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Optimization of consolidation procedures for dredged fine sediments in confined disposal facilities

Optimisation des procédures de consolidation des sédiments fins dragués dans un dépôt à terre

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ABSTRACT: Confined disposal facilities (CDFs) are increasingly used in land reclamation to provide a sustainable solution that ensures both the storage of contaminated dredged sediments and the development of new lands. The management of CDFs should be carefully designed to match disposals and soil improvement treatments with the aim of saving times, material resources and costs. When the filling phases take very long time, a smart strategy is to split the overall capacity of the CDF in sectors to be separately filled and separately consolidated. To the purpose, a solution that minimizes volume losses and ensures a proper containment during consolidation process of sediments is herein proposed. Once sectors are provided, preloading by embankment, combined with prefabricated vertical drains (PVDs), is particularly suitable as consolidation technique in each sector since the embankment can be used as a "moving bank" reducing the material supply. To aid designing of PVD-assisted preloading, a closed form equation that link the three design parameters (preloading, waiting time and drain spacing) is presented and applied to a CDF case-history to test its potential chances in terms of cost-saving and sustainability enhancement.

RÉSUMÉ: Les dépôts à terre imperméabilisés (sigle anglais: CDF) sont de plus en plus utilisés pour les remblaiements afin de donner une solution durable qui garantisse à la fois le stockage des sédiments de dragage contaminés et l'aménagement des terres gagnées sur la mer. La gestion des CDF doit être conçue en vue de rapprocher les dépôts avec les traitements d'amélioration des sols, dans le but d'optimiser les temps, les ressources matérielles et les coûts. Lorsque les phases de remplissage sont très longues, une bonne stratégie consiste en répartir la capacité totale de CDF en secteurs à remplir et consolider séparément. A cet effet, on propose ici une solution pour minimiser les pertes de volume et assurer aussi un efficace confinement lors du processus de consolidation. Dès que les secteurs sont prévus, le précharge au moyen d'un remblai, associé aux PVD, convient particulièrement bien comme technique de consolidation puisqu'il peut servir comme "berge mobile", réduisant ainsi l'approvisionnement en matière. Pour faciliter le projet du précharge combiné aux PVD, une équation qui relie les trois paramètres de projet (précharge, temps d'attente et espacement des drains) est présentée et appliquée à une étude de cas pour tester son potentiel en réduire les coûts et améliorer la soutenabilité.

KEYWORDS: dredged sediments, consolidation, preloading, vertical drains

1 INTRODUCTION

In the last few decades, land reclamation from the sea arose all over the world to meet the growing need of land for residential housing, industries, and transport infrastructures. Several large-scale land reclamation projects concerned – and still concern – the expansion of harbors and seaports. Such works are frequently associated to dredging activities, since dredged sediments can be used as raw filling material. In this scenario, nearshore confined disposal facilities (CDFs) provide a twofold opportunity: on one hand, they ensure a definitive safe location of polluted dredged sediments; on the other hand, once completed, they allow to develop new lands to improve logistics and port infrastructures operativity. In that light, a CDF is a profitable investment, as it offsets initial construction costs by combining sustainable management of contaminated dredged sediments with infrastructural enhancement.

After disposal in a CDF, dredged sediments typically have slurry consistency, with very high water-to-solid volumetric ratios and poor mechanical properties. Hence, land reclamation requires their mechanical improvement. Preloading is commonly adopted as consolidation technique to anticipate post-construction settlements prior to service life. It can be applied by means of the vacuum technique (Chu et al. 2008, Griffin & O'Kelly 2014), by surcharging the ground surface, or both (de Lillis & Miliziano 2016). Surcharging by earthen embankments is the simplest option from an operational standpoint, and the cheapest one when coarse material is available close to the site.

In low permeable fine-grained soils, preloading embankments are usually combined with a vertical drainage system to accelerate the consolidation process. Prefabricated vertical drains (PVDs) are widely used in common practice due to their high productivity of installation.

