# Soft sediments consolidation back-analysis under preload with wick drains

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**ABSTRACT:** A new container terminal was promoted by APBC at Cadiz Port.
A reclaimed area of 22 ha over a very soft muddy layer overlying sands and firmer bottom formations, ranging from 3 to 14m thick, intended for container storage required an specific ground treatment analysis.
After assessing different options, wick drains were proposed to be installed through hydraulic fills. Subsequently a preload was also placed over the fill. Instrumentation included 103 settlement plates, 50 CPTUs before and 50 CPTUs replicated after the preload, 59 piezometers, 52 boreholes, 10 inclinometers, 7 extensometers.
As there are several stages and variables an iterative new developed model supported by Asaoka's final settlements criterion assumption and CPTU data was developed to fit the settlement plates curves to the theoretical model resulting an markedly accurate method.
Several analysis were performed based on the piezometric readings and comparison of CPTUs performed before and after the preload.

**Keywords:** wick drains, soft soil improving technique, reclaimed land, Asaoka´s method

## *1. Historical introduction*

Cádiz is a very old town, founded by phoenicians. It is the oldest in Europe, according to written records, existing since sometime between XI to XIII centuries B.C. Its port has a long history related to ships going through the Atlantic Ocean from Spain to America.

Among the many seafront structures along the shoreline of the bay of Cádiz, there is an impressive dry dock able to build and repair ships up to one million tons.

Recently a new container terminal was promoted by APBC (Bay of Cádiz Port Authority) with a reclaimed area of 22 ha bordered by a berthing line for vessels up to 16m draught below low waters level, around 590 m long in a 1st stage intended to be 1030m at subsequent stages.

## *2. Project description*

### *2.1. Initial conditions*

Initial geotechnical conditions include a sea bottom formed by a very soft clayey layer overlying sands and stiffer deeper formations, 3 to 14m thick characterized by very low consolidation coefficients, on the range of $3 \cdot 10^{-4}$ cm$^2$/s, with fines content averaging 76%, some of them over 90%.

Once the full removing of muds was discarded because of economic and technical reasons, other potential approaches were considered implying soil improvement methods or rigid or soft inclusions.

Heavy tamping, vacuum consolidation and preloading (both with wick drains installation) were the final methods after discarding other ones.

**Figure 1.** Cadiz port. During the third phase preload.

Having in mind that berths would be composed of floating caissons founded on rubble mound bed placed on a previously dredged trench, the treatment could be divided into zones because of variable remaining soft soil thickness.

CEDEX was contracted by APBC to validate the civil design and works and its monitoring.

IBERINSA, later on ACCIONA INGENIERÍA (designer of the Project) proposed the following phases for construction after completing the perimeter of the reclaimed land:

a) Filling from floating barges up to elevation +0

b) Closing the area for containers by lateral rockfill embankment

c) Filling from (then) current shoreline by pipeline discharge and rainbowing up to, roughly, +5 elevation.

d) Installing wick drains (PVD) through fill and soft layers down to bottom natural sands.

e) Preloading with additional earths up to elevation +12

f) Removing preloading down to level of future pavement (subgrade)

In order to guarantee that future settlements (in operation) would be lower than 10 cm in 10 years, according to ROM 05-05 (Recommendations for Maritime Works), monitoring was proposed consisting in settlement plates, CPTUs before and after preloading, boreholes for soil exploration and piezometers, inclinometers and extensometers installation.

Some explanations follow about several interesting features, but the focus will be placed on the numerical analysis of settlements according to Asaoka method [1], taking into account the different stages from the point of view of consolidation conditions, from only weight of fills, the acceleration because of vertical drains and subsequent radial consolidation, and additional earths weight because of preloading.

## 2.2. Soil improvement design

As soft marine muds thickness is not homogeneous, different spacings are defined for wick drains according to different areas.

