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Electro Osmotic Piles

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Abstract

The paper introduces the concept of electro osmotic piles, a concept similar to that of soil displacement ground improvement systems but instead of introducing material it uses electro osmotic treatment to stiffen the ground by reducing the water content through electrodes in the form of prefabricated vertical drains. The drains are installed vertically to form a grid of anodes and cathodes. The cathodes act as the drains; the anodes become the centres of the ‘piles’ at which the maximum increase in stiffness occurs. Laboratory tests using different configurations, time of treatment and voltage showed that there is a balance between the improved overall capacity of the ground, the efficiency of the system and the operational energy. Unlike other ground improvement systems this concept allows the final capacity to be predicted from the improvement process.

Notation

V is the applied voltage;

u is the pore pressure

γ_w is the unit weight of water;

k_h is the coefficient of hydraulic conductivity;

k_e is the coefficient of electro osmotic conductivity

Keywords: - geotechnical engineering; piles and piling; research and development

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1. Introduction

A review of papers on electro osmosis published in the last sixty years starting with those seminal papers written by Casagrande (1949) showed that studies have included laboratory and field work to understand the underlying science and its application to improve friction pile capacity (Mohamedelhassan, 2011, Micic et al., 2002a, b, Butterfield and Johnston, 1980), to stabilise trenches and excavations (Bjerrum et al., 1967), to prevent swelling and shrinkage in foundation soils (Micic et al., 2001, Casagrande, 1952a, b, 1949, and Bjerrum et al., 1967), to stabilise slopes (Casagrande et al., 1961, Chappell and Burton, 1975, Casagrande, 1952a, b) and to improve ground through consolidation (Burnotte et al., 2004, Bergado et al., 1994, Casagrande, 1952a, b, and Bjerrum et al., 1967). This paper introduces a new concept of electro osmotic piles.

Electro osmosis in soils is the movement of pore fluid induced by an electric current created by the voltage difference between a positive anode and a negative cathode within a soil. The voltage difference generates a negative pore pressure at the anode thus simulating consolidation due to an external load. Providing the anode is closed, i.e. there is no replenishment of pore fluid, and the cathode acts as a drain, then the degree of consolidation will vary between the cathode and anode, the majority occurring at the anode. If the electrodes are installed vertically then the effect around the anode can be compared to the effect of a displacement column such as a vibro compacted stone column; the excess pore pressure generated at the anode by the voltage difference being comparable to the increase in radial stress due to the installation of a stone column. Thus a layout of vertically installed anodes and cathodes could produce a similar effect to a stone column grid though in this case the consolidation radiating from the anode produces a 'soft' pile with the stiffness reducing with distance from the anode. If that is the case, electro osmotic piles could be considered to be an alternative replacement ground improvement method. This paper describes experiments to demonstrate this and recommendations on how the principle can be applied in practice.

2. Electro Osmosis

The principle of electro kinetics and its effects are described in detail by Mitchell and Soga (2005) and Mitchell (1993). It was first reported in 1809 by Reuss who demonstrated water would flow through clay if a voltage difference was applied. The voltage difference forces water to flow from an anode to a cathode thus generating negative pore pressures at the anode (if it is closed, that is no replenishment of pore fluid). This in turn generates a hydraulic gradient between the cathode and anode which would force the pore water to flow in the opposite direction. In clays, the flow of water due to the electric potential difference exceeds that due to the hydraulic potential difference resulting in pore water flowing from the anode to the cathode. As the hydraulic conductivity increases this effect reduces until it is no longer viable. The electrical conductivity of soil is about 5×10^{-9} m^2/sec-V and is similar for all soils when compared to the hydraulic conductivity which ranges from 10^{-1} m/s in gravel to 10^{-11} m/s in clay. Thus in clays electro osmosis works; in sands it does not. However, it also means that electro osmosis is time limited because the excess pore pressure dissipates resulting in an apparent balance between the flow of water due to the electrical and hydraulic potentials. Electro osmosis will also cease in time because of the degradation of the anode. However, this concept produces a permanent solution that does not require maintenance since at the end of osmotic treatment the soil has consolidated.

