

UNIVERSITÀ POLITECNICA DELLE MARCHE
Repository ISTITUZIONALE

Modeling PVD-Assisted Consolidation of Dredged Sediments in a Confined Disposal Facility

This is the peer reviewd version of the followng article:

Original
Modeling PVD-Assisted Consolidation of Dredged Sediments in a Confined Disposal Facility / Di Sante, M., Bellezza, I., Fratalocchi, E., Mazzieri, F.. - ELETTRONICO. - (2026), pp. 200-207. (9th Italian National Conference of the Researchers of Geotechnical Engineering - CNRIG 2026 L'Aquila - Italy 1-3 Luglio 2026) [10.1007/978-3-032-30669-2_24].

Availability:
This version is available at: 11566/362120 since: 2026-08-31T08:58:45Z

Publisher:
Springer Nature

Published
DOI:10.1007/978-3-032-30669-2_24

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. The use of copyrighted works requires the consent of the rights' holder (author or publisher). Works made available under a Creative Commons license or a Publisher's custom-made license can be used according to the terms and conditions contained therein. See editor's website for further information and terms and conditions.
This item was downloaded from IRIS Università Politecnica delle Marche (https://iris.univpm.it). When citing, please refer to the published version.

Publisher copyright:

Springer (conference paper) - Postprint/Author's accepted Manuscript

This version of the conference paper has been accepted for publication, after peer review (when applicable) and is subject to Springer Nature's AM terms of use https://www.springernature.com/gp/open-research/policies/accepted-manuscript-terms, but is not the Version of Record and does not reflect post-acceptance improvements, or any corrections. The Version of Record is available online at: 10.1007/978-3-032-30669-2_24.

(Article begins on next page)

01 November 2026

Modeling PVD-Assisted Consolidation of Dredged Sediments in a Confined Disposal Facility

Marta Di Sante[1[0000-0003-1216-3440]], Ivo Bellezza[1[0000-0002-7567-2253]], Evelina Frataloc-chi[1[0000-0001-9162-2929]], Francesco Mazzieri [1[0000-0001-9815-4048]]

[1] SIMAU Department, Università Politecnica delle Marche, via Brecce Bianche, 12 - 60131 Ancona – Italy
m.disante@univpm.it

Abstract. A confined disposal facility was constructed at the Ancona Harbor (Italy), to host marine contaminated dredged sediments and use it as a container storage area. In the framework of a research agreement of the Ancona Port Authority and Università Politecnica delle Marche, a study was carried out to improve the mechanical characteristics of the dredged fine-grained sediments by preloading combined with prefabricated vertical drains (PVDs). After the site investigation phase, a full-scale test field was set up, equipped with settlement gauges, piezometers and load cells. The paper presents and discusses a finite element model with plane strain geometry (simpler and more affordable than a 3D tool) to simulate the dredged sediments behaviour during the consolidation process. Modelling discrete mono-dimensional PVD elements in plane strain conditions was applied, taking into account the smear effect due to their installation. Model results are compared with the actual settlements to evaluate the model suitability for the case of concern.

Keywords: Dredged Sediments, Confined Disposal Facility, Vertical Drains, Preloading, Ground Improvement.

1 Introduction

Consolidation of dredged sediments in confined disposal facilities (CDFs) is an essential step to safely achieve the sustainable aim of land reclamation. Since dredged sediments are characterized by high void ratios and water contents, large consolidation strains are expected (e.g. De Lillis & Miliziano, 2016). Among the possibilities to improve the mechanical characteristics of dredged sediments, prefabricated vertical drains (PVDs) combined with preloading is a viable option. This is the improvement method selected to consolidate the marine contaminated dredged sediments of the CDF of the Ancona Harbor (Italy), which will be used as reclaimed land for container storage. Since sediment disposal is staggered over years, specific sequences of disposal and consolidation of sediments have been set up in order to make the area available soon after the overall filling: the facility will be divided into sectors to progressively consolidate the disposed sediments while filling adjacent sectors. Starting from the peripheral CDF walls, each sector will be built by means of internal walls made of

special geotubes filled with the sediments themselves to avoid loss of the CDF capacity. Preloading will be applied by a mobile embankment made by coarse recycled material.

The present paper analyses the consolidation of dredged sediments of the full scale instrumented test field built in the first sector of the Ancona harbour CDF. Due to the construction mode, sequence of loading and non-homogeneous sediment properties, instead of analytical solutions, consolidation was modelled by the finite elements method (FEM), through a plane strain approach, simpler and more affordable than the 3D. The axisymmetric unit cell of the vertical drains was converted into equivalent linear draining systems (Indraratna & Redana, 2000).

