abdullah and Al-Abadi, 2010; Kaniraj and Yee, 2011; Keykha et al., 2014; Yuan et al., 2016; Gargano at al., 2020; Gan et al., 2022). A literature review of articles based on different soil types is mentioned below in Table 2.2.

Table 2.2. Review of literature based on electrokinetic consolidation of soil

Soil type	Researcher
Expansive soils	Abdullah and Al-Abadi, 2010; Gingine et al., 2013; Wu et al., 2015; Hamza and Ikin, 2020; Kherad et al., 2020
Organic soil, Peat and Loams	Asadi et al., 2011; Kaniraj and Yee, 2011; Moayedi et al., 2011; Kaniraj, 2014; Huey, 2016; Pandey and Rajesh, 2019; Safdar et al., 2021
Clayey soils	Kaniraj and Yee, 2011; Paramkusam et al., 2011; Jayasekera, 2015; Gingine and Cardoso, 2017b; Kollannur and Arnepalli, 2019; Gargano et al., 2020a
Mine tailings, sludge and Dredged mud	Fourie and Jones, 2010; Mahmoud et al., 2010; Alcántara et al., 2012; Rozas and Castellote, 2012; Kong and Orazem, 2014; Zhuang, 2015; Xiao, 2017; Martin, 2019; Zou et al., 2020; Xiao et al., 2021
Marine soils	Colacicco et al., 2010; Pradeepan et al., 2016; Azhar et al., 2017; Xue et al., 2020; Malekzadeh and Sivakugan, 2021; Wan et al., 2021

2.4.6.2 Zeta Potential

Zeta potential is a potential that exists at the interface of soil and water under the effect of an applied electric field. It provides data regarding the interface of the soil particles, stability of the particles, state of charges, and their effect on electro-osmotic flow. Soft soils possessing high negative zeta potential will have a greater affinity towards water flow through the soil mass which makes them more favorable for electrokinetic treatment. With increasing ionic strength of the soil, the zeta potential becomes more positive. At a specific pH level, soil particles can possess no electric charge without any movement of particles (Cameselle and Reddy, 2012; Yukselen-Aksoy and Reddy, 2012). This is normally referred to as zero point of charge (ZPC) or isoelectric point Malekzadeh (2016). Soils with higher negative zeta potential will result in high dewatering efficiency, lower power consumption and higher osmotic dewatering (Martin, 2019; Gargano et al., 2020). Based on the values of zeta potential the stability characteristics range is also mentioned (Esrig, 1968).

2.4.6.3 pH

For electrokinetic treatment, soils with high buffer capacity are preferred to withstand the pH fluctuation that occurs during the process. pH value of the soil is responsible for the formation of a stabilizing agent during the process. In alkaline conditions, a pozzolanic reaction can occur which may result in an increase in soil strength, liquid limit and plastic limit of the soil near the cathode but reduces near the anode (Jayasekera and Hall, 2007; Chien et al., 2010; Kim et al., 2011). It is necessary to maintain the pH level of the soil to 7 or more to maximize its efficiency and reduce the corrosion rate of the anode and increase the soil precipitation, resulting in better efficiency and higher soil strength (Kim et al., 2011; Malekzadeh et al., 2016). In contaminated soils, lower pH near the anode causes desorption and increases the solubility of cationic metals, such as nickel, cadmium and lead enhancing their electromigration towards the cathode (Reddy, 2013). This low pH level of soil results in an increase in the corrosion rate of the anode, therefore, it is desirable to have high extreme pH values (Malekzadeh et al., 2016; Sadeghian et al., 2022). Increasing acidity and ionic strength cause the zeta potential to become less negative and even to attain positive values at low pH (Jeyakanthan et al., 2011)

2.4.6.4 Temperature

The temperature has a significant effect on the thickness of the double diffused layer and soil dielectric constant. With an increase in temperature, the diffused double layer of soil particles increases for the same surface charge and the soil dielectric constant decreases (Malekzadeh et al., 2016). During the process, the temperature near the electrodes increases due to the thermal energy flow which results in loss of electrical contact between soil and electrodes. On the contrary, higher temperatures increase the permeability and pore water pressure, which results in the improvement of soil consolidation and reduces the pre-consolidation pressure (Mitchell and Soga, 2005).

2.4.6.5 Water Content

The soil moisture content plays an important role to permit the electromigration flow within fine-grained soils on the application of electric gradient. Soil porosity, void ratio and electrical resistivity are dependent on the initial moisture content of the soil. Slurry-type of soils with high initial moisture content shows significant moisture reduction up to 100% on electroosmosis application. Various geotechnical applications based on treating high initial moisture content are soil stabilization, soil dewatering, soil strengthening, soil reinforcement and soil consolidation (Fourie and Jones, 2010; Jones et al., 2011; Bourgès-Gastaud et al., 2017; Saeedi et al., 2018)

2.4.6.6 Level of Soil Salinity

The zeta potential and electro-osmotic permeability are factors dependent on the level of soil salinity which affects the electroosmotic flow (Mitchell and Soga, 2005). If the soil salinity increases, the zeta potential reduces, and this can reduce the electroosmotic flow. The level of soil salinity can be either estimated in terms of electrical conductivity (S or mS) or amount of salt content (ppm). The defined limit for total dissolved salt is 6000 ppm (Bergado et al., 2003). The soil with electrical conductivity above 2.5 mS/cm might not give a good response for electroosmotic treatment (Malekzadeh et al., 2016). Soils with electrical conductivity of 16 mS/cm are considered to be ‘‘extremely saline’’ (Jayasekera and Hall 2007; Malekzadeh et al., 2016). Despite much research in this area, no limiting value of soil salinity has been assigned.

