Embankment design with DMT and CPTu: prediction and performance

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Keywords: CPTu, DMT, settlement, deformability, stiffness, deltaic, embankments

ABSTRACT: Ongoing enlargement of the Barcelona Airport at Prat de Llobregat required a major road access redesign. Major earthworks were necessary both for preloading purposes and to build the final motorway embankments. Accurate settlement prediction was necessary, and it was largely based on "in situ" tests. DMT was the basic tool to predict final settlements, while CPTu provided the necessary information to evaluate consolidation times. The motorway embankments are now approaching completion. Several instrumented sections have been employed for the detailed monitoring of settlements. Instrumentation-revealed settlements are presented and compared with those predicted at the design stage. Comments are made on the adequacy or else of the several hypothesis employed for design.

1 INTRODUCTION

Barcelona is the second largest city in Spain. The Llobregat delta plain is located just south of Barcelona and is the location of our study. It hosts an expanding population, a large number of basic infrastructures, important industrial areas as well as several natural reserves and tourist resorts.

1.1 *Geological setting*

The geological structure of Llobregat delta is similar to other Mediterranean deltas. A wedge of low plasticity silty and clayey deposits, increasing to a thickness of 60 m near the shoreline, overlies a deep sandy and gravelly aquifer and is overlaid by a roughly 10 m thick, well-graded, medium-dense sand layer. A superficial thin deposit of alluvial and marshy clays sometimes occurs on top. A detailed CPT-based stratigraphic and sedimentological analysis of Llobregat delta is presented by Devincenzi et al. (2004).

The water table is located in the upper sand, generally at 1 to 1.5 m depth. These sands are highly permeable with equivalent permeability of 10^{-2} cm/s. On several isolated spots the sands had been quarried, being generally replaced by uncontrolled fills.

1.2 *Local geotechnical practice*

Past experience in the area clearly indicates that the main foundation problem appears as a consequence of the medium to high compressibility of the intermediate silts and clays. The upper sand offers a fairly good foundation level, but large settlements may ensue when the load extent is such that silts and clays are also affected.

The depth of the lower aquifer makes any attempt to support foundations using piles non-feasible. Apart from that, the lower aquifer is also a vital water resource of the area, and stringent environmental rules severely limit its perforation by piled foundations. On the other hand the frequent presence sandy layers within the silty and clayey levels, generally results in a relatively fast consolidation. These circumstances make preloading a sensible choice in many instances (e.g. Alonso et al. 2000, Gens & Lloret, 2003).

Settlement evaluation requires an estimate of soil stiffness. The critical silty and clayey layers present great sampling difficulties, partly due to the presence of finely interbedded sandy layers. There-fore intact sample recovery is problematic and laboratory measurements of "in situ" stiffness are scarce and probably biased. For large projects, large instrumented load tests have been employed to overcome the ensuing uncertainty.

The traditional "in situ" measurement in the area was SPT. Since the early 90's CPTu testing has become common practice. Pressuremeter testing is also

BACK

sometimes performed. There was no previous large-scale experience of DMT testing.

Figure 1. Projected enlargement of El Prat airport (Barcelona). A solid line encloses the motorway project area.

2 EMBANKMENT DESIGN

2.1 *Project description*

The new terminal building of Barcelona Airport will serve up to 25 million passengers per year (Fig. 1). The road access to this new terminal is de-signed as a 8-lane motorway. This motorway flies over a relocated 6-lane motorway, a major flood de-fence waterway, railway access to the airport and various minor roads.

These many obstacles force the motorway into heights of 12 m and above for more than 2 km. A number of large embankments alternate with several bridges and caisson type structures. The expected schedule for work completion is less than 3 years and the construction sequence may include several successive enlargements.

It was clear from the onset that the width and length of the embankment loads wouls cause large settlements. Embankment settlement was important “per se” and also because of its possible influence on old or recently built structures

It was also anticipated that structural loads, even if smaller than those induced by the earthworks, would cause settlements unacceptable for good structural performance. Preloading was the obvious solution. However, the preloaded embankments were subjected to a strict schedule, since the material available for earthworks was very scarce, and needed for the motorway embankments.