3. Performance indicators for electro osmotic piles

In order to assess the performance of the osmotic piles and contribute to the design of the layout three indicators are suggested:- improvement factor, system efficiency and energy consumption. The first is a measure of the outcome of the success of the treatment; the second a measure of the optimisation of the design and the third a measure of the cost of the operation.

Priebe (1995) suggests that an indicator of performance of stone columns is the ratio of the settlement of the untreated layer to that of the treated layer which is, in effect, the square root of the ratio of the average constrained modulus. This, in stone columns, is related to the ratio of the area of the columns to the treated area, and Poisson's ratio and the angle of friction of the column material. It is assumed that that the stone columns support the applied load by behaving in a similar manner to a triaxial specimen with the soil providing lateral restraint. Electro osmotic piles could be considered displacement piles like stone columns because there is an increase in mean effective stress around the anodes. Note however, the stiffness of electro osmotic piles increases from the cathode to the anode but with stone columns there is a step change at the stone column/soil interface.

Priebe (1995) also assumed that the soil between the columns does not contribute to the overall capacity other than through the lateral restraint to the column. This is not the case for electro osmotic piles because of the gradual variation in stiffness between the anode and cathode. This implies the design guidelines for stone columns may not apply to electro osmotic piles.

Table 1 shows the costs of two case studies. In both cases it is the fabrication and installation of the electrodes that amount to more than 50% of the cost. Hence the layout of the electrodes is not only critical to produce the most effective increase in capacity but also to increase efficiency by reducing cost. Thus a second indicator could be the efficiency of the system which is the settlement (or water expelled) per unit of electrical charge over the time of treatment. The third indicator, and related to cost, is the energy consumption during treatment which is the power consumption per unit volume of soil treated. Table 2 lists these three indicators.

4. The test equipment

The equipment was designed so that: (1) the test chamber was non conductive, to ensure the cell did not affect the current flow; (2) a vertical pressure could be applied to ensure a positive pressure at all times to prevent cracking due to electro osmosis and model the effect of a working platform necessary to install the electrodes; (3) the sample was constrained to move vertically to create a one dimensional study; (4) settlement and volume changes could be measured; and (5) vertical electrodes could be installed with the cathode(s) acting as drain(s).

The electro osmotic consolidation chamber was a modified Rowe Cell with the body of the cell being replaced by a non conductive PVC tube. This had the further advantage that it reduced the effect of the wall friction because of the length to diameter ratio (1.2 for the soil sample) and the fact that the wall of the tube was smooth. Figure 1 shows a section through the consolidation chamber. Figure 2 is a view of the laboratory set up. The voltage and vertical pressure were controlled; the settlement and current were monitored.

There are three sections to the test chamber:- the body, the base and the top cap. The body of the test chamber, shown schematically in Figure 1, is a 345 mm high 251 mm diameter PVC tube (7) with a wall thickness of 10.9mm and a 45 mm thick flange and collar. The top flange was 56 mm wide to ensure that there was sufficient area to clamp the diaphragm (3) of the Rowe Cell pressure system in place.

The base (9) of the cell was used to support the electrodes (6) and act as a drainage system. The upper plate of the base (8) was supported on a configuration of O-rings which could be altered if the electrode layout was changed. The cathodes acted as drains (10) and were connected via the gap between the upper and lower plates of the base to the drainage ports (11). The voltage supply for the electrodes passed though glands in the lower plate and, for the anodes, glands in the upper plate (12).

The electrodes were copper springs (6) to provide limited resistance to the compression of the clay. Copper was used because of its superior performance in electro osmosis over other metals. Filter paper tubes were placed in the cathodes so that they acted as drains. In practice these are known as electrical prefabricated vertical drains (ePVDs). The location of the glands in the base allowed different configurations of electrodes to be tested as shown in Figure 3. The effective areas of osmotic treatment are based on the suggestions of Al-Shawabkeh et al (1999).

5. The test procedure.

The experimental procedure started with (1) assembling the osmotic chamber; (2) then installing the electrodes; (3) filling the chamber with clay; (4) assembling the cell; and (5) loading the sample in three stages.

