Improving marine soils by different consolidation methods for stability of harbour structures

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Abstract. Marine geotechnics is one of the most difficult specialties and is part of coastal engineering. The geotechnician is interested in soils as these are the main element of the context in which the stability of a structure will be designed. The methods of improvement of vibroflotation (VF), dynamic compaction (DC) and the pre-loading took a scale in Algeria these last years, they are applied at the port of Djendjen in Jijel province, object of our study, in the framework of its extension and its development, in order to improve the support soil which will receive the foundations of the protections structures and the container terminal in caissons. The main objective is to establish numerical studies of the stability of the protection structure realized on the improved soil which was itself taken into consideration in the modelling, while respecting also the real phasing of construction of this structure. However, soil improvement was checked before and after treatment to verify its influence on the stability of the harbour structures.

Keywords: Harbour structures, Soil improvement, Vibroflotation, Dynamic compaction, Preloading, Numerical modelling.

1. Introduction

The construction of a port, its equipment, the development of its access, shoreline protection against the action of the sea are a set of complex operations, usually subsumed under the name of "marine works" [1,2]. The geotechnical soil is interested in since these constitute the main element of the context in which the stability of a structure will be designed [3]. It was therefore quickly considered to study the mechanisms of rupture to increase their bearing capacity (or lift) and eliminate settlements and risks of liquefaction [4]. Soil improvement methods are one of the tools available to the engineer to solve stability problems or deformations he encounters when developing a project. A large number of processes exist [5]; on one hand and another, some consolidation methods have been applied at the Djendjen port, which is the subject of our study, in order to improve the support soil that will receive caissons' quay walls and protection structures.

2. Port Structures

The dike is made up of blocks or caissons made of reinforced or prestressed concrete, which with their own weight resist the forces imposed by the swell: they must therefore be large enough to be heavy enough. When the foundation soil offers good resistance (rocky soil, pebbles, compact sand), the quays are made in the form of massive structures capable of withstanding the horizontal forces
(towards the ground, caused by the berthing of ships and towards the basin, caused by thrusting embankments and mooring of vessels) and vertical forces due to their own weight [1,2]. Failures are usually due either to the action of the swell or to geotechnical factors which are influenced by the self weight, the hydraulic actions and the seismic actions. We must carry out checks for each potential failure modes. The main failure modes for caisson breakwater are shown in Figure (1a).

![Figure 1](image1.jpg)

**Figure 1.** Failure mechanisms of a caisson's breakwater. (b) Quay wall [1,6].

3. **Consolidation methods for soil improvement**

Surveys of the sites are determined by their needs and their impact, specific requirements, the specific site and its environment, as well as Economic [7]. During the feasibility study of a project, the use of soil treatment methods implies knowledge of their respective performances and limits. A question then arises: how to represent in an easily usable way the fields of application of each process. We have chosen to represent the ability of a method to treat a soil according to the granulometry (grain size) of the latter. It has the advantage of only using identification criteria obtained by simple laboratory measurements (figure 2) [8].

![Figure 2](image2.jpg)

**Figure 2.** Distribution of treatment methods according to soil's particle size.
3.1. Vibroflotation technique (VF):

Vibroflotation is a technique for in situ densification of thick layers of loose granular soil deposits. It consists of generating, with the aid of a vibro-depth vibrator (vibroflot), horizontal vibrations in the gritted soils in order to shear them and cause a localized liquefaction and an immediate settlement [9,10]. Treatment with this method can generally achieve the following goals: the increase of bearing capacity; the reduction of settlement; acceleration of consolidation; eliminating the risk of liquefaction; no adverse effects have been reported on the environment [11, 12,13].

![Figure 3](image-url)  
**Figure 3.** The steps of the vibroflotation operation (VF)[11].

The real results of the vibroflotation treatment of the DjenDjen port [14] are taken into account in the two-dimensional numerical study of the stability of the protective structure on the treated soil which was itself taken into consideration in the modelling, with respecting the actual phasing of construction of this structure "vertical breakwaters" (figure 4), and the results of the settlement (figure 5) are in excellent agreement with the actual results, which reinforces our study. It is concluded that; vibroflotation gives very satisfactory results in terms of soil improvement.

