Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0401

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Numerical study of the mechanical behavior of fine-grained dredged sediments

Etude numérique du comportement mécanique des sédiments de dragage à grains fins

A. de Lillis
Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Italy

G. M. Rotisciani, S. Miliziano
Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Italy

ABSTRACT: In the last few decades dredging activities have experienced a significant growth. An efficient way to manage the dredged material is to reuse it to reclaim coastal confined containment facilities. When fine-grained sediments are involved, hydraulic dredging is a common, highly appreciated choice. This technology causes the dredged mud to sediment at very high water-to-solid volumetric ratios and then undergo dramatic deformations during consolidation. The paper presents the results of a numerical study conducted simulating the whole filling-consolidation process. The soil behaviour was modelled adopting the well-known Modified Cam-clay model, in conjunction with a strongly non-linear void ratio:permeability law. A series of parametric analyses was performed to investigate the influence of the hydro-mechanical properties on the dredged mud behaviour during the hydraulic filling and the subsequent consolidation process. The numerical results emphasize that the design of the filling works can significantly benefit from a deeper knowledge of these processes.

RÉSUMÉ: Au cours des dernières décennies, les activités de dragage ont connu une croissance significative. Un moyen efficace de gérer les matériaux de dragage consiste à les réutiliser pour récupérer les zones de confinement. Lorsque des sédiments fins sont impliqués, le dragage hydraulique est un choix apprécié. Cette technologie amène les boues de dragage à sédimenter à des rapports volumétriques eau/solide très élevés, puis à subir des déformations considérables au cours de la consolidation. L'article présente les résultats d'une étude numérique menée pour simuler l'ensemble du processus de remplissage-consolidation. Le comportement du sol a été modélisé en adoptant le modèle de Cam-clay modifié avec un loi indice des vies:perméabilité fortement non linéaire. Une série d'analyses paramétriques a été réalisée pour étudier l'influence des propriétés hydromécaniques sur le comportement de la boue draguée pendant le remplissage et la consolidation. Les résultats numériques soulignent que la conception des travaux peut bénéficier d'une connaissance plus approfondie de ces processus.

Keywords: Hydraulic dredging; land reclamation; large-strain consolidation; numerical modelling.

1 INTRODUCTION

In the last few decades, the navigation requirements of continuously growing ships in need of deeper sea beds have led to an increase in dredging activities, emphasizing the importance of optimizing the management of dredged sediments. A virtuous and efficient way to handle the dredge material, treating it as a resource rather than a waste, is to reuse it to fill confined coastal containment facilities and then reclaim their areas, typically to integrate them into the port infrastructure.

In most cases, if large volumes are involved, the dredging is carried out hydraulically. This technology involves the transportation of the soil as a slurry, at high water-to-solid volumetric ratios. With specific reference to fine-grained soils, when the slurry is deposited in the containment facility, the soil first settles at high void ratios and then undergoes significant state changes due to the self-weight. The design of filling works aimed at land reclamation can significantly benefit from the knowledge of these processes. This is particularly important when only small (with respect to the dredging volume) containment facilities are available, or when big ones get partialized to reclaim smaller fractions.

The mechanical and hydraulic properties of fine-grained materials at high water content have been extensively investigated in the past (e.g.: Abu-Hejleh et al., 1996; Berilgen et al., 2006), as has been their behaviour when they are subject to ground improvement works, such as mechanical or vacuum pre-loadings (e.g.: Indraratna et al., 2011). Still, very few studies focused their attention on the behaviour of the dredged sediments during the whole filling-consolidation-improvement process.

In the following, the distinctive features of this class of problems are briefly described and the constitutive laws suitable to simulate the hydro-mechanical behaviour of dredged materials are introduced. The numerical model is then presented and the main results discussed. Finally, the results of some parametric analyses investigating the influence of both the permeability and compressibility laws are illustrated and discussed.

2 HYDRAULIC DREDGING

When a soil is hydraulically dredged, its *in-situ* void ratio increases drastically (admitting a broader definition of the void ratio also valid for slurries). The soil is transported through pipes as a slurry having water-to-solid volumetric ratios ranging between 6÷12. The slurry is then poured into the containment facility and a combined sedimentation-consolidation process initially takes place; with the length of the sedimentation phase being a small fraction of the whole duration. The soil settles at high void ratios, according to its chemo-psychical properties, and then starts to develop effective stresses consolidating under its own weight, experiencing dramatic volume changes as it reaches a normally consolidated profile. Finally, in order to reclaim the area, ground improvement works are necessary to give the soil the required mechanical characteristics.