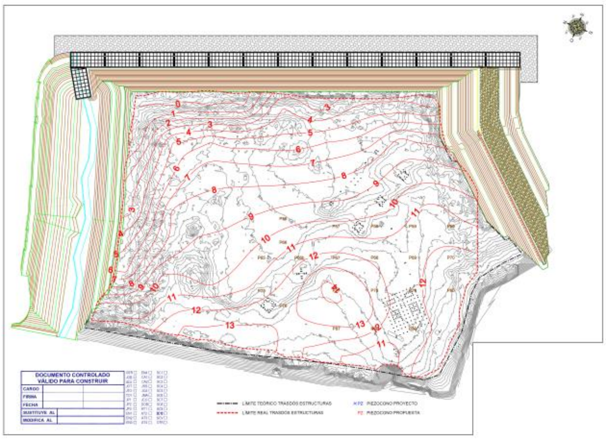

**Figure 2.** Mud thickness contour line after filling the area. Detected with a 50 CPTu and 32 borehole survey on the reclaimed land.

On the other hand, trench dredging for future caissons implies partial removal of soft soils, so another area is defined where remaining marine muds are less important, so easier to consolidate.

Thus, 1.5 to 3.5m spacing were proposed according to a triangular grid through the whole area to be loaded by containers when in operation.

## 3. Geotechnical investigation and monitoring

Several different instruments and/or tests have been forecasted.

Main tests are piezocones (CPTU) both before and after reclaimed land was performed, with a multiple aim. First of all, getting a good appraisal of soft soil thickness, by means of interpretation of (SBT) soil behavior types [2]. CPTu survey was performed by IGEOTEST. An example of CPTU profile is presented (Figure 3) where it is clearly seen that acceleration of consolidation is needed in soils SBT=1, 2 or 3 (maybe SBT=4), this is, roughly, soil behaviour types indexes above 2.95 (maybe above 2.6). Repeating those tests, before and after preload, allows easy comprehension of decreasing thickness of above mentioned soils.

Dissipation tests were performed at selected depths in those CPTUs, including in fills in order to check on their goodness (meaning coarse draining soils), besides than inside the finer soils susceptible of long consolidation if no wick drain would have been placed.

Piezometers are other interesting instruments to be placed inside boreholes, performed through the fills down to bottom draining layer. Many recordings have been made, so that potential errors due to factors as the tides are compensated. Up to 59 piezometers were installed in most of the boreholes performed as a part of the works. Their behavior was according to expectations, that is, slow decrement of pore pressure, quicker decreasing when driving wick drains, sudden increment when placing overload, then again slow gradual decreasing, with somehow rebounding effect when removing earths.

Because of the risk of slope instability of previously existing Levante Dike and the new ones becoming the other two borders (beside Caissons new quay and Levante dike), 10 inclinometers were installed in selected locations, in order to warn of potential movements.

Additionally, 7 extensometers were also installed within the fill material to follow fill and mud vertical settlements independently.

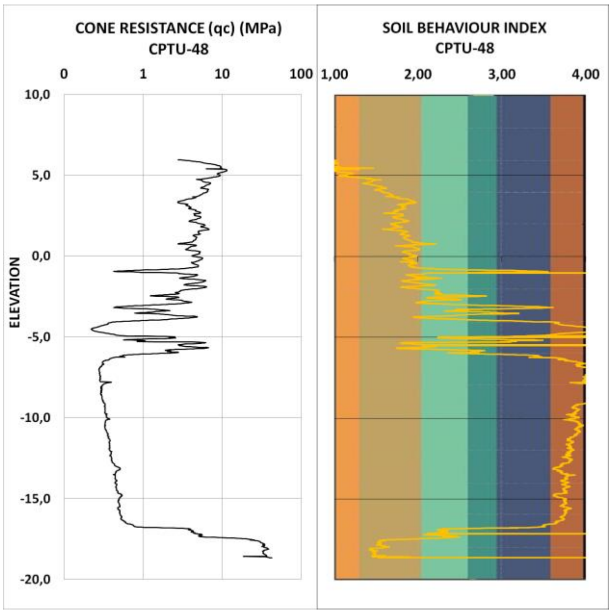


**Figure 3.** CPTU 48. On the left, cone resistance in logarithmic scale. On the right, Soil behavior type index.

Dissipation tests from the CPTu survey shows a median value of 0.0103 $cm^2/s$ (Figure 4).

