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APPLICABILITY OF ELECTRO-OSMOSIS TO REDUCE CLAY ADHERENCE IN A TBM

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ABSTRACT

When boring a tunnel with a tunnel boring machine (TBM) through stiff clays, clay tends to stick to the cutting wheel, to the inside of the excavation chamber and in the slurry transportation line. Several solutions are available to prevent the adherence of clay, but these are not always satisfactory. An alternative solution may be the use of electro-osmosis. By applying an electric charge to the steel parts of a TBM, water can be transported through the clay by electro-osmosis to the interface between the clay and the steel. This creates a film of water at the clay-steel interface and therefore reduces the adherence. Because of this film, the hydraulic force of the slurry can easily remove the clay.

To investigate the effect of electro-osmosis on clay adherence, laboratory tests were performed on four different clay soils using two test methods, the tilted plate and the direct shear box. It is shown that both tests can be used to reveal the sensitivity of a clay soil to a reduction in the adherence by electro-osmosis. Apart from a so-called threshold potential below which little reduction in adherence is observed, the shear box test allows the determination of the shear stress drop due to electro-osmosis.

Finally, a feasibility study is carried out in order to investigate the applicability of electro-osmosis to reduce the adherence inside a TBM. This depends on three factors: properties of the excavated clay soil, practical limitations or negative side effects and the energy consumption.

INTRODUCTION

Due to the high population density in the Netherlands there is a lack of space for new infrastructure in urban areas. Hence, the subsurface will have to be used for the construction of new infrastructure. Recently the TBM technology has been employed to excavate the Second Heinenoord tunnel. As not much experience was available on boring large diameter tunnels in the typical Dutch soils, some unexpected problems were encountered. One was the adherence of stiff clays to the inside of the TBM. In the near future, several tunnels will be built through other Dutch clay formations, where similar problems may be expected. Solutions to prevent clay adherence have to be found; one of them could be the use of electro-osmosis. To apply electro-osmosis in a TBM, first a thorough investigation is needed on the process of electro-osmosis and its effect on the adherence of clay in practice.

The first successful field application of electro-osmosis in soil was performed by Casagrande in 1939 by stabilising an excavation in a soft clayey silt. Since then electro-osmosis has been used for many other practical applications. For example, Dick & Cooper (1998) describe the possibility to prevent clay adhering to a drilling bit by using electro-osmosis. In this paper the results of a research to investigate whether electro-osmosis can be applied inside a TBM are presented.

ELECTRO-OSMOSIS

Water trapped within a micro-pore between two clay particles flows along the charged surface of the clay particles when an electric field is applied parallel to this surface. This is due to the excess of cations that are present inside the diffuse double layers next to the negatively charged surfaces of the two clay particles. The applied electric field causes these cations to migrate from the anode towards the cathode, see Figure 1. Water molecules that are attached to these cations as water of hydration are also transported towards the cathode. In fact this results in a transport of water. However, the total amount of water transported by electro-osmosis is significantly greater than can be explained by this water of hydration alone.

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As the cations migrate towards the cathode, a drag force is created between the hydrated water molecules around the cations and the surrounding unhydrated (free) water molecules of the pore water. This drag causes the free water molecules to move (see Figure 1) and thus creates an additional transport of water. The macroscopic effect of electro-osmosis is then seen as a flow of water through the clay mass.

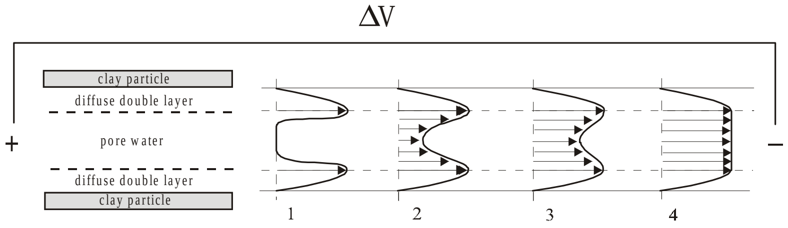

Figure 1 : Development of electro-osmotic flow between two clay particles, with arrows representing flow velocities. **1)** switching on of electric field, **2)-3)** development of electro-osmotic flow, **4)** steady-state flow (after Tikhomolova, 1993).