2.4.6.7 Electrical Resistivity and Conductivity

Soil conductivity is the ability of the soil particle to transfer electrical current. Factors affecting the soil's electrical conductivity are temperature, water content, soil porosity, pore fluid resistivity, soil composition, soil salinity, particle and pore size and shape (Pandey and Rajesh, 2019).

The formulation for the electrical conductivity of soils is expressed in equation 2.14:

$$\sigma = \frac{L}{RA} \qquad \text{(Eq. 2.14)}$$

Where, σ, R, L and A, represents electrical conductivity, electrical resistance, length and cross-sectional area of the sample respectively. The SI unit for electrical conductivity is Siemens per meter and the acceptable range lies within the range of 0.05 S/m – 0.005 S/m (Jones and Glendinning, 2006; Glendinning et al., 2015). Many researchers adopted different values of initial electrical conductivity for the treatment (Cang et al., 2013; Jang et al., 2015; Wang et al., 2016).

2.4.6.8 Type and Configuration of Electrodes

The electrode material plays an important role in the efficiency of the electrokinetic process. It should be of low cost, resistant to the heat generated when the electric current is applied, and resist possible corrosion. Different kinds of electrodes such as inert metals, non-inert metals, carbon-based and electrokinetic geosynthetic electrode materials have been used by many researchers (Malekzadeh, 2016; Sara, 2020). These can be installed in different configurations, for example: unidirectional, bidirectional, radial – pairs or radial–bidirectional (Gill et al., 2014). When a metal electrode is used, the anode starts to electrolyse which results in the loss of soil-electrode contact and stops the current and water flow (Malekzadeh and Sivakugan, 2017). The redox chemical equation involved with the electrolysis process are mentioned in equation 2.15 and 2.16 respectively-

Oxidation at the anode:

$$2H_2\mathrm{O} - 4\mathrm{e}^- \rightarrow \mathrm{O}_2 + 4H^+ \qquad \text{(Eq. 2.15)}$$

Reduction at the cathode:

$$2H_2\mathrm{O} + 2\mathrm{e}^- \rightarrow H_2 + 2OH^- \qquad \text{(Eq. 2.16)}$$

According to the literature, an addition of an alkaline solution to the soil through the anode can reduce the acidity of the soil and prevents the corrosion of anodes due to the reduction of pH near the anode (Sadeghian et al., 2022). In past literature, different types of metal electrodes have been used and are mentioned in Table 2.3

Table 2.3. Review of literature based on metal electrodes

Electrode type	Properties	Researchers
Titanium and Platinum-coated titanium	Corrosion resistance, lightweight, low thermal expansion and shrinkage, too expensive	Almeira et al., 2012; Ou et al., 2013; Chien et al., 2013; Guedes et al., 2014; Moayedi et al., 2014; Citeau et al., 2016; Shang and Xu, 2019; Cameselle et al., 2021
Copper	Current resistant, lower wear rate, high loss of power and voltage	Jeyakanthan et al., 2011; Wu and Hu 2014; Hsieh et al., 2015; Hu et al., 2015; Wu et al., 2015; Hu et al., 2016; Wu et al., 2016; Bourgès-Gastaud et al., 2017; Xue et al., 2019; Tao et al., 2020; Xue et al., 2020; Sadeghian et al., 2022; Xiao et al., 2021; Ferreira et al., 2022; Sadeghian et al., 2022
Silver	Superior electrical conductivity, high purity, expensive	Cardoso and Santos, 2013; Santos, 2013; Gingine and Cardoso, 2017a; Gingine and Cardoso, 2017b
Aluminium	High current resistant, light weight, good conductor of electricity, less environment friendly	Zhou et al., 2015; Tao et al., 2016); Reshma and Leander 2017; Xiao et al., 2021; Babu et al., 2021; Sadeghian et al., 2022
Steel, mild steel and Stainless steel	Good conductor of electricity, High corrosion resistant less brittle, low maintenance	Jayasekera and Hall, 2007; Jami and Iwata, 2008; Hu and Wu, 2014; Boulakradeche et al., 2015; Wu et al., 2015; Wu et al., 2015; Hu et al., 2015; Tajudin et al., 2016; Wu, Hu and Zhang, 2016; Xue et al., 2017; J and Leander, 2017; Malekzadeh and Sivakugan, 2017b; Malekzadeh and Sivakugan, 2017; Azhar et al., 2018; Wan et al., 2019; Xue et al., 2019; Saeedi and Mollahosseini, 2019; Nordin and Chan, 2020a; Sadeghian et al., 2022; Rotte et al., 2022
Iron	Highly corrosive and magnetic, brittle and malleable, high maintenance	Wu and Hu 2014a; Wu et al., 2015; Zhou et al., 2015; Jones and Leander, 2017; Ling et al., 2020; Xiao et al., 2021