Vertical consolidation coefficients from the survey prior the construction had a mean value of $Cv \approx 0.0003$ $cm^2/s$. This means $Ch_{(CPTU)} / Cv_{(oedometers)} \approx 35$

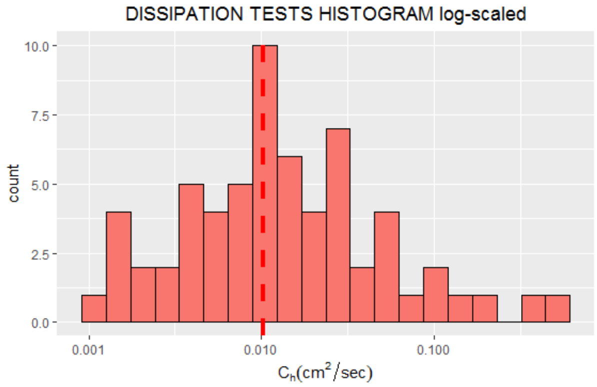

**Figure 4.** Dissipation tests density plot. Logarithmic scale. Median.

## 4. Fitting method to estimate consolidation and deformation parameters

The next sections describe the process followed to assess and fit the plate‘s readings to an ideal consolidation plot based on a coupled [3], vertical [4] and radial [5], consolidation.

### 4.1. Extrapolating settlements with Asaoka's criteria

Several methods (hyperbolic, Sridaharan, etc…) have been developed to foresee and estimate settlements and consolidation parameters based on monitoring of ground surface settlement. Among them, Asaoka's is still, likely, the most popular and commonly used to this days.

It can be easily found large bibliography regarding this method both in basic geotechnical literature and recent published paper revisiting its basis.

Fundamentally, the method computes the total consolidation settlements by extrapolating the trend of the readings according to certain assumptions. As a consequence, and knowing the thickness of the layer, the parameter goberning the consolidation rate under regular conditions (Cv, vertical consolidation coefficient) can be estimated.

The method is largely used due to the simplicity and practicality, only requiring settlement readings of the ground surface along the time. It is based on the idea that, in a general case of a homogenous unique layer, at the first order approach, the total consolidation settlement derived from Terzaghi‘s theory is as follows:

$$S_\infty = S(t) + \alpha \cdot S'(t) \qquad (1)$$

Where, assuming Cv constant, $\alpha$ is a constant given by:

$$\alpha = {}^{4 \cdot H^2}/_{C_v \cdot \pi^2} \qquad (2)$$

The meaning of "equation (1)" can be explained in words as follows: considering equally spaced periods of time, the rate at which the settlement rate (when comparing with its previous step) decreases is constant.

$$ {}^{S_i - S_{i-1}}/_{S_{i+1} - S_i} = {}^{S_{i+1} - S_i}/_{S_{i+2} - S_{i+1}} \qquad (3)$$

However, it is even easier to represent graphically. This feature indeed boosted its spreading among the geotechnical community (Figure 5)

Two key aspects should be considered when using Asaoka's method to extrapolate long term consolidation settlements:

a) In case of very thick layers of soft deposits (such as marine mud), even for high degrees of consolidation, the remaining settlements can be still significant. This means that the same relative error in the estimation leads to a larger absolute error, logically, than for a deposit with less deformability.

b) Additionally, the effects of the secondary consolidation (rate), due to both the thickness and the natural behavior of this type of material can be of a similar order of magnitude (than those due to the remaining primary consolidation settlements) [6]. As a consequence, there will be a stage during the consolidation in which the secondary consolidation settlements can induce a non-negligible error resulting in a lack of applicability of the method. This is, accordingly, reduced to ranges of consolidation degrees below 90% or so.

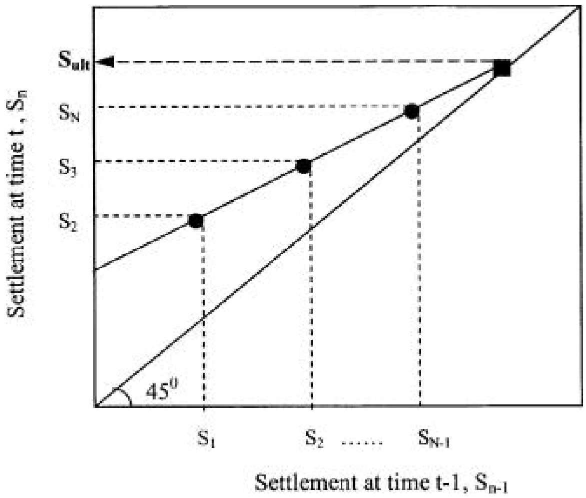

**Figure 5.** Graphical representation of Asaoka's approach

c) According to some investigations, Asaoka's method is less reliable for degrees of consolidation below 50-60% [7]. As a consequence, the applicability requires significant development of primary consolidation in order to correctly infer a reasonable estimation. This point has also been checked in this project.

