Very soft dredged mud improvement in the Port of Valencia (Spain)

Amélioration d'un terrain argileux très mou dragué dans le Port de Valence (Espagne)

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ABSTRACT
The Valencia Port Authority plans to incorporate a new area of 140,000 m^2 for the storage of containers. A zone with a 65,000 m^2 surface in the area has been back filled with about 1,000,000 m^3 of dredged mud of a very low consistency. In order to improve the mud, a project has been done that basically consists of: the creation of a soil-cement crust with the mass-stabilization method, the installation of vertical drains, the construction of a horizontal drainage and the placement of a 9.5 m high preload. Afterwards, it has been necessary to wait for around 10-13 months for the mud to consolidate. Later, it will be necessary to remove the preload and to construct the pavement. In order to control this process, a complete monitoring system has been installed. In this paper, the project that is now reaching its final stages is described, as well as the data obtained from the job site and the instrumentation.

RÉSUMÉ
L'Autorité Portuaire de Valence prévoit incorporer une nouvelle zone de 140.000 m^2 pour le stockage de conteneurs. Une zone de 65.000 m^2 a été remplis avec 1.000.000 m^3 de matériaux argileux draguées, avec une très basse consistance. Pour améliorer ce matériel, un projet a été proposé qui contemple la création d'une croûte horizontale de terrain-ciment utilisant la méthodologie de la stabilisation en masse, l'installation de drains verticaux, la construction un système de drainage horizontale, y le placement une surcharge de 10 m de remblai. Une fois mis en place ces travaux, il faudra attendre environs 10-13 mois pour que le terrain argileux se consolide, avant de pouvoir retirer la surcharge y construire la chaussée. Pour contrôler ce procès, un système complet de contrôle de mouvement sera installé. Cet article décrit le projet qui est en ce moment en construction, incluant aussi les premières informations concernant le contrôle des travaux et de l'instrumentation.

Keywords : port, soft dredged mud, improvement, soil-cement crust

1 INTRODUCTION

In ealier phases at the South Dock of the Port of Valencia, around 1,100,000 m^2 were reclaimed. Once this area was improved using preloading (with or without vertical drains) it has been put into service in order to store containers.

As a result of the backfilling of that area, an artificial "lagoon" made up of dredged mud with a very low consistency has been created at the dock's end, presenting very peculiar problems.

The present paper describes the work carried out to improve the dredged mud and the data gathered on site and the instrumentation installed for this purpose.

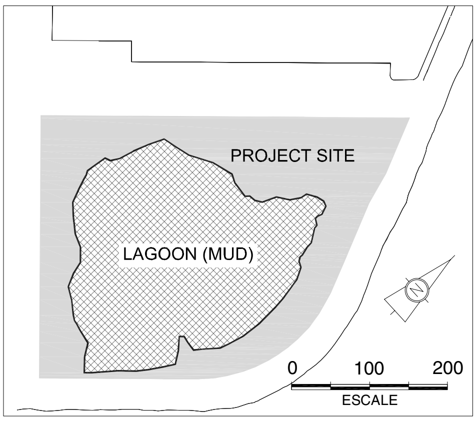

Figure 1- Initial state

2 INITIAL DATA

2.1 *Structure and geotechnical characteristics of the subsoil*

The area originally had a draught of about 12 m. The subsoil below this depth was formed by the following materials:

- From the -12 m to the -24 m level: Fine sands of medium compacity ($10<N_{30}$ SPT<30)

- From level -24 m until at least level -31 m: Clays and sandy silts of medium consistency (25kPa< s_u<125kPa).

A hydraulic backfill was then performed from the -12 m to +2 m level, creating a "lagoon" of very soft dredged mud, with an dried upper layer around 0.5 m thick.The water table is situated at the level 0.0 m, with minimum variations due to the tides.