As the described processes involves significant changes in volume of the dredged material, the volume of the containment facility must be as large as the maximum soil volume, even though the final soil configuration will only occupy a small portion of it. In this study, the behaviour of the dredged sediments was investigated with reference to an optimized filling-consolidation procedure, specially developed for the reclamation of small containment facilities, which has several apparent advantages.

This procedure, whose details are reported by de Lillis and Miliziano (2016), consists in dividing the filling phase in a number of sub-steps in between which drainage and vacuum systems are installed into the containment facility. More specifically, after a dredging sub-step is completed, horizontal drainage pipes are installed on top of the dredged mud and connected to the vacuum pumps (Figure 1). Then the dredging and filling phases resume and once the drainage system is covered by soil the vacuum pumps are turned on, inducing negative pore water pressures (up to 60÷70 kPa) in the dredged mud. This allows to accelerate the consolidation processes significantly and to increase the effective stresses in the dredged mud – reducing its volume drastically – while the hydraulic filling is still taking place. Furthermore, once the consolidation process is exhausted, turning off the vacuum pumps induces a significant pre-loading effect. This procedure

Figure 1. Horizontal drains and connections with the vacuum pumps circuit (de Lillis and Miliziano, 2016).

optimizes the management of fine-grained dredged soils and can be used satisfactorily either when only small containment facilities are available or when the reclamation of small fractions of large containment facilities is a priority.

2.1 Governing equations

As the void ratio of the dredged soil experiences significant changes, numerous basic assumptions of Terzaghi's consolidation theory lose validity. Hence, to consider the evolution of geometry, soil stiffness and permeability, the large-strain consolidation theory (Gibson et al., 1967) should be adopted.

The governing equation is:

$$\pm\left(\frac{\rho_s}{\rho_f}-1\right)\frac{\mathrm{d}}{\mathrm{d}e}\left[\frac{k(e)}{1+e}\right]\frac{\partial e}{\partial z}+ \\ +\frac{\partial}{\partial z}\left[\frac{k(e)}{\rho_f(1+e)}\frac{\mathrm{d}\sigma'_\mathrm{v}}{\mathrm{d}e}\frac{\partial e}{\partial z}\right]+\frac{\partial e}{\partial t}=0 \tag{1}$$

where z is the geometric variable, ρ_f and ρ_s are the fluid's and the solid grain's densities, respectively, e is the void ratio, $k(e)$ is the permeability law and σ'_v is the vertical effective stress.

Several constitutive relations have been proposed to describe the hydro-mechanical soil behaviour starting from very low stress states (and high void ratios), where soils exhibit high compressibility and permeability. Two relations that well-reproduce the experimentally observed soil behaviour over a wide range of void ratios are the following:

$$e=\mathrm{A}\left(\sigma'_\mathrm{v}+\mathrm{Z}\right)^\mathrm{B} \quad \text{(Liu and Znidarcic, 1991)} \tag{2}$$

$$k=\mathrm{C}\,e^\mathrm{D} \quad \text{(Krizek and Somogy, 1984)} \tag{3}$$

where A, B, Z, C and D are empirical constants to be determined experimentally. The curves depicted in Figure 2 refer to the parameters adopted in de Lillis and Miliziano (2016).