Within these project constraints, estimating the magnitude and rate of embankment induced settlement became a critical design issue.

2.2 *Site investigation*

The site investigation program included rotary coring, laboratory tests, DMT and piezocone probes. The resulting stratigraphic picture fell well within expectations. In the project area the mean depth of the lower aquifer was 40 m. A roughly 30 m thick intermediate layer of silts and clay appeared between the upper sands and the lower aquifer. In some places the upper sand had been replaced by uncontrolled fills.

More details from the site investigation program and the results obtained might be found in Arroyo et al. (2004).

2.3 *Design approach*

As expected, sampling problems were pervasive on the softest layers, resulting on very few quality samples to obtain stiffness with. SPT values were numerous, but also deemed too unreliable and approximate to be employed as a design tool. Therefore, the general design approach relied mostly on in-situ probes. DMT probes were selected as the basic tool to evaluate settlement magnitude, while CPTu data were mostly used to ascertain set-tlement rate.

The DMT-based settlement evaluation procedure was pretty standard. The method (Marchetti, 2001) involves approximating a 1-D integral of deformation using an expression like

$$S = \int_{E}^{H} \varepsilon(z)\,dz \approx \sum_{z_i=E}^{z_i=H} \frac{\Delta\sigma_v(z_i)}{M_D(z_i)}\Delta z \qquad (1)$$

The formula uses two depth-dependent distributions, that of constrained moduli, $M_D(z)$, obtained from a DMT test and an incremental stress distribution $\Delta\sigma_v$ (z). The latter was obtained from elastic closed-form solutions; this process involved some extra approximations, particularly considering the highly contrasted stiffness profile. The S value thus obtained corresponds to a drained, long-term, post-consolidation, settlement

The above procedure can be easily generalised to account for consolidation. To do so, $\Delta\sigma'_v$ (z,t), a time-dependent effective incremental stress distribution is used in (1). This distribution is computed by means of

$$\Delta\sigma'_v(z,t) = \Delta\sigma_v(z)\,U\left(\frac{tc_v}{H^2}\right) \qquad (2)$$

where U represents a consolidation degree given by the classical Terzaghi 1-D theory. Apart from time, t, U depends on the vertical consolidation coefficient, c_v, and the distance to a free draining surface, H. These two values were obtained using the CPTu probes.

Piezocone dissipation tests were interpreted following Teh & Houlsby (1991) to obtain horizontal

BACK

consolidation coefficients (c_h). Some results from laboratory oedometric tests on the most fine-grained layers were also available. In Figure 2 both datasets are plotted together, revealing large differences between field and laboratory results.

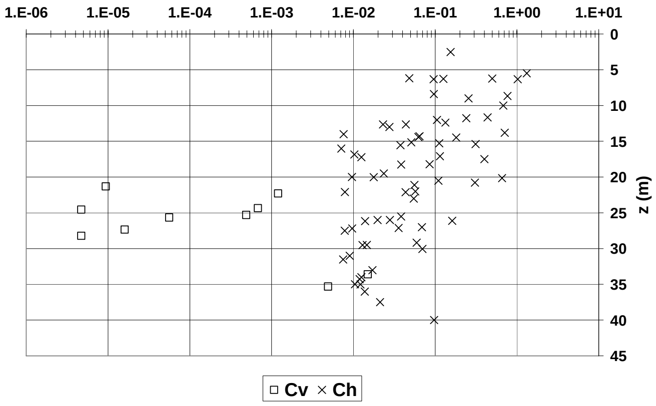

Figure 2. Consolidation coefficients obtained from field (Ch) and laboratory data (Cv).

Admittedly, such differences are not uncommon (Schnaid, 2005), but they still leave ample room for choice. In this case, and based on previous load test results in the area (Alonso et al. 2000), a unique c_v of $4*10^{-3}cm^2/s$ was chosen for the silty and clayey deposits. The upper sands were considered as free draining.