Table 1- Initial characteristics of the mud

Index	Value
Sand (%)	< 10
Silt (%)	40-60
Clay (%)	40-60
Liquid limit, LL (%)	25-45
Plasticity index, PI (%)	5-20
Organic matter (%)	1-2
Ca content (%)	15-18
Water content, Wn (%)	30-60
Dry unit density,γ (kN/m^3)	12-14
Void ratio, e_o	0.9-1.3
Compresion index, C_c	0.20-0.25
Coefficient of vertical consolidation, C_v (cm^2/s)	8*10^{-4}
Coefficient of horizontal consolidation, C_h (cm^2/s)	8*10^{-4}
Undrained shear strength, Su (kPa)	3-25

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2.2 *Characteristics of the future works*

Once the jobs corresponding to the project have been carried out, and the preload has been removed, the construction of a port pavement, made up of 0.30 m of concrete, 0.25 m of gravel and 0.80 m of rock fill, with a combined weight of about 28 kPa will take place.

Later on, the area will be used as a storage site for containers. In accordance with the Spanish Port Norms, the containers are equivalent to an overload of 60 kPa, and the settlements for the pavement to bear must be less than 10 cm in the 10 years following its construction.

3 ADOPTED SOLUTION

The projected jobs basically consist of:

- the improvement of the upper 4 m of the mud by mixing it with cement, creating a crust that, among other things, will allow the equipment to pass through, which was initially impossible.
- the wick drains driving, whose objective is to dissipate the pore pressures of the mud
- the installation of a horizontal drainage (which includes a drainage blanket, collecting ditches, wells and channels from them to outside of the preloaded area), for the evacuation of the water collected by the vertical drains.
- the layout of a preload with a weight greater than that of the port pavement and the containers combined, so that the mud will gain the necessary resistance and its deformability will decrease.

These works are described in more detail below.

3.1 *Soil-cement crust*

The soil-cement crust has two goals: the creation of a platform that have allowed the circulation of equipment, and the improvement of the mud, so that they will allow for the future construction of a port pavement and the load of containers to be applied.

A 4 m-thick crust has been carried out with equipment especially developed for this purpose, which adds dry cement to the mud, mixes as uniformly as possible. Adding 90-110 kg/m^3 of type II/B-V 42.5 R cement, it was possible to step on the crust after 3-7 days, which have allowed advancing on an already treated soil. If this were being done differently, the circulation of machinery over these materials would not be possible (and the circulation of people would be difficult).

The mixing was performed in cells with dimensions of about 4.0 m (depth) by 4.5 m (length) by 3.2-3.8 m (width), in front of which the mixer was placed (resting on an already stabilized zone), and started adding cement and mixing it with the mud in an operation that lasts a total ranging from 60 to 90 minutes.

The soil-cement crust, with a total volume of some 250,000 m^3, was completed in June 2006.

The project demanded that the soil-cement meet the following conditions:

- the undrained shear strengh (c_u) of the samples made in the laboratory should be greater than 450 kPa at 28 days.
- the field undrained shear strengh (c_u) should be greater than 75 kPa at 28 days. With this condition, a laboratory/field ratio of 3 has implicitly been adopted.

The most effective method to control this aspect has been the CPT test. The undrained shear strength (c_u) have been deduced from the cone tip resistance (q_c) of this test, with the Equation 1.

$$q_c=N_c*c_u \tag{1}$$

where N_c usually ranges between 10 and 13. In this case, N_c=12 has been adopted.

In consequence, the tip resistance (qc) should be greater than 900 kPa at 28 days.

Due to the heterogeneity of the crust, it has been necessary to carry out a large number of these tests and analyze them with statistical methods.

Two criteria have been put forward in order to verify that a certain zone meets the project conditions: that this be true for the average of the values at each depth or that this be the case for the 50th percentile of the values. Given the heterogeneity of the results obtained, this second criterion seems more correct.

Figure 6 shows that the design criteria are verified in the study area.

3.2 *Vertical drainage*

Once the crust was completed, vertical drains were set to relieve interstitial pressures in the lower 10-11 m of the mud.

The total legnth of these drains was then some 15 m. These elements were driven at a density of one drain per every 2 m^2. Very flexible drains were employed, which guarantee a high discharge capacity in spite of the predicted settlement, and with a external geotextil filter with a characteristic opening size (0_{90}) equal o lower than 80 μm.

The installation of the vertical drains was completed in September 2006 with a total run of some 500,000 m.