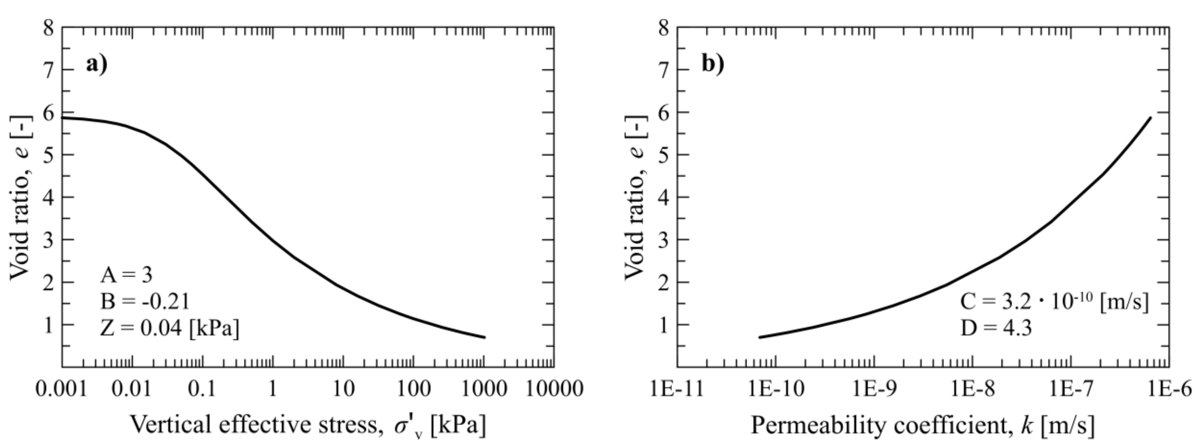

Figure 2. Constitutive relations: a) compressibility law, eq. 2; b) permeability law, eq. 3.

3 NUMERICAL MODEL

A numerical model was developed using the finite element code ABAQUS/Standard to simulate the whole filling-consolidation process described above. Due to the specific geometry, the problem was modelled as one-dimensional. To take into account the significant deformations, the model works in large strain.

3.1 Construction stages

The gradual filling of the containment facility was modelled by generating the whole soil column at the beginning of the analysis and applying gravity to each element at different times, defined according to the dredging speed.

The dredging is equally divided in three 15-days phases (each depositing 4 m of dredged mud), in between which a 30-days period is considered to account for the installation of the drainage and vacuum systems, numerically modelled by prescribing a fixed pore pressure. The vacuum pumps are activated during the second and the third dredging phases respectively, once the drainage system is covered by roughly 1 m of soil, reaching a suction of 60 kPa over the course of four days. At the bottom of the soil column, a zero pore pressure condition is imposed, assuming that another drainage system, hydraulically connected to the sea level, is present in the underlying soils. At the top, the ponding surface condition is imposed, consistently with the hydraulic filling. 30 days after the end of the dredging, a 60 kPa suction is gradually applied at the top (over a 30-days period), simulating the desiccation of the dredged mud and the development of negative pore pressures. Finally, once drained conditions are attained, the vacuum pumps are switched off and the soil swells accordingly. The simulation scheme is reported in Table 1.

Table 1. Stages of the simulation.

#	Phase	Start time [d]
1	I dredging	0
2	drainage installation	15
3	II dredging	45
4	I vacuum	≈50
5	drainage installation	60
6	III dredging	90
7	II vacuum	≈95
8	consolidation	105
9	top suction	135
10	swelling	215
11	final conditions	280

3.2 Constitutive law

The soil mechanical behaviour was simulated adopting the well-known Modified Cam-clay model, to exploit its logarithmic compressibility law. As shown in Figure 3, to take into account

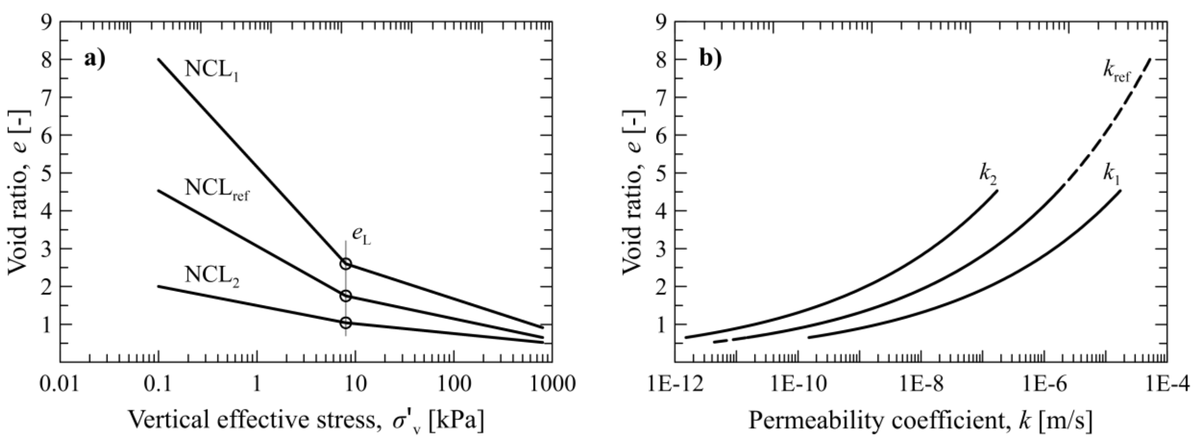

Figure 3. Constitutive relations: a) modified Cam-clay compressibility laws; b) permeability laws.

the high compressibility at low stresses, two different NCLs were used, depending on the relative position of the void ratio with respect to that associated with the liquid limit (e_L), corresponding to a vertical effective stress of 8 kPa (Skempton, 1969). The slope of the swelling line was assumed to be 1/8 of that of the NCL. The permeability was simulated adopting eq. 3.