2.4.7 Methods to enhance the efficiency of electro-osmotic consolidation

With advancement, enhancement techniques such as polarity reversal, alternating current (AC) or addition of saline solution techniques have been adopted. Details related to the enhancement techniques are discussed below-

2.4.7.1 Polarity reversal

During the electrokinetic process, the fluid movement from anode to cathode results in the drying of the anode area leading to cracks further results in loss of soil-electrode contact, and resists the electric current flow (Malekzadeh et al., 2016; Gargano et al., 2020). To eliminate the problem of non-homogeneous settlement and maintain uniform pH conditions, the electrode polarity is reversed at regular intervals. This technique also leads to a decrease in corrosion level, and increased electro-osmotic flow, and is effective at removing the products of electrochemical reactions deposited on the electrode surface, which can reduce the active surface area of the electrode and increase its efficiency (Gill et al., 2014; Iwata et al., 2017).

2.4.7.2 Alternating current application

The alternating Current method is accepted more than polarity reversal because of its low drainage duration, high efficiency, low energy consumption and cost. Use of an AC power supply instead of DC, electro-osmotic dewatering under the AC condition is effective mainly in the range of frequency around 1Hz (Gingine et al., 2013). The principle of AC applied in the consolidation drainage is similar to polarity reversal treatment, the energy consumption under AC is much higher than under DC, and the efficiency is lower than under DC (Conrardy et al., 2016; Xue et al., 2017).

2.4.7.3 Injection of chemical solution

Due to potential loss, the interface resistance is increased which affects and limits the application of potential gradient up to 35%. So, to improve the problem of electrode erosion and corrosion, chemicals are introduced such as NaCl, $CaCl_2$ and others that result in an increased rate of ion exchange and results in accelerated drainage and consolidation rate (Ye, 2016). Recently, chemical grout reagents like aluminium hydroxide, sodium silicate, calcium chloride and calcium oxide were added to stabilize soft soils such as peat (Moayedi, et al., 2014).

2.4.7.4 Use of Electrokinetic geosynthetics (EKG)

Major developments in the last decade in EKG electrodes have overcome the major problem of corrosion in the field of the electro-osmosis process. These EKGs comprises of conductive polymeric material made singly or from a combination of woven, non-woven, extruded, needle-punched knitted or laminated materials and can be shaped in any 2-D or 3-D shapes (Jones et al., 2011). The major application of EKG electrodes in past civil engineering includes consolidation of highly compressible soils, treatment of contaminated soils and stabilization/strengthening (Chew et al., 2004; Hamir et al., 2001; Jones and Glendinning, 2006; Kaniraj and Yee, 2011; Kaniraj, 2014; Lamont-Black et al., 2015; Ling et al., 2021; Xiao et al., 2021). In the case of mining, applications include dewatering and consolidation (Fourie et al., 2007; Fourie and Jones, 2010; Lamont-Black et al., 2015). In the case of the water industry, the major phenomenon is the dewatering and consolidation of sewage and old sludge lagoons (Glendinning et al., 2008; Fourie and Jones, 2010; Zhuang et al., 2014). Based on this a brief review is mentioned in Table 2.4.

Table 2.4. Review of literature based on the usage of electrokinetic geosynthetic electrodes

Authors	**Aim of the study**	**Important features**
Glendinning et al., (2005)	Soil reinforcement, retaining wall	• Improved shear strength with the initial water content of 65%. • Analysis for short-term analytical methods: critical height, Coulomb, discrete theory, and composite theory.
Jones and Glendinning, (2006)	Improvement of slope Stability	• Increase in undrained shear strength. • Drainage of water and gas bubbles.
Fourie et al., (2007)	Electrokinetic dewatering of mine tailings	• Increased water removal efficiency by up to 158% • Reduced energy consumption (< 1 kWh) per dry tonnes of tailing. • Improved stability and increased storage space.
Kalumba et al., (2009)	Dewatering of tunnelling slurry waste	• Increased electrode element surface area and potential gradient. • High pore water removal.
Fourie and Jones (2010)	Dewatering of kaolinitic mineral sands tailings and smectitic diamond tailings	• Improved performance for lower voltage gradient. • Easy installation, no corrosion and durable.
Jones et al., (2011)	Increased slope stability	• Improvement in bond strength. • No slope movement after the treatment.
Kaniraj and Yee (2011)	Electro-osmotic consolidation, electrical vertical drain (EVD)	• Increased dewatering efficiency. • Installation with lime or cement columns increased the undrained shear strength. • Very soft soil was treated and gained undrained shear strength of > 50 kPa.
Tajuddin et al., (2014)	Electrokinetic stabilization	• Overcome the problem related to the soil-electrode interfaces • Increase in average cone resistance and undrained shear strength
Zhuang et al., (2014)	Electrokinetic consolidation of Hydraulic reclaimed sludge	• Highly reduced water content from 62 to 36%. • Reduced consolidation time from 3 years to 36 days. • Increased bearing capacity up to 70 kPa

Table 2.4 Continued.