When applied to very large CDFs, preloading embankments require large amounts of material. To overcome these limitations, the CDF can be designed and filled into closed sectors and the embankment applied as a "moving bank" (Felici et al. 2017): after PVDs installation on a sector, the embankment is built and left in place for the time required to reach the target degree of consolidation (waiting time), then it is dismantled and the procedure replicated in an adjacent sector, until completion of the whole area.

The "moving bank" method allows to consolidate the sediments in one sector while filling an adjacent sector. Hence, the moving bank associated to sectorization allows to optimize resources and costs, to significantly reduce the overall time of improvement, as well as to ensure flexibility in managing the dredged sediments, since it can be adapted according to different disposal schedules.

In this paper, a design method is proposed to optimize the consolidation procedures of dredged fine sediments in a sectorized CDF by preloading and PVDs. The method links the three design parameters i.e. preloading, waiting time and drain spacing, with the aim to support geotechnical engineers in drawing up the filling and consolidation steps of the sectors in a CDF. The proposed method is then applied to a real CDF in the Ancona Harbor (Italy), which is currently being filled with marine dredged sediments to be consolidated in view of reusing the reclaimed area for storage of containers. The proposed method allows to schedule filling and consolidation actions, leading to the anticipated provision of the reclaimed area.

2 SUBDIVISION OF A CDF INTO SECTORS

Subdivision of a large CDF into sectors was used for the first time in the case of the facility built in the Ancona Harbor (Central Italy) for disposal of contaminated sediments, thus taking the opportunity for a land reclamation project as a virtuous alternative to landfilling (Pasqualini et al. 2014).

The CDF, located in the commercial dock, has a volume capacity of about 180,000 m^3 and an overall surface of 9.5 hectares (Figure 1). The lateral landside and seaside confinement is provided both by a continuous 22 m long steel sheet piling driven through a sandy layer into the impervious natural clayey layer. To ensure the hydraulic performance requirement (hydraulic conductivity, $k \leq 1\times10^{-9}$ m/s), the piles interlocks were sealed for their whole length with a polyurethane hydro-expansive waterproof resin. At present the CDF construction is over and it is being filled with marine dredged sediments coming also from nearby ports.

A first lot of dredged sediments has early been disposed soon after the CDF construction. For this reason, a layer of soft sediments with a thickness ranging from about 2 to 4 m already covers the bottom. Above it, there is a water head of about 3-4 m inside the facility. The water into the CDF and the sea are independent hydraulic systems, as proved by a continuous monitoring of meteorological parameters and water levels for several years.

Given the fine-grained nature of the sediments and the availability of coarse material (e.g., demolition waste of port structures, boulders, etc.) at the CDF site, a preloading by embankment coupled with PVDs was selected as improvement technique. Subdivision into sectors by internal walls has been chosen as the strategy to optimize disposal and consolidation activities.

The sectorization requires internal walls to get a proper containment during sediment disposal and consolidation activities. The walls should be easy to build and should minimize volume loss of the CDF. With these purposes, Felici et al. (2017) proposed special internal walls made by woven geotextile tubes filled with the sediments themselves. In particular, a special MacTube® 50 m long with a final height of about 3 m was installed to create the first sector (Figure 1). The geotube was placed above the layer of sediments already disposed in the CDF, which were still very compressible. To provide an adequate support surface, a layer of gravel was spread on the geotube footprint by specialized divers.