Darcy's law describes the flow of water through porous media caused by a hydraulic gradient. Non-hydraulic driven fluid flow is generally denoted as osmosis. Electro-osmosis is the flow of water driven by an electric potential gradient, hence it can be described by an equation similar to Darcy's law:

$$q_e = k_e \, i_e \, A \qquad (1)$$

Where q_e = flow rate [cm^3/s], k_e = coefficient of electro-osmotic hydraulic conductivity [cm^2/(Volt $\times$ s)], i_e = electric potential gradient [Volt/cm], and A = cross-sectional area normal to direction of flow [cm^2].

Soil properties that affect the response to electro-osmosis include electrical resistivity, grain size distribution, water content and surface charge density. Chemical properties such as pH, and type and concentration of electrolyte present in pore water, also influence the behavior of clay soil with regard to electro-osmosis. However, they are specific to each soil sample and can be difficult to determine.

Because many of these clay soil properties are determined by the clay mineral composition, it is important to investigate the effect of electro-osmosis for different clay minerals. In this research kaolinite and illite clays have been used. Kaolinite clay minerals are larger and have a higher external surface charge density than illite clay minerals (Lambe & Whitman, 1979). The higher surface charge density causes a higher concentration of cations near the surface and therefore a greater drag force onto the free water molecules. However, a large drag force does not necessarily lead to a large electro-osmotic water transport; a large amount of free water molecules inside the pore space is also needed in order to create a large flow of water. This depends on both the water content of the clay and on the size of the pore spaces. The latter is dependent on the size of the clay particles and the degree of consolidation. The size of the clay particles is mainly controlled by the mineralogy.

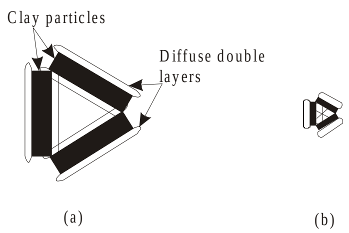

Figure 2 : A model (not to scale) of a cross-section of the pore space in relation to the diffuse double layers. **a:** Three large kaolinite clay particles. **b:** Three small illite particles. (after Shang, Lo and Quigley, 1994)

For a clay soil with kaolinite minerals the pore diameter is much larger than the thickness of the diffuse double layers of those clay particles. As the diffuse double layers do not interact in the micro-pores (see Figure 2) there is a large amount of free water molecules inside the pore space. If the diffuse double layers are thick enough and the clay particles are small, as in the case of an illite clay mineral, the overlapping diffuse double layers reduce the amount of free water molecules. Hence, the drag force can transport little water. As a result, lower electro-osmotic flow rates are observed for illite clay minerals than for kaolinite clay minerals.

Reduction of clay adherence by electro-osmosis

Adherence of clay is determined by two factors: adhesion and friction. According to Thewes (1999) capillary stresses and differential fluid pressures are mainly responsible for clay adhesion to a steel surface. By applying an electric charge to the steel parts of a TBM, water can be transported through the clay by electro-osmosis to the interface between the clay and the steel. This transported water reduces capillary stresses and differential pressures, which result in a reduction in adhesion. In addition, a film of water is created at the cathode, which lubricates this surface and therefore reduces friction. Thus, the hydraulic force of the slurry can easily remove the clay lumps sticking to the steel of a slurry shield TBM for example.

EXPERIMENT

To test the applicability of electro-osmosis to reduce the adherence of clay, two different testing devices were used: the tilted-plate test and the direct shearbox. The tilted-plate test is a relatively simple test that was carried out to investigate the suitability of electro-osmosis to reduce the adherence for a certain clay type. The direct shearbox test is a standard test, which is used to measure the external (or adhesive) shear strength of a clay-steel interface. For this research it has been used to measure the reduction in adhesive shear stress by electro-osmosis.

The tilted-plate test

For the tilted-plate test a clay sample is topped with a round steel disc and is pressed onto a steel plate using a normal stress of 37 kPa for 15 minutes to obtain a good and consistent adherence (see Figure 3). When the stress is removed the sample does not detach itself even if the plate is held upside down. The steel plate is inclined at an angle of 30° and it is negatively charged, while the round disc on top is positively charged (see again Figure 3). After a certain period of time the clay sample slides off. This period of time is dependent on both the adherence and the rate of electro-osmotic water flow towards the surface. The latter can be demonstrated by applying different potential gradients to the sample.