The parameters adopted in the reference analysis are similar to those assumed by de Lillis and Miliziano (2016) to describe fine-grained soils from the port of Gaeta (Italy). Analysing the boundary value problem, the permeability was amplified by a factor of 5, accounting for site effects (de Lillis et al., 2017). The main soil parameters are listed in Table 2, together with those assumed in the parametric analyses.

The soil state was initialized with a void ratio and an effective stress consistent with the end of the sedimentation phase (e_{sed} = 4.53; σ'_v = 0.1 kPa).

Table 2. Main soil parameters.

Analysis	λ_1 (e>e_L)	λ_2 (e<e_L)	C [m/s]	D
Ref.	0.63	0.24	2E-10	6
NCL_1	1.23	0.37	2E-10	6
NCL_2	0.22	0.11	2E-10	6
k_1	0.63	0.24	2E-9	6
k_2	0.63	0.24	2E-11	6

3.3 Results

The results of the reference analysis are shown in Figure 4, together with an undrained curve, representing the height of the soil assuming that consolidation doesn't take place (filling curve), and another curve corresponding to a scenario, investigated just for comparison, in which no drainage and vacuum systems are installed.

The maximum height of the dredged mud is 5.9 m, while the final drained height is 4.8 m; without the installation of the drainage and vacuum systems the maximum height is 7 m (about 20% more than the reference one) and the final height is 5.8 m. In this last case, drained conditions are attained almost 9 months later.

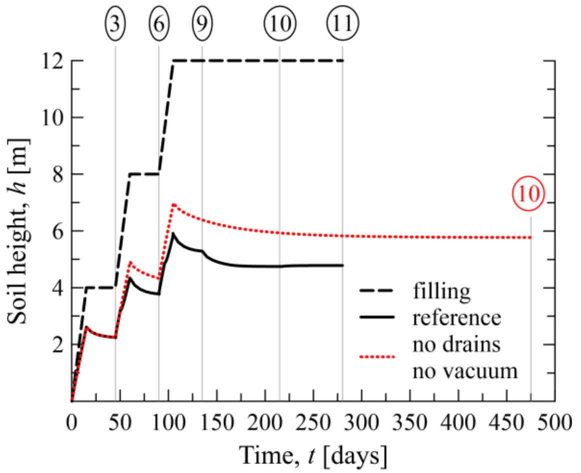

Figure 4. Reference analysis results.

Thus, in addition to the acceleration of the consolidation process, the procedure allows for a drastic reduction of the dredged mud height already during the filling works.

Figure 5 shows the state evolution of the soil in terms of pore pressure, vertical effective stress and void ratio, comparing the most significant work phases of the reference analysis. The most influential feature is the application of the vacuum pressure in between the dredged sub-strata and on top of the soil column (phases 6, 9 and 10), which significantly increase the effective stress inducing a great reduction of the void ratio. The final dismission of the vacuum pumps (phase 11), causes an almost negligible swelling of the dredged mud, associated to the reduction of the effective stresses.

4 PARAMETRIC ANALYSES

To investigate the influence of the hydro-mechanical soil properties, some parametric analyses were performed exploring a wide range of fine-grained soil characteristics (Tab. 2, Fig. 3).

Hence, two further analyses were conducted assuming permeability laws increased and decreased by an order of magnitude with respect to the reference one (Fig. 3b), while maintaining the reference compressibility law.

