Monitoring and evaluation of movements in gravity quay walls

Auscultation et évaluation des mouvements de murs par gravité des quais

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ABSTRACT

This paper summarizes the observed foundation settlements of several recently constructed Spanish quays. When the quay walls are founded on soft soils, the settlements observed could be larger than 50 cm. The paper indicates the values of the ground deformations parameters obtained by the back-analysis of the observed settlements and compares those parameters with the original values used to predict settlements at the design stage. The predictions of the movements and the back-analysis have been made using numerical models. In addition, if the monitoring of the movements is good enough, it is possible to study the evolution of the consolidation of the natural ground under different loads.

RÉSUMÉ

Cet article présente les observations des tassements de plusieurs quais récemment construits en Espagne. Quand les murs des quais sont fondés sur des sols moules, des tassements supérieurs à 50 cm ont été observés. L'article compare les valeurs des paramètres de déformation obtenus de l'analyse rétrospective des déplacements observés avec les valeurs originales qu'avaient été utilisées dans le Project pour prédire les tassements. Des modèles numériques ont permis la prédiction et l'analyse rétrospective des déplacements. En plus, si l'auscultation des mouvements est suffisamment bonne, c'est possible d'étudier l'évolution de la consolidation du sol naturel sous l'action de différentes surcharges.

Keywords: gravity quay wall, caisson, monitoring, movements

1 INTRODUCTION

In the last few years, numerous quays with a similar structural arrangement have been constructed in Spain – with gravity walls made of hollow reinforced-concrete caissons placed on a rockfill supporting berm.

Owing to the high stresses transmitted by this type of structures, soft foundations may undergo substantial deformation. In some cases, settlements as large as 50 cm have been measured under the caisson's own weight.

Such large displacements make it necessary to monitor the movements of the caissons during the different stages of the quay construction. Most Spanish quay walls are controlled by monitoring surveys (several control monuments are placed on top of the caisson). When the quay is founded on soft soils, inclinometers and sliding micrometers are sometimes used to observe deformation of the natural ground at depth.

This paper summarizes the observed caisson movements of several quay walls recently built in Spain and the agreement between measured values and the results of numerical models.

Figure 1 shows the typical cross-section of this type of quay, including the position of the monuments used to measure displacements of the caisson crest.

2 SOME SPANISH QUAYS

It tends to be relatively easy to obtain the resultant of the vertical loads that are transmitted to the natural ground. However, there are more uncertainties in calculating the horizontal resultant, because it depends on the pressure that the backfill may develop on the wall. The value of this earth pressure depends both on the height of the caisson and the type of fill material.

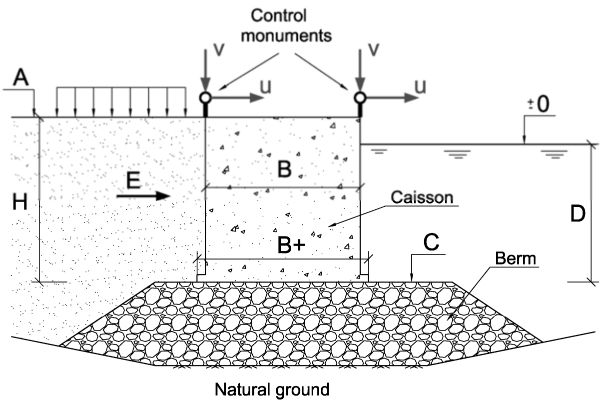

Figure 1.- Cross-section of a typical quay wall

Table 1 summarizes some parameters for several quay walls recently constructed in Spain and Figure 2 shows their geographical location.

Figure 3 relates the maximum horizontal design load acting on the quay wall to the height of the caissons for the quays indicated in Table 1.

