How to get a good match with Cv

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ABSTRACT

It is difficult to get accurate magnitudes when dealing with consolidation coefficient, decisive when clays and clayey silts, are compressing, especially if secondary consolidation is in play. This is a typical condition in harbours when new areas are to be reclaimed to get more and more loading/unloading areas. There are several approaches to assess consolidation rate.

The oedometer cell is the main lab test used to get the compressibility parameters. It is accepted that 24 hours is a good time for each pressure. However, some soils consolidate slowly, and they need more time. Especially when slope is far from horizontal. On the other hand, "true" consolidation coefficient is obtained when surpassing the preconsolidation pressure. Thus, values obtained below preconsolidation pressure are usually discarded.

Horizontal coefficient of consolidation can be assessed with dissipation tests from piezocones.

If piezometers are installed within the consolidating layer, comparing with the theoretical isochrones we may derive the "true" consolidation coefficient.

If settlements are measured, a comparison with theoretical ones can be informed on the predominant consolidation phenomenon.

Much care is to be applied and not misunderstand the process in play. Dissipation tests give way to much higher consolidation values than laboratory tests. This could be due to anisotropic effects, but the main reason is that dissipation occurs in a reloading process, while oedometer tests are in primary consolidation, at least from the preconsolidation pressure and on.

This paper shows some ideas to properly assess the process involving consolidation.

Keywords: Reclaimed land, Soft soils, Cv, CPTU

1. Introduction

Overseas Shipping business is growing more and more. So, reclaiming lands is a big need to comply with commercial context.

When doing that either by hydraulic filling or by an embankment crossing through the water (colloquially called "mota" in Spanish), the big question is: how long the new land will be consolidating and how much?

If (as usual) there are big thicknesses of compressible soils below water, there will be a need for more loose material to take into account settlements of compressible material (natural one plus added one).

Then the amount of settlements is very important but the velocity at which they are produced too. It is easily understood because coefficient of permeability of soils goes from 1E-12 cm/s (fat clays) to 1E+02 cm/s (open graded gravels)

2. Methods of computing Cv

When dealing with laboratory tests in oedometer cells, two classical methods are used:

a) Casagrande, from T50 (time for 50% of consolidation)

$$Cv=0.196\ H^2/T50$$

H being half the thickness of the sample when there is drainage by both borders

b) Taylor from T90, as an intersection of time-lectures curve and the straight line with a slope 1,15 times the initial one for first seconds in a log time-lectures graphics

$$Cv= 0.848\ H^2/t90$$

Other methods are based on curve-fitting, as the one proposed by Sridharan log (H/T)-U% (degree of consolidation). The method proposed by Sridharan et al (1995), was originally designed for the retrospective interpretation of laboratory consolidation tests. However, due to its simplicity, it proves to be somewhat useful in predicting the behaviour of preloading methods of soil improving with or without drains.

Several other methods can be used such as that developed by the authors for Cadiz new container terminal using iterative curve-fitting from monitoring data.

2.1. Comparison between Casagrande and Taylor methods

In our experience both results are different when clayey fraction (%< 0.002 mm) is low, let’s say less than 10%. However, they become similar when clayey fraction is large, let’s say more than 30%.

2.2. Influence of OCR

As typical loads to be applied begin at 0.05 Kg/cm^2, doubling each stage until 6 or 12 Kg/cm”, it is easily understood that first stages are below the preconsolidation pressure, p'_c, but final ones are above p'_c, that is with a Overconsolidation Ratio (OCR) bigger than one.

Many times, it has been observed that Cv values are very big for lower pressures as compared with higher pressures. So, the latter are considered the actual ones.