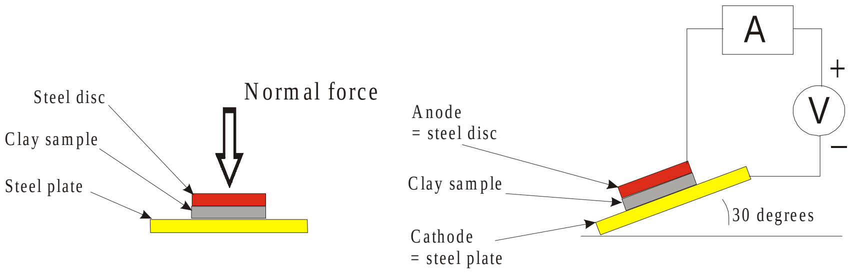

Figure 3 : Tilted-plate test. **Left:** a force is applied to the sample. **Right:** the plate is tilted and an electric current is applied.

The direct shearbox test

The shearbox permits a better quantification of the response of clay soil to electro-osmosis, as the drop of adhesive shear stress obtained by electro-osmosis can be measured. In order to apply an electric current to a sample inside the shearbox, the testing procedure and equipment were modified as follows: to avoid a short circuit of the electric current, the water in which the sample shears over the steel plate was removed and the shearbox was insulated using plastic parts. All tests were performed under consolidated and drained conditions at a rate of 0.1 mm/min. The roughness of the steel plate was 0.4 μm.

During shearing, horizontal displacement and shear stress were measured. When the shear strength of the sample was reached, a direct current was switched on, as can be seen in Figure 4. Almost immediately the shear stress reduced quite quickly whilst the water was being transported towards the negatively charged steel plate. This drop in shear stress took place in just 39 seconds. It did not decrease to zero kPa and it did not remain constant for a period of time at a certain value. Instead a sharp turning point can be seen from where the shear stress is dropping to where the shear stress is increasing again. This observation seems to indicate that during testing the amount of water transported by electro-osmosis was not constant in time.

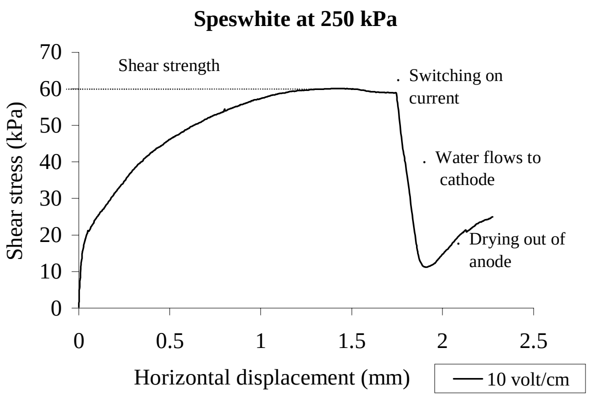

Figure 4 : Effect of electro-osmosis on the shear stress of Speswhite clay at 250 kPa normal stress using a potential gradient of 10 Volt/cm.

There are two possible explanations: drying out of the clay around the anode and chemical osmosis. When water is flowing away from the anode the clay around the anode dries out; this was observed visually. As a result the electric conductivity is reduced, as well as the electro-osmotic water flow. Chemical osmosis is a flow of water caused by a chemical gradient, i.e. a difference in ionic concentration. Because positive ions are transported from the anode to the cathode, a difference in ionic concentration is created, which can cause a flow of water in the reverse direction, i.e. from the cathode to the anode, and thus reduces the amount of water transported by electro-osmosis.

Clays used and sample preparation

To test the applicability of electro-osmosis, four different clays were used: two so-called powder clays, Speswhite and Boom clay and two non-powder clays, K122 and Kedichem clay. The two powder clays were mixed with demineralized water and consolidated in an oedometer at stresses of 100, 175, 250 and 500 kPa. Powder clays were chosen in order to create a homogeneous sample and to vary the water content. The other two clays were stiff clays with a fixed water content. Properties of all four clays are given in Table 1.

