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Relative relevance of factors affecting the electrokinetic dewatering of soft clayey soils

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Electrokinetic (EK) treatment is becoming increasingly important in the geotechnical field, especially for treating fine-grained soils. Above all, dredged sediments (slurries) need to be treated in order to be reutilised. Applying an electric potential difference within the soil, three phenomena take place: electrophoresis, electro-osmosis and electromigration. Negative particles move towards the positive electrode while water and cations move towards the negative electrode. Although the literature is full of cases describing the parameters that affect the EK process, there is a need to understand its limits and fields of application. This paper summarises the results collected from several case studies to understand the influence of some parameters on the efficiency of EK treatment, specifically in terms of dewatering rate. Soil conditions (soil type, pH, pore fluid salinity and water content) and set-up design parameters (electrode materials, configurations and operational mode) are analysed. Finally, parameter ranges for assessing the acceptability of electro-osmotic treatment are proposed. The results show that there are optimum values for the previously mentioned parameters that improve the dewatering and thus enhance the behaviour of the treated soils. EK treatment can be effective when applied on dredged sediments with low salinity.

Notation

A	cross-section area
DE	dewatering efficiency
E	power consumption
$\bar{E}$	specific power consumption
i	current intensity
k_e	coefficient of electro-osmotic permeability
k_h	coefficient of hydraulic permeability
k_i	electro-osmotic water transport efficiency
n	soil porosity
P	electric potential gradient
q_e	flow rate
R	electrical resistance
s_c	salt concentration
t	treatment time
W_0	initial volume of water
w_0	initial water content
w_f	final water content
w_L	liquid limit
ΔW	volume change
$\Delta\Phi$	applied electric potential
ε	dielectric constant of the pore fluid
ζ	zeta potential
η	dynamic viscosity
λ	electrical conductivity

1. Introduction

Dredged sediments are produced in huge quantities every year. Their disposal is an important challenge in many countries as there is often a lack of available surfaces for their location (Wang *et al.*, 2019). For this reason, dredged sediments must be considered a resource (Gargano *et al.*, 2019a, 2019b, 2020a) to be reused in civil fields. From an engineering viewpoint, submerged soils have proprieties similar to undisturbed natural soils. However, after the operations of excavation, removal, remodelling and repositioning, they show drastic changes in soil structure and properties (low shear strength, high compressibility, low permeability and high water content).

Typical geotechnical properties of marine soil deposits or dredged sediments worldwide are shown in Table 1. The table shows that these soils around the world are, as previously noted, characterised by a high water content.

The most often used dewatering techniques are mechanical ones. When treated mechanically, the soils cannot reach a very low-water content, especially low-permeability fine-grained soils, for which it is necessary to find other options.

Among the different options for improving slurry dewatering, the application of an electric field has proved to be effective to expel the water that cannot be removed using mechanical dewatering alone (Bjerrum *et al.*, 1967; Casagrande, 1983; Flora *et al.*, 2017; Gargano *et al.*, 2019a, 2019b, 2020a; Gray and Mitchell, 1967; Lockhart, 1983).

When an electric current is applied to the soil by the use of electrodes, the pore water moves from the anode (positive

Table 1. Geotechnical properties of marine and dredged soils worldwide

Source	w_0: %	w_L: %	w_0/w_L	PI: %	Clay: %	λ: S/m	Soil location
Banoune *et al.* (2016)	12–13.2	36.8–41.5	0.3	13.9–15.1	2–10	—	Dam of Kherrata and Soummam River (Algeria)
By and Skomedal (1992)	47–70	60	0.8–1.2	37	—	—	Norwegian Trench (Troll East Field)
Chew *et al.* (2004)	80	80	1	45	44	—	Singapore marine clay
Dyvik *et al.* (1993)	34–57	40–55	0.9–1.4	21–33	28–39		North Sea (Snorre site)
Fakue and Nakamura (1996)	120–140	54–120	1.0–2.2	30–70	—	—	Seto Inland Sea, Sagami and Tokyo Bay (Japan)
Felici *et al.* (2019)	62–136	52	1.2–2.6	22	36	High (s_c = 39.9 g/l)	Ancona port (Italy)
Flora *et al.* (2017)	42.9–51.8	33.4	1.3–1.6	10.1	20	—	Gaeta port (Italy)
Fu *et al.* (2017)	58.3	54.51	1.1	28.19	—	High (s_c = high)	Wenzhou (China)
Gargano *et al.* (2019b)	36.2–37.8	27.6	1.3–1.4	4.6	22	0.33–0.48	Napoli port (Italy)
Hong *et al.* (2010)	60–273	61–74	1–3	31–53	19–23	—	Lianyungang, Baimahu, Kemen clay (China)
Hongtao *et al.* (2007)	92.7	58	1.6	32	—	—	Wenzhou (China)
Hongtao *et al.* (2019)	78	72	1.08	34	—	—	Wenzhou (China)
Lacasse and Lunne (1998)	45–60	—	—	—	—	—	Voring (Norwegian Sea)
Li *et al.* (2009)	41.2–86.2	25.5–46.9	1.6–1.8	9.5–22.1	—	—	Qindao and Lianyungang (China)
Liu *et al.* (2017)	60	51.5	1.2	29.5	—	0.04–0.05	Wenzhou (China)
Micic *et al.* (2001)	79.3–93.0	59	3.2–3.8	27	23	1.2	Yulchon (Korea)
Micic *et al.* (2003)	39	31	1.26	11	28	5.4	Welland River sediment (Canada)
Mohamedelhassan and Shang (2002)	65.5–143	59	1.1–2.4	27	23	0.08–2.4	South-west coast of Korea
Reddy *et al.* (2006)	78.6	45	1.7	13	91.5	0.29	Indiana Harbor (USA)
Wang *et al.* (2019)	120	61.3	2	25.7	2.7	—	Nanjing (China)
Zhang *et al.* (2018)	52.4	40.2	—	15.9	—	High (s_c = 35 g/l)	Yingkou (China)

pole) to the cathode (negative pole). This method is used for different applications; however, investigations into its use in dredged sediments dewatering are limited.

