Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 158 (2016) 3 – 8

Procedia Engineering

www.elsevier.com/locate/procedia

VI ITALIAN CONFERENCE OF RESEARCHERS IN GEOTECHNICAL ENGINEERING – Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale, CNRIG2016

Effect of Electro-kinetic consolidation on fine grained dredged sediments

Alessandro Flora[a,]*, Sara Gargano[a], Stefania Lirer[b], Lucia Mele[a]

[a]*Department of Civil, Architecture and Environmental Engineering, University of Naples Federico II, Via Claudio 21 - 80125 Naples, Italy*
[b]*Department of Engineering Sustainability, University of Guglielmo Marconi, Via Plinio 44 - 00193 Rome, Italy.*

Abstract

The management of the huge amount of dredged sediments is an important issue to be solved worldwide, and dewatering is by far the most critical step when fine grained sediments are involved. Different technologies have been proposed in time to speed up the process. Even though electro-kinetic treatment is in principle one of them, it has not been implemented yet at an industrial scale, and only few trial applications are known. For such a reason, a multidisciplinary research activity is ongoing at the University of Napoli Federico II in the framework of the EU commitment ROSE with the aim to analyse the effectiveness and feasibility of such a technology from the lab to the site scale. In this paper, some evidences stemming from lab tests are presented. The results indicate that the application of low voltages improves the mechanical behaviour of the tested soil. In this case, however, the improvement is due more to a change in microstructure than to a decrease in void ratio.

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016

Keywords: Dredged sediments; dewatering; electro-osmotic consolidation

1. Introduction

Dredged materials are slurries composed by solid grains (from fine to coarse) and a large amount of water (depending on the adopted dredging technology), whose chemical characteristics depend on the dredging

* Corresponding author. Tel.: +39-081-768-3467
E-mail address: flora@unina.it

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016
doi:10.1016/j.proeng.2016.08.396

environment. Because of the shortage of disposal capacity, and the worldwide interest to tap the full potential of primary and secondary raw materials, dredged sediments must be considered as a resource [1] and many strategies and methodologies for their beneficial reuse are being developed throughout the world [2]. The typical treatment processes for contaminated dredged sediments are: dewatering; particles separation; contaminant destruction or removal and/or immobilization. The most employed mechanical dewatering techniques are: centrifugation, dewatering by belt filter press, plate and frame press, screw press. Electro-kinetic treatment is not usually considered, even though it may be beneficial for more than one of the treatment processes previously listed (namely dewatering and contaminant removal). A research program has been recently started at the University of Napoli Federico II to check if such a treatment may be considered as a feasible technology to dewater and improve fine grained dredged sediments at an industrial scale. To this aim, lab and site tests have been planned to check the effects of treatment on different soils. The paper reports and comments the first experimental results.

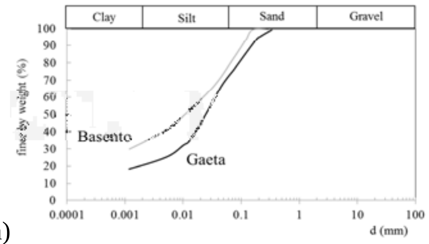
2. Electro-kinetic soil treatment

Electrokinetic soil remediation is a technology that has attracted increasing interest among scientists in the last decades, due to several promising laboratory and pilot-scale studies and experiments [3]. The principles of such a treatment method involve applying a direct current or low electric potential gradient to electrodes inserted into a saturated soil. When a current is applied to a soil, it stimulates the migration of electricity, pore fluid, ions and fine particles across the soil towards the oppositely charged electrodes, thus creating a combined effects of chemical, hydraulic and electrical gradients. In particular, an electrokinetic process goes through three phases: (1) electrophoretic sedimentation, (2) electro-osmotic consolidation and (3) electro-migration. Under an applied direct electric current, the polarized clayey colloids (with a negative charge on their surface) tend to migrate through the surrounding stationary liquid phase to the positive electrode (anode). This represents a dominant electrophoretic mechanism. On the other hand, the positive ions (cations) in the surrounding liquid and in the outer diffused part of the electric double-layer migrate towards the negative electrode (cathode), modifying the microstructure of the clayey particles. These cations mechanically drag with them the residual mass of free water, which results in a movement of liquid in the pores towards the cathode. This latter phenomenon, known as electro-osmosis, has been applied in soft clay engineering since the first successful field application by Casagrande in 1948 [4]. When the electric current is applied, another phenomenon occurs, named electro-migration, which involves transport of ionic species in the pore fluid, and can play an important role in the process of soil decontamination. The combined effect of the three previously mentioned electrochemical processes (namely electrophoretic sedimentation, electro-osmotic consolidation and electro-migration) results into a significant change in the physicochemical, hydrological and engineering properties of the soils [5]. For such a reason, the electro-kinetic treatment can be considered as a soil improvement technique [6] and has been used for the production of barriers for the containment of chemical pollutants, and sometimes even for the stabilization of landslides.