3.3 *Horizontal drainage*

In order to collect the water drained by the vertical drainage, a drainage blanket was formed, consisting of a 0.5 m thick layer of gravel protected in both upper and lower sides by two geotextile sheets.

On the account of the large dimensions of this drainage layer, with a maximum width of 250 m and a maximum length of 290 m, and the fact that the “lagoon” is surrounded by less deformable zones and forms a low area once the preload is applied, drainage ditches were built to collect the water held in the layer and to run this off to wells where the water would then drain outside the zone.

The drainage ditches run in to 9 wells, in which pumps were initially installed. These have been raised as the height of the preload embankment grows. The run-off water is channelled outside by a network of flexible hoses. A flow meter has been installed in each hose to control the amount of pumped water.

In the end, it was possible to concentrate the pumping in two wells on account of the correct operation of the drainage layer.

The work on the horizontal drainage was completed in September 2006.

3.4 *Application of the preload*

Following the previous, the preload embankment has been constructed, with a volume of about 1,100,000 m^3. In the “lagoon” zone, where settlements in the order of 2.5 m were expected, a 9.5 m high preload was laid in order to provide an effective height of 7 m by the end of the application period. This preload is 30% greater than the load that will be applied during service. In the rest of the zone, where the expected settlements are about 50 cm, the height of the preload was reduced to 6 m.

This preload has been built with materials coming from the excavations carried out around the city of Valencia, and in layers no thicker than 1 m, so that a uniform distribution of the load over the crust exists, avoiding its rupture. Taking into account the results coming from various instruments, the pace at which soil was added to the preload was regulated, so that this would not affect the stability of the breakwater.

It took 11 months to construct the preload on account of the large volume of material required and work was completed in July 2007.

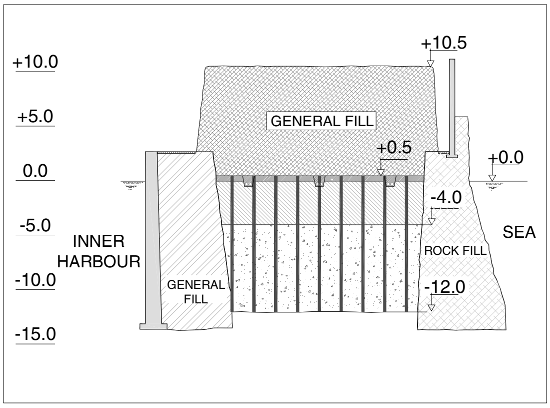

Figure 2- Application of the preload

3.5 *Following works*

Later on, it is necessary to carry out the following operations:

- To wait until the consolidation of the mud has taken place. This occurred in May 2008. During this time readings have been continually taken from the instrumentation described in the following section, and the drained water was continually pumped. Readings are still being recorded.

- Removal of the preload. In August 2008, 13 months after the completion of the preload, the removal of this preload began. As of January 2009, this process is not finished. The removal is being carried out by leaving a 50m-wide intermediate berm (In such a way that the height of each step is 3,5 m) in order to avoid a rupture in the crust the underlying mud.

- Construction of the port pavement.

- Application of the load from the containers

3.6 *Instrumentation*

The following sensors have been installed:

- A network of 92 settlement plates, situated every 25 m x 50 m, resting on the soil-cement crust.
- 3 continuous settlement lines with lengths of up to 350 m.
- 6 benchmarks for GPS control of movements of the breakwater as a result of applying the preload.
- 5 inclinometers with a length of 45 m to control the influence of the preload on the adjacent breakwater.
- 15 vibrating wire piezometers to control the interstitial pressure of the mud. These piezometers have been designed to perform suitably in such soft mud.
- 9 flow meters to control the water pumped from the wells
- Control of the water level in the 9 wells

4 BEHAVIOUR OF THE WORK

Up to the end of December 2008, the response was noted as follows:

4.1 *Settlements*

From the analysis of the settlement plates and continuous settlement lines, the following settlements were observed:

- Within the interior of the lagoon, settlements were around 150-270 cm under a preload around final level +9,5 in this area.