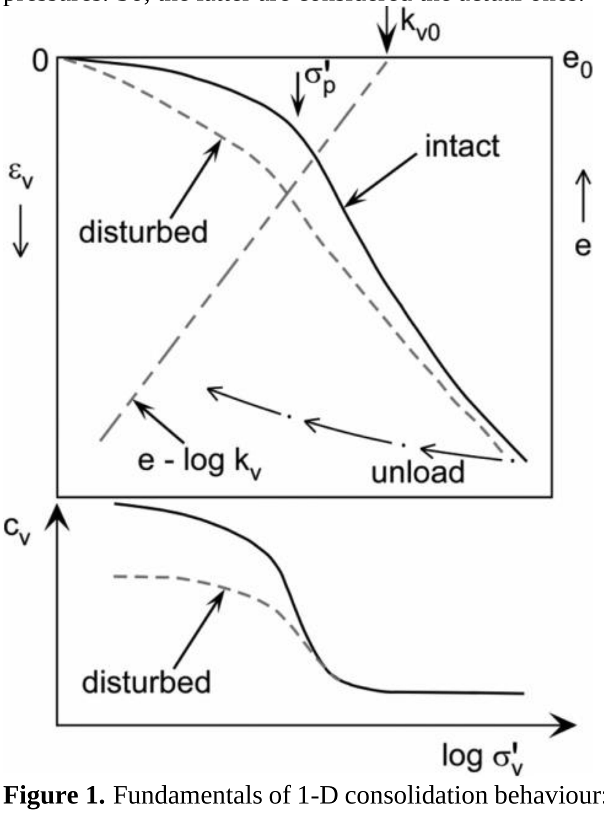

Figure 1. Fundamentals of 1-D consolidation behaviour: compressibility, hydraulic conductivity, coefficient of consolidation vs. vertical effective stress (after Ladd & DeGroot 2003).

2.3. Dissipation tests in piezocones

When performing Cone Penetration Tests with measurement of Pore Pressures CPTU(u) (colloquially piezocones) one may order stopping the penetration and then waiting the dissipation of excess pore water pressure (Δu).

Then mathematical formulae allow computing the coefficient of consolidation. This will be Ch because it is a radial phenomenon, thus horizontal instead of vertical (Ch instead of Cv)

The actual Cv will be derived from Ch dividing by Cc/Cs rapport, where Cc and Cs are the coefficients of compressibility in virgin and unloading/reloading actions. The reason is that there is a recompression phenomenon when dissipation is produced (less Δu means more effective stress). Thus, caution must be applied and not taking Ch from dissipation tests without correction.

3. Case histories

Three experiences of the authors are to be commented as follows.

3.1. Centenary Dock at a Coruña Port

This work intended to provide a new dock 540m long with a reclaimed land 540mx175m for stocking ore and other materials within A Coruña bay. It was performed during years 1978 to 1984.

3.1.1. Geotechnical report

There were 8m to 20m thick, soft fine deposits over some sands and gravels, then bedrock.

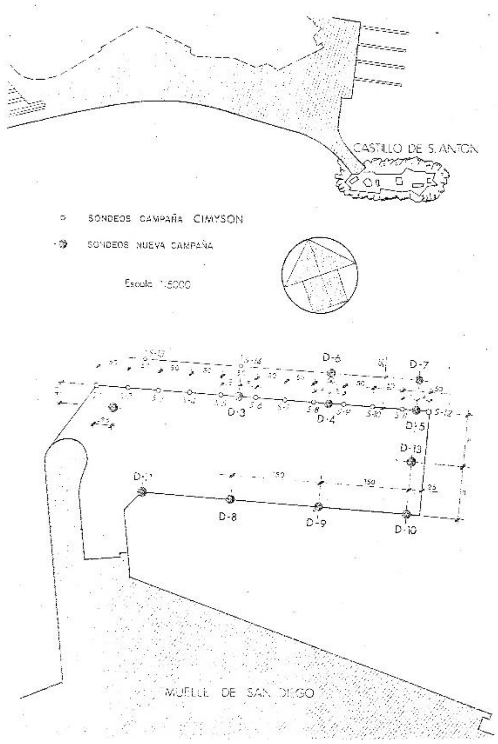

Figure 2. Layout of borings from a platform at A Coruña Bay

Compressibility index ranged from Cc= 0.11 to 0.65, average being 0.385, going to 0.47 when discarding extreme values.

As to $CR=Cc/1+e_0$, its range goes from 0.06 to 0.20 (much higher than many soils). Average was 0.136 going to 0.145 when discarding extreme values.

Computing settlements when filling up to level +6 (referred to 0 of the port) since previous sea bottom (at -6 to -10) was about 3m and higher.

Many undisturbed samples were taken from boreholes drilled from platform and/or floating barges, then tested in oedometer cells among other tests from which Cv values were computed.

Large differences were observed when comparing Casagrande and Taylor methods.