d) Authors have observed erroneous application of Asaoka´s method to non-suitable ground characteristics such as a multiple layered soil profile. It has been also observed fitting linear regressions to non-regularly time-spaced readings.

The need to select equidistant time measurements to present graphically the Asaoka´s approach is usually considered as a drawback. However, current technologies allow a massive record of readings make appear this drawback as less relevant. On the other hand, whenever existing readings are roughly equidistant, linear interpolation between consecutive readings give way to reasonably accurate computation of final settlement.

The error produced by linear interpolation between any two readings is smaller than those produced by climatic variations or due to tidal effects (significant in harbour areas). As much as the linear regression fitting of readings is looked for (regularly by least squares), avoiding bias becomes of greater importance.

Because readings could be prone to error, it is essential avoiding that it falls always on the same side, so that it results an aleatory deviation around the mean tendency. This is why it is considered it is more important that settlements readings will be taken roughly at regular intervals. And so under the same climatic actions or at aleatory distributed times along any day.

Applicability of Asaoka´s method for the case of vertical drains is not obvious. Its fiability will be bigger as much as the actual model of the soil fits to the one-dimensional model from which equation (1) is derived. In other words, if some drainage dimensión becomes significantly predominant against the other one, the method will fit properly. Tan et al [8] showed results indicating that, as a matter of fact, Asaoka´s method fitted with better accuracy to a right estimation of settlements than classic hyperbolic method or its own modification of this model for soils with vertical drains.

## *4.2. Application to this project*

A description was presented here above of ground log and so of location, layout and readings of surface monitoring instruments on the full reclaimed land. Readings were taken roughly every 2, 3 or 4 days.

A script was written in order to get automatized settlements computations for each plate for different time intervals. As explained previously the consolidation process of marine muds progress though 4 stages:

1. Granular fill pouring on sea bottom (mud).
2. Settlement plates placing and recording begins
3. Wick drains driving with variable spacing according to different soft soil thicknesses
4. Preloading placing up to 5.7 – 7.7 m high (up to elevation +12), depending on the ground elevation.

Three of these 4 stages are clearly shown at settlement plates recordings.


**Figure 6.** Main milestones during the preload process

The script is defined for the different stages. Settlement computation would be performed along the readings after the preload is placed (in blue in Figure 7).

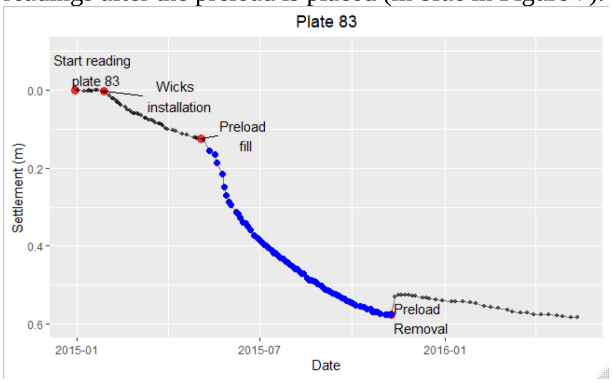


**Figure 7.** Readings used to estimate long term settlements.

Although the script uses the full recordings marked in blue, in practice:

a) Readings corresponding to the preload building period or could belong to instantaneous settlements can be visually neglected to apply Asaoka.
b) An initial set of readings can be neglected when clearly inconsistent when compared with other estimations made by the method.