- In the outer areas, settlements were seen to be between 40-80 cm under a preload around final level +8.

These settlements, which are within expectations, show a greater deformability of the mud in relation to the backfilled outer area of the lagoon.

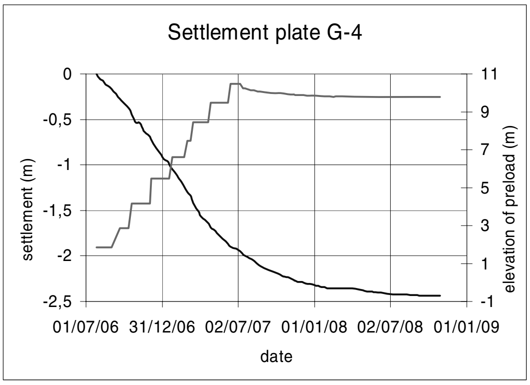

Figure 3- Settlement plate

4.2 *Horizontal movements*

The horizontal movements recorded by the inclinometers were up to 45-50 mm towards the centre of the plot in direction perpendicular to the breakwater and equal or less than 20 mm parallel to the breakwater.

These movements towards the center of the plot do not indicate any instability in the breakwater, but do show that it has a slight tilt towards the interior due to the compression of the materials on which it bears, caused by the preload.

Ever since their placement (December 2006) the benchmarks have shown slight horizontal movements (normally less than 30 mm) which concurs with the readings from the inclinometers.

4.3 *Interstitial pressures*

At the time of installing the vibrating wire piezometers an overpressure (above the hydrostatic) of some 4-6 m of water head was recorded, this being attributed to the underconsolidation of the dredged mud.

Monitoring was also made of the immediate response of the piezometers to the application of the preload layers, with thicknesses of around 1 m and which corresponded to a pressure of around 17 kPa and a water head of approximately 1.7 m. A slow and progressive fall of the piezometric level was subsequently recorded prior to the addition of further layers on account of the dissipation of the interstitial pressure due to the drainage system.

The piezometers recorded a maximum water head (excess of pore pressure) between the +15 m and +20 m levels at the end of the construction of the preload. However, this was not higher than the maximum established at the end of the preload application (+20) and therefore assured a suitable factor of safety.

After the preload was finished, reductions in the piezometric level at a rate that decreased with time have been verified. As a result, by the end of December 2008 it was at around elevations +2 and +4, with virtually all interstitial pressures having disappeared if we also take into account the decrease measured by the piezometers as a result of overall settlements.

4.4 *Drainage flows and water level in the wells*

By the end of May 2008, when the pumping from the wells was stopped, some 72,000 m^3 of water had been drained from these wells. This volume should correspond mainly to the water expelled by the mud due to its consolidation.

It was established that it was necessary to pump a sufficient quantity of water to ensure that the water level in the wells did not exceed the +1.0 level, in order to guarantee the efficiency of the preload, and that this did not fall below the +0.0 level, in order to ensure that the extracted water came from the dredged mud and not purely seawater.

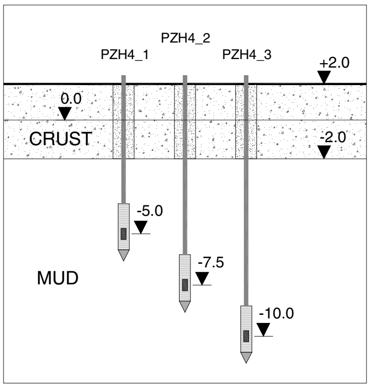

Figure 4- Installation of vibrating wire piezometers

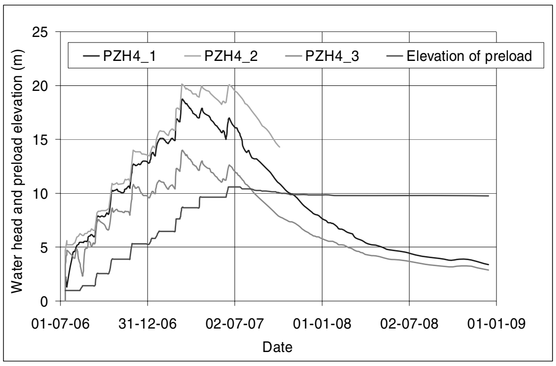

Figure 5- Water head in the piezometers and preload elevation

5 SUBSEQUENT INVESTIGATION

Once the consolidation of the mud finished in May 2008, a campaign of in situ tests was started, aiming to determine the geotechnical parameters of both the soil-cement crust and the mud found under it.