A more thorough study is therefore necessary to assess the effectiveness of electrokinetic (EK) treatment in dewatering soft soils such as dredged sediments that have an extremely high water content.

After a brief explanation of the phenomenon, this paper examines the results collected from several case studies to comprehend the influence of some parameters (soil conditions and set-up design parameters) on the efficiency of EK treatment in terms of dewatering rate.

2. Background

Over the years, EK treatment has been utilised to treat low-permeability soils with different aims: stabilisation of excavations (Bjerrum *et al.*, 1967); improvement in load-carrying capacity of foundations (El Naggar and Routledge, 2004), slope stabilisation and strengthening of backfill (Chappell and Burton, 1975); stabilisation of soils by consolidation (Kaniraj and Yee, 2011; Lefebvre and Burnotte, 2002; Shang, 1998); soil improvement stabilisation of fine-grained soils (Casagrande, 1949; Estabragh *et al.*, 2020; Flora *et al.*, 2017; Gargano *et al.*, 2019a; Guo *et al.*, 2018; Micic *et al.*, 2001); dewatering of slurries (Flora *et al.*, 2017; Gargano *et al.*, 2019a, 2019b, 2020a, 2020b; Yuan and Weng, 2003); and remediation of contaminated soils (Lageman *et al.*, 2005).

2.1 EK phenomena in soil

The application of an electric potential gradient to a fine-grained soil generates different mechanisms (Figure 1): electrophoresis, electromigration and electro-osmosis (Mitchell, 1993).

Due to the applied electrical field, extremely fine particles and ionic species (cations and anions) migrate to the oppositely charged electrodes (anode and cathode), producing phenomena respectively called electrophoresis and electromigration.

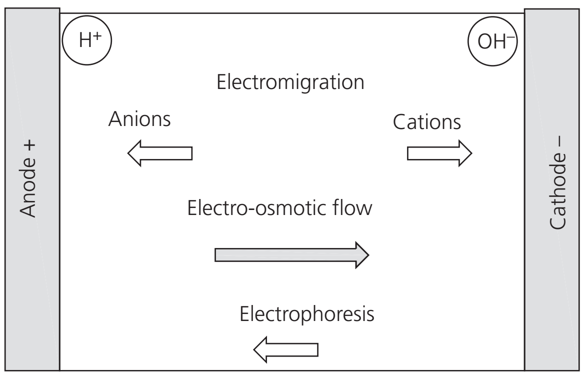

Figure 1. Mechanisms induced by the application of an electric field to soil (Gargano *et al.*, 2019a)

Electrophoresis is the migration of negatively charged clayey particles (colloidal particles) towards the anode (positive pole). The electrolysis of water, that is water decomposition at electrodes, occurs due to redox reactions (oxidation–reduction reactions).

I. $2H_2O - 4e^- = 4H^+ + O_2$ anode

II. $2H_2O + 2e^- = 2OH^- + H_2$ cathode

The oxidation reaction results in the reduction of pH near the anode (Reaction I), while the reduction reaction increases the soil pH near the cathode due to the dissolution of hydrogen ions (Reaction II).

The migration of positive ions (Figure 1) mechanically draws water towards the negative electrode (cathode), with the result of a significant movement of liquid in the pores towards the cathode (electro-osmotic flow).

Casagrande (1949) proposed a simple relation for the calculation of electro-osmotic flow by analogy with Darcy's law:

1. $$q_e = k_e P A$$

where P is the electric potential gradient (V/m) and k_e is the coefficient of electro-osmotic permeability (m^2/s V):

2. $$k_e = \frac{\zeta\varepsilon}{\eta} n$$

According to the Helmholtz–Smoluchowski theory (Mitchell and Soga, 2005), the value of k_e is not dependent on the pore size, while the hydraulic permeability k_h varies with the square of the pore size. In a fine-grained soil, the pore size is small, therefore the hydraulic gradient is low, but electro-osmosis is still effective because k_e is independent of the pore size.

The EK technique can be beneficial to dewater and decontaminate fine-grained soils. There is plenty of experimental evidence to show that, with electro-osmosis, bulk and adsorbed water are both dragged by the electrical current (Gingine and Cardoso, 2017) while, using the most common mechanical technologies, interstitial water cannot be removed.

Due to this evidence, EK treatment was proposed as a soil dewatering and stabilisation technique (Bjerrum *et al.*, 1967; Casagrande, 1983; Micic *et al.*, 2001; Reddy *et al.*, 2006).

Although technical solutions are available and basic physicochemical mechanisms at the base of the treatment are well known, EK soil treatment is still considered a new technology and some aspects need further investigation to understand and quantify its effect on the dewatering rate of soft soils.

3. Electro-osmotic efficiency

The amount of water transported per unit of charge determines the efficiency of electro-osmotic dewatering. This amount can be quantified by the electro-osmotic water transport efficiency k_i (m^3/(A/s)) (Acar *et al.*, 1989):

3. $$k_i = \frac{q_e}{i} = \frac{k_e P A}{i}$$

where i is the current intensity (A). By means of Ohm's law, k_i can also be expressed as:

4. $$k_i = \frac{k_e}{\lambda}$$

where λ is the soil electrical conductivity (S/m).