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Number	Name	Port authority	Crest elevation A (m)	Foundation elevation C (m)	Quay wall height H (m)	Shaft Width B (m)	Base Width B+ (m)	Base Width / Wall Height	Tidal range D (m)	Maximum service horizontal thrust E (kN/ml)
1	Muelle Sur y Oeste San Juan de Nieva	Avilés	6.30	-12.00	18.30	12.60	13.60	0.74	4.6	1,272.4
2	Muelle nº 3	Bilbao	6.85	-20.00	26.85	18.60	18.60	0.69	4.5	2,043.4
3	Muelle de las Azucenas	Motril (1)	3.50	-14.00	17.50	13.60	15.10	0.86	1.1	738
4	Muelles comerciales	Baleares (2)	2.00	-11.00	13.00	9.67	11.67	0.90	0.8	630
5	Muelle Norte de Isla Verde	Algeciras	3.00	-18.40	21.40	12.87	15.87	0.74	1.4	1,263.8
6	Muelle Ferrazo	Villagarcía	5.50	-13.00	18.50	12.50	14.20	0.77	4	1,231.4
7	Prolongación muelle Dársena Norte	Valencia	2.70	-16.50	19.20	10.62	11.12	0.58	0.4	781.1
8	Muelle del Bajo de la Cabezuela	Cádiz	6.00	-15.00	21.00	13.50	14.60	0.70	3.4	1,210.1
9	Muelle de León y Castillo	Las Palmas	4.50	-19.00	23.50	15.55	16.55	0.70	2.8	1,271.5
10	Muelle nº 9	Málaga	3.00	-16.00	19.00	15.55	16.65	0.87	0.8	1,250
11	Muelle adosado	Barcelona	2.50	-16.00	18.50	12.56	13.70	0.74	1.6	900
12	Prat I	Barcelona	3.70	-16.00	19.70	18.50	20.50	1.04	1.6	1,130
13	Prat II	Barcelona	3.70	-16.50	20.20	12.07	13.56	0.67	1.6	1,070

Table 1.- Some examples of Spanish caisson quay walls

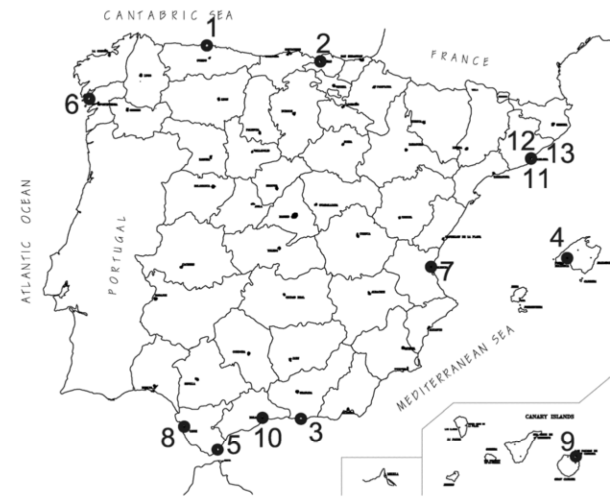

Figure 2.- Location of the studied quay walls

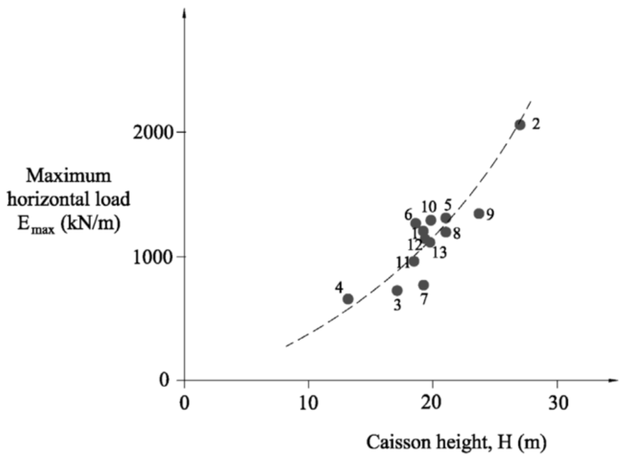

Figure 3.- Maximum horizontal loads on some Spanish quay walls

This figure shows a relationship between the height of the quay and the horizontal load. For a 20 m high caisson, the maximum horizontal load is about 1,200 kN/m.

3 PREDICTED AND MEASURED DISPLACEMENTS IN SOME QUAY WALLS

In this section the results of monitoring some of the quays included in Table 1 are described.

For most of them, the construction was completed without incidents, but sections of two of these quay walls (Prat I in Barcelona and Muelle nº 9 in Málaga) experienced a failure at the end of construction, when some preloading operations were being undertaken with the purpose of preconsolidating the fill behind the caissons. Both quays required a considerable effort to be repaired.