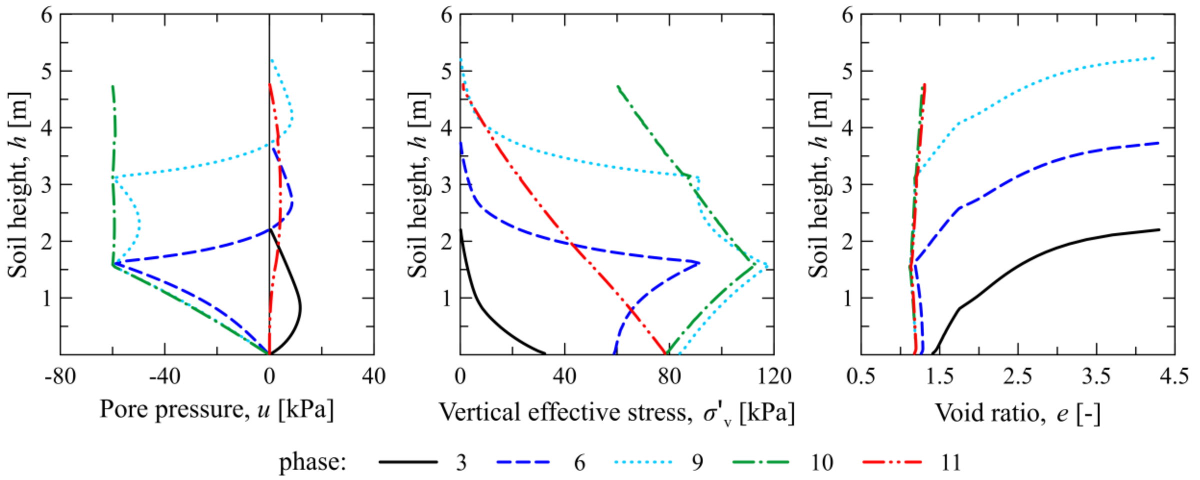

Figure 5. Reference analysis: profiles of pore pressure, effective stress and void ratio at different phases.

Then, two final analyses were performed assuming different NCLs (Fig. 3a) and maintaining the reference permeability law. Said NCLs were defined assuming a great variety of sedimentation states (e_{sed} = 8÷2), while e_L and e_P (void ratio at the plastic limit, corresponding to 800 kPa of vertical effective stress) were identified assuming the following values for the liquid and the plastic limits, respectively: w_L = 100 - 35; w_P = 40 - 20.

4.1 Permeability

The influence of the permeability law on the time evolution of the dredged mud height is shown in Figure 6.

The permeability law k_1 is such that the dredging speed is comparable to that of the consolidation process, thus the filling occurs almost in drained conditions. Adopting the law k_2 the height of the dredged mud reaches higher values, due to the slower rate of the consolidation process. The maximum heights, $h_{max,k1}$ and $h_{max,k2}$, are 90% and 140% of the maximum reference height, respectively. Drained conditions are reached few days after the end of the filling operations assuming the more permeable soil and 1 year after the reference drained time assuming the less permeable one.

Figure 7 reports the profiles of pore pressure, vertical effective stress and void ratio along the soil column, obtained assuming different permeability curves. The profiles refer to phase 9, when the dredging is already ended and the consolidation process is ongoing.

The reference and the k_1 analyses profiles are almost equal, except for the middle dredged substratum, in which some excess pore pressures remain in the reference case. The k_2 profiles, instead, show a much larger amount of excess pore pressures. The lower permeability adopted in this case doesn't allow for a speedier development of effective stresses and the associated reduction of the void ratio.

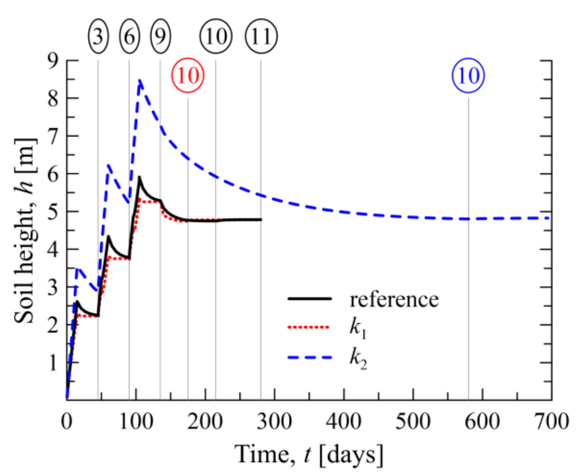

Figure 6. Dredged mud height evolution adopting different permeability laws.