The parameter k_i varies from 0 to 1.2 cm^3/(A/s); it is obviously related to the coefficient of electro-osmotic permeability (k_e) and the electrical conductivity of the soil (λ). The soil conductivity is a function of water content, cation exchange capacity (CEC) and free electrolyte content (Gray and Mitchell, 1967). For this reason, pore fluid salinity is a crucial parameter for the assessment of electro-osmotic efficiency. Gray and Mitchell (1967) showed that k_i decreases with a decrease in water content and an increase in soil activity.

The more the reduction in water content, the higher the dewatering efficiency (DE). From a quantitative point of view, the DE can be assessed as the difference between the final (w_f) and the initial water content (w_0) over the initial one (w_0), that is equal to the amount of expelled water (ΔW) over the initial volume of water (W_0). It is therefore defined, in this study, as

5. $$\mathrm{DE} = \frac{w_0 - w_f}{w_0} = \frac{\Delta W}{W_0}\ (\%)$$

and can be related to k_i (Equation 5), showing a good agreement (Figure 2).

For a more comprehensive study on the parameters that affect the EK efficiency, some case studies are summarised in Tables 2 and 3 and analysed in the following sections.

For these cases, when multiple values of water content were reported (e.g. for different positions across the soil specimen), an average value was chosen.

A threshold can be established below which it is not worth applying the EK treatment. This threshold for DE was established as 20% in this study.

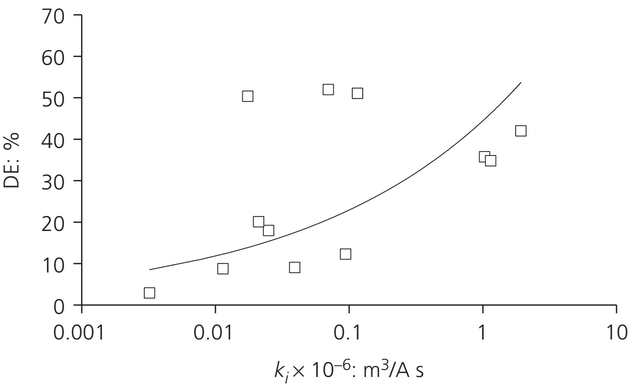

Figure 2. Dependence of the DE on k_i (Table 2)

Considering a DE of 20% means obtaining a water content after applying the electro-dewatering (final water content, w_f) equal to 0.8 times the initial water content (w_0). This reduction in water content is responsible for an increase in soil strength, in different amounts depending on the soil.

4. Controlling parameters

Factors that influence the EK process are divided into two main groups. The first group is related to the initial soil conditions (soil type, pH, zeta potential, salinity and water content) and the second group is represented by set-up design parameters (electrode materials, configurations and operational mode).

4.1 Soil type

Being the magnitude of electrical charge related to the surface area of the soil particles, EK treatment works more efficiently in fine-grained materials. Typically, EK treatment is more efficient in soils where more than 30% of particles are finer than 2 μm (Shang and Lo, 1997). Previous experimental studies (Lockhart, 1983) showed that EK is more effective in silty clays with modest plasticity rather than in high-plasticity clays.

The CEC indicates the ability of soil particles to interchange attracting ions; its magnitude is directly related to the surface area of the clay particles. This means that the higher the specific surface area (m^2/g) of a clay, the higher the electrical charge it carries. Montmorillonite is the clay mineral with the largest specific surface area and therefore carries the most electrical charge. EK treatment is more effective in soils with high CEC, such as, for instance, montmorillonitic, illitic and bentonitic clays.

Furthermore, EK treatment is not effective in soils with a high buffer capacity and in soils containing high-carbonate buffers (Mosavat *et al.*, 2012). Soils with high organic contents show a better response to EK treatment (Kaniraj and Yee, 2011).

The clay contents reported in Figure 3 are all higher than 20%; the reason for this is the lack of available data to evaluate the DE when the clay content is lower than this. Information on clay type, CEC and soil surface charge is also generally missing in the literature studies reported in Tables 2 and 3. However, from Figure 3, it can be observed that a DE higher than 20% can be obtained mostly when the clay content is higher than 20% and when the salt concentration (s_c) is low (<8 g/l).

As regards the plasticity and conductivity, the validity of the correlation proposed for the acceptability of soils is shown in Figure 4. Some electro-osmotic case studies are shown (Bjerrum *et al.*, 1967; Casagrande, 1952; Hamir, 2001; Pugh, 2002). Casagrande (1983) proposed a range of acceptance for the electrical conductivity equal to 0.05–0.005 S/m, for which the corresponding range of plasticity indexes (PI) varies from 5 to 30%.

Other research studies (Tables 2 and 3) were also analysed and some results are reported in Figures 5 and 6.

Figure 5 shows the DE against electrical conductivity (λ). It seems that electro-dewatering is effective when λ is lower than 0.3 S/m (since most of the data points are located in this area). However, for the same values of electrical conductivity, there are also markers corresponding to DE < 20%. This means that the factor λ alone cannot be used to assess the DE.

In addition, the DE is higher than 20% mostly when the PI increases from 13 to 46% (Figure 6). Nevertheless, there are some data points in the range 13% < PI < 46% with DE < 20%. For this reason, even the PI alone cannot be used to ascertain if it is worth applying electro-dewatering.

Comparing these data with those of Casagrande (1983), it should be noted that some data are located outside the limits mentioned earlier (0.05–0.005 S/m for electrical conductivity and 5–30% for plasticity). This means that not all the soils located outside these limits show bad results in terms of dewatering when an electric field is applied.