Preloading of backfills is, by large, the most critical situation for quay walls. In some occasions, as was the case of Prat I and Málaga quays, the thrust to the caissons was much higher (due to the intensity of preloading) than that considered at the design stage.

3.1 *Bajo de la Cabezuela Quay*

The Bajo de la Cabezuela Quay is located in Cadiz. The caissons making up its wall are some 14.60 m wide and are placed on a supporting berm at elevation –15.00 m. From the geotechnical point of view, there are two singular zones where the bedrock is very deep (the shell limestone locally known as *ostionera* appears at elevations -32 m / -35 m). These paleo-stream channels are filled with gray silty clay deposits, which are somewhat soft (N_B<20). Under the rest of the wall, the *ostionera* bedrock appears at elevation -16 / -18 m.

Figure 4 and 5 show the settlement and the horizontal movements of the caissons in the center of the two paleo-stream channels, when the caissons were founded on the rock-fill and during the fill of the back of the quay.

Figure 4 indicates settlements of about 20 cm when the caissons were founded and their cells filled. The other 20 cm were measured during the backfill stage.

As can be seen in Figure 5, the top of the caisson on paleo-stream 2 initially moved landwards with the backfill operation. As the backfilling progressed, however, this displacement changed direction and the caisson crest eventually was displaced about 15 cm seawards.

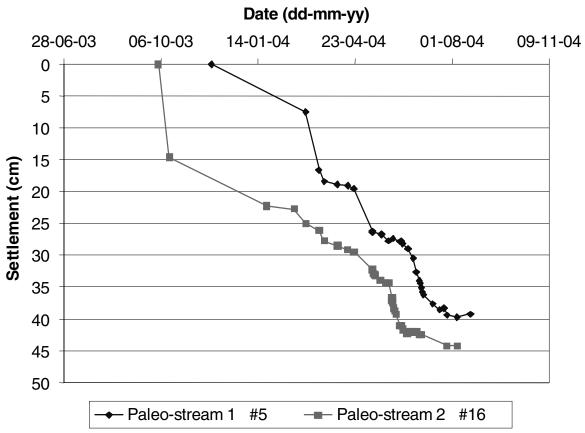

Figure 4.- Settlements at the Bajo de la Cabezuela quay

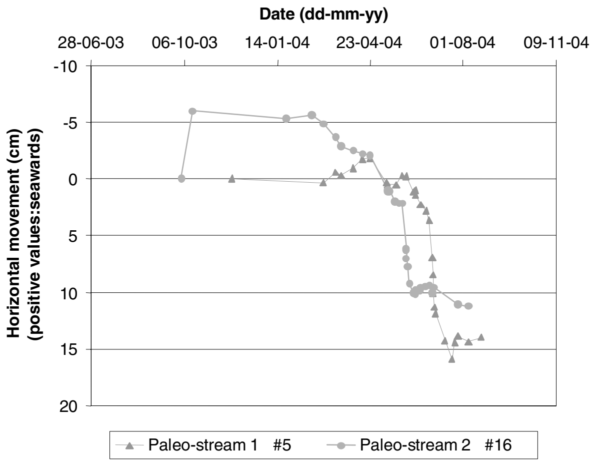

Figure 5.- Horizontal displacements at the Bajo de la Cabezuela quay

Figure 6 represents a schematic plan view of the quay with the maximum values of the settlements and horizontal movements in each caisson.

It is sometimes necessary to estimate the magnitude of the movements of quay walls at the design stage, because their values could condition the feasibility of the chosen solution.

Such was the case of Bajo de la Cabezuela quay. For this reason, deformational analyses were made to estimate the settlements in the paleo-stream channel areas. The computations were undertaken with a finite-difference numerical program (FLAC).

The results of these calculations depend on several factors (González, 2007): deformational characteristics of the materials (natural ground and rock-fill berm), the geometry of the mesh, the friction angle at the contact between the caisson and the fill…

An important aspect in these calculations is the deformability of the material of the supporting berm. In many projects it is usual to consider a high modulus of deformation for this material. However, the results of laboratory tests and in-situ measurements could indicate (Cano et al., 2000, Perucho, 2004) that the rockfill moduli of deformation are lower. Experience shows that the values of the modulus of deformation when the caissons are foundered could be about 5-8 MPa. Under the caisson's own weight, the rock fragments adjust to each other. After this stage, the modulus of deformation could be over 25 MPa. These values are considered in the calculations presented here. The other deformational parameters used were the data included in the original design (see Table 2).