5.1 *Resistance of the crust*

In accordance to that previously explained, the project demanded that the field undrained shear strengh (c_u) should be greater than 75 kPa at 28 days, which corresponds to a tip resistence (qc) of 900 kPa in the CPT test. In figure 7 we can appreciate the increase in undrained shear strength right from the very first campaigns that were conducted, when it was about 28 days old up until the last campaign, in which the crust was about 2 years old. In the first case, the average value (50th percentile) of the undrained shear strength is about 125 kPa (qc= 1500 kPa), while in the second case it is around 165 kPa (qc= 2000 kPa).

5.2 *Resistance of the mud*

Vane-tests carried out in situ have proven the most effective in determining the undrained shear strength of the mud. The values expressed in the following paragraph come from the results of those tests.

Before starting the job, the undrained shear strength of the mud went from 3-5 kPa in the first meters to around 20-25 kPa at the bottom. Once the improvement of the mud had concluded, the undrained shear strength varied from 30-35 kPa in the first meters to 65-85 kPa at the bottom. These last values surpass those assumed in the project. As a result, the increase in undrained shear strength of the mud as a consequence of the improvements that were carried out has ranged from 30 to 60 kPa.

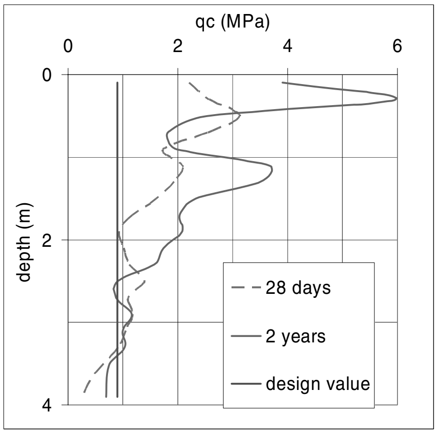

Figure 6- Cone resistance of CPTU tests.

On the other hand, in the upper half of the mud the predictable theoretical undrained shear strength according to the pressure exerted by the preload has not been reached, while in the lower half it was surpassed. The theoretical undrained shear strength (s_u) is given by Equation 2.

$$s_u=0.2* \sigma'_v \quad (2)$$

where σ'_v is the maximum vertical efective pressure applied.

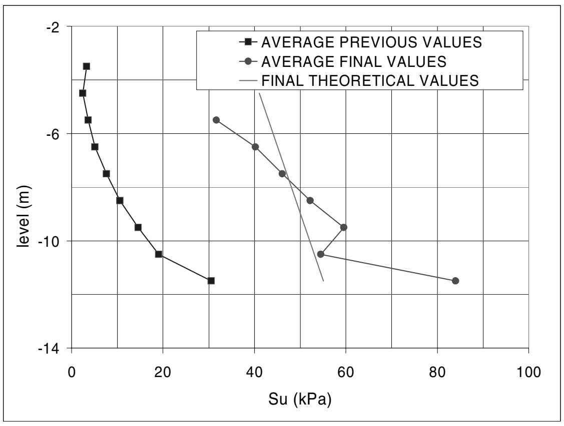

Figure 7- Undrained shear strength of the mud

6 CONCLUSIONS

As a result of the back filling in previous stages of other areas in the South Dock of the Port of Valencia, a “lagoon” of mud with a very soft consistency has been generated with a surface area of about 65,000 m^2 and a volume of around 1,000,000 m^3. This “lagoon” is contained within a 140,000 m^2 zone where the construction of a port pavement on which containers will be stored is intended.

From the investigations and studies conducted, a project has been elaborated for the improvement of these peculiar soils. The project described in this paper is now reaching its final stages, showing up until now a behavior that generally responds to that expected.