4.2 pH and zeta potential

Soils with a high buffer capacity better tolerate pH fluctuations. Since during the EK treatment these fluctuations are very common (Malekzadeh *et al.*, 2016), soils with high buffer capacity are preferable.

At the anode side, an acidic pH is generated (Reaction I), while at the cathode side, an alkaline environment (low pH) is generated (Reaction II). These different pH values cause different consequences. For example, variation in the pH level and the presence of insoluble hydroxyls during EK treatment can cause a reduction in the electric potential in the soil (Liaki *et al.*, 2010). If the pH of kaolinite is less than 5, the aluminium ions migrate and cause soil strengthening (Liaki *et al.*,

Table 2. Case studies

	PI: %	Clay: %	s_c: g/l	k_e: m^2/s V	k_e/k_h: m/V	DE: %	w_0/w_L	Material
Asavadorndeja and Glawe (2005)	60	78		$1.2–1.3 \times 10^{-11}$	—	4.8	0.89	Bangkok clay
Bergado *et al.* (2003)	63	79	0.5[a]	—	—	9.8–12.7	1	Bangkok clay
Bjerrum *et al.* (1967)	5	37	0.9	2.0×10^{-9}	—	12.3	1.6	Norwegian quick clay
Casagrande (1952)	—	—	—	$2–6.9 \times 10^{-9}$	$4*10^{-3}$–200	—	—	Various soils
Chappell and Burton (1975)	—	—	—	5.0×10^{-9}	—	48.7–51.4	—	Blue/grey clay
Fourie *et al.* (2007)	26	75	—	—	—	52.5	2.55	Mine tailings (Africa)
Fourie and Jones (2010)	38	32	—	—	—	45.9	2.36	Diamond mine tailings
Fu *et al.* (2017)	28.2	—	High	—	—	18.5	1.1	Chinese marine clay
Gargano *et al.* (2019b)	4.6	22	0.2–30	—	—	11.9–15.6	1.31–1.37	Napoli sand with silt
Gargano *et al.* (2020b)	36.5	56	0.2–30	$2.8–6.3 \times 10^{-9}$	0.18–0.40	2.9–20.1	1.4	Bologna clay
Guo and Shang (2014)	22.5	20	2.1[b]	$0.77–1.4 \times 10^{-8}$	4.2–8.0	34.8–42.0	1.8	Oil sands tailings
Hamir *et al.* (2001)	20	—	—	—	—	5.0–15.2	1.55	Kaolin
Hongtao *et al.* (2007)	32	—	—		—	38.2	1.60	Dredged clay (Wenzhou)
Hongtao *et al.* (2019)	34	—	—		—	37.1–49.5	1.08	Dredged clay (Wenzhou)
Hu *et al.* (2018)	46	—	0–2.34	—	—	27.3–37.5	1.12	Kaolin
Jeyakanthan *et al.* (2011)	66	53.7	14	1.2×10^{-9}	12.0	18	0.85	Australian black clay
Kalumba *et al.* (2009)	14.5			—	—	52.6–62.9	1.4	Tunnelling slurry
Kaniraj and Yee (2011)	90	—	—	—	—	5.7–32.9	0.9–1.0	Organic soil (Malaysia)
Lefebvre and Burnotte (2002)	20–52	80	—	—	—	7.4–22.6	0.85–1.55	Canadian clay
Liu *et al.* (2017)	29.5	—	0–16.7	—	—	21.7–26.7	1.17	Chinese marine clay
Micic *et al.* (2001)	27	23	30	—	—	5.2–20	3.2–3.8	Marine clay (Korean)
Micic *et al.* (2003)	11	28	32	—	—	—	1.26	Wellar river sediment
Mohamedelhassan and Shang (2002)	27	23	0.5–23	$6.1–15 \times 10^{-9}$	0.8–11.8	—	1.1–2.4	Marine sediment (Korea)
Reddy *et al.* (2006)	13	91.5	High	—	—	29.1	1.75	Dredged sediment (Indiana H.)
Shang (1997)	13–25	40–60	0.11–0.13[a]	$0.72–2.9 \times 10^{-9}$	—	50.3–52.0	1.8–3.5	Grey/brown clay (Ontario)
Shang and Lo (1997)	98	68	0.16[c]	5.2×10^{-10}	—	51.1	4.0	Phosphate clay (Florida)
Xue *et al.* (2019)	21.5	20	4.1–14.1	—	—	45.7–49.3	1.6	Chinese clay
Yang *et al.* (2019)	18	—	—	—	—	38–89.6	1.6	Taizhou soft clay
Yuan and Weng (2003)	—	—	—	—	—	4.5–28.7	—	Wastewater treatment plant sludge
Zhang *et al.* (2018)	15.9	—	35	—	—	0.91	—	Soft marine clay (Yingkou)

[a]Calculated from the value of the pore water electrical conductivity (0.032 and 0.029 S/m)
[b]Calculated from the value of the pore water electrical conductivity (3.59 mS/cm)
[c]Calculated from the value of the pore water electrical conductivity (0.037 S/m)

2010). Under alkaline conditions, the formation of a stabilising agent occurs and there is a reduction in anode corrosion. For instance, pozzolanic reactions take place and the cementing agent leads to a higher soil strength (Adamson *et al.*, 1966). For this reason, a basic soil can be preferred to an acidic one and, in order to increase the EK DE, the pH of the soil should be retained above 7. Furthermore, regarding EK decontamination, an acid pH is preferable, since it allows the solubilisation and transport of metal contaminants that can therefore be removed. For this reason, when decontamination is required, it is necessary to inject reagents into the soil to create an acidic environment (Alshawabkeh *et al.*, 1999).