Material	E (MPa)	ν
Silts with sands and clays, soft ($5 < N_B < 10$)	3.5	0.40
Medium dense sands with fines ($10 < N_B < 50$)	20	0.30
Dense silty sand	60	0.30

Table 2.- Deformational parameters at the Bajo de la Cabezuela quay site

When analysing horizontal displacements, an important parameter is the friction angle between the wall and its backfill.

The conservative assumption that there is no friction leads to higher horizontal pressure and, consequently, larger horizontal movements. A null value was adopted in this case.

Table 3 shows FLAC results for the end of backfill as compared with the in-situ values that were measured afterwards.

	FLAC		In-situ measurements	
	Settlement (cm)	X-displac. (cm)	Settlement (cm)	X-displac. (cm)
Paleo-stream channel 1	37.0	12.8	40 to 47	14 to 28
Pale-stream channel 2	41.0	11.0	37 to 47	8 to 24

Table 3.- Comparison of movements at the Bajo de la Cabezuela quay

An excellent agreement exists between predicted and measured values in this particular quay.

3.2 *León y Castillo Quay*

This work is located in the port of Las Palmas. The caisson stems are 15.65 m wide (16.65 m wide at the base slab) and are supported on a berm placed on the sandy seabed. In the southern section of the quay, the caissons were founded at elevation –18 m, on a 2 m thick berm, which rests on the firm sandy natural soil.

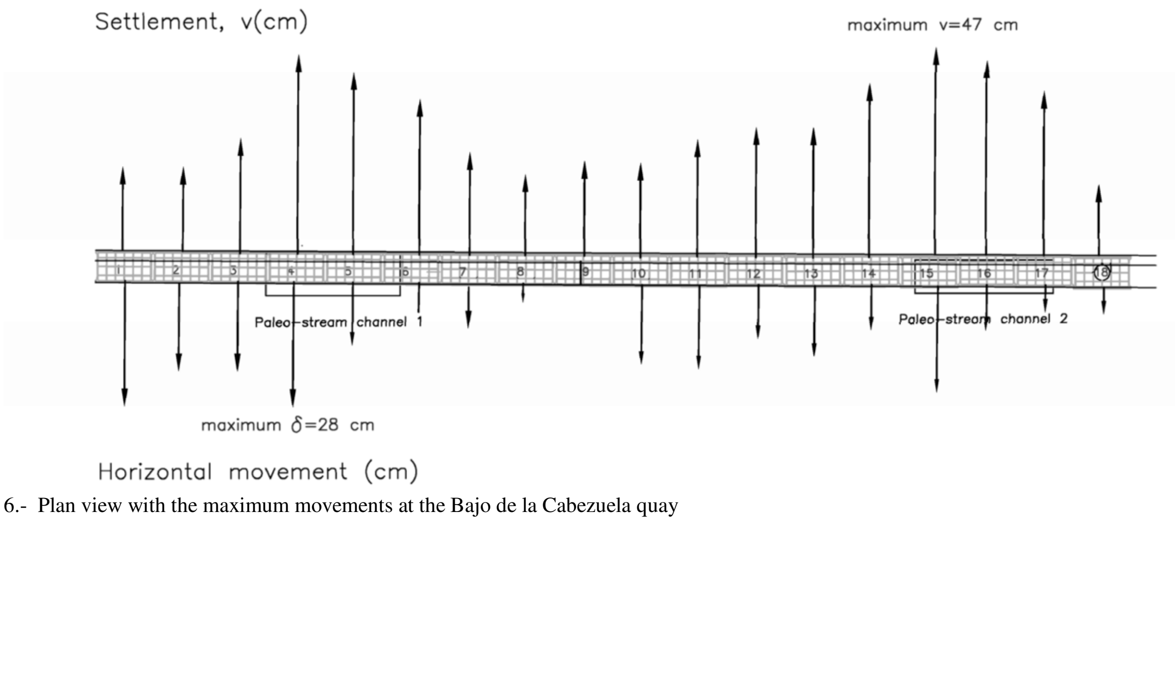

Figure 6.- Plan view with the maximum movements at the Bajo de la Cabezuela quay

However, in the northern section, the berm is 7 m thick (from elevation –25 m to –18 m) and, furthermore, its base level was reached by partially dredging a sand fill that went from the seabed elevation (-33 m) to elevation –22 m. The remaining 8 m of sand fill was assigned a friction angle of 36º.