Results from modelling the PVD-improved sediments in plane strain analysis are discussed and compared with the monitoring measurements during and after the construction of the loading embankment, with the main aim to evaluate the model suitability for the future consolidation phases of the overall CDF.

2 The confined disposal facility and the design of the test field sector

The CDF, located in the commercial dock of the Ancona Harbour, will be used after filling to store containers of service load of 47 kPa. The CDF was built by steel sheet piles sealed by hydro-expansive epoxy resin; the piles were embedded in a clayey layer at 12 m of depth from the seabed that performs as the natural impervious base (details in Pasqualini et al., 2014). Over the clayey layer, there is a natural dense sandy layer about 4 m thick.

The CDF area is about 9.5 ha; it is currently in part filled with sediments, some of them emerging from the water level. The sidewalls of the test field sector were created by special geotextile bags (geo-tubes) in adjacency to one of the CDF walls (Felici et al., 2017). The test sector, roughly rectangular (50 m x 70 m), consists of sediments disposed several years ago and, in the upper part, sediments recently dredged from different harbours.

A layer of coarse material, about 0.7 m thick, was placed above the sediments to act as top drainage for the vertical drains and to allow construction vehicles to operate for in situ investigations and PVDs installation. The bottom drainage for the sediments is the natural sandy layer.

PVDs were chosen owing to ease of installation by light vehicles; moreover, their durability, of concern in a contaminated marine environment (Rollin and Lombard, 1988), is certainly compatible with the time for consolidation process, estimated in some months.

The sediments located in the upper part were characterised by laboratory tests to determine nonlinear constitutive laws for compressibility and permeability (Felici at al., 2019). In-situ tests (CPTs, CPTUs and dissipation tests) were also performed to to identify the stratigraphy of the test area, investigate the mechanical characteristics of the sediments and their consolidation properties. After modelling the consolidation process both by the classical Hansbo theory (1981) and by the Tang and Onitsuka

(2000) analytical method (time dependent loading and vertical and radial flows combination), PVDs (6 m long) were installed in a square pattern with a spacing of 1 m to achieve full consolidation within few months (details in Felici et al., 2021).

The monitoring system, consisting of settlement gauges, piezometers and load cells, was installed just after the PVDs. Then the preloading embankment was gradually built, placing coarse material on a square area of 30 m side in three phases (see Fig. 1 and Fig. 2) to prevent stability problems during construction.

3 Methods for modelling PVD in plane strain conditions

The finite elements code Plaxis v.8 was used in the present study. A plane strain model with 15 node elements was chosen; drains are modelled in the code as traces of a linear drainage system in which the excess pore pressure is set to zero. Discrete mono-dimensional PVD elements in plane strain conditions were modeled according to the approach by Indraratna & Redana (1998, 2000) which requires to calculate a fictitious horizontal matching permeability, $k_{h,match}$, that reduces the actual value of the horizontal permeability of sediments, k_h, to account for the 1D geometry of the drains instead of the linear drainage configuration included in the plane strain conditions. The value of $k_{h,match}$ is derived assuming that the radius of the axisymmetric drainage unit cell is the same as the half width of the matched plane strain unit cell. Considering the smear effect and neglecting the well resistance, the expression of $k_{h,match}$ is:

$$\frac{k_{h,match}}{k_{hp}} = \frac{\beta}{\frac{k_{hp}}{k_h}\left[\ln\left(\frac{n}{s}\right)+\left(\frac{k_h}{k'_h}\right)\ln(s)-0.75\right]-\alpha} \quad (1)$$

where k_{hp} is the plane strain permeability ignoring both smear and well resistance, calculated as follows

$$\frac{k_{hp}}{k_h} = \frac{0.67}{[\ln(n)-0.75]} \quad (2)$$

$n = R/r_w$, where R is the radius of the influence zone of the drain, r_w is the radius of the drain; $s = r_s/r_w$ is the smear ratio with r_s = radius of the smear; α and β are parameters introduced to adapt the coefficient μ of the Hansbo solution (1981) to the plane strain geometry (additional notation in Indraratna & Redana, 2000); k'_h is the reduced permeability due to the smear effect.

4 The geotechnical model

Fig. 1 shows a cross section and the soil profile below the test preloading embankment and the location of the PVDs.