Lamont-Black et al., (2015)	Electrokinetic dewatering of nuclear waste	• Higher removal of nuclear waste. • Increase in volume of waste storage.
Lamont-Black et al., 2016)	Electrokinetic strengthening of slopes	• 29% reduction in cost. • 40% reduction in carbon footprint.
Tang et al., (2017)	Electrokinetic strengthening	• Water content and shear strength parameters under different temperatures applied with different loading pressure. • Increased shear strength with an increase in temperature to 35 °C and on increasing voltage from 6 to 12V reduced water content.
Ling et al., (2021)	Electrokinetic treatment of subgrade soil	• The contact resistance of the iron electrode would reach 1.8–4.1 times that of the EKG and graphite electrodes due to material corrosion. • Reduced moisture and contact resistance.
Xiao et al., (2021)	Electrokinetic Consolidation	• At a voltage gradient of 150 V/m, EO with EKG electrode was more efficient than aluminium, copper and iron electrodes • With increased voltage gradient had a better consolidation effect but it increased the energy consumption
Zhuang (2021)	Consolidation with EKG electrode	• Roll polling programme adopted for the control system of smart DC power source. • Reduction in current intensity upto 1/3; which decreases the energy consumption to <1 kW·h/m^3

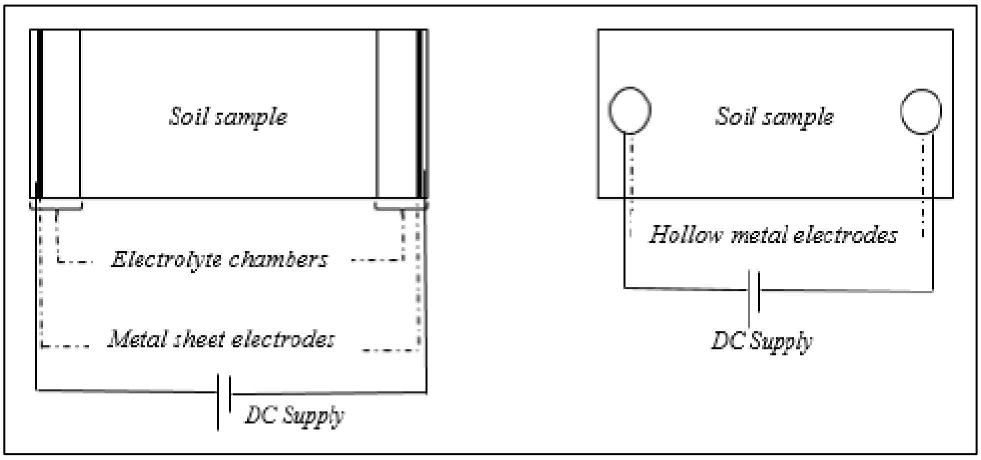
2.4.8 Experimental and field studies

Electrokinetic consolidation is not a routine laboratory test, as there is an unavailability of suitable apparatus and standard methodology that can be adopted in geotechnical engineering. Therefore, individual researchers have designed and developed their laboratory setups of various shapes, sizes, and materials, to understand the coupled behaviour and various parameters as per the requirement. Sometimes, these setups are designed and fabricated from existing consolidation apparatus i.e., an oedometer or a triaxial cell available in the laboratory. Some of the experimental set-ups which pioneered the development of apparatus in the last two decades are presented in the literature and are reviewed and discussed. These models are classified into three models as expressed below-

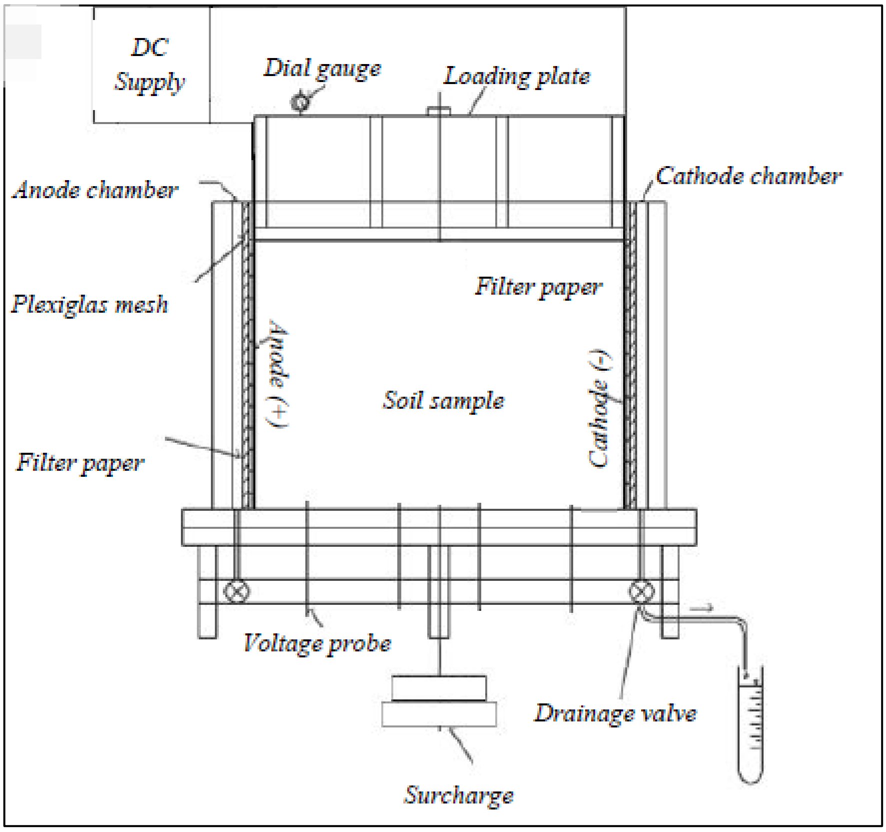
The first model (Model 1) depicts a plan view of the setup, including the electrokinetic cell, soil, anode, and cathode compartments known as electrolyte chambers. The anode and cathode compartments can be separate or designed as perforated hollow electrodes within the cell for electrolyte solution removal. This configuration is commonly used for soil decontamination and small-scale geotechnical electrokinetic simulations.