Figure 7 and 8 show the settlement and the horizontal movements of the crest of the quay caissons in both sections: in the north (over a layer of sand fill) and in the south (where the thicker supporting berm was placed on natural dense sand).

As can be seen, the thicker rockfill berm more than compensates the supposedly softer material underneath and settlements were similar in both cases (even lower in the northern section). The final value overall was about 50-55 cm. The horizontal movements measured were about 30 cm. This value includes the influence of the preloading applied to improve the geotechnical characteristics of the general fill.

To summarize the measurements, Figure 9 shows a plan view representing the maximum values obtained along the quay wall.

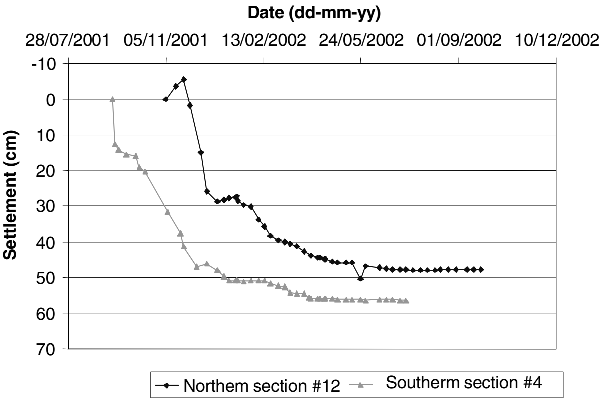

Figure 7.- Settlements at the León y Castillo quay wall

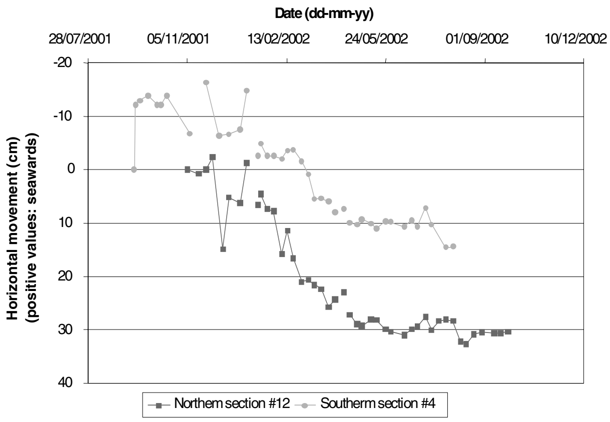

Figure 8.- Horizontal displacements at León y Castillo quay wall

3.3 *Prat Quay*

This is part of the port of Barcelona extension, constructed in two phases: Prat I and Prat II (16.0 and 16.5 m in draught).

Both phases employ walls with concrete caissons. The width of the shaft of the caissons in Prat I is 18.5 m - and their base is 20.5 m wide, resting on a 9 m thick berm. The caissons of Prat II are narrower (shafts are 12.08 m wide with two footings of 0.74 m) and are supported by an 8 m thick berm. In both cases the rock-fill berm is placed on the natural soil, which is constituted by an alternation of clays, very fine sands, silty sands and gray silts. The upper meters of the natural ground are sandier than the deeper material, where there also exist levels of sand a few centimeters thick. Both Prat I and Prat II were supposed to be backfilled with sands. Prat II -with caissons of smaller width- had, in addition, a rockfill wedge immediately behind the caissons.

The settlement and the horizontal movements of the caisson crests in Prat I and Prat II are shown in Figure 10 and Figure 11. The curves represent values when the caissons were founded and during the backfill. Figure 12 represents the maximum displacements recorded for each caisson of both phases.