The top soil (0.7 m thick) consists of a coarse grained material that acts as top draining layer overlying the dredged sediments, of average thickness of 6.7 m. Within this layer, CPTs allowed to identify two lenses with a higher tip resistance, named Sediments 2 and 2D (Fig. 1), located next to the upper boundary of the sediments layer

and in the middle, respectively; these lenses can be assigned to silty sand, according to the unified approach by Robertson & Wride (1998). The remaining layers (named Sediments 1 and sediments 1D, Fig. 1) were identified as clayey silts or silty clays. The sediment classification was consistent with laboratory classification. The in-situ sandy layer (Sand, Fig. 1) was found at a depth ranging from a minimum of 6.5 m to 7.6 m, with the clayey layer located beneath. The groundwater level is at the bottom of the top draining layer; it corresponds to the internal water level in the CDF before filling the test sector.

The installed PVDs were Colbonddrain® PVDs, of rectangular shape: width, a = 0.1 m; thickness, b = 0.005 m. They consist of a polyethylene core on which a needle-punched polypropylene geotextile filter is pasted.

The embankment load was applied in stages, as shown in Fig. 2. The height of each layer was back calculated from pressure data from the load cells. Consolidation analyses (staged construction) were performed by means of the "staged construction" option of the code.

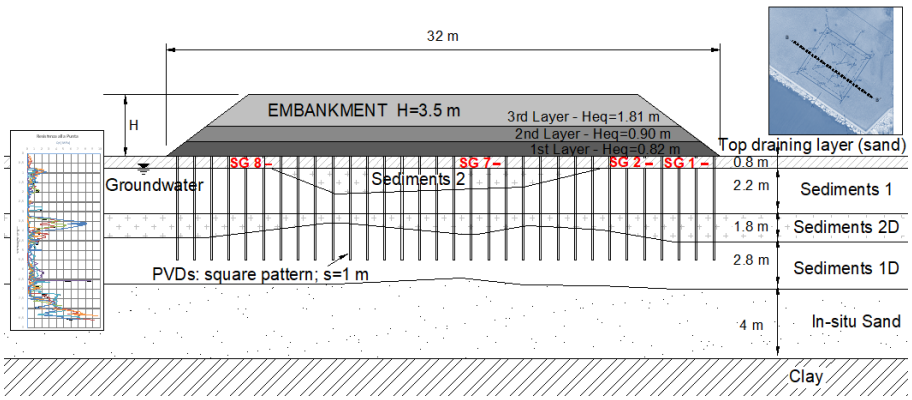


Fig. 1. Cross section of the test field with the subsoil profile and the monitoring equipment.

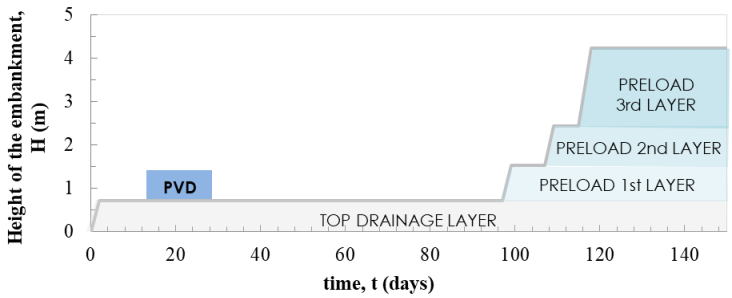


Fig. 2. Construction history: drainage layer, PVD installation and pre-loading stages.

Sediments were simulated through the Soft Soil Model (Cam-Clay type, especially meant for primary compression of NC soils). The permeability value for Sediments 1

was estimated by a dissipation test (CPTU – Teh & Houlsby, 1991) whereas for Sediments 2 it was measured by direct laboratory tests and corrected through a real scale factor, calculated comparing lab and in situ data on Sediments 1. Permeability of sediments was reduced through the index dependent on the initial void ratio not considering anisotropy (Tavenas et al., 1983). The geotechnical parameters of the layers are listed in Table 1.