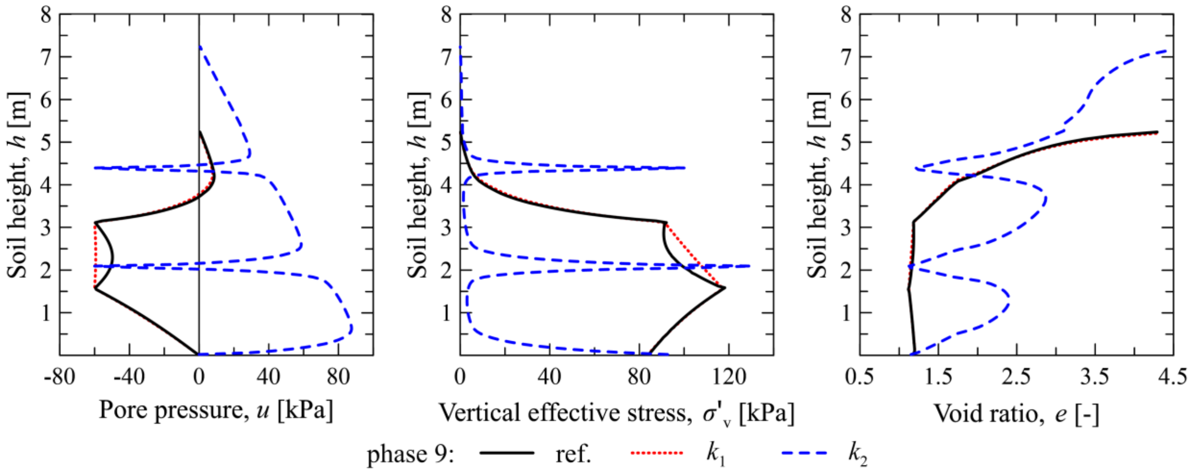

Figure 7. Profiles of pore pressure, vertical eff. stress and void ratio at phase 9 adopting different permeabilities.

4.2 Compressibility

Based on the assumption of equal *in-situ* volumes of normally-consolidated soils to be dredged, adopting different NCLs implies that different amounts of solid grains get dredged and then settle in the containment facility (at different e_{sed}). It is also worth noting that the same permeability law, associated to different NCLs, entails different permeability for equal stress states.

The results of the NCL_1 analysis, reported in Figure 8, show that the height of the dredged mud is similar to the reference height. Even though the NCL_1 is associated to higher void ratios, especially at low stress states, the higher permeability allows for a speedier consolidation process, making the two curves rather similar. The final height is less than the reference one because the amount of solid dredged material is inferior.

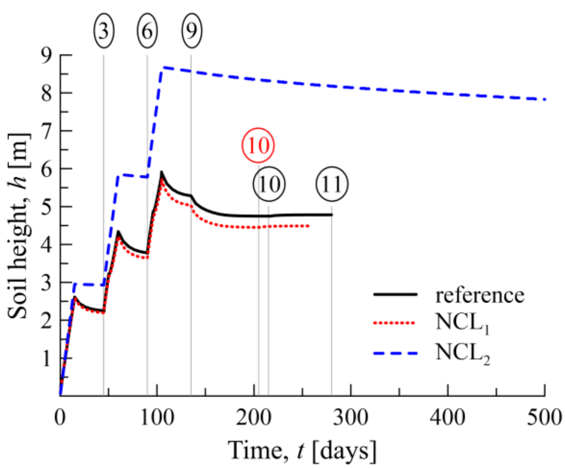

Figure 8. Dredged mud height evolution adopting different compressibility laws.

Adopting the NCL_2, the soil height is greater than that found in the reference analysis and evolves very slowly with time. The maximum height is 150% of the reference one; the consolidation process lasts significantly longer than in the reference case.

The spatial distributions of pore pressure, vertical effective stress and void ratio at phase 9 are shown in Figure 9. Adopting the NCL_2, it can be noticed that the soil is still under substantially undrained conditions. In a large portion of the soil domain, the void ratio remains unchanged at the starting value, that is much lower than that corresponding to the NCL_1 and to the reference curve. Considering the more compressive soil, most of the pore pressure excesses have been dissipated after 30 days from the dredging ending, similarly to what observed in the reference analysis. In both cases, the soil experiences significant volume changes and the void ratios become lower than those found adopting the NCL_2.

5 CONCLUSIONS

The study presented herein investigates the behaviour of dredged sediments during the filling works and the subsequent consolidation process.