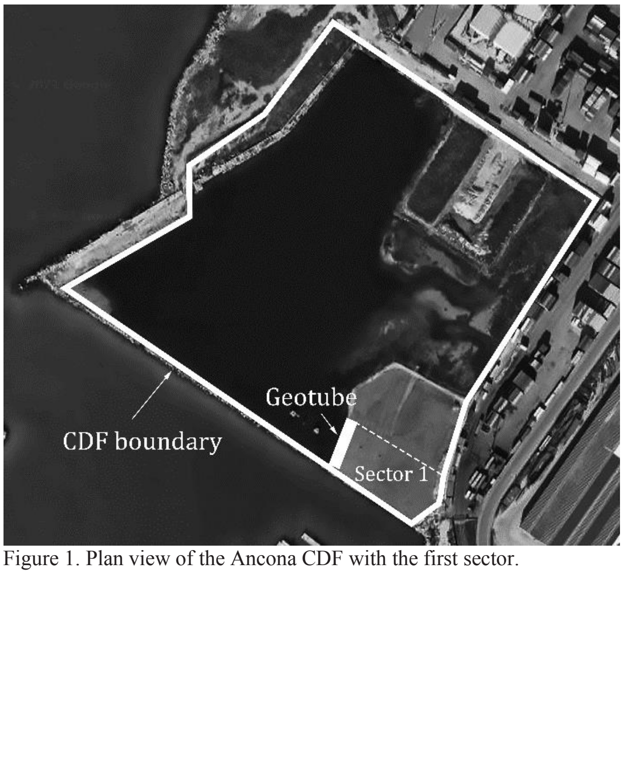

Figure 1. Plan view of the Ancona CDF with the first sector.

The installation of this kind of geotube resulted quite easy and fast: first the geotextile bag was floated over the water surface on the design position, taking care to fix both its ends to stabilize it against wind (Figure 2), then the dredged slurry was pumped inside through each of the top filling ports (Figure 3), giving the geotube an oval shape (Figure 4). Frequent switching of the pumping inlet along the tube assured a quite uniform filling and sinking of the tube. During pumping, sediments remain inside the tube and water drains out through the geotextile wall. The filling time is variable, depending on several factors such as the type and quantity of available equipment, weather conditions, etc. For the first sector, the installation of the geotube in the Ancona CDF (including preliminary operations) was completed in 1 week.

Figure 2. Geotube placement at the Ancona CDF.

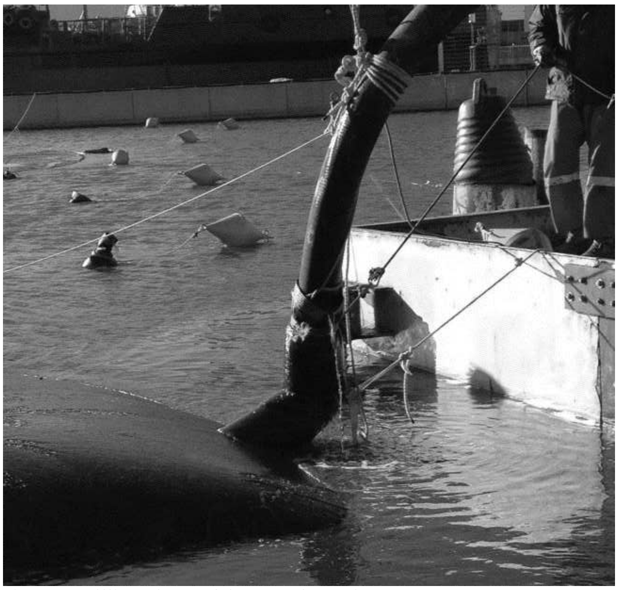

Figure 3. Filling phase of the geotube at the Ancona CDF.

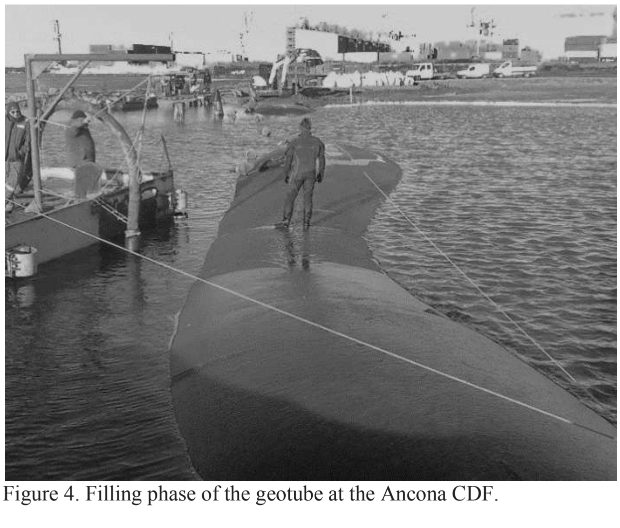

Figure 4. Filling phase of the geotube at the Ancona CDF.

The solution proposed for construction of the internal walls can be adapted to the CDF depth: if necessary, more than one geotube can be overlapped.