3. Experimental programme

Since the processes induced by the application of an electric field are both a reduction in water content and a modification of microstructure, it is of the outmost importance to check their relative importance from the ground improvement point of view. To this aim, two materials have been tested: one coming from the port of Gaeta, and the other one from the Basento river (Fig. 1a). The main physical characteristics of the two dredged materials are reported in Figure 1b, and clearly show that the Basento soil is finer and more plastic than the Gaeta one.

All laboratory tests have been carried out on remoulded specimens, obtained by drying the dredged material in stove at 105° and then mixing it with tap water to obtain an initial water content $w \sim 1.5\ w_L$. The oedometric tests were carried out in two identical floating oedometers designed to allow large displacements (maximum specimen height H= 20 cm, internal diameter D = 5 cm), having a non conductive stiff polimetilmetacrilate confining ring. Conductive porous stones were used both at the top and bottom bases of the specimen. In the electro-kinetic tests, the upper (anode) and the lower (cathode) end plates have been connected to a (DC) power supply, operating under constant voltage $\Delta\Phi$. The water is therefore electrically driven towards the bottom base. Mechanical and electric loads were applied following different loading and unloading paths, that can be classified as follows: mechanical (M), electric (E), and contemporary electric and mechanical (EM) paths. Different combinations were adopted as reported in Figure 2b and briefly sketched in Figure 2a. To reduce the risk of desaturation during the application of an electric field, small increments of voltage were applied ($\Delta\Phi$ = 6, 12 and 20 V) and the maximum voltage never exceeded 20 V (roughly corresponding to a voltage gradient of 1V/cm).

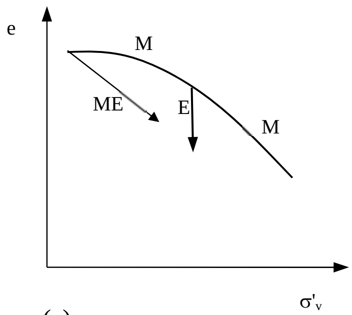


(a)

Material	Gs	clay fraction (%)	w_P	w_L	PI (%)	organic content (%)
Basento	2.70	35	0.129	0.310	18.1	0
Gaeta	2.69	20	0.233	0.334	10.1	10.87

(b)

Fig. 1. (a) Grain size distribution of the tested soils; (b) Physical properties of the tested soils.



(a)

Material	Oedometric Tests						Triaxial Tests	
	Test name	Path	e_0	$\sigma'_{v,max}$ (kPa)	$\sigma'_{v,f}$ (kPa)	$\Delta\Phi$ (V)	Test name	σ'_c (kPa)
Basento	B-OE1	M	1.5	15	15	-	-	-
	B-OE2	ME	1.5	30	30	12		
Gaeta	G-OE1	M+E	1.16	30	15	-	TX-G1	15
	G-OE2	M+E	1.16	30	15	-	TX-G2	15
	G-EOE3	M+E	1.06	10	10	6-12-20	TX-G3	10
	G-EOE4	M+E	1.19	15	15	6-12-20	TX-G4	15

(b)

Fig. 2. (a) Stress path in the oedometric apparatus; (b) Experimental programme.

At the end of some of the oedometric tests, the specimens were trimmed and tested in a triaxial cell (specimen D=36 mm and H=72 mm); in the triaxial tests, the specimens were isotropically consolidated at an isotropic effective stress equal to the final vertical stress applied in the oedometer (thus with a slight increase in the mean stress) and then sheared in undrained conditions.