The second model (Model 2) is modified triaxial or oedometer equipment with a similar concept to the first model. It introduces electrode chambers, including a cathode chamber with drainage, and allows for applying surcharge via a loading plate to enhance the electrokinetic method. However, this model is limited to laboratory experiments and unsuitable for soil slurry applications.

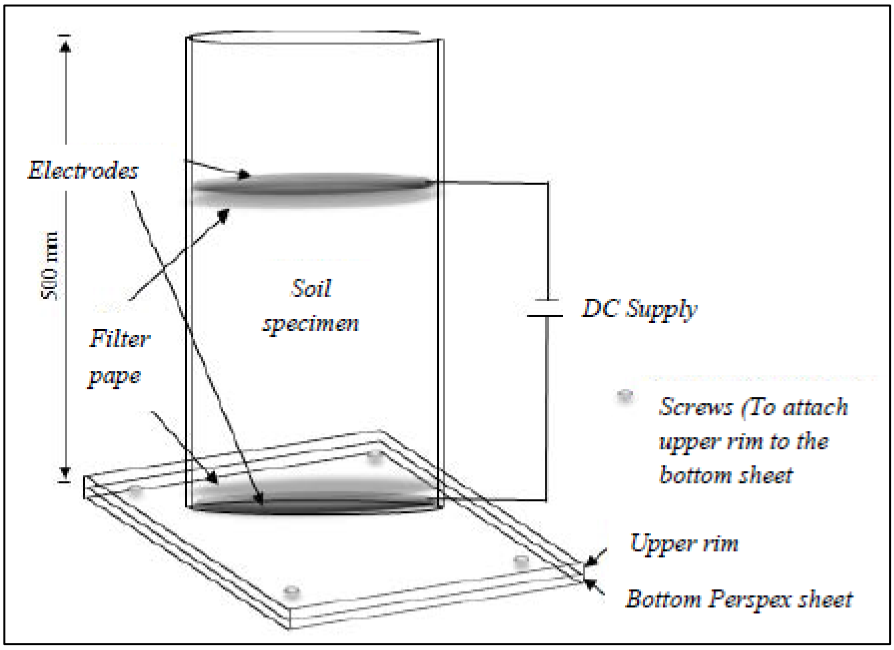
The third model (Model 3) is designed for dewatering and stabilizing slurries. It consists of an electrokinetic cell with a settlement column attached to a plain Perspex sheet at the base. Electrodes are placed both at the top and bottom of soil sediments with a filter paper in between. The process commences by connecting the electrodes to a direct current supply via an opening in the plain Perspex sheet at the center of the rim.



Model 1



Model 2



Model 3

Figure 2.8 Types of Electrokinetic models as considered in Literature (Malekzadeh, 2016)

Bergado et al. (2000) presented a laboratory-based consolidation study performed to carry out electrokinetic coupled with the vertical drain on Bangkok clay as shown in Figure 2.9. Based on the results achieved, the time required for a 90% degree of consolidation with the coupled technique was 1.2-2.2 times faster than the Vertical drain technique.

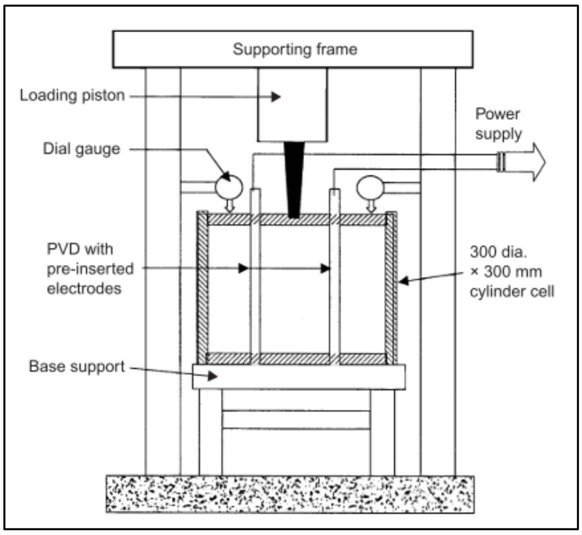


Figure 2.9 Electrokinetic coupled with vertical drain model for consolidation. (Bergado et al., 2000)

Jeyakanthan et al., (2011) performed multiple electro-osmotic consolidation tests with modified triaxial testing equipment available in the laboratory as shown in Figure 2.10. In this study, axial deformation, base pore-water pressure, volume change, and electric current were monitored with a specially designed apparatus. Based on the test conducted, results were analysed and discussed to determine the pre-consolidation pressure and electrolysis effect on soil.