With this technology a first sector was already created and then filled, having an approximately rectangular area of 50 m × 80 m (Figure 1). On two sides it is bordered by the steel sheet piles, while a third side is provided by the sediment already present inside the facility, which emerges about 1 m above the internal water level.

As far as the filling and consolidation sequences of a sectorized CDF, an example is shown in Figure 5, with reference to the Ancona CDF. Particular care should be paid to the consolidation of the zone close to the geotube, considering also its mechanical behavior and properties. To this regard, stability analyses must be performed to assess the minimum distance between the geotube and the mobile bank. The area around the geotube has to be consolidated together with the adjacent sector (Figure 5d), or after (Figure 5e and 5f), depending on the sector dimension.

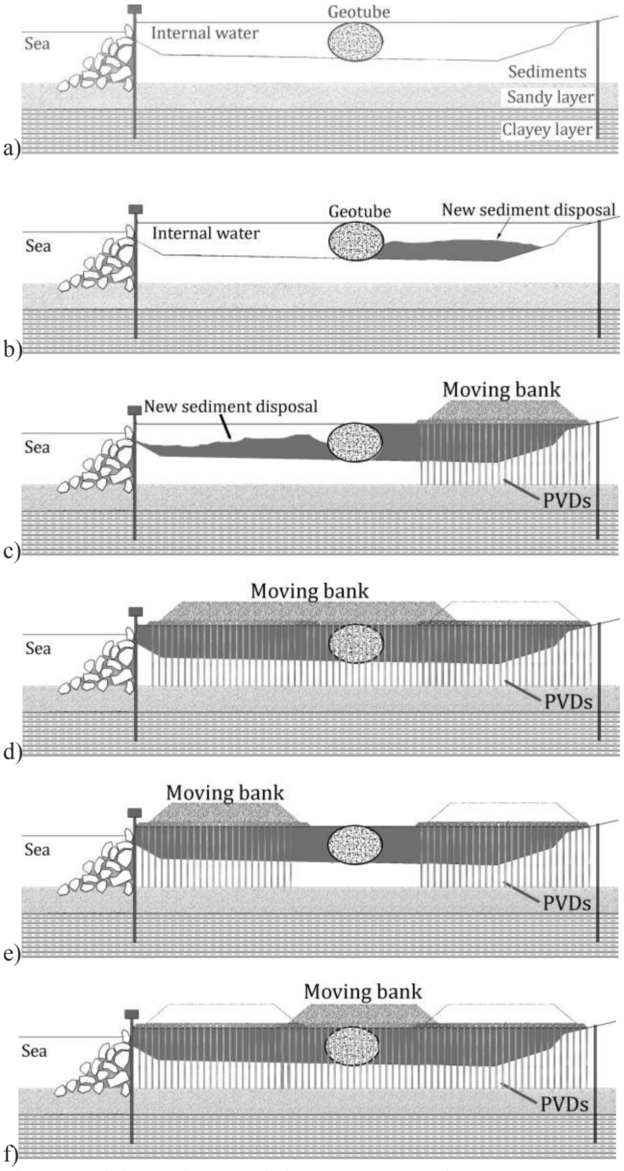

Figure 5. Filling and consolidation sequences at the Ancona CDF: a) geotube placement; b) disposal of sediments in the first sector; c) consolidation of sediments in the first sector and simultaneous fill of the second sector; d) consolidation of the second sector and the geotube area; e) consolidation of the second sector; f) consolidation of the geotube area.

3 DEVELOPMENT OF A DESIGN EQUATION

In the case of consolidation by PVDs assisted preloading with a moving bank, the design variables are the vertical pressure to be applied by the bank (q_R), its waiting time (t_R) and the drains spacing (S).

Provided that the embankment width is larger than the double of the thickness of the compressible layer, H_0, the final settlement due to q_R can be assessed assuming a one-dimensional deformation as:

$$\delta_R = \frac{H_0}{1+e_0} C_c \log\left(\frac{\sigma'_{v0}+q_R}{\sigma'_{v0}}\right) \tag{1}$$

where e_0 is the initial void ratio and σ'_{v0} is the effective vertical pressure at the middle of the consolidating layer.