3.1 Dewatering effects of electro-kinetic treatment

Figure 3 reports one consolidation step for the Basento and Gaeta materials, during M and ME tests. The figure shows the results at a vertical stress of 15 kPa, without (M) or with (ME)) the application of a voltage of 12 V, but are well representative of all the other steps. The beneficial effect of the electric field in terms of the reduction of void ratio and the speeding up of the dewatering process is striking for the Basento material, while its effect is minor for the Gaeta one. The finer and more plastic material is extremely more sensitive to the application of the electric field, confirming what is well known in literature. Electro-kinetic treatment is thus mechanically effective for the Basento material. The question than arises if it has any sort of effect on the Gaeta material, for which the reduction of porosity upon treatment is small. In Figure 4a, the curve w/w_{100}-logt of test G-EOE3 is reported to show the effect of subsequent increments of the voltage: at the end of the mechanical consolidation process (w_{100} is in this case the consolidation settlement attained at the end of the load step σ'_v = 10 kPa), a first voltage difference ($\Delta\Phi_1$ = 6V) has been applied to enhance a new dewatering stage. As soon as the equilibrium state has been attained (no soil settlements), an increased voltage is applied ($\Delta\Phi_2$ = 12 V and then $\Delta\Phi_3$ = 20 V). As previously mentioned, the application of the electrical field to the Gaeta material induces measurable but very small extra displacements (w_{ek}). During the electro-kinetic consolidation process, the current intensity (i) has been also measured. The current is initially high, tending to decrease in time because of the reduction of ionic species in the pore water (Fig. 4b) induced by chemical changes, electro-migration and electro-osmotic flow. It can be also observed that the current intensity (i) and the settlements (w_{ek}) are closely related: for each applied voltage $\Delta\Phi$, the settlements rate decreases as the current decreases.

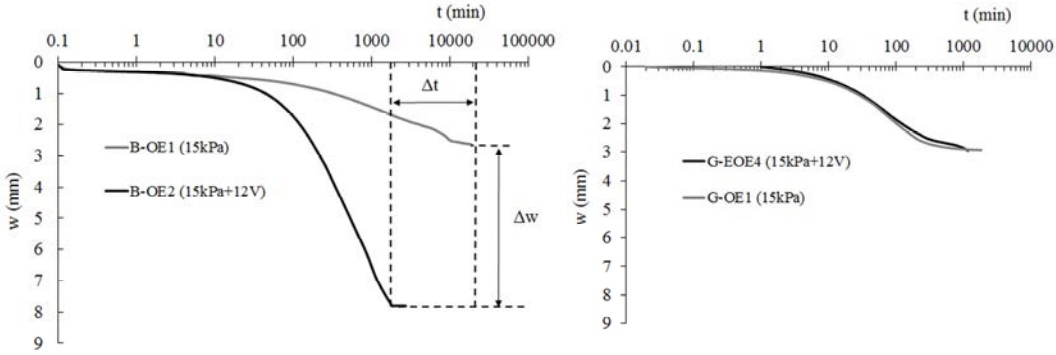


Fig. 3. Results of the oedometric tests.

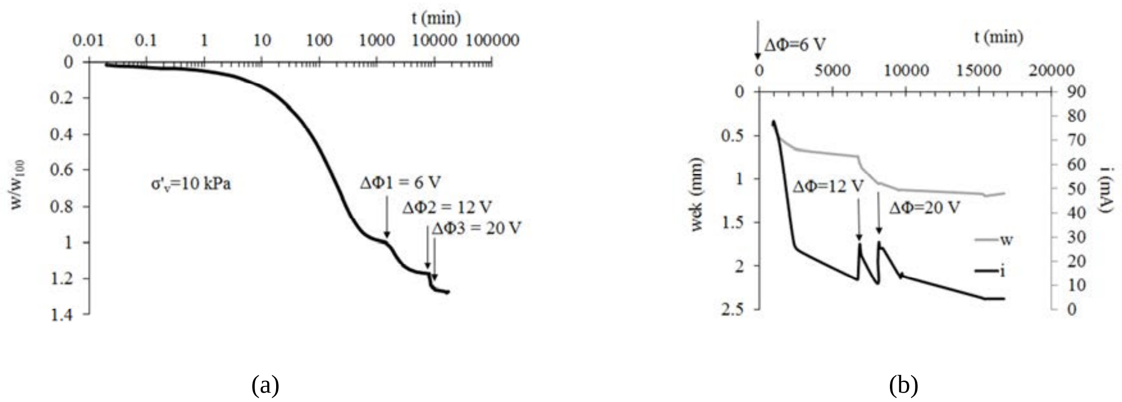


Fig. 4. Results of electrified oedometric test G-EOE3: (a) normalized soil settlement (w/w100) versus the time (t), soil settlements w_{ek} and current intensity i (b).