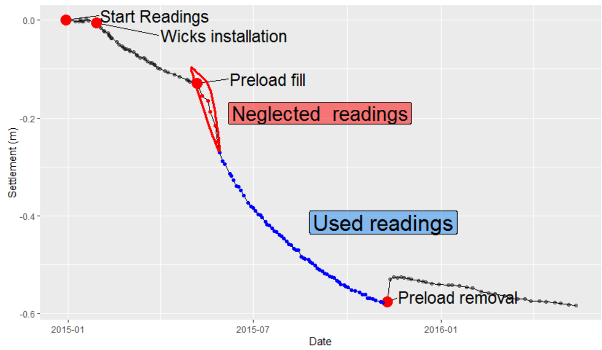


**Figure 8.** Readings used to estimate long term settlements. Neglected readings.

From last recorded date, equidistant dates are taken toward previous times of the selected set of readings. Different computations are performed according to different time intervals, thus giving way to a values matrix where 1st row represents considered time intervals used, while remaining computed settlements are at 2nd row (for each plate) (**Figure 9** only for clarifying purposes it can not be displayed all the ouptus):

| | | Plates | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 76 | 75 | 65 | 60 | 59 | 58 | 57 | 56 | 55 |
| TIME SPACING | 20 days | -0.10633 | -0.11422 | -0.16570 | -0.03116 | -0.06625 | -0.10579 | -0.10854 | -0.12900 | -0.11225 |
| | 19 days | -0.06157 | -0.12810 | -0.17226 | 0.00000 | 0.00000 | -0.01188 | 0.00000 | -0.04748 | -0.03657 |
| | 18 days | -0.08966 | -0.08707 | -0.12586 | -0.03109 | -0.06851 | -0.10432 | -0.11426 | -0.13654 | -0.11428 |
| | 17 days | -0.05472 | -0.11870 | -0.17151 | 0.00000 | -0.02374 | -0.05390 | -0.05485 | -0.07815 | -0.06122 |
| | 16 days | -0.08537 | -0.08747 | -0.12710 | -0.04232 | -0.07412 | -0.11260 | -0.11583 | -0.14170 | -0.12163 |
| | 15 days | -0.05812 | -0.11521 | -0.17031 | -0.03112 | -0.05951 | -0.10326 | -0.11320 | -0.13707 | -0.12072 |
| | 14 days | -0.09242 | -0.10916 | -0.15364 | -0.01952 | -0.05069 | -0.09335 | -0.10025 | -0.11982 | -0.09272 |
| | 13 days | -0.08105 | -0.09861 | -0.13625 | -0.01750 | -0.04966 | -0.09285 | -0.10028 | -0.12152 | -0.10059 |
| | 12 days | -0.06398 | -0.08762 | -0.12786 | -0.02979 | -0.06022 | -0.10293 | -0.11345 | -0.13712 | -0.11143 |
| | 11 days | -0.07057 | -0.09525 | -0.13745 | 0.00000 | -0.01563 | -0.04883 | -0.05503 | -0.08470 | -0.05741 |
| | 10 days | -0.07958 | -0.11326 | -0.16137 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | -0.03354 | -0.02504 |
| | 9 days | -0.05187 | -0.08940 | -0.12542 | 0.00000 | 0.00000 | -0.01028 | -0.00098 | -0.04921 | -0.03440 |
| | 8 days | -0.05261 | -0.08601 | -0.12520 | -0.00580 | -0.03619 | -0.08022 | -0.08693 | -0.10569 | -0.09374 |
| | 7 days | -0.05927 | -0.11245 | -0.16039 | 0.00000 | 0.00000 | -0.00834 | -0.00119 | -0.04708 | -0.03103 |
| | 6 days | -0.06266 | -0.08429 | -0.12237 | 0.00000 | -0.02729 | -0.07030 | -0.08203 | -0.09456 | -0.07445 |
| | 5 days | -0.05224 | -0.11463 | -0.15972 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | -0.03415 | -0.01998 |
| | 4 days | -0.05254 | -0.08513 | -0.12082 | 0.00000 | -0.00502 | -0.02459 | -0.01944 | -0.06121 | -0.04536 |
| | 3 days | -0.05295 | -0.08553 | -0.12193 | 0.00000 | 0.00000 | -0.00578 | 0.00000 | -0.04710 | -0.03394 |

**Figure 9.** Remaining settlements (in meters) resulting for some plates during a moment of monitoring according to different interval times

### *4.3. Complete curves fitting*

### *4.3.1. Assumptions*

The model is supported by several hypothesis. Reach or sensitivity of some of these assumptions is not evaluated; however, some comments about its influence are included.