Using the preloading technique to consolidate the marine sediments stored in a given zone, the load of the moving bank must be maintained for a time t_R such as the settlement δ_R (for $t = t_R$) is equal to δ_E, i.e. the settlement induced by the service load (q_E). This service load is known on the basis of the future use of the area and the associated settlement δ_E can be computed by (1) substituting q_R with q_E.

The consolidation process in the presence of vertical drains has been studied by many authors and several solutions with different levels of complexity have been proposed in the literature (Kjellman 1948, Barron 1948, Carrillo 1942, Yoshikuni & Nakanodo 1974, Olson 1977, Hansbo 1981, Onoue 1997, Tang & Onitsuka 2000, Leo 2004, Zhu & Yin 2004, Bellezza & Fentini 2008, among others).

In this paper, with the aim to find a general and relatively simple correlation among the variables involved in the design (q_R, t_R and S), the consolidation due to radial flow is analysed by the Hansbo theory that, despite some simplifying assumptions, gives results in good agreement with the aforementioned more complex solutions (Onoue 1988).

Therefore, an equivalent cylindrical vertical drain with a discharge capacity, q_w, and negligible stiffness is considered. Around it, an influence zone (i.e., where the drain is capable to collect water) with a radius R and a permeability k_h can be assumed, while a smear zone with a radius r_s and a reduced permeability $k_s < k_h$ is developed close to the drain, due to remoulding effects induced during installation.

For vertical drains of radius r_w, length L and radius of influence R, in a soil with a coefficient of horizontal consolidation c_h, the average degree of consolidation at the time t, U_h, due to the radial flow can be calculated as:

$$U_h = 1 - \exp\left(-\frac{2c_h t}{R^2 F}\right) \tag{2}$$

where F is a numerical coefficient given by:

$$F \cong \ln\frac{R}{r_s} - 0.75 + \left(\frac{k_h}{k_s}\right)\ln\frac{r_s}{r_w} + \frac{2}{3}\frac{\pi k_h L^2}{q_w} \tag{3}$$

The radius of the influence R in (2) and (3) can be directly expressed as a function of the drain spacing S; specifically, $R = 0.564S$ and $R = 0.525S$ for a square and a triangular mesh, respectively.

For PVDs with a rectangular cross-section, an equivalent diameter producing the same effect on the consolidation process is generally introduced. Rixner et al. (1986) expressed this equivalence by matching the perimeter of the band shaped PVD with the circumference of the equivalent cylindrical drain:

$$r_w = \frac{a+b}{\pi} \tag{4}$$

where a and b are the width and the thickness of the actual drain, respectively.

Similarly to other studies (e.g. Chai et al 2001), the theoretical solution of Carrillo (1942) is here used to combine the vertical and radial drainage:

$$U = 1 - (1 - U_h)(1 - U_v) \tag{5}$$

where U_v is the average degree of consolidation for vertical flow only, which can be computed by the classical Terzaghi theory on the basis of the coefficient of vertical consolidation c_v and the maximum vertical drain path. It should be pointed out that (5) is strictly valid only for ideal drains and instantaneous load. However, the error involved in using (5) is generally quite small even in the presence of ramp loading (Tang & Onitsuka 2000). Therefore, the use of (5) can be considered a reasonable approximation if compared with the uncertainties associated with determination of soil parameters, smear, well resistance and equivalent drain radius.

Finally, by imposing that the overall degree of consolidation at the time t_R is equal to δ_E/δ_R and combining (1) and (5) the following equation is obtained:

$$q_R = \sigma'_{vo}\left\{10^\wedge\left[\frac{\delta_E(1+e_0)}{H_0 c_c\{1-(1-U_h)(1-U_v)\}}\right] - 1\right\} \tag{6}$$

Equation (6) can be used for a quick evaluation of the influence of drain spacing, waiting time and surcharge load in the design of a PVD assisted preloading treatment.

Note that (6) assumes implicitly a step loading. Actually, the construction of the moving bank requires a finite time which reasonably can be considered proportional to q_R. This aspect must be taken into account in using (6) for design purpose. In the absence of more detailed data about the rate of loading to reach q_R, a simple ramp loading scheme can be assumed and the actual time required for the preloading treatment can be roughly obtained as the sum of t_R given by (6) and a fraction (0.5-1) of the construction time.