3.2 Micromechanical effects of electro-kinetic treatment

In Figure 5, the results of the oedometric tests carried out on the Gaeta material applying a sequence of mechanical (M) and electric (E) loads are plotted in the semi-log vertical stresses (σ'_v) vs. void index (e) plane. In the two M tests (without electric field), the maximum value of the applied vertical stress σ'_v is 30 kPa and an unloading path has then been applied up to σ'_v=15 kPa, inducing a final OCR=2. In the other two tests reported in the figure, electric loads were applied in three subsequent steps ($\Delta\Phi$ = 6, 12, 20 V) after the end of the consolidation process induced by the mechanical loads. Interestingly, since the dewatering caused by the application of the electric field is reduced, the final states of the M and M+E tests are similar (practically identical for tests G-OE2 and G-EOE4, slightly different for the other two tests G-OE1 and G-EOE3). Because of this, the effect of the different loading paths (either M or M+E) can be investigated by means of triaxial tests.

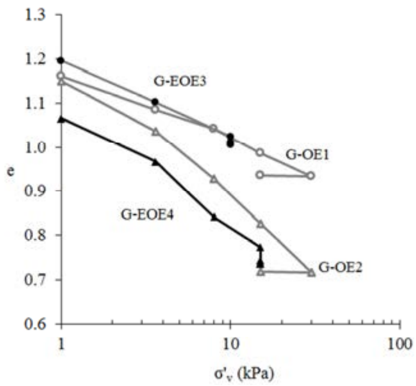
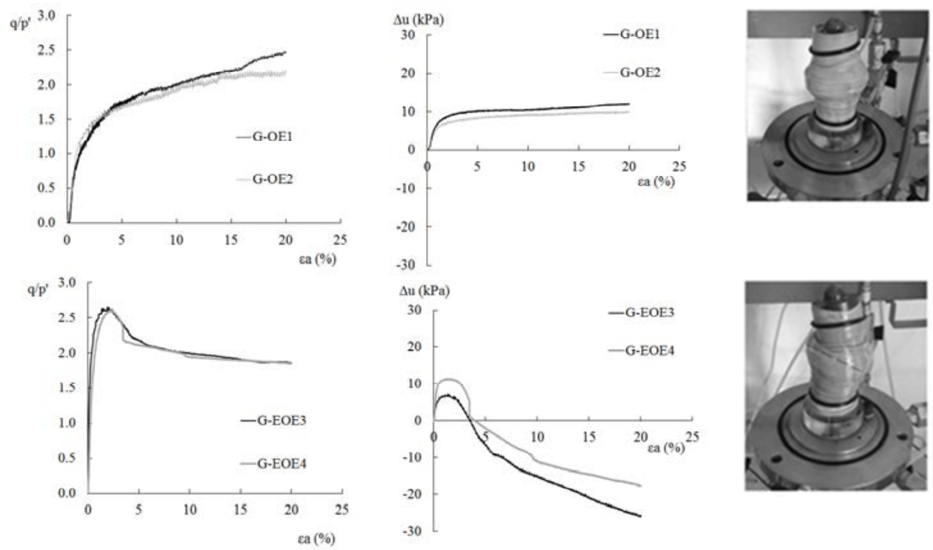


Fig. 5. Results of the oedometric tests on the Gaeta material.

Four isotropically consolidated undrained triaxial tests have been therefore performed (Fig. 2b) on specimens coming from the special oedometer apparatus. The results are reported in Figure 6 in terms of the stress ratio q/p' and pore water pressure increment (Δu) versus axial strains (ε_a). Notwithstanding the basically identical initial state, the G-OE specimens show the behaviour of normally consolidated soils, while the G-EOE ones show the peculiar stress-strain behaviour of over-consolidated soils, with a peak in undrained shear strength.



(a) (b)

Fig.6. Results of the CIU triaxial tests (a) and pictures of the specimens (b) after triaxial tests.

This means that by removing the electrically bonded water molecules and some ions, the electro-kinetic treatment has significantly modified the structure of the soil, largely increasing the overconsolidation pressure. In order to quantify the corresponding increase in overconsolidation ratio (OCR), the results of the triaxial tests can be used calculating the undrained shear strength s_u and expressing it using the well known relation [8]:

$$\frac{s_{u,OC}}{\sigma_v'} = \alpha \cdot OCR^{0.8} \tag{1}$$

with α=0.22±0.03 (in this case, the value α=0.22 was adopted). The value of OCR calculated for the M+E specimens (having s_u≈80 kPa) is OCR≈6, while for the M specimens (having s_u≈20 kPa) OCR≈1.9, consistently with the one induced during the test (OCR=2).