The base was assembled first to allow the electrodes glands to be positioned correctly with respect to the drainage system. The upper plate (8) was supported on O-rings around each of the anodes to ensure that there was no drainage from the anodes. Water from the cathodes flowed into the void between the upper and lower plates and out through the drainage port (11) in the base. The glands in the upper plate supported the electrodes which were held vertical with steel mandrels when the clay slurry was poured into the cell. The mandrels were removed when the clay was in place. Kaolin (PL = 34%; LL = 55%) was used because it was could be mixed to a consistent state as it was supplied as a dry powder. Kaolin powder was mixed with deaired water at 150% of the liquid limit. The clay behaved as a highly viscous liquid or slurry.

The clay slurry, at a water content of 70%, was placed in 50mm layers and the cell vibrated on a shaking table briefly after each layer was placed to remove entrapped air. The depth of slurry was about 300mm at the start of a test. Kaolin was chosen because there is a significant body of knowledge of its properties and the spatial variability of samples could be controlled. This helped ensure a saturated sample.

The pressurised rigid plate on top of the clay represented a working platform and the subsequent loading due to an embankment/foundation. The working platform was modelled by a uniform pressure of 15 kPa; approximately equivalent to a 0.9m thick platform. This also had the effect of converting the clay slurry at a water content of 70% to a soft clay and, during osmotic treatment, overcoming cracking due to osmosis. The initial pressure of 15kPa was maintained throughout an experiment; the model foundation of 35kPa was applied after treatment to establish what effect the osmotic treatment had upon the clay.

A control test was used to establish the characteristics of the untreated clay. A total of twenty three electro osmotic consolidation tests and one control test were performed. The time of treatment, voltage and electrode layout (Table 3) were investigated. The cathodes were open; the anodes closed to allow a negative pore pressure to be developed at the anode.

6. The results

Figure 4 shows the average settlement for all three phases of the tests; Figures 5, 6 and 8 show each phase separately. It is clear that the osmotic treatment had an impact on the overall compression of the clay and, in all but one case, the osmotic treatment reduced the total settlement. Note that this is an overview of all the tests. One consequence of this is that tests with the same electrode configuration and voltage but carried out over different times are superimposed on one another in Phases 1 and 2. The start of Phase 3 depended on when Phase 2 was stopped.

Figure 5, the average settlement for Phase 1, shows, as expected, the rate of settlement increased as the number of cathodes (i.e. the number of drains) increased. Note that the anodes are not drains. The total settlement, however, was unaffected by the drainage path. Note that tests carried out to show the effects of time are superimposed on one another. Fig 3 shows the electrode layouts identified on Fig 5.

Figure 6 shows the settlement due to the osmotic treatment. The upper lines, which are actually a number of tests superimposed on one another to look at the effect of time of treatment at a constant voltage, show that effect with either one or two anodes. The other lines show more settlement either because of increased number of anodes or voltage or both which are collectively referred to as voltage density. Thus the amount of settlement during osmotic treatment is a function of the voltage density.

Figure 7a, the settlement during Phase 2, shows that the initial settlement is a function of the number of anodes and this is followed by an increase in settlement with time of treatment which maybe independent of the number of anodes. The end of those tests that lasted more than 14 days coincided with the treatment terminating either due to the disintegration of the anode(s) or due to hydraulic flow reaching equilibrium. In these tests settlement had all but ceased. Figure 7b, the total settlement during Phase 3, shows the impact the time of treatment had upon the settlement during the third stage (35kPa). Increasing the time of treatment n Phase 2 increased the stiffness.

Figure 8 shows the settlement in Phase 3 indicating of how the time of treatment, voltage and number of anodes affected the amount of settlement post treatment. Osmotic treatment clearly increases the average constrained stiffness. The number of cathodes affects the rate of settlement. Increasing the voltage density (number of anodes, spacing or voltage or a combination) increases the stiffness.

7. The performance of the osmotic piles

Figure 9 shows the improvement factor (reduction in settlement compared to the settlement of the untreated soil) can be significant if the number of anodes are increased. The performance factors (including the improvement factor) are listed in Table 2.