In the following an application of the aforesaid procedure is shown with reference to the Ancona CDF.

4 EXAMPLE OF APPLICATION

The use of (6) requires a preliminary careful assessment of soil and drain characteristics. For the first filled sector of the Ancona CDF (area of about 4,000 m^2), both laboratory and in situ tests (CPT and CPTU with dissipation) have been performed to achieve a comprehensive characterisation of the soil prior to the consolidation process. On the basis of CPTs a uniform thickness of the sediment layer of about 6.7 m has been assumed. Table 1 lists the values assumed for the parameters involved in the analysis. Further details on both laboratory and in-situ tests can be found in Felici et al (in press).

The chosen draining system consists of band shaped PVDs (Colbondrains®) made by a polyethylene core coated with a needle punched polypropylene geotextile filter (Table 2). Based on a trial driving, a smear ratio $s = r_s/r_w$ equal to 6 was considered. According to Terzaghi et al. (1996) the horizontal permeability in the smear zone was assumed a half of the undisturbed soil permeability ($k_h/k_s = 2$). A 0.7 m layer of coarse material was placed over the sediment layer to provide an adequate work surface and a top drainage boundary as well as to improve stability. The sandy layer underlying the sediments provides a bottom drainage (Figure 6).

Finally, the service load has been computed as $q_E = 47$ kPa considering the intended use of the area as storage of overlapped containers. Consequently, the expected settlement at the end of the primary consolidation (δ_E) has been calculated by (1) of about 0.53 m.

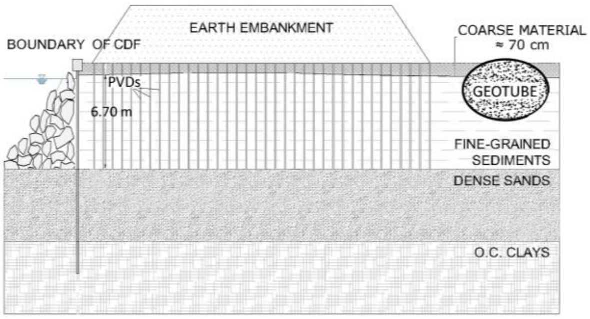

Figure 6. Stratigraphy of sector 1.

Table 1. Input data for the sediment layer.

Parameter	Value
Top layer thickness, H_{cm} (m)	0.7
Sediment layer thickness, H_0 (m)	6.7
Unit volume weight of the blanket, γ_{cm} (kN/m^3)	17.0
Unit volume weight of the sediments, γ_{sed} (kN/m^3)	16.5
Unit volume of the sea water, γ_w (kN/m^3)	10.1
Mean geostatic vertical effective stress, σ'_{v0} (kPa)	21.6
Initial void ratio, e_0 (-)	1.65
Compression index, c_c (-)	0.42
Coefficient of horizontal consolidation, c_h (m^2/day)	$1.6\cdot10^{-2}$
Horizontal hydraulic conductivity, k_h (m/day)	$2.2\cdot10^{-4}$
Coefficient of vertical consolidation, c_v (m^2/day)	$1.2\cdot10^{-2}$

Table 2. PVDs characteristics and design parameters.

Parameter	Value
Width, a (m)	0.100
Thickness, b (m)	0.005
Equivalent radius, r_w (m)	0.033
Discharge capacity, q_w (m^3/day)	12.1
Axial permeability, k_w (m/day)	$2.4\cdot10^{4}$
Smear ratio, $s = r_s/r_w$ (-)	6
Radius of the smear zone, r_s (m)	0.2

By the data of Tables 1 and 2, design charts in Figures 7 and 8 can be obtained by Eq. 6. The effect of the construction time, t_c, is included in the charts, always considering a gradual construction of the embankment of 1.5 m/week, i.e. 3.5 kPa/day and assuming that the effect of a ramp loading is equivalent to a step loading starting at $t_c/2$. As expected, the required drain spacing S increases at increasing the waiting time t_R and preloading pressure q_R. On the contrary, for an assigned drain spacing, the preloading pressure decreases for increasing waiting time.