Consulting late Professor Jiménez Salas on the reliability of Taylor's results, he backed first author to use data with that method, in spite of very optimistic values, in such a way that Cv=1E-02 cm^2/s was adopted even discarding higher figures

Cv values changed from 2E-03 cm^2/s to 1.7E-01 cm^2/s. Average is 2.4E-02cm^2/s going to 3.35E-02 cm^2/s average being 3.11% becoming 3.44% when discarding extreme values.

Liquid Limit is between 45% and 99% and Plasticity Index ranges from 11% to 47%, being the average 23.68%

Not surprising that these soils are classified as MH (high plasticity silts) and A-7-5 (AASHTO) with index group going from 7 to 20, being the average 15.9, going to 16.9 when discarding extreme values.

Void ratio was found to be between 0.65 and 2.35, being the average 1.61 going to 1.725 when discarding extreme values.

As to coefficient of compressibility is concerned, minimum was 0.11 and maximum 0.65, average 0.385 going to 0.47 when discarding extreme values.

CR= Cc/1+e0 goes from 0.06 to 0.20, average 0.136 going to 0.145

Range of computed Cv values is from 2E-03cm2/s to 1.7E-01 cm2/s, being the average 2.4E-02cm2/s becoming 3.55E-02 cm"s, thua the adopted value of Cv=1E-02 cm2/s was taken from the safe side. However, monitoring was provided in order to check on that issue.

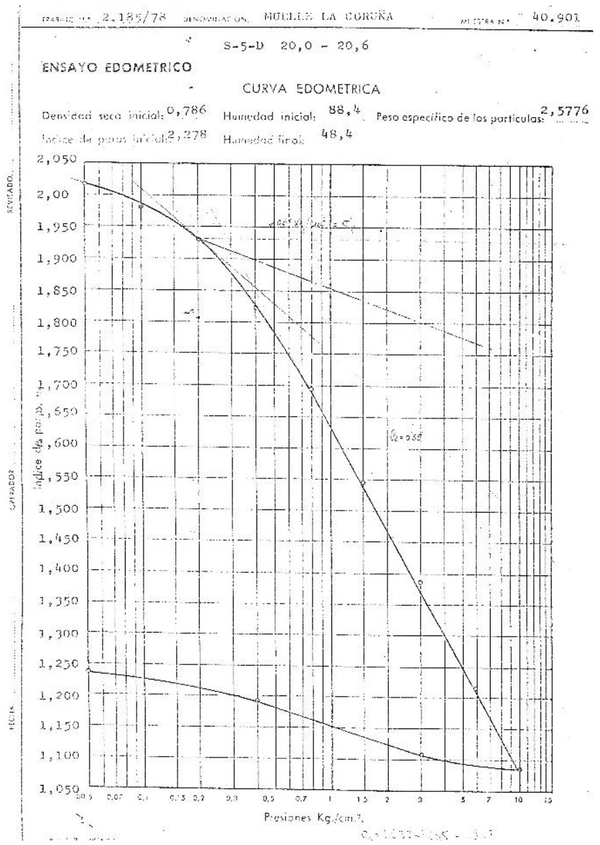

Figure 3. Example of 1-D Consolidation test

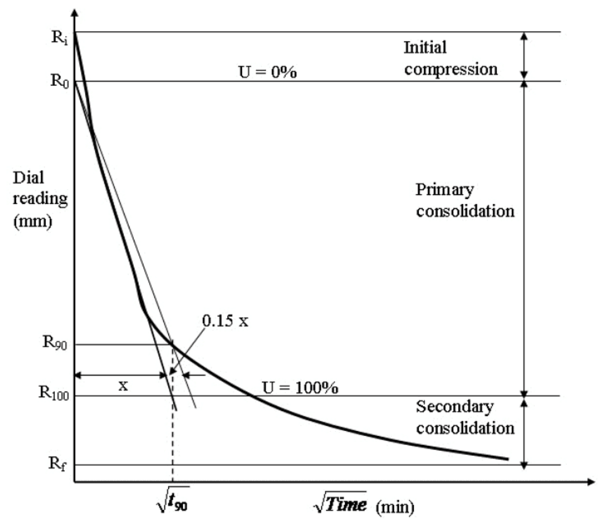

Figure 4. Taylor's construction to get Cv (cm^2/s)

Thus, no need for wick drains or other settlements accelerating method was decided and a working schedule was proposed compatible with bid requirements.