pH and zeta potential are directly related. The zeta potential can be defined as the electric potential between the slipping plane (which separates mobile fluid from fluid that remains attached to the surface) and the bulk fluid. When the zeta potential is negative (as is the case of clayey soils), the water

Table 3. Case studies

Source	Electrode material	*P*: V/m	*λ*: S/m	DE: %	*E*: kWh/m^3
Asavadorndeja and Glawe (2005)	—	200	—	4.8	118–119
Bergado *et al*. (2003)	Carbon	60–120	0.223	9.8–12.7	0
Bjerrum *et al*. (1967)	Steel	20	0.02	12.3	15
Chappell and Burton (1975)	—	22.5	—	48.7–51.4	0.5
Fourie *et al*. (2007)	EKG	11	0.051	52.5	0.33
Fourie and Jones (2010)	Copper	110	—	45.9	—
Fu *et al*. (2017)	Steel	30	—	18.55	0
Gargano *et al*. (2019b)	Graphite	92.3	0.33–0.48	11.9–15.6	22.1–43.3
Gargano *et al*. (2020a)	Graphite	92.3	0.16–0.86	2.9–20.1	45.8–314.6
Guo and Shang (2014)	Titanium and steel	21.4–51.4	—	34.8–42.0	42–160
Hamir *et al*. (2001)	EKG and copper	109	2.5	5.0–15.2	—
Hongtao *et al*. (2007)	Iron	105.3	—	38.19	—
Hongtao *et al*. (2019)	Iron	50–125	—	37.1–49.5	—
Hu *et al*. (2018)	Graphite	100	0.063–0.168	27.3–37.5	—
Jeyakanthan *et al*. (2011)	Copper	37.3	0.048	18	—
Kalumba *et al*. (2009)	EKG	300–1000	5.26	52.6–62.9	3.43–26.54
Kaniraj and Yee (2011)	EVD	80	—	5.7–32.9	—
Lefebvre and Burnotte (2002)	Steel	35	0.05–0.07	7.4–22.6	52–102
Liu *et al*. (2017)	—	100	0.044–0.049	21.7–26.7	—
Micic *et al*. (2001)	Steel	12.8–25.6	1.2	5.2–20	—
Reddy *et al*. (2006)	Graphite	100	0.291	29.1	0.489
Shang (1997)	Steel	50	0.041	50.3–52.0	7.3–11.7
Shang and Lo (1997)	Copper and steel	78.1	0.0045	51.05	16.5
Xue *et al*. (2019)	Copper and steel	60	—	45.7–49.3	—
Yang *et al*. (2019)	Graphite and carbon	100–225	—	38–89.6	—
Yuan and Weng (2003)	Graphite	250–500	—	4.5–28.7	11.5–249.7
Zhang *et al*. (2018)	Iron	100	—	0.909	9.7

EVD, electric vertical drain

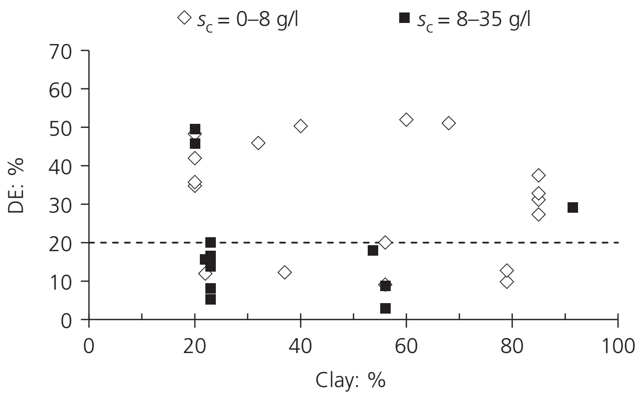

Figure 3. DE against clay content (Table 2)

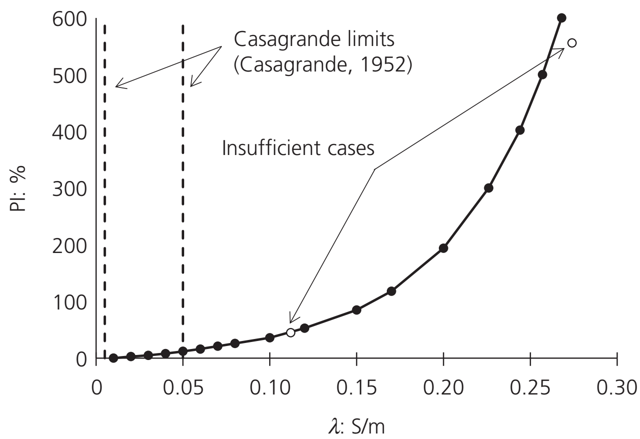

Figure 4. PI against electrical conductivity (modified from Pugh (2002))

has a greater tendency to flow through the soil mass. The higher the zeta potential, the higher the electro-osmotic dewatering (Chen *et al*., 1996; Kaniraj and Yee, 2011). The zeta potential depends on soil pH; a reduction in the pH level determines a reduction in the zeta potential (Acar *et al*., 1989), which, consequently, leads to a reduction in k_e and therefore in the electro-osmotic flow (Equation 1).

Therefore, the coefficient of electro-osmotic permeability k_e plays an important role. This is shown in Figure 7, where the DE is plotted against the ratio k_e/k_h.

From the collected data, it can be said that when the pore fluid salinity (s_c) is lower than 8 g/l, the DE is always higher than 20% for $k_e/k_h \geq 0.3$ m/V. When the pore fluid salinity (s_c) is higher (between 8 and 30 g/l) the trend shows that k_e/k_h needs to be higher than 10 m/V, in order to have DE ≥ 20%.