![Figure 4](image-url)  
**Figure 4.** The plastic points of seabed (a) before and (b) after VF.
3.2. Dynamic compaction technique (DC):

Land reclamtion is generally defined as the process of creating new land by raising the elevation of a seabed, or other land at low altitude (figure 6). It can be carried out by a movement of dry earth, also by hydraulic filling (embankments). Some possible failure modes in the embankment body and different failure modes need to be analyzed. From the point of view of the foundation, this can pose a significant risk of partial or complete liquefication and, consequently, reduction of soil resistance. Global Failure Stability Analysis provides suggestions for improvement methods to be performed [15, 16].

Dynamic compaction (DC) is one of the techniques of soil improvement. It depends on the rearrangement of the soil particles using the dynamic energy produced by the falling of a weight (tamper) from a certain height, (Figure 7). The concept of this technique is to improve the mechanical properties of the soil by transmitting high-energy impacts on loose soils that have low initial bearing capacity and potential of high compressibility [18]. The feasibility of this technique ensure the stability of the manufacturing workshop of the caissons of the DjenDjen port and minimize the risk of liquefication during manufacture. When the entire sequence of compaction has ended; the results of the
safety factor of the rotational sliding (figure 8) were presented after compaction of the embankment of the caisson fabrication workshop. The results are perfectly satisfactory, which gives us the authorization to begin the construction of a 1.75 m thick platform on the treated backfill in order to install the sliding formwork and start the construction of the caissons. Since the construction of the first 1st caisson until the forty-fourth 44th; we did not notice any soil settlement and did not encounter any geotechnical problems [17], which gives a great reliability of this method of the treatment of the coastal hydraulic embankments.

Figure 7. steps and free fall of a 20 ton tamper at Djen-Djen port [17].

Figure 8. Examination of rotational slip; caissons' manufacturing platform area (minimum stability factor: FS 2.373> 1.50 ∴ OK) (Active load (caissons' manufacturing platform area = 42.34 kN / m² (caissons' load)) [19].
3.3. Preloading technique:

Pre-loading is a simple solution recommended for highly compressible saturated soils with a view to partially accelerating their primary consolidation which is accompanied by a reduction in settlement and as a result of an increase in their undrained cohesion. When it comes to building on saturated low bearing capacity and/or relatively compressible soil, preloading is the simplest technique to ensure short-term shear strength improvement [20]. The purpose of this study is to verify the stability of the caissons’ quay walls, as well as their foundation, of the Djen-Djen port of, in Jijel province, Algeria, during the works of the new container terminal; to ensure the stability and strength of the foundations of the structure and to determine the effect of the pre-loading method on soil improvement of foundations. Bearing capacity, rotational slip and liquefaction, settlement and horizontal displacement hazards for each profile of the three quay walls are evaluated according to the progress of the work such as the operation of the quay or during the earthquake as illustrates in table (1).

![Figure 9](image)

**Figure 9.** West and North quay walls of new DjenDjen Port Container Terminal; cross-section for stability examination during pre-loading [21].

4. Conclusion

Depending on the type of foundation soil, the dike can be built directly on the bottom or on special filters, made of riprap or a geotextile. In the case where the foundation soil is particularly bad, it may be necessary to apply soil improvement measures (or others) for the structure to be stable from the geotechnical point of view. Methods of soil improvement should be determined only after the development and analysis of the complete geotechnical companion. This companion includes the movement of the sea (waves), stratification of the basement, the strength and type of soil, the characteristics of consolidation and compaction, permeability, liquefaction strength and dynamic deformation characteristics. The three soil improvement methods used during the work of the DjenDjen port: Vibroflotation, dynamic compaction and pre-loading give satisfactory results in terms
of bearing capacity and reduction of the risk of liquefaction of settlements. As Professor KIRESSEL says: "we will build more and more heavy on soil more and more loose", So I said: “We need more and more methods of treatment of high quality, less costly, and respecting the environment”.

Table 1. Examination of the stability of the anchor layer of the quay walls [22].

| Detailed analysis | Liquefaction risk review |
|-------------------|-------------------------|
| ① Liquefaction risk review | F.S= 4.31 > 1.25 ∴ O.K. |
| ② Review of bearing capacity | F.S= 2.336 > 1.50 ∴ O.K. |
| Take into account soil resistance, profile formation, and load combination as work progresses |  |

| Examination of the amount of settlement | Rotational slip | Stress and displacement analysis |
|-----------------------------------------|-----------------|---------------------------------|
| ③ Additional embankment volume 0.2m | ④ 2.192 > 1.5 ∴ O.K. | ⑥ Differential settlement 1/1 980 < 1/300 ∴ O.K. |
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