Schedule works included Preloading with fill material in a strip wider than future concrete platform, then building cast-in-place concrete piles 1.8m and 1.5m diameter and up to 40m long.

Muddy soils present a fines content between 50% and 96%, notwithstanding most of them are medium silts. Average is 83.46%. Clay contents are from 0% to 8%, the

Schedule of works forecasted an initial large "mota" intended to cover a width of 40m at elevation +6, much more than final concrete piled structure.

Then cast-in-place circular concrete piles, 1.5m and 1.8m were performed, following this sequence:

a) Driving metallic pipes (somehow larger than nominal diameters) through the fill, muddy soils and sands and gravels, reaching at bedrock bottom.

b) Excavation within the pipes, even in the bedrock for good toe embedment

c) Placing of reinforcement bars cage

d) Pouring pumped concrete inside

e) Removing pipes as concrete filled the subsequent void

This procedure was much less expensive than piling from floating or fixed platform with spuds.

The key factor to allow the cast-in-place piles through the fill and soils coming into the rock was the speed of consolidation, that is, the amount of Cv value.

3.1.2. Monitoring

Casagrande and pneumatic piezometers were installed as soon as possible when landfilling advanced from previously existing docks toward the worst geotechnical conditions. Thus, Cv was proved to be even higher than 1E-02 cm^2/s. However, it was observed some apparent delay later on.

The explanation was that increasing vertical pressure happened because of settlements. In fact, maintaining the fill at elevation +6 was possible adding more filling material ("jabre" a soil coming from weathering granitic rock) to compensate for (big) settlements, previously computed as over 3m.

The other reason for increasing excess pore pressure was enlarging the initial "mota" both longitudinally and transversally, so vertical pore pressure experimented more and more increments again and again.

As curiously as it could happen, open Casagrande piezometers worked better than pneumatic ones.

3.1.3. Conclusions

It was proven that consolidation velocity was very quick. Subsequently, there was no need for wick drains nor for heavy overloading That would be very risky from a point of view of slope stability, still being unstable at first stage (about 16m high), but becoming safer and safer as pore pressure dissipation give way to an increasing safety factor.

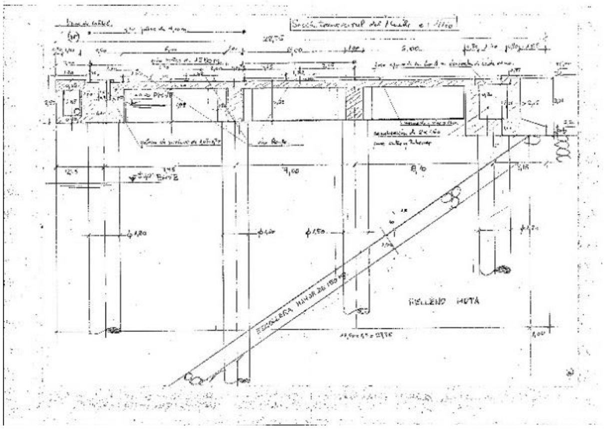

Figure 5. Cross-section of new Centenary Quay

3.2. Moll Adossat at Barcelona Port

Along the outer breakwater, adjoined docks were built on the inner side. However, a section was not completed because of poor geotechnical conditions. A solution was proposed inspired in Centenary Dock of A Coruña.

3.2.1. Monitoring and new geotechnical investigation

A narrow "mota" was built departing from one to the other end of "the problematic area", just wide enough to allow earthmoving equipment to go through.

Every 50m or so, a punctual enlargement of the "mota" was provided in order to place drilling equipment to perform boreholes to get undisturbed samples to be tested at soil laboratories.

Another aim was installing piezometers at different depths and following the excess pore pressure evolution as time went on.

Piezometers were of VW (vibrating wire) type.

Beside taking undisturbed samples, SPT (Standard Penetration Tests) were performed every 3m deep, and FVT (Field Vane Tests) at selected depths.

On the other hand, CPTU(u) (Cone Penetration Tests with measuring of Pore Pressures) were performed at each enlargement points. See example at figure 6

3.2.2. First findings

Piezocones reach at deeper levels than previous DPTs (continuous Dynamic Penetration Tests) proving the soft deposits were much thicker than previously thought.