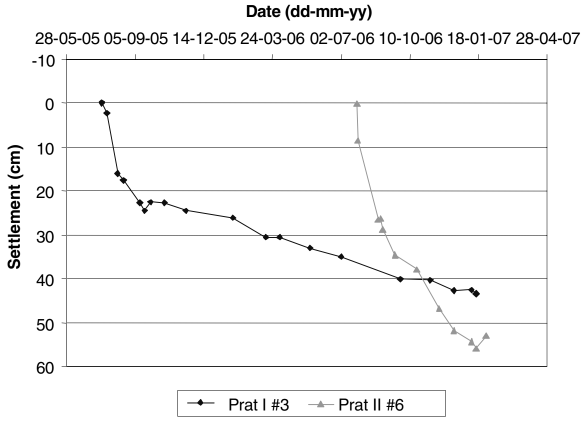

Figure 10.- Settlements at Prat quay wall

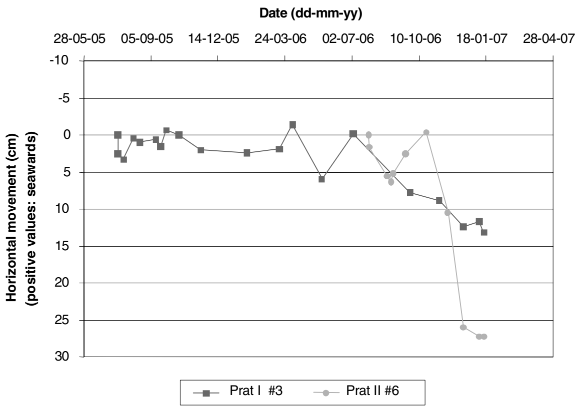

Figure 11.- Horizontal displacements at Prat quay wall

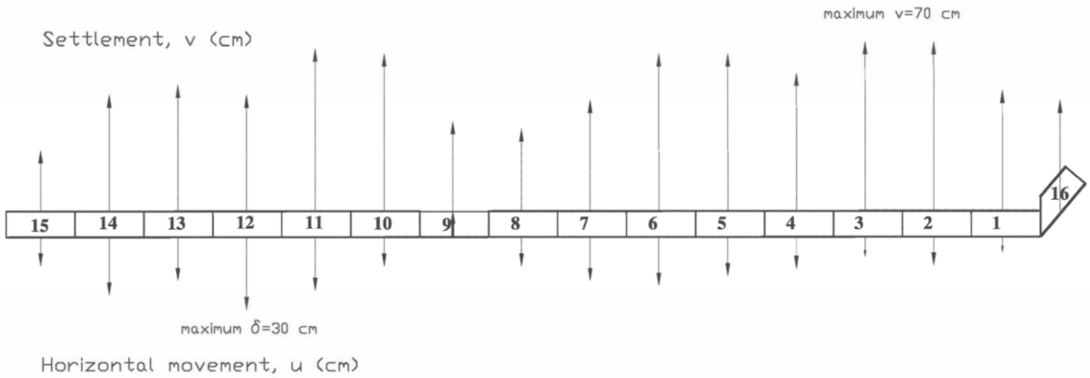

Figure 9.- Plan view with the maximum movements at the León y Castillo quay

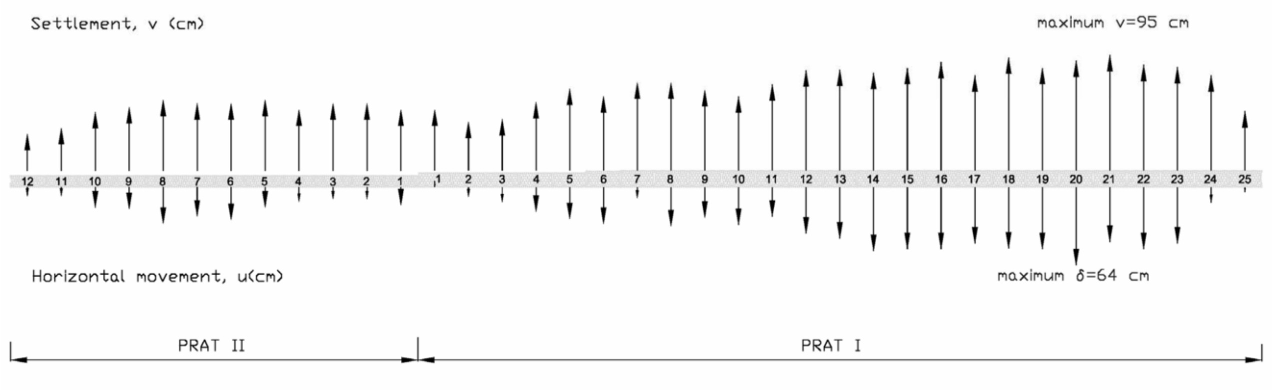

Figure 12.- Plan view with the maximum movements at the Prat quay

The displacements of caissons were evaluated in the design for the stages of founding, backfilling and operation of the quay.