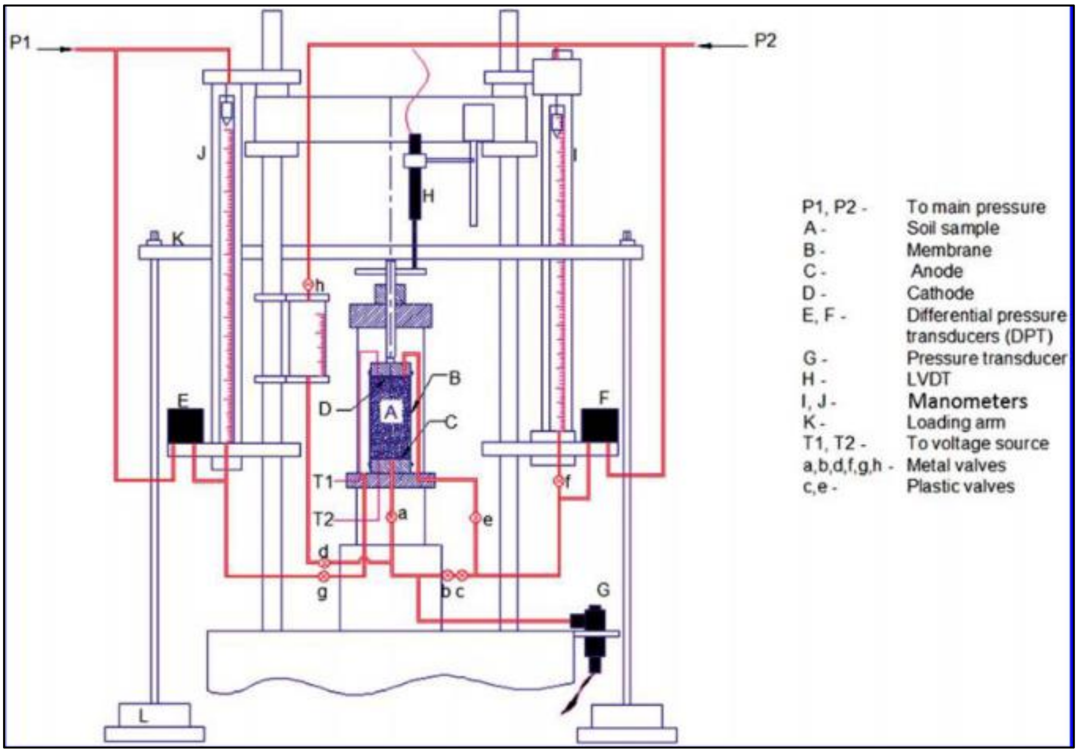


Figure 2.10 Laboratory electro-osmotic stabilization setup using Modified triaxial assembly (Jeyakanthan et al., 2011)

Yusof and Marto (2013) presented a laboratory electroosmotic consolidation test on kaolin slurry with a single positive terminal (anode) surrounded by eight negative terminals (cathode) arrangement as shown in Figure 2.11. Based on the experiment, the void ratio and the coefficient of volume compressibility behaviour were studied. A sample was tested to implement the electro-osmotic consolidation at a laboratory approach.

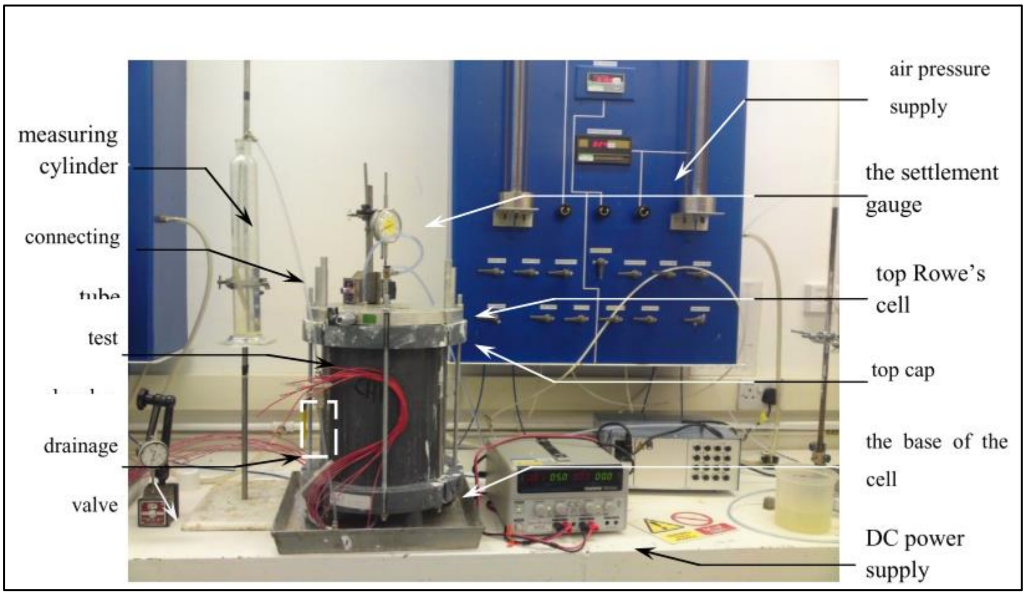


Figure 2.11 Electroosmotic consolidation setup (Yusof and Marto, 2013)