A further proof of the beneficial modifications induced at the microscale from the electro-kinetic treatment is reported in Figure 7, where the results of X-ray diffraction tests carried out on specimens with and without electric treatment are shown . A higher reflection of the existing clayey phases is observed (rectangles in the figure) for the electrically treated soil, proving a modification in the microstructure, with a higher crystallinity of the treated soil likely due to a rearrangement of the flat clayey particles.

4. Concluding remarks

The application of an electric field to an underconsolidated clayey soil has the beneficial effect of removing water at a faster speed and of modifying its micromechanical structure. Both effects are beneficial from the mechanical point of view. The paper shows that the first one may be extremely different depending upon the amount and plasticity of fines in the soil. The latter can be extremely relevant even in cases where water removal is almost negligible, and results in an increase of the overconsolidation pressure. Because of this, the electro-kinetic treatment deserves high attention to the aim of treatment and stabilization of underconsolidated fine grained dredged materials.

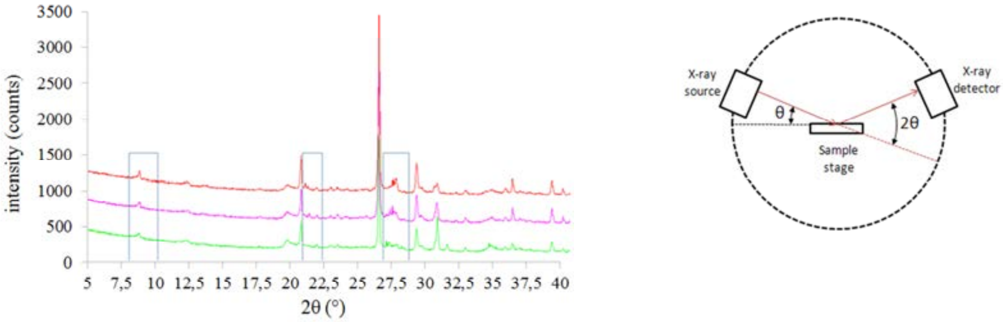


Fig. 7. X-ray diffraction patterns of the analysed samples (line green=spec. G-OE1; line violet: spec. G-OE1; line red: spec. G-EOE3). [vertical axis: intensity of the reflected x-rays in counts per second; horizontal axis: diffraction angle of the x-rays].

Acknowledgements

The authors gratefully acknowledge Profs. Domenico Caputo and Barbara Liguori for carrying out the X-ray diffraction analyses and for their advice in the interpretation of the chemical modifications induced by electro-kinetic treatment.

References

[1] S.E. Apitz, Waste or resource? Classifying and scoring dredged material management strategies in terms of the waste hierarchy, J Soils Sediments, Vol. 10 (2010) 1657–1668.
[2] R. J. Collins, Dredged silt as a raw material for the construction industry, Resource Recover and Conservation, Vol. 4(4) (1980) 337–362.
[3] J. Virkutyte, M. Sillanpaa, P. Latostenmaa, Electrokinetic soil remediation: critical overview, The Science of the Total Environment 289 (2002) 97–121.
[4] L. Casagrande, Electro-osmosis, Proceedings, 2nd International Conference on Soil Mechanics and Foundation Engineering, Rotterdam, Vol. 1 (1948) pp. 218–223.
[5] A. Mahmoud, J. Olivier, J. Vaxelaire, A.F.A. Hoadley, Electro-dewatering of wastewater sludge: Influence of the operating conditions and their interactions effects, Water Research 45 (2011) 2795–2810.
[6] J.K. Mitchell, Fundamentals of soil behaviour, 2nd ed. John Wiley & Sons, New York, 1993.
[7] K. R. Reddy, A. Urbanek, A. P. Khodadoust, Electroosmotic dewatering of dredged sediments: Bench-scale investigation, Journal of Environmental Management 78 (2006) 200–208.
[8] D.C. Koutsoftas and C.C. Ladd, Design strengths for an offshore clay, J. Geotech. Engrg. 111(3) (1985) 337–355.