Table 1. Materials used in the simulation and related parameters

Material name	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	$k_x = k_y$ (m/day)	e_0 (-)	c_k (-)	Eref (kPa)	ν (-)	c_{ref} (kPa)	Φ (°)	Ψ (°)
Embankment	18.5	20	0.1	-	-	5,0E+04	0.3	0.2	38	0
Draining Layer	20	21	0.864	-	-	1,0E+05	0.3	0.2	34	0
Sand	17	18.8	0.262	-	-	4.45E+04	0.3	0.2	40	0
Clay	15.7	19.7	7.0E-07	-	-	8.91E+03	0.3	4	26	0
	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	$k_x = k_y$ (m/day)	e_0 (-)	c_k (-)	C_c (-)	C_s (-)	c_{ref} (kPa)	Φ (°)	Ψ (°)
Sediments 1	15	17	3,04E-04	1.65	0.83	0.3	0.062	5	26	0
Sediments 2	18	20	3.30E-04	0.77	0.35	0.13	0.011	5	26	0
Sediments 1D	15	17	3,04E-04	1. 5	0.83	0.3	0.062	5	26	0
Sediments 2D	18	20	3.30E-04	0.7	0.35	0.13	0.011	5	26	0

In order to assess the suitability of modelling the actual geometry (square footprint) by the plane strain condition, preliminary comparisons were done between the plane and the axis-symmetric condition (circular equivalent footprint) without accounting for the drain presence, for simplified soil profiles with sediment thickness much lower than the embankment width, as in the case of concern. No significant differences in predicted settlements were found.

5 Results

The settlements were monitored for about 170 days close to the centre and near the embankment toes (SG locations in Fig. 1)).

The settlements measured vs time and those predicted by the horizontal matching permeability method (§ 3) are compared in Fig. 3 considering different smear effect. In particular, three values of s were considered, constant for all the layers (Fig. 3 a - permeability ratio = 2): s = 6 was used for pre-dimensioning of the PVD spacing; s = 10 was calculated taking into account the observed surface disturbance (about 0.33 m); s = 17 is the limit value of disturbance covering the entire PVD spacing. As shown in Fig. 3, all the three simulations well catch the final value of the settlement (31 cm); the one considering the overall disturbance (s = 17) gives the best simulation of the settlements measured during the construction phase while the one related to s = 10 better describes the final phase. Using a least squares optimization criterion (RMSE values - Fig. 3 a) the simulations with s = 10 and s = 17 show similar performance. Local robust analysis (dividing the data set in beginning, central and final phases) shows that a superior performance in specific regions of the domain is obtained with s = 10, particularly in the central and final parts.

A generally worse fitting is obtained increasing the permeability ratio over 2 (Fig. 3 b).

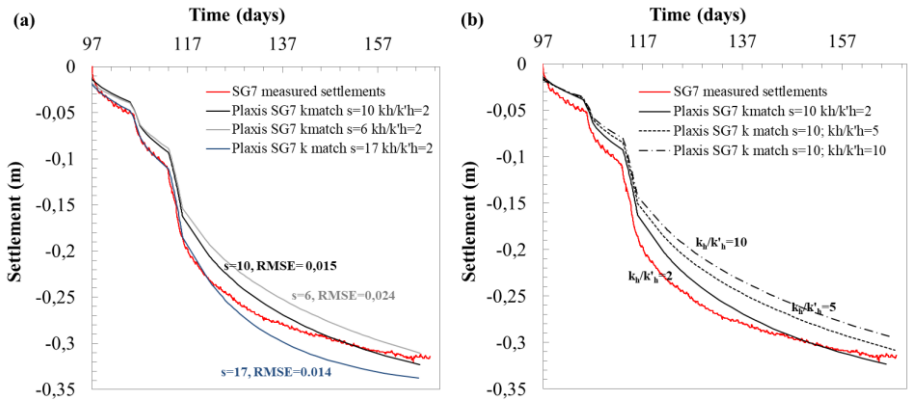


Fig. 3. Surface settlement at the centerline of the embankment (SG7 location) - k_{match}: varying the smear ratio (a) varying the permeability ratio (b)

The prediction of the surface-settlement profile along the base of the embankment is shown in Fig. 4 for the case of *s* =10 and the permeability ratio = 2. As expected, the settlements increase with time, especially close to the embankment centerline. By comparing the predicted profile with the measurements in the strain gauge locations, it is possible to state a good accordance, also in proximity of the embankment toes (SG1, SG2 and SG8 locations).