4.3 Pore fluid salinity

When the pore fluid salinity increases, the double layer thickness decreases, which leads to a reduction in the zeta potential,

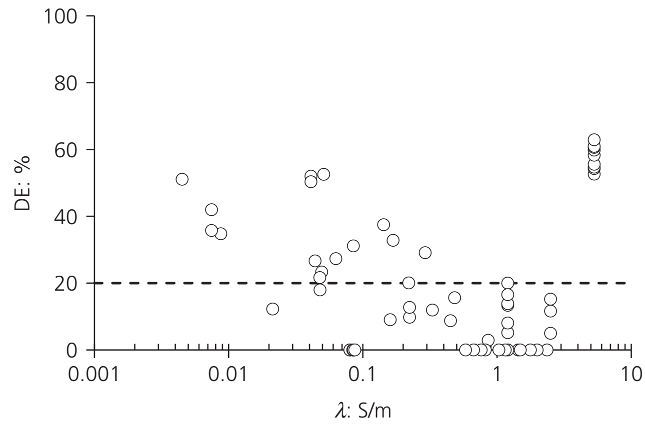

Figure 5. DE against electrical conductivity (Table 3)

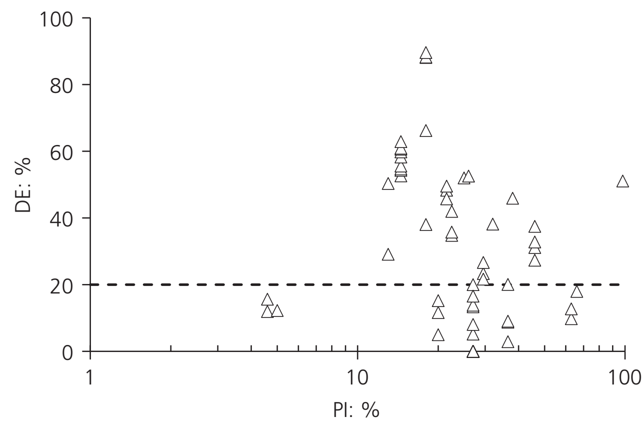

Figure 6. DE against PI (Table 2)

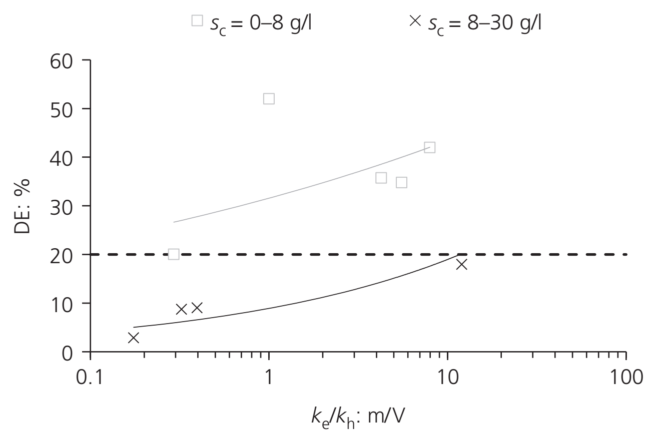

Figure 7. DE against k_e/k_h ratio (Table 2)

and therefore in the electro-osmotic permeability (Equation 2). The pore fluid salinity is a key parameter, as also shown earlier and in Figures 3 and 7.

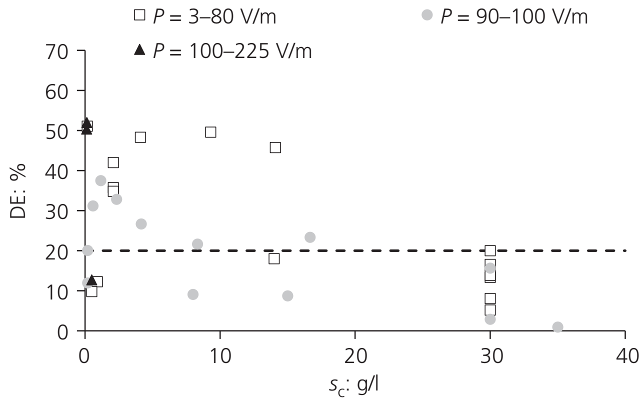

Figure 8. DE against pore fluid salinity (Tables 2 and 3)

In general, all the successful applications of EK involved soils of low salinity (with pore fluid salinity lower than 2 g sodium chloride per litre. For clays with a high pore fluid salinity, such as marine sediments, some literature studies indicate that high salinity can radically decrease the electro-osmotic flow in soils (Casagrande, 1949; Gray and Mitchell, 1967; Lockhart, 1983; Mitchell, 1993). Bergado *et al.* (2003) found out that soils with salinity higher than 6000 ppm are not responsive to EK stabilisation. Lockhart (1983) found optimum dewatering results at a salinity of 0.59 g/l, while Mohamedelhassan and Shang (2002) found the optimum at 8 g/l. These results indicate that optimum results in EK dewatering can be achieved at different pore fluid salinities, depending on the different physico-chemical properties of the soil.

In general, when the salt concentration is high, EK treatment is not effective, while a modest pore fluid salinity allows a better dewatering at lower voltages and consequently reduces the power consumption.

This can be explained as follows: when the salinity increases, more positive sodium (Na^+) ions are present in the pore fluid; they trap water molecules and therefore the EK flow is enhanced (Gargano, 2020).