Premises are:

- While 7 months is the period to complete fill, 3.5 months is assumed to be the initial time before the end of the process. This assumption is likely to derive into the most significant error of the model. However for periods of time sufficiently large, and given the rate of consolidation is also significantly low reducing the impact of potential errors.
- Thickness of marine mud layers when piezocones are performed is known. Both, plates and piezocones, were located, roughly in the same location (within a 5 square meters area). Deformable soil thickness can be estimated with a low margin of error.
- It is assumed that the average unit weight of both the hydraulic fill and the preload are known. Hence the loads (height multiplied by unit weight) are also known in the one-dimensional consolidation model.
- It is considered that the consolidation curves are additive. So both curves are just added up in terms of settlements in spite of its mathematical correction.

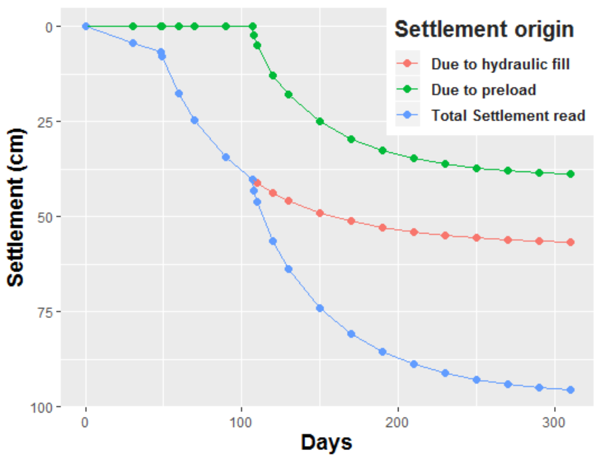


**Figure 10.** Settlements are added up assuming different stages independent.

- It has not been considered any smearing effect when calculating horizontal consolidation.
- Equivalent diameter of the band drain has a not negligible effect on the results. It has been used Rixner's [9] definition of the equivalent diameter.

### *4.3.2. Average slope estimation before wick drains driving.*

At first approach best fitting straight line for the time before wick drains driving. The least squares criterion is used.

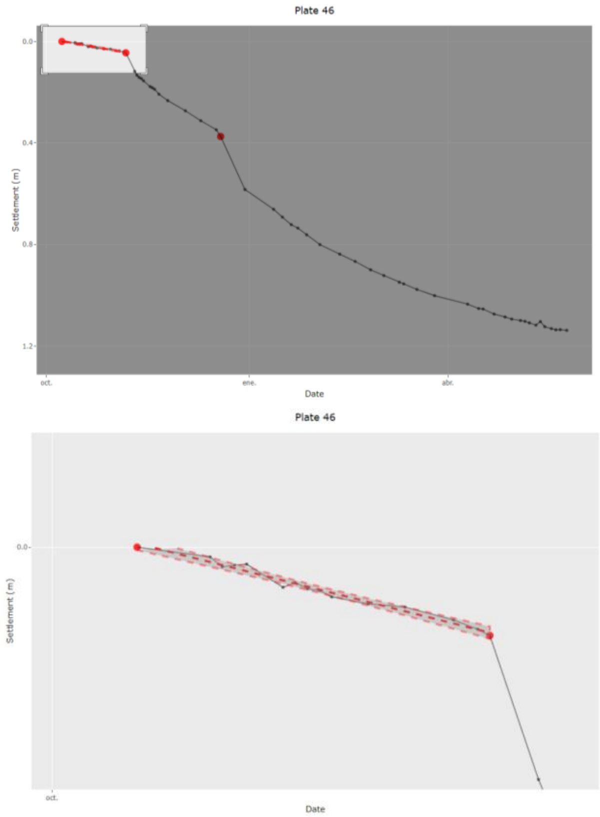


***Figure 11.*** Initial stage slope computation by least squares criterion. Average settlement slope computed by means of least squares regression straight line. Shaded area is the 95% confidence interval.

This slope represents settlement average rate since plates readings started until the wick drains driving.