Figure 7 shows how much deeper piezocones (red lines) reached at as compared with previous DPTs (black lines going to refusal)

The explanation is typical: increasing friction as penetration is longer gave way to apparent refusal (to penetration) but not actual one, according to piezocones results.

Subsequently no shallow foundation nor piled was considered from then on, and new designs were proposed.

Consolidation tests in oedometer cell gave way to Cv=1.7E-03 cm^2/s, much slower than Coruña muds but quicker than other sites.

3.2.3. Piezometer readings

VW piezometers performed well. The relative position (middle, ¼ and ¾ of consolidating layer thickness allowed comparing with theoretical isochrones corresponding to different Cv values. Then, a new (actual) computation was conducted, concluding that Cv=7E-03 cm2/s, that is, 4 times the one got from lab tests.

3.2.4. Other conclusions

The original design concept was discarded and a sheetpile wall was proposed with subhorizontal anchorage near the head of the sheetpiles wall, as it was built later on.

This case history was explained at ISC'2 (Porto, Portugal, 2004)

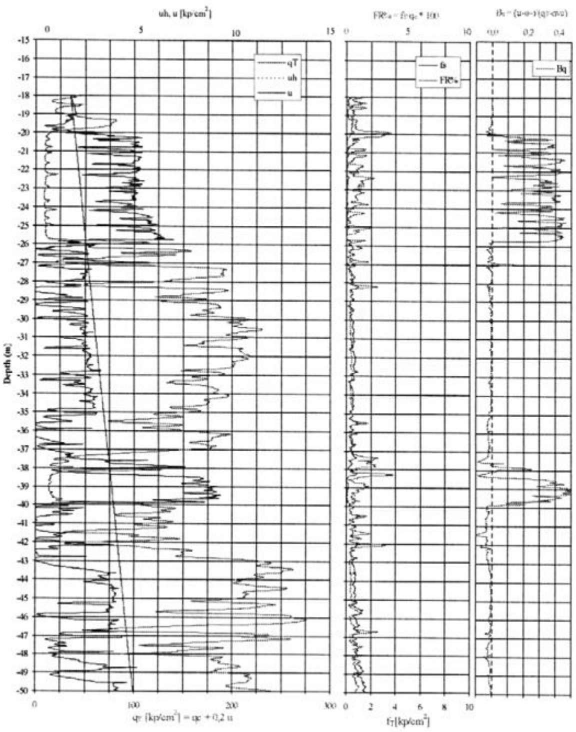

Figure 6. CPTU-2 at Barcelona port project

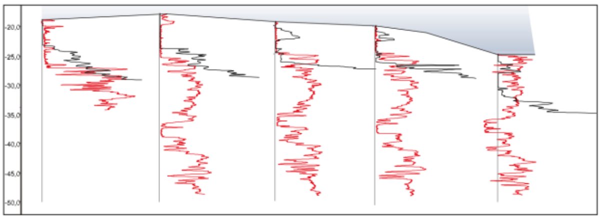

Figure 7. Comparison between DP and qT from CPT (up to –50 m) results at Barcelona Port

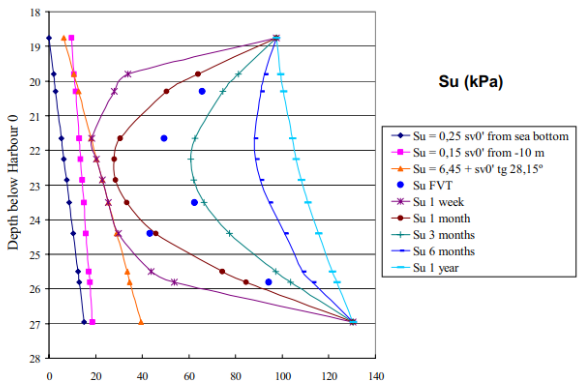

Figure 8. First estimates and evolution of undrained shear strength in the first clay layer at Barcelona Port Project

3.3. New Container Terminal at Cadiz Port

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 a 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 after and 50 CPTUs replicated before 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 a markedly accurate method.