Figure 8 shows how the DE depends on the pore fluid salinity (s_c) for some data collected from case studies (Tables 2 and 3). In general, as the pore fluid salinity increases, the DE decreases. This is because, as the pore fluid salinity increases, k_e decreases because the zeta potential decreases (Equations 1 and 2)

However, some controversial results should also be noted in Figure 8; for example, different DE values at $s_c = 30$ g/l. They are obviously related to the different applied voltage gradients (P): at the same pore fluid salinity, a different voltage is required to give the same DE (i.e. not necessarily the highest

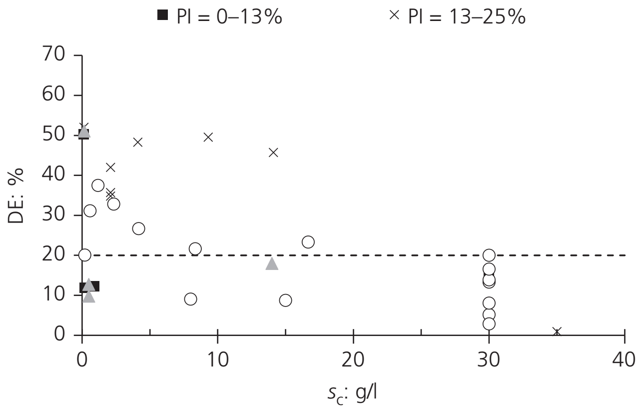

Figure 9. DE against pore fluid salinity (Table 2)

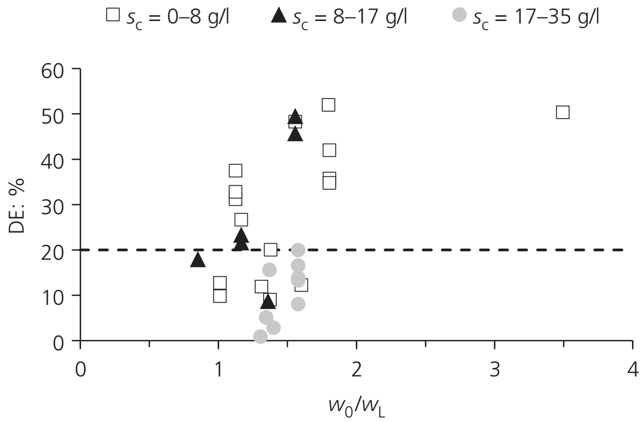

Figure 10. DE against w_0/w_L (Table 2)

one). The highest values of DE (>20%) were obtained for $s_c \leq 16.7$ g/l.

To sum up, materials with high pore fluid salinity (and therefore high electrical conductivity) are not very suitable for EK treatment, while the DE can be maximum at a specific salinity (i.e. not necessarily the lowest one).

It is therefore hard to establish a threshold beyond which EK treatment is not efficient and this threshold depends on the different proprieties of each soil.

For example, the dependence of the DE on pore fluid salinity is shown in Figure 9. In this case, markers are grouped according to their PI. The highest values of DE (≥20%) were obtained mostly for $s_c \leq 16.7$ g/l and $13\% \leq \text{PI} \leq 46\%$ (as in Section 4.1).

Furthermore, some experimental studies (Gargano, 2020; Gargano *et al.*, 2020b) showed that as pore fluid salinity increases, the homogeneity of the treatment decreases, with a higher difference of void ratio within the treated soil (the void ratio is lower at the anode and higher at the cathode). This is the consequence of a desaturation front generated in the anodic area that moves towards the cathode (Alshawabkeh *et al.*, 2004), which is responsible for an inhomogeneous degree of saturation along the specimen. Due to desaturation, the hydraulic continuity of the soil is compromised and so is the permeability of the soil, which decreases, causing a reduction in water flow.

4.4 Water content

The initial water content (w_0) can be very different in different soils, especially regarding dredged sediments. Several case studies were analysed (Table 2) and it was observed that EK treatment is very effective for soft soils with a high water content, basically because they can conduct more electrical current.

It is clear from Table 2 that EK treatment has been mostly applied to soils with an initial water content from one or two times the liquid limit. Figure 10 shows the DE against the initial water content over the liquid limit (w_0/w_L), where w_0 in Figure 10 and Table 2 is the water content at the beginning of the EK treatment. It can be said that, from the collected data, the DE is higher than 20% mostly when w_0/w_L is higher than 0.9 and, again, the pore fluid salinity (s_c) is between 0 and 8 g/l.

4.5 Electrode material

The efficiency of EK treatment can be affected by the electrode materials. Different materials have been used over the years (Table 3). Precious metals are not corrodible but are expensive. Carbon is cheaper, but low-conducting, which leads to a higher power consumption. Metallic electrodes can be corroded by electrolysis (Reaction I) at the anode side. The corrosion of metallic electrodes decreases the effectiveness of the EK treatment (Lefebvre and Burnotte, 2002) and the precipitation of metal oxides increases the power consumption, thus reducing the efficiency. Furthermore, the dissolution of metallic electrodes leads to the generation of undesirable corrosion products at the anode in an acidic environment. For this reason, graphite is the most used material for electrodes in laboratory tests (Table 3), being chemically inert and electrically conducting (Gargano *et al.*, 2020a).

Electrokinetic geosynthetics (EKGs) have been developed at the University of Newcastle, UK. They are very innovative electrodes (Table 3) prepared by using a conductive polymer that is not susceptible to electrochemical reactions (Hamir *et al.*, 2001).

Most of the high DE values in Table 3 are associated with graphite and EKG electrodes. This can be mainly attributed to the non-corrodibility of these materials, which does not lead to an interruption of the EK flow.