The assumption that linear regression correctly fits or represents the behaviour of the consolidation can imply, occasionally, non negligible statistical adjustment errors. However, due to the very slow consolidation rate and fact that the number of readings in this first stage is large enough and quite consistent this issue has a minor effect.

### *4.3.3. Estimation of vertical consolidation coefficient and compressibility*

The following step consist in finding the consolidation curve for which the average slope between the dates the plates reading started and the wick drains installation matches the slope estimated in the previous section. Since the long-term settlements are known they are splitted into those caused by the fill and those caused by the preload.

This implies assuming an initial thickness for the soft layer before the hydraulic filling. Since this is an "unknown" variable, it will require iterating a few steps. First it is assumed an initial thickness and found the complete consolidation curve for this specific initial thickness. This thickness is corrected iteratively with the actual initial thickness estimated from hypothetical consolidation settlement obtained with the fitted curve. With only two iterations the initial thickness obtained and the thickness when starting the plates readings are consistent with minor variations in the next iterations.

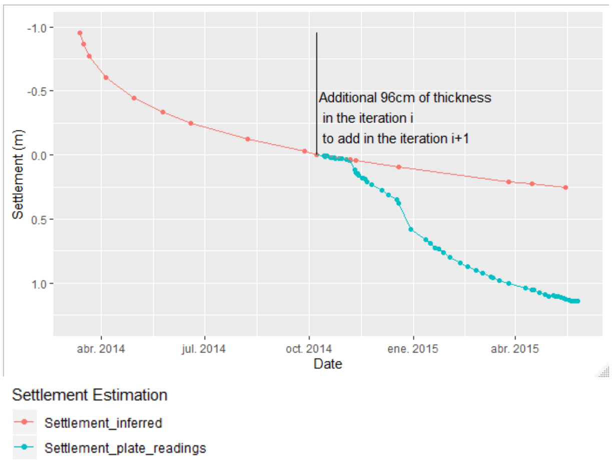


**Figure 12.** Estimated consolidation curve fitting with the first section. Negative settlement means settlement not read and occurred in the past. Plate's readings start from zero settlements

The process to fit the consolidation curve in every iteration implies moduling the pair of values CR(=$C_c/(1+e_0)$), and Cv until finding this pair of values making the slope (of this first stage) and the remainig settlement from the point the wicks were installed onwards to match the expected. This could mean it exists several solutions, however:

- The origin in time ($t_0$) is known (assumed), so; for a specific deformability (CR=$C_c/(1+e_0)$), there is only one coefficient of vertical consolidation that matches the slope from $t_1$ to $t_2$
- For a specific rate of consolidation ($C_v$) there is only one CR that makes the slopes match from $t_1$ to $t_2$
- It seems to be only a specific pair of values meeting both conditions (remaining settlements from $t_2$ onwards and slope from $t_1$ to $t_2$) because both, (CR and Cv) affect also both the slope at $t_1$ and the remaining settlements (from $t_2$ onwards).

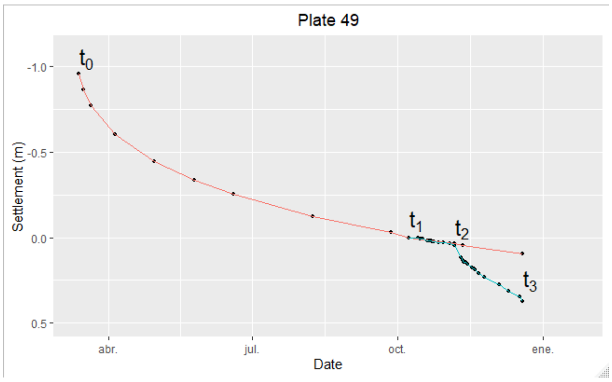


**Figure 13.** Estimated consolidation curve fitting with the first section.

After finding these parameters defining the soil behavior and original thickness of the layer, the goal is finding the Ch that makes remaining settlement at t3 matching the expected previously assessed by Asaoka.