For the first sector of the Ancona CDF the drain spacing is assumed to vary from 0.8 m (i.e. the double of the diameter of the smear zone) and 2.4 m which is significantly lower than the vertical drainage path. The preloading pressure is considered in the range 47-100 kPa. The upper value has been determined from stability analyses.

As an example, considering a maximum waiting time $t_R = 6$ months (depending on the time necessary to fill the adjacent sector) the curves of Figures 7 and 8 allow to obtain different combinations of spacing and preloading pressure to be used in the design. For a triangular mesh two bound solutions are obtained (Figure 8): the first solution involves a drain spacing of $S = 1.4$ m and preloading pressure $q_R = 50$ kPa, which implies about 18,900 m of PVDs (of length 8 m) and about 11,000 m^3 of material for the embankment (considering a 45° slope of the embankment); the second solution requires a drain spacing of 2.4 m combined with preloading load equal to $q_R = 78$ kPa, which implies about 6,400 m of PVDs and about 16,000 m^3 for the embankment. The optimal solution will be chosen considering costs of both PVDs and the material used for the embankment. This latter mainly depends on the availability of the material in situ or close to the site.

It can be observed that the design charts of Figures 7 and 8 are specific only for the first sector of the Ancona CDF. For the other future sectors the same procedure can be applied, provided that a new preliminary characterization of sediments is performed. The consolidation process in the sectors will be monitored to assess the validity of the proposed approach.

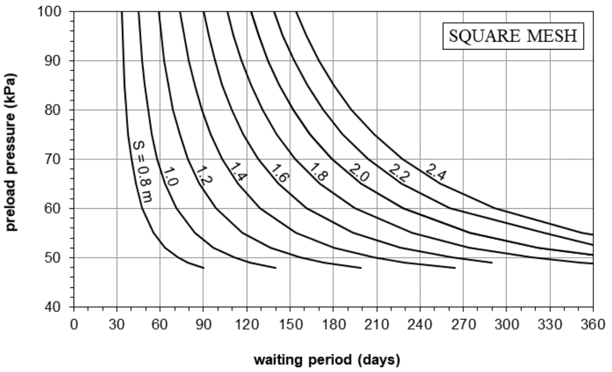

Figure 7. Design chart for PVDs square grid for the Ancona CDF.

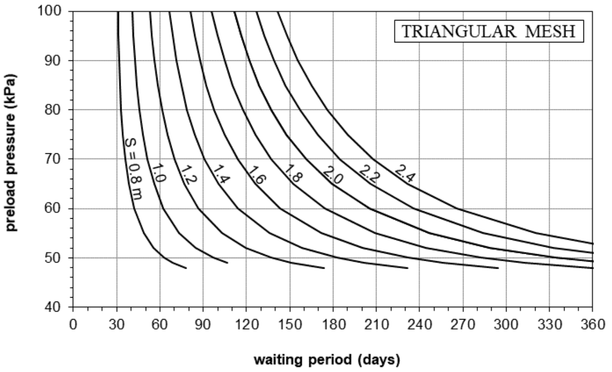

Figure 8. Design chart for PVDs triangular grid for the Ancona CDF.

5 CONCLUSIONS

The paper focused on nearshore confined disposal facilities (CDFs) describing an attempt to optimize its use during the service life. A case history has been presented in which the CDF has been subdivided in sectors to be completely filled and consolidated. This strategy allows to make part of the CDF available for its intended use before completing the whole area.

An innovative technique has been developed to construct the internal walls to create the sectors in the CDF. Specifically, a woven geotextile tube is sunk after it has been filled with the sediments themselves, in order to minimize the volume losses of the CDF.

Finally, a procedure for the design of a PVD-assisted preloading by embankment is proposed, which allows to consider all the variables involved in design, for a given drain mesh geometry. By this approach it is possible to evaluate the best design choice in economic terms, based on site-specific costs (e.g. distance from quarries or from supply points of resulting materials, PVDs installation costs and daily production, etc.).

6 ACKNOWLEDGEMENTS

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