Figure 10 shows that there is a relationship between the energy (expressed as the total energy (VIt) per unit volume of soil) and the improvement factor. In this case the total volume of soil is used rather than the estimated area affected by the osmosis process. This is valid as the equipotentials will extend beyond the area bounded by the electrodes. There is a limit to the amount of improvement that can be achieved and there is an increasing cost to this benefit. Hence, it is important at the design stage to assess what improvement is required to keep operational costs to a minimum. There is also a relationship between the reciprocal of the efficiency and the improvement factor (Figure 11). This indicates that an increasing amount of current is needed to increase the improvement factor. Given that these were constant voltage tests, the current reduced with time (Figure 12) to near zero. Therefore in order to increase the current it is necessary to increase the voltage and hence the cost. Note that Figures 10 and 11 are based on tests that lasted at least twelve days which is the time it took for primary consolidation of untreated clay. In some cases the osmotic process was continuing which suggests that further improvement could be made if the osmotic process was allowed to continue. This would have increased the amount of energy required and reduced the efficiency.

In order to allow design engineers to make use of this concept it is necessary to determine the capacity of the ground or more simply the improvement factor. Al Shawabkeh et al (1999) showed that a hexagonal layout with anodes is optimal with anodes at each point of the hexagon and a cathode at the centre. Theoretically the negative pore pressure (u) generated at the anode is given by equation (1) and it is simply assumed to vary linearly between the anode and cathode with there being no excess pore pressure at the cathode as it is acting as a drain.

$$\mathrm{u} = -\left(\frac{\mathrm{k_e}}{\mathrm{k_h}}\right)\gamma_\mathrm{w}\,\mathrm{V} \tag{1}$$

where V is the applied voltage; γ_w is the unit weight of water; k_h is the coefficient of hydraulic conductivity; and k_e is the coefficient of electro osmotic conductivity.

Assuming that all the negative pore pressure dissipates during the osmotic treatment then the mean stress at the anode is simply increased by the excess pore pressure which for the majority of these tests with kaolin was about 250kPa. The stiffness of the soil is a function of the effective stress therefore the improvement factor should be related to the excess pore pressure. The average increase in mean stress between a cathode and anode is 50% of the pore pressure generated at the anode if the variation in pore pressure is linear. Using typical values of conductivity the increase in mean stress for this experiment would be typically between 10kPa to 135kPa. This is unlikely given the amount of water expelled during osmotic treatment (compare Figures 6 and 8).

The constrained stiffness of the soil, derived from the control test, was about 550kPa. The constrained stiffness post treatment varied between 600 and 2400 kPa which confirms that the increase in stiffness is not a linear relationship with the theoretical increase in mean stress but will be a function of that increase.

However, unlike stone columns it should be possible to use the treatment phase to predict the performance post treatment. The constrained stiffness of the treated soil will be a function of the settlement that occurs during treatment and the Phase 2 settlement will be a function of the negative pore pressure and the area of influence of the anodes. Figure 9 suggests that this is the case. This shows the relationship between settlement during treatment and settlement post treatment. There is a linear relationship which is primarily a function of the voltage density. Hence the settlement during osmotic treatment can be used to predict the settlement in service. This together with the energy and efficiency factors allow the design engineer to optimise the layout, voltage and time of treatment and predict the performance post treatment with some confidence at the treatment stage.

7. Conclusions

The concept of electro osmotic piles has proven to be valid based on these laboratory tests. This means that it is possible to install electrodes in the form of vertical drains (known as ePVDs) to create an overall improvement in the ground stiffness. Unlike replacement methods which rely on the soil to provide lateral resistance to the replacement material and therefore the design is based on the replacement columns, electro osmotic piles improve the soil. Thus the average stiffness of the soil is mobilised. The improvement is a function of the time of treatment and the voltage density. The voltage density is a function of the electrode spacing, the applied voltage and the number of anodes. The design engineer can specify the layout, voltage density and time to treatment. The performance post treatment can be predicted from the behaviour during treatment.

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