Several different instruments and/or tests have been forecasted. Main tests were piezocones (CPTU) both before and after reclaimed land was performed, with a multiple aim. First, getting a good appraisal of soft soil thickness. Dissipation tests were also performed.

Several methods (hyperbolic, Sridaharan, etc…) were 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 these days.

A new curve-fitting model was developed to assess Cv values. The model is supported by some hypothesis. This model was developed in three steps:

- At first approach best fitting straight line for the time before wick drains driving. The least squares criterion is used. And Cv is estimated.
- Iterative model to fit consolidation curve based. The process to fit the consolidation curve in every iteration implies modeling the pair of values CR and Cv until finding this pair of values making the slope (of this first stage) and the remaining settlement from the point the wicks were installed onwards to match the expected.
- After finding these parameters defining the soil behavior and original thickness of the layer, the goal is finding the C_h that makes remaining settlement at t_3 matching the expected previously assessed by Asaoka.

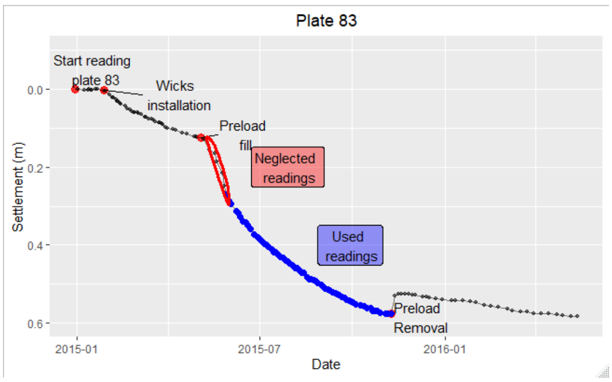

Figure 9. Readings used to estimate long term settlements. Neglected readings.

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

Table 1. Basic statistics of the resulting analysis

	mean	median	range	se
CR	2.33E-01	2.3 E-01	9.95 E-02	8.2 E-03
Cv (cm^2/sg)	2.6E-03	2.72E-03	3.03E-03	2.E-04
Ch (cm^2/sg)	2.8E-03	2.66E-03	1.26E-03	1E-04
Ch/Cv	1,1500	1,05000	1,00000	0,1031

With these results, it is worth noticing the significant difference of this figures with that obtained from in situ tests and laboratory tests (Ch ≈ 1.03E-02 cm2/s and Cv ≈ 3E-04 cm2/s). However, this would be concurrent with several studies such as Leroueil et al or 0 for homogenous clays.

4. Summary and conclusions

Three case histories are presented.

The common features are:
a) Reclaiming land is in play, as there is growing need for more and more stocking facilities in ports
b) All of them are situated in Spain
c) Big settlements are forecasted because of existing thick soft sediments
d) Use of piezometers as part of monitoring tasks
e) Preloading as a mean of reducing residual settlements
f) Taylor method is preferred in order to derive the coefficient of consolidation in lab

Differential ones are:
z) Two of them are in Atlantic Sea; Coruña at NW and Cádiz at SW with high tides, while the other one is located at Mediterranean Sea with low tide, in Barcelona
y) Coefficient of consolidations are very different: from 1E-02 cm2/s (Coruña) through 1.7E-03 cm2/s (Barcelona) and as low as 3E-04 cm2/s , according to oedometer tests in laboratory
x) Actual values of Cv were obtained, being many times the lab value, 4 in Barcelona case, 8.3 in Cádiz case (in this case Ch was predominant over Cv because of wick drains installation. In Coruña case, it was enough to confirm the high value of Cv, essential to confirm the possibility of using “terrestrial” methods for cast-in-place concrete piles-
w) Confirmation of previous thought conceptual design in Coruña and Cádiz (with wick drains in this case), but shifting from piled concrete structure to sheetpiles anchored wall in Barcelona
v) A curve-fitting method for computation of Cv is proposed starting from settlements readings.
It is highlighted the importance of a good monitoring, including piezometer readings at different positions inside the (more) compressible layer.
Besides, Cone Penetration Tests with measurement of pore pressures, colloquially piezocones are strongly recommended. In Barcelona case, they resulted essential in decision of changing the conceptual previous design. At Cádiz case they were performed before and after preloading with more earth fills. They were not available in Spain before 1990, so in Coruña case they were not implemented.

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