All four clays were subjected to the tilted-plate test. Since no normal stress was applied during testing with electro-osmosis all clays are considered to be overconsolidated clays. The shearbox tests were carried out on the powder clays only. The samples were sheared under the same normal stress as used for consolidation. Hence, the clay samples are considered to be normally consolidated clays. All samples used were cylindrical shaped with a diameter of 63 mm and a height of 10 mm.

Table 1 : Properties of four types of clay used.

Property	*Speswhite*	*Boom*	*K122*	*Kedichem*
Clay minerals According to XRD- and XRF analysis	Mainly kaolinite with small amount of illite	More illite than kaolinite	More kaolinite than illite	Mainly illite
Type of clay	Powder	Powder	Industrial	Natural
Fraction < 2 μm [%]	79	70	53	51
Plastic limit [%]	32	24	29	20
Liquid limit [%]	62	55	62	48
CEC [meq/100g]	4.7	8.5	14.8	16.9
Water content [%] (at different consolidation stresses)	52 (at 100 kPa) 49 (at 175 kPa) 46 (at 250 kPa) 42 (at 500 kPa)	39 (at 100 kPa) 36 (at 175 kPa) 35 (at 250 kPa) 31 (at 500 kPa)	38	28

TEST RESULTS

In Figure 5 the results of the tilted-plate test on the four clays are shown. Measurements were made for potential gradients of 1, 2.5, 5, 7.5, 10, 12.5, and 15 Volt/cm. The results obtained for clay type K122 are discussed. When a potential gradient of 1 Volt/cm was applied, no sliding of the sample was detected. At a potential gradient of 5, 7.5, and 10 Volt/cm the period of time before sliding was found to decrease steadily from about 20 seconds to about 10, and 5 seconds. At a potential gradient of 12.5 or 15 Volt/cm, the sample slid off almost instantaneously within about 1 second. All tests were performed twice and showed good repeatable results.

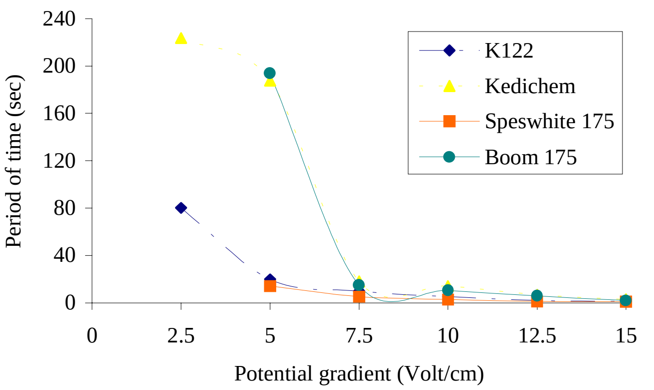

Figure 5 : Effect of the potential gradient for all four clays.

For potential gradients of 7.5 Volt/cm or higher, all four clays showed similar behavior and slid off within about 10 seconds. At 5 Volt/cm, both Speswhite and K122 were found to slide off within about 15 seconds. Whereas Boom and Kedichem were stationary for approximately 190 seconds before sliding occurred. According to Table 1 Speswhite and K122 contain mainly kaolinite and Boom and Kedichem contain mainly illite clay minerals. As predicted by the theory more water was found to be transported in soils rich in kaolinite than in illite.

When this experiment was repeated with the plate inclined at an angle of 10°, the period of time before sliding for all clays had only changed slightly for measurements made at a small potential gradient; at a high potential gradient there is almost no difference. Hence, it can be concluded that electro-osmosis is an effective method to detach a clay sample from a steel plate, even when the driving forces, that initiate movement of the sample, are quite small.

The shearbox test

The results for Speswhite and Boom clay are presented in figure 6. In the left graph a so-called threshold potential can be seen between 2.5 and 4 Volt/cm, below which there is no drop in shear stress. Beyond the threshold potential there seems to be little extra benefit in increasing the potential gradient. According to the right graph of Figure 6, showing the results for Boom clay, the drop in shear stress with increasing potential gradient is more gradual. The threshold potential is less obvious, but can still be identified somewhere between 5 and 7.5 Volt/cm.