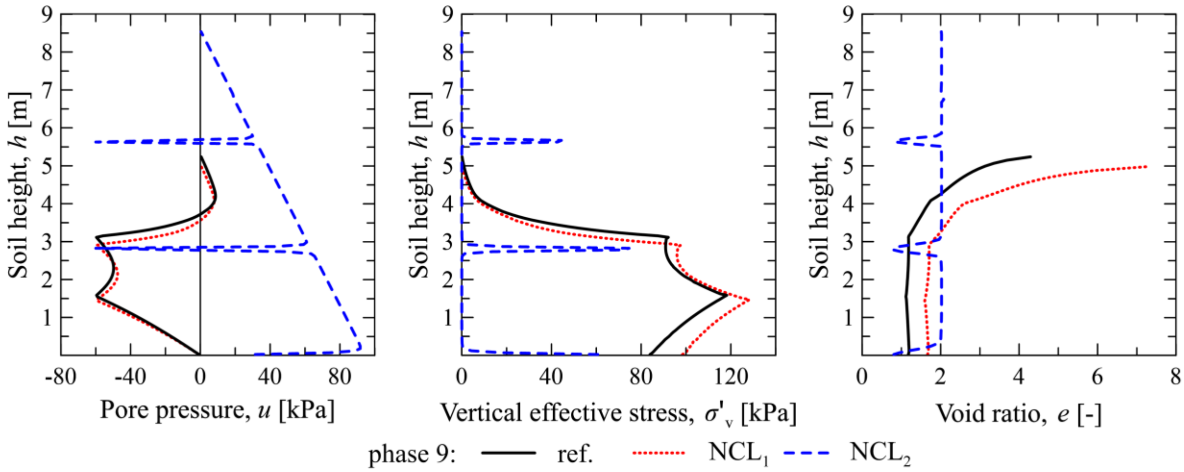

Figure 9. Profiles of pore pressure, vertical effective stress and void ratio at phase 9 adopting different NCLs.

A numerical model was developed to reproduce the main features of a filling-consolidation-improvement strategy optimized for small containment facilities, including the installation of horizontal drainage and vacuum systems into the dredged mud during the filling works.

The numerical results show the great advantages of this strategy, which allows not only to accelerate the consolidation (and thus the reclamation) but also to reduce greatly the volume of the dredged mud.

The parametric study demonstrates the great influence of the soil characteristics on both the length of the consolidation process and the maximum mud height reached upon completion of the dredging and, thus, on the design of the containment facilities and of the reclamation works.

These results emphasize the importance of knowing and well-reproducing the evolution of the soil's permeability and compressibility, especially in the range of very-low effective stress states, which is rather difficult to experimentally investigate using conventional equipment.

6 REFERENCES

Abu-Hejleh, A.N., Znidarčić, D., Barnes, B.L. 1996. Consolidation characteristics of phosphatic clays, *Journal of Geotechnical Engineering* **122**(4), 295-301.

Berilgen, S.A., Berilgen, M.M., Ozaydin, I.K. 2006. Compression and permeability relationships in high water content clays, *Applied Clay Science* **31**(3-4), 249-261.

de Lillis, A., Miliziano, S. 2016. Geotechnical aspects of the design of the containment area of the port of Gaeta (in italian), *Rivista Italiana di Geotecnica* **50**(4), 3-22.

de Lillis, A., Miliziano, S., Flora, A., Fasano, G. 2017. Reclamation of a containment area: measurements and back analysis of the height of dredged mud. *Unearth the Future, Connect beyond: Proceedings of the 19th ICSMGE, International Conference on Soil Mechanics and Geotechnical Engineering*, 2965-2968.

Gibson, R.E., England, G.L., Hussey, M.J.L. 1967. The theory of one-dimensional consolidation of saturated clays, *Geotechnique* **17**(3), 261-273.

Indraratna, B., Rujikiatkamjorn, C., Ameratunga, J., Boyle, P. 2011. Performance and prediction of vacuum combined surcharge consolidation at Port of Brisbane, *Journal of Geotechnical and Geoenvironmental Engineering* **137**(11), 1009-1018.

Krizek, R.J., Somogy, F. 1984. Perspectives on modelling consolidation of dredged materials. *Proceedings of the Symposium on Sedimentation-Consolidation Models: Predictions and Validation.*

Liu, J.C., Znidarčić, D. 1991. Modelling one-dimensional compression characteristics of soils, *Journal of Geotechnical Engineering* **117**(1), 162-169.

Skempton, A.W. 1969. The consolidation of clays by gravitational compaction, *Quarterly Journal of the Geological Society* **125**, 373-411.