Hu et al. (2016) adopted deep electro-osmotic consolidation (DEC) to study its effectiveness based on a series of laboratory experiments as shown in Figure 2.12. In this study, the influence of effective anode length with the intermittent current technique was performed. The intermittent current technique was used to enhance the flow condition, restrain the crack condition, and restrict power consumption. Based on the test results, electro-osmotic consolidation was effective for an optimal effect for two-thirds anode length.

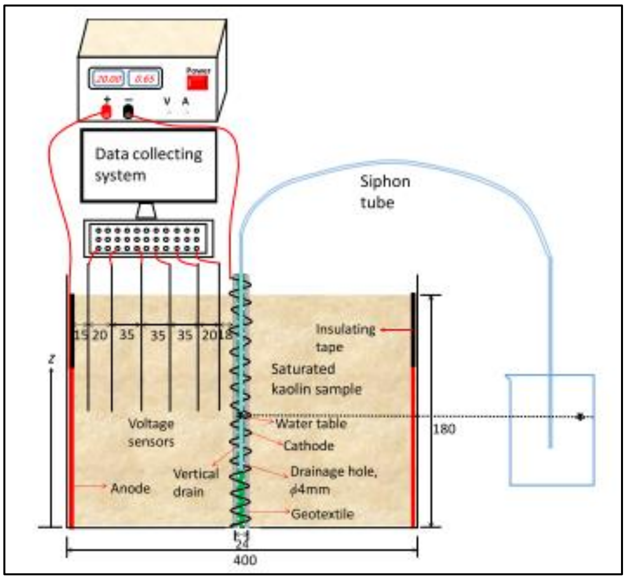


Figure 2.12 Electro-osmotic consolidation through axisymmetric apparatus (Hu et al., 2016)

Malekzadeh and Sivakugan, (2021) presented a study on the application of intermittent and constant current to singly and doubly drained dredged mud sediments as shown in Figure 2.13. With the application of intermittent current, the settlement and volume of drained water increased, but simultaneously, doubled the power consumption which was a major drawback.

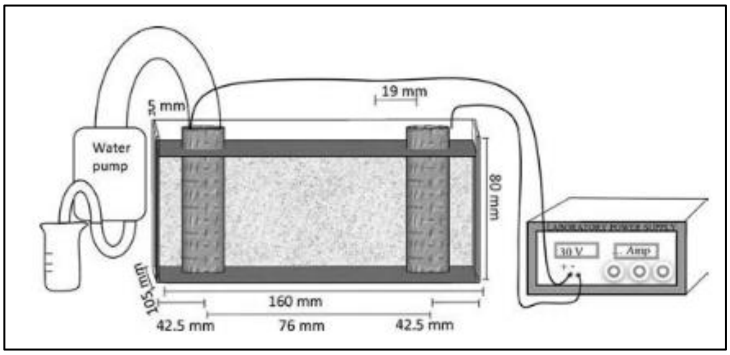


Figure 2.13 Schematic view of the one-dimensional electrokinetic stabilization method (Malekzadeh and Sivakugan, 2017)

Gargano et al. (2019) performed mechanical and electro-osmotic consolidation experiments on sandy clay with two different oedometer namely a special oedometer (EdS), and an electro-osmotic cell (CeO) as shown in Figure 2.14. Later, the experimental results were validated by 1-D finite-difference numerical code Lassec1 with two small strain (SS) and large strain (LS) models considering their pros and cons.

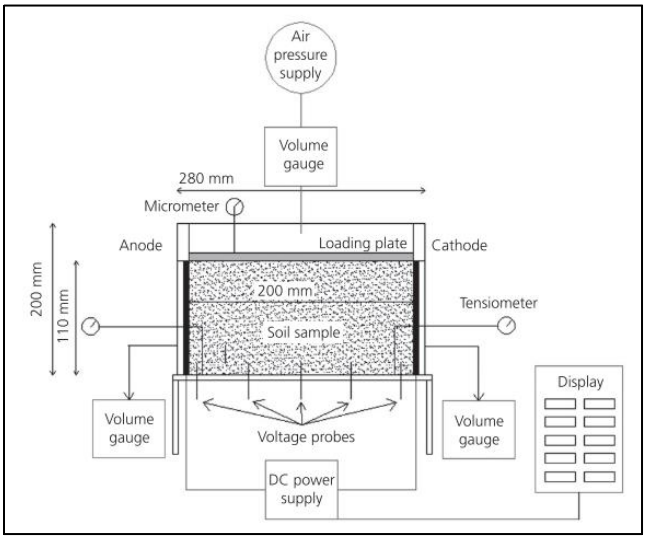


Figure 2.14 Sketch diagram of the electro-osmotic experimental setup (Gargano et al., 2019)

Xue et al. (2020) presented a study to explore the complex mechanism comprising coupled electrochemical–temperature-mechanical behaviour during the electro-osmotic consolidation experiments as shown in Figure 2.15. The tests were conducted on an indigenously fabricated electro-osmotic consolidation system at voltages. During the study, the pH value, temperature, and volume drained increased with voltage, whereas the difference reached a constant value, and was proportional to the voltage rise.