In general, regarding the choice of electrode material, it would be good practice to take into account different aspects, such as the electrical conductivity of the material, its availability, ease of installation in the field and cost.

4.6 Electrode spacing and configuration

The electrode configuration is an important factor to determine the productivity of EK treatment. The best electrode layout is one where the effective area is maximised in order to treat the soil more uniformly.

There are two different electrode configurations. A configuration is called one-dimensional or two-dimensional if one or more cathodes are installed for each anode. With a two-dimensional configuration (hexagonal, square or triangular electrode type), the acidic soil at the anode side (generated by electrolysis) extends over a wider area and this is preferred when there is no cementation at the cathode side (Asavadorndeja and Glawe, 2005). Most of the reported studies on EK treatment have been performed with a one-dimensional configuration (Tables 2 and 3). Limited data are available to evaluate the field performance of the different electrode configurations.

As regards the electrode spacing, a larger electrode spacing reduces the number of boreholes and installation costs but increases the processing time required and the operation costs (Alshawabkeh *et al.*, 1999). To minimise the ineffective area, Casagrande (1983) suggested a spacing between opposite electrodes from 1 to 3 m. Furthermore, the spacing between two electrodes of the same sign should not be very small (less than 12 times the diameter of the electrode), otherwise the electrode group will function as a single electrode. The spacing between electrodes in the field varies within the range of 1.2–6.0 m (Chew *et al.*, 2004). Most of the case studies shown in Table 2 are laboratory studies, where the spacing between the electrodes varied from a few centimetres to 1 m.

4.7 Voltage gradient and power consumption

The voltage gradient should not exceed 50 V/m (Casagrande, 1949) in order to avoid a considerable loss of power due to ground heating. However, the most common voltage gradient (P) used in geotechnical field applications can be higher, but within the range 20–100 V/m (Table 3).

The energy consumption E (W.h) is the power consumption during the total treatment time (t):

$$E = \Delta\Phi \times i \times t = R \times i^2 \times t \quad (6)$$

where the power consumption is equal to $\Delta\Phi \times i$ (the applied electric potential times the current intensity) and can also be expressed as $R \times i^2$ (where R is the electrical resistance). An interesting factor to assess the economic practicability of EK treatment could therefore be the energy consumption to treat 1 m^3 of soil, $\bar{E}$ (W.h/m^3).

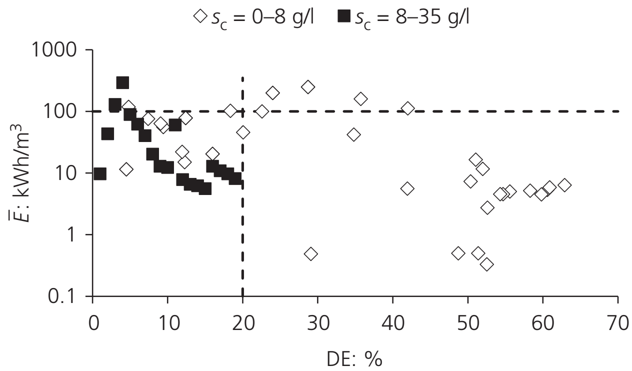

Figure 11. Power consumption against DE (Tables 2 and 3)

A power consumption of 100 kWh/m^3 is considered, in this study, as a threshold beyond which the EK treatment is not feasible due to high power consumption costs (Gargano, 2020).

It is evident that the higher the pore fluid salinity, the higher the current intensity. For this reason, from Equation 6, energy consumption increases with the pore fluid salinity.

From Figure 11, it is worth noting that in order to obtain the prefixed DE (≥20%) and consuming <100 kWh/m^3, a low pore fluid salinity must be considered ($s_c \leq 8$ g/l).

5. Conclusions

Sometimes, there is a lack of quantitative information on the effectiveness of EK treatment on different types of soils. A deep analysis is necessary from this point of view, for the use of EK treatment in the field, particularly when it is not possible to carry out laboratory tests.

In this paper, the effect of different factors on the efficiency of EK consolidation has been described and analysed, based on previous research studies.

The comparison was made among studies with different soil conditions (soil type, pore fluid salinity and water content) and

Table 4. Parameter ranges for assessing acceptability of electro-osmosis

Parameter	Acceptability range
Clay fraction (Section 4.1)	≥20%
PI (Section 4.1)	13–46%
Electrical conductivity, λ (Section 4.1)	≤0.3 S/m
k_e/k_h (Section 4.2)	≥0.3 m/V
s_c (Sections 4.3–4.7)	≤8 g/l
Water content, w_0 (Section 4.4)	>0.9w_L

set-up design parameters (applied voltage) to evaluate the feasibility of using the electro-osmotic technique to dewater soils with a high water content, such as dredged sediments.

To summarise the results of various research studies, the parameter ranges for assessing the acceptability of the electro-osmotic treatment are shown in Table 4. As mentioned above, acceptability is meant as a DE higher than 20%.

Marine soils and dredged soils (Table 1) have proprieties that locate within the ranges shown in Table 4 in terms of clay content, water content–liquid limit ratio and PI, except for only a few cases.

As regards the electrical conductivity (which depends on the pore fluid salinity), it can be high for dredged sediments, especially when they are from the sea. For this reason, EK treatment meets some limits. In such cases, dredged materials could be mixed with tap water to obtain a reduction in salinity (Macía *et al*., 2014), therefore resulting in lower conductivity (<0.3 S/m). This means that, in order to be effective, EK dewatering needs to be applied after a pre-treatment of desalination.

It can be therefore said that, with further developments, this technology can be applied for reducing the water content and increasing the resistance of soft clayey sediments for their advantageous reuse.

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