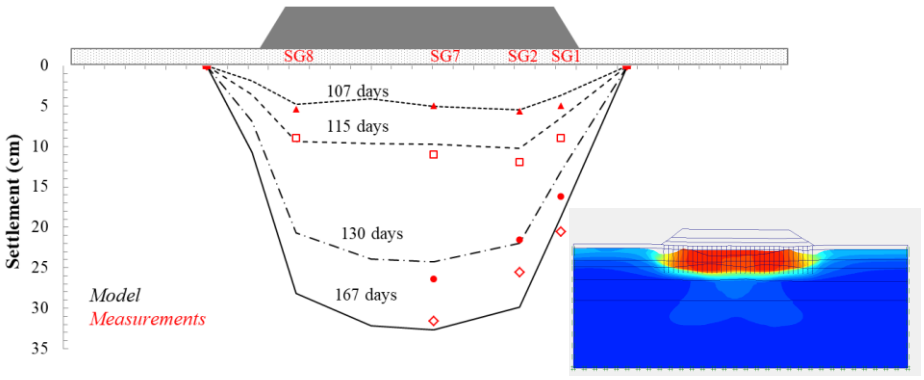


Fig. 4. Surface settlement profiles predicted for the base of the embankment (s=10; k_h/k_h'=2)

6 Final Remarks

An instrumented full scale field test was built in a sector of the Ancona harbor CDF to analyze consolidation of disposed dredged sediments by preloading combined with PVDs. The square footprint loading embankment (30 m side) was much greater than the sediment thickness (6.5-7 m).

FEM modelling in plane strain condition was used after checking its suitability to assess the sediment settlements for the geometry of concern without PVDs. Drains were modelled as linear drainages, by the permeability matching method.

Modelling resulted in good agreement with the measured consolidation settlements, in particular assuming the smear ratio = 10 and permeability ratio = 2 of the Hansbo radial model.

Since the sectors of the CDF will be progressively consolidated with the same procedure by the same (or a larger) mobile embankment, the model can be useful to assess the settlement trends and consolidation time of sediments, on the basis of the consolidation parameters of the sediments disposed in each sector and adopting the same PVDs type and installation procedures.

Aknowledgements

The authors would like to thank Port System Authority of the Central Adriatic Sea (IT) for allowing the publication of the data.

References

1. De Lillis A., Miliziano S.. Geotechnical Aspects of the Design of the Containment Area of the Port of Gaeta. Italian Geotechnical Journal 50(4), 3-22 (2016) (in Italian).
2. Felici M., Domizi J., Di Sante M., Mazzieri F.: Consolidamento di sedimenti marini in vasca di colmata. attività sperimentali e risultati preliminari. Atti IAGIG (2017) (in italian).
3. Felici M., Fratalocchi E., Di Sante M., Pasqualini F., Pasqualini E.:PVD-assisted consolidation of dredged sediments in a CDF: design of the test field. Japanese Geotechnical Society Special Publication 9(4):124-129 (2021).
4. Felici, M., Domizi, J. and Fratalocchi, E.: Consolidation of dredged sediments in a confined disposal facility: hydraulic conductivity constitutive relations. Proc. 8th ICEG, Hangzou, China, Springer, 288-294 (2019).
5. Hansbo S, Jamiolkowski M, Kok L.: Consolidation by vertical drains. Géotechnique 31(1),45-66 (1981).
6. Indraratna B., Redana I.W.: Numerical modeling of vertical drains with smear and well resistance installed in soft clay. Canadian Geotechnical Journal 37, 132-145 (2000).
7. Indraratna, B. and Redana, I. W.: Laboratory determination of smear zone due to vertical drain installation. Journal of Geotechnical and Geoenvironmental Engineering 124(2), 180-184 (1998).
8. Pasqualini, E., Cianca, C. and Fratalocchi, E..: Fanghi di dragaggio e casse di colmata. Giornata di studio: Il contributo della geotecnica alla protezione del sottosuolo dagli inquinanti. AGI, Napoli (2014) (in Italian).

9. Robertson P. K. Wride C. E.: Evaluating cyclic liquefaction potential using the cone penetration test. Canadian geotechnical journal, 35(3), 442-459 (1998).
10. Rollin A., Lombard G.: Mechanisms affecting long-term filtration behaviour of geotextiles. Geotextiles and Geomembranes 7(1-2), 119-145 (1988).
11. Tang X.-W., Onitsuka K.: Consolidation by vertical drains under time-dependent loading. Int. J. Numer. Anal. Meth. Geomech. 24, 739-751 (2000).
12. Tavenas F., Jean P., Leblond P., Leroueil S.: The permeability of natural soft clays. Part II: Premeability characteristics. Canadian Geotechnical Journal 20, 645-660 (1983).
13. Teh, C. I. and Houlsby, G. T. (1991): An analytical study of the cone penetration test in clay. Geotechnique, 41(1), 17-34.
14. Teh, C. I., Houlsby, G. T.: An analytical study of the cone penetration test in clay. Geotechnique 41(1), 17-34 (1991).