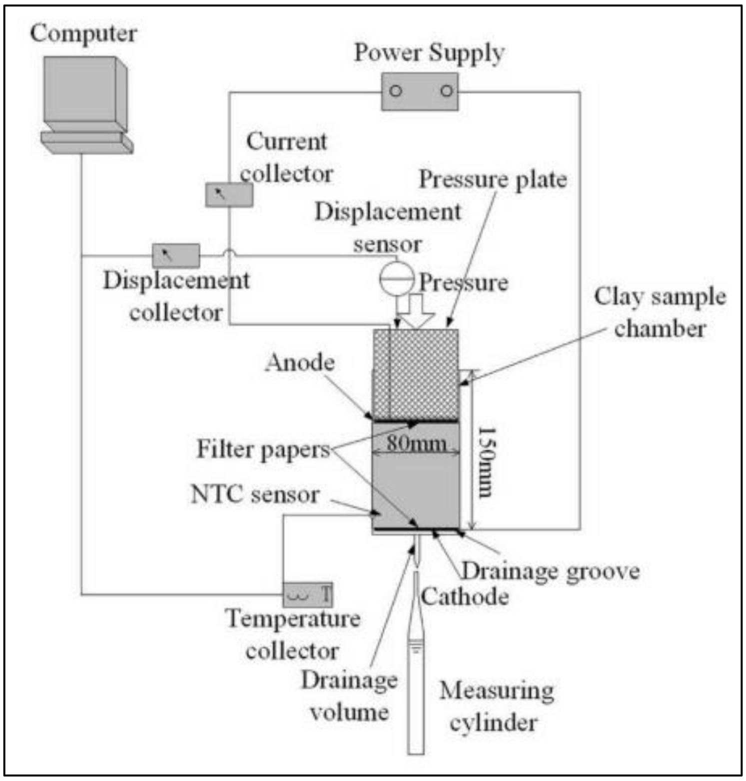


Figure 2.15 Schematic diagram of consolidation setup (Xue et al., 2020)

Deleon et al. (2022) presented a successful laboratory setup to study the consolidation behaviour of bauxite mine tailings with electrokinetic dewatering application to assess the feasibility of applying this technique using the setup shown in Figure 2.16. Based on the results, an increase in the electro-osmotic flow produced a higher final with the increase in the initial applied voltage application. This also states that the higher the electric gradient more will be the final solids content. In the case of no voltage condition, fewer final solids contents were found as compared to the experiments performed with voltage gradient application.

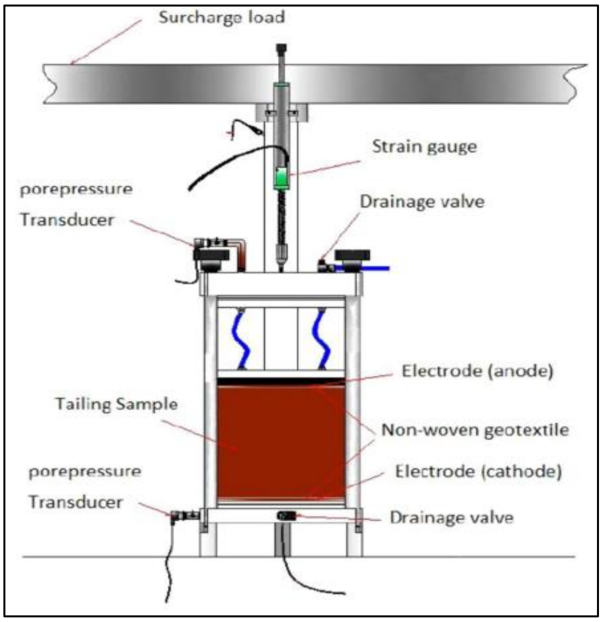


Figure 2.16 Schematic diagram of the Electrokinetic consolidation setup used for Bauxite tailing consolidation (Deleon et al., 2022)

2.5 Summary

Based on the literature review, it is obvious that the electro-osmotic consolidation technique has gained acceptance in the field of problematic soils and sediments. To enhance existing consolidation techniques, it is very much useful to use the knowledge of electrokinetics in soft soils. The electroosmosis phenomenon is highly favourable in soft soils due to the presence of very fine size particles which occupies a larger surface area and possess a negative charge. Despite enormous results, no design criterion has been established by any researcher concerning laboratory-based devices that helps in a faster rate of determination consolidation parameters. Therefore, a laboratory-based electrokinetic coupled consolidometer apparatus helps in overcoming the deficiencies of the prior art, providing a simple, convenient accurate, and faster determination of the compressibility and consolidation characteristics of fine-grained soils.