Settlement analyses for Prat I were done with the parameters shown in Table 4. Value *z* represents the depth of each point, in meters, with zero starting at the original ground level, which is elevation –8.00 m.

FLAC analyses, using these values, led to a set of results that Table 5 compares with in-situ measurements.

Material	E (MPa)	ν
Rockfill berm (During caisson placement)	5	0.30
Rockfill berm (After caisson placement)	15	0.30
Natural ground	0.27 · z	0.30

Table 4.- Deformational parameters at Prat I (z in metres, see text)

	FLAC results		In-situ measurements	
	Settlement (cm)	Horiz. Displ. (cm)	Settlement (cm)	Horiz. Displ. (cm)
Founding	81.6	7.7	25 to 43	-7 to +6
Backfilling	97.7	24.0	40 to 95	-5 to +64

Table 5.- Comparison of movements at the Prat I quay

As can be seen, estimated settlements do not agree with in-situ values very well, since they are about twice as large as the real values for caisson founding. Horizontal displacements, however, were much larger than predicted. This major deviation on horizontal displacements is in agreement with a major deviation on the horizontal thrust of the backfill against the caissons. Prat I caissons #10 to #24 failed by sliding over the foundation berm on the 1st of January 2007. That day, the fill behind the caissons of Prat I was a hydraulic landfill that reached an elevation about four meters above see level. Details of this failure had been investigated by an "Expert International Committee" (2007).

When estimating Prat II settlements, the first measurements from Prat I were already available. As a result, deformational parameters were modified, both for the berm and natural ground. Numerical models for Prat II employed these values:

- Rockfill: E= 7.5 MPa.
- Natural ground: E= 0.405 · z MPa (again, *z* is depth, in meters, under elevation –8.00 m).

Table 6 summarizes the results for these new parameters.

	FLAC results		In-situ measurements	
	Settlement (cm)	Horiz. Displ.(cm)	Settlement (cm)	Horiz. Displ.(cm)
Founding	35.0	≈ 0	25 to 35	-4 to +8
Backfilling	55.0	7.24	30 to 58	+5 to +30

Table 6.- Predicted vs. measured displacements in Prat II

In this case, settlement values have been better predicted than in Phase I, but not so with horizontal movements. This difference is due to the fact, previously mentioned, that the material actually used for the backfill had a lower quality than expected and the hydraulic fill elevation was higher than that assumed for the calculations.

In Prat II, the design included a rockfill that was placed immediately behind the caissons, preventing the sliding failure, which otherwise would also had taken place.

In addition to the monitoring surveys done at the Prat quay, inclinometers were installed to observe deformations at depth. Clinometers were also used to determine the caisson rotations. These instruments were installed after the backfill was placed.

3.4 *Muelle nº 9 at Málaga Port*

This *Muelle nº 9* quay has been designed for a draught of 16 m. The width of the caisson shafts is 15.65 m (with two footings of 0.5 m).

In the area, tertiary marls constitute the rocky substrate, overlaid by more recent deposits. Above the marls there exists a dense granular formation of gravel and cobbles, on which loose sediments are deposited. These sediments were dredged to place the supporting berm, approximately 10 m thick.

In this case, the control surveys only allowed obtaining settlements (see Figure 13), so there is no information available about horizontal movements.