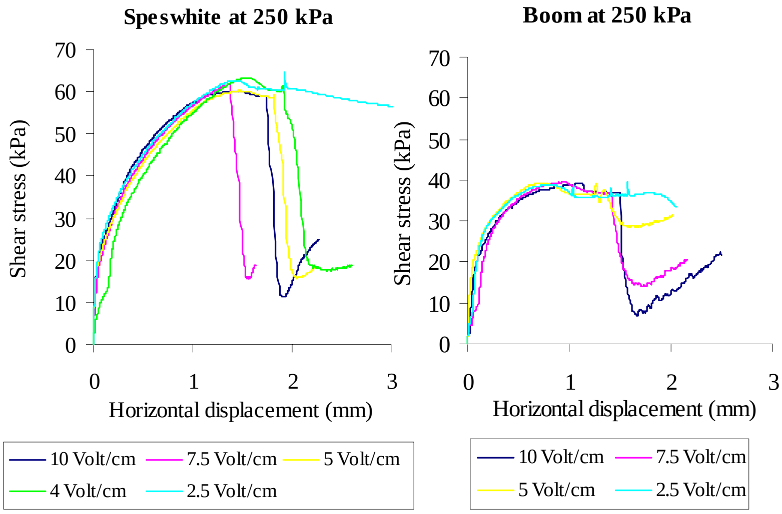

Figure 6 : Effect of the potential gradient for (left) Speswhite and (right) Boom clay at a normal stress of 250 kPa.

The abrupt threshold potential for Speswhite can be explained as follows: the reduction in shear stress is caused by a sudden reduction in adhesion at the surface. The capillary stresses suddenly diminish when the drag force needed to transport the free water molecules is overcome and water is flowing to the surface at a certain rate. In Figure 7, the result of an increasing potential gradient can be seen clearly. At a potential gradient of 2.5 Volt/cm the contact surface of the clay-steel interface, after it has been sheared over a steel plate with electro-osmosis under a normal stress of 250 kPa, shows no flow pattern of water. At higher potential gradients a flow pattern that increases in intensity with increasing potential gradient is observed. This means that the flow rate is faster at higher potential gradients. These pictures indicate that lubricating the surface also causes the reduction in shear stress and that only a thin water layer is required. A thicker lubricating layer does not further reduce the shear stress and thus increasing the potential gradient has little effect.

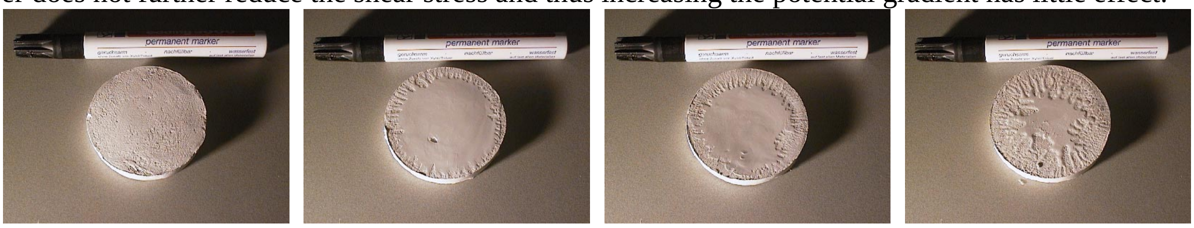

Figure 7 : Picture of contact surface of samples using from left to right: 2.5, 5, 7.5, and 10 Volt/cm.

The contact surface of Boom has not revealed the flow lines that were observed for Speswhite, even at a potential gradient of 10 Volt/cm. This means that either the electro-osmotic flow rate is much less for Boom than for Speswhite or the fabric of Boom is more "solid" and it is not eroded by the water flow. A combination of these two explanations seems likely.

To investigate the influence of the high pressure inside a TBM tests were performed at normal stresses up to 500 kPa on both Speswhite and Boom. The results obtained with a potential gradient of 10 Volt/cm are presented in Figure 8. These results indicate that electro-osmosis is an effective way to detach clay even for high normal stresses.