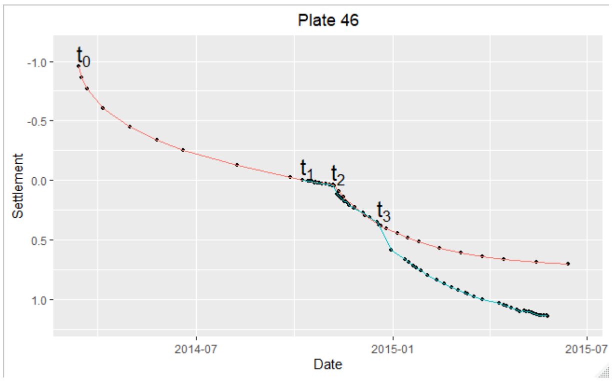


**Figure 14.** Estimated consolidation curve fitting with the first and second sections

This fitting could be not completely accurate and is tested somehow by "applying" the extension of the model to the section where the preload is applied and comparing with the last section of the plot (t3 onwards).

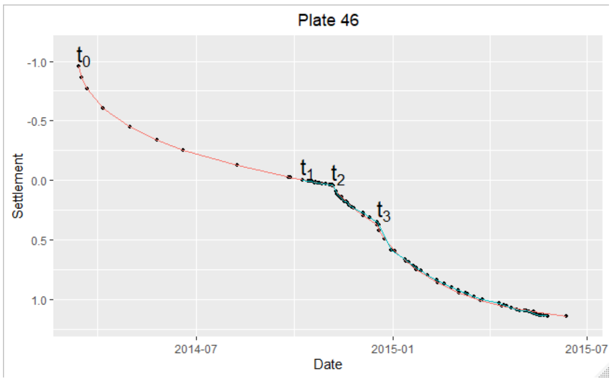


**Figure 15.** Consolidation curve completely fitted.

This final adjustment works also to confirm if the Ch used to fit the previous section is approximately correct or needs corrections.

This final adjustment also needs to add certain amount of elastic settlements assumed inmediate after preload was placed.

## *5. Results*

Not all the plates were assessed, but the results were somehow consistant with those computed.

**Table 1.** Basic statistics of the resulting analysis

| | mean | median | range | Standard error |
|---|---|---|---|---|
| **CR** | 0,2333 | 0,23091 | 0,09955 | 0,0082 |
| **Cv ($cm^2/s$)** | 0,0026 | 0,00272 | 0,00303 | 0,0002 |
| **Ch ($cm^2/s$)** | 0,0028 | 0,00266 | 0,00126 | 0,0001 |
| **Ch/Cv** | 1,1500 | 1,05000 | 1,00000 | 0,1031 |

With these results, it is worth noticing the significant difference of this figures with those obtained from in situ tests and laboratory tests (Ch ≈ 0.0103 cm2/s and Cv ≈

0.0003 cm2/s). However, this would be concurrent with several studies such as Leroueil et al [10] or [11] for homogenous clays in which a ratio below 1.2 for homogenous marine clays is observed .

## 6. Other considerations

The comparison between computed values of consolidation coefficients according to this paper and those obtained from 1-D Consolidation tests in oedometer cells give way to a ratio of 9:1. It is generally accepted that actual in field values are bigger than those obtained in laboratory. In [12], this ratio was 4:1, but with bigger lab Cv.

Another curiosity is the ratio Ch/Cv amounting only to 1,15 in this study, while in vertically trimmed samples in laboratory the consolidation anisotropy ranged between 1,00 and 1,50.

In a study with many lab tests [13] a correlation was obtained between %fines passing through the sieve No.200 (75µm) and Cv from oedometer tests: 10000Cv(cm2/s)= 195 -2,05 %#200. This was the best among several other correlations in that study, in the province of Cádiz, too. Applying this formula for Cv= 0.0003 cm2/s (average in lab tests) fine content would be 93.65%, more than average and near maximum of lab tests

## 7. Acknowledgement

The new container terminal of Cadiz Bay is considered a paradigmatic and exceptional example of cost-efficient investment in geotechnical investigation and monitoring both, for design and guarantee of good performance. For this reason, the authors and geotechnical comunity are indebted with APBC (Cadiz Bay Port Authority) for its perception and vision of the importance of geotechnics within the scope of civil engineering. This virtue is, unfortunately, unusual.

The autors want to express gratitude to CEDEX (Centre for Public Works Studies and Experimentation) for its guidance and support. This institution and its representatives are, without doubt, the reference in terms of geotechnical understanding in marine inveronment in general, and in particular in the Cadiz Bay.

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