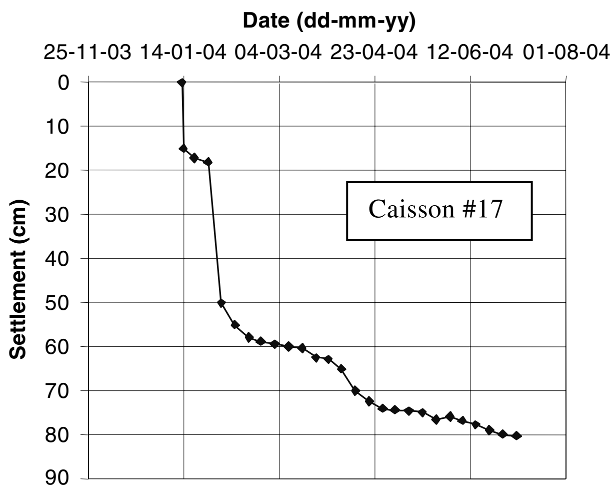

Figure 13.- Settlements at the Muelle nº 9 quay wall in Málaga

As can be seen in Figure 13, the settlement -averaged over the four control monuments of the caisson- is over 80 cm.

Figure 14 shows a plan view representing the maximum settlement measured on the quay wall.

These four caissons of the Málaga quay failed by deep sliding (through the base of the rockfill berm), due to some silty clays that were not well cleaned inside the dredging trench and due to overloading (loads were applied above the design elevation) during the process of backfill consolidation by preloading.

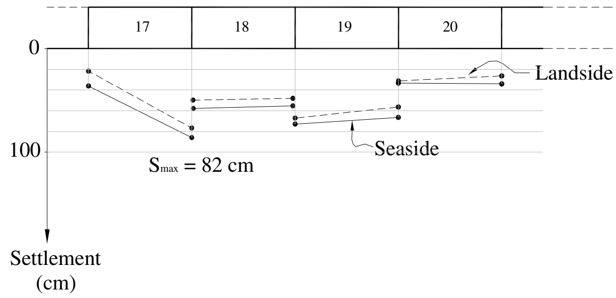

Figure 14.- Plan view of the Muelle nº 9 quay with the maximum settlement recorded

4 FINAL COMMENTS

As way of summary, the usual practice in Spain is to instrument the quay walls to observe their foundation's settlements and horizontal movements (Gens et al., 2004). Four control monuments are normally placed at the corners of the caisson crest (only three control points would be strictly necessary to ascertain the displacements in the crest plane). From the survey data, settlement, horizontal displacement and rotation are readily derived.

When ground deformations at larger depths are of interest, inclinometers or sliding micrometers are placed in borings that can be drilled through the caisson itself and reach down several meters under its foundation. Inclinometers make it possible to know displacements along two orthogonal axes and micrometer probes record settlements.

The largest fraction of the overall caisson settlement is measured when it is placed on the supporting berm and its cells are filled. Operation surcharges on the caisson and crane loads increase caisson settlements. Instead, the maximum horizontal movements are due to the earth pressure produced by the backfill and the surcharges acting on it.

Monitoring data about displacements in several quay walls make it possible to derive the following conclusions:

- In many projects, deformation moduli of supporting berms are actually lower than the values adopted in the design stage, especially when analysing settlements during the caisson's founding phase.
- It has been consistently observed that the beginning of the backfill operation induces a rotation in the caisson, manifested in the crest displacing landwards. See Figure 15.
- When the backfill is completed, the caisson crest is normally displaced seawards.

Two of the reported 13 quays have experienced failure by sliding of some caissons. Back-analyses indicate today that horizontal movements in Prat I were much larger than those predicted at the design stage and that recorded settlements were locally much larger than expected (Málaga quay).

A previous estimate of movements is very convenient for this type of works. A close observation of them is needed. And large deviations should be properly analysed, because they could be an indication of impending failure.

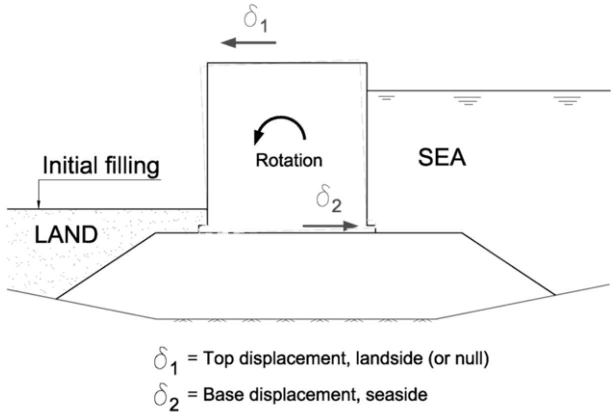

Figure 15.- Initial horizontal displacement

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