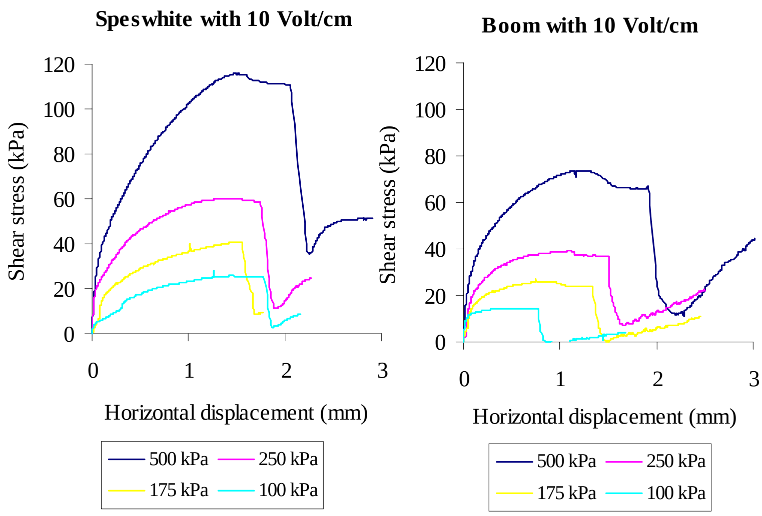

Figure 8 : Effect of normal stress for (left) Speswhite and (right) Boom clay using a potential gradient 10 Volt/cm.

FEASIBILITY STUDY

In order to investigate the applicability of electro-osmosis inside a tunnel boring machine (TBM) a feasibility study was performed. The locations where adherence of clay could occur for two tunneling techniques (Kooistra 1998) are given in Figure 9. The main difference between these techniques concerning electro-osmosis is the position of the anode. For the slurry shield machine it will be positioned in the slurry and for the earth pressure balance shield (EPB) it will be in direct contact with the clay. Whether electro-osmosis is applicable depends on three factors: the properties of the excavated clay soil, several practical problems and the energy consumption.

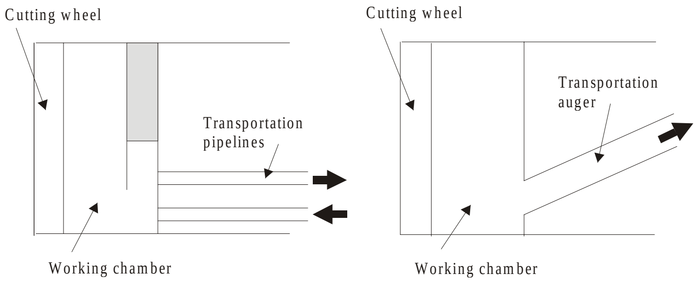

Figure 9 : Locations were adherence can occur. **Left:** at a slurry shield machine **Right:** at an EPB shield machine

Hence, before actually applying it, the clay soil properties were examined in the laboratory and it was found that the type of clay minerals was especially important. Regarding the practical problems some were investigated including: the high pressure inside a TBM, drying out of the anode and its position. The latter problem was investigated by performing the tilted-plate test under water with the anode placed remotely within the water. It was found that it was still very possible to detach the clay. Other problems which should be considered include: influence of bentonite slurry, scaling, stability of the bore front, corrosion, gas and heat development, anode and cathode surface ratio and prevention of a short-circuit.

Finally the energy consumption was established based on laboratory test results and was found to be very small compared to the total energy used to drive a TBM. To reduce the amount of energy, electro-osmosis could also be applied occasionally as a means to clean the TBM when adherence is giving large problems.

CONCLUSIONS

The tilted plate is a good index test capable of assessing the sensitivity of a material to electro-osmosis. Knowing that K122 and Speswhite contain mainly kaolinite and Kedichem and Boom illite, the clays rich in kaolinite have shown a lower threshold potential and a shorter period of time needed before sliding was observed than those rich in illite. Nevertheless all clays responded to electro-osmosis.

The modified shear box test is more sophisticated. It allows the quantification of the drop in shear stress caused by electro-osmosis. It also permits the accurate determination of the threshold potential and of the duration of the drop of shear stress. It was found that Boom and Speswhite do not have the same sensitivity to electro-osmosis and that electro-osmosis was effective even for normal stresses of 500 kPa

The feasibility study shows that it is possible to apply electro-osmosis in both a slurry and an EPB shield TBM, although several practical problems still need to be investigated.

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