The choice of a drainage distance value, H, is of greater consequence to the computation than that of the consolidation coefficient. In our case the H value to employ in (2) was directly based on piezocone logs. A depth-dependent H(z) was selected inspecting the excess pore pressure log of the piezocone. This resulted in H(z) distributions for each piezocone, an example of which is shown in Figure 3. The selection procedure had a deliberately conservative bias, intended to roughly compensate possible lateral discontinuities of the draining layers.

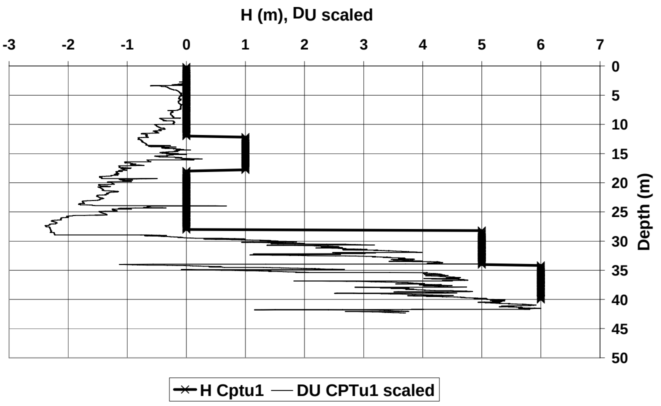

Figure 3 Excess pore pressure log (scaled) and interpreted undrained average distances, H.

Two final aspects of the design approach are worth mentioning. One is that, initially, a relatively small amount of secondary consolidation was also taken into account, since there were some reports pointing to its importance (Alonso et al. 2000). Secondary consolidation was conspicuously absent from the monitoring measurements, and therefore the "predicted" results in this paper have been removed of these extra settlements. The second aspect is that a performance-based relation between CPTu and DMT (Arroyo et al., 2004) was employed to supplement the lack of direct DMT data on some emplacements. None of the cases described in the following lacked direct DMT data, and therefore none is analyzed using such relation.

3 CASE STUDY DESCRIPTION

Results from three monitored case studies, including five different embankments will now be presented.

The first case study corresponds to three closely spaced pre-loading embankments, located in an area where the geotechnical profile is fairly typical of the Llobregat delta average.

The second case study corresponds to a permanent embankment, located in an area where the site investigation revealed an important layer of very soft mud.

The third case study corresponds to an embankment located in an area where the upper sand layer was replaced by made ground.

3.1 *Case study 1*

Three embankments (P-10, P-10s, and P-10m) were built nearby to pre-load the area of construction of a box culvert and two overpasses.

Preload embankment P-10 was the largest. It has an irregular plan area, with length of about 100 m at the top and an average width of about 50 m. The maximum embankment height was 12.75 m and it was constructed in 78 days.

Preload embankment P-10s was approximately square in plan, with 50 m per side. It was raised to 11.85 m and the construction lasted 150 days. Preload embankment P-10m was also square in plan, with a 40 m side. It was raised to 12.20 m in a 60 day period.

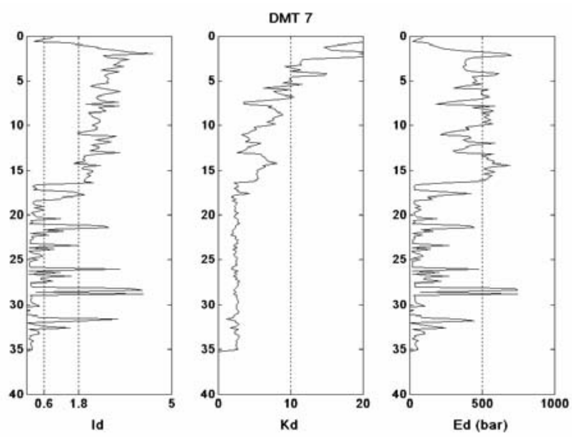

Figure 4: Typical DMT profile at Case 1 location

BACK

Settlement evaluations for embankments P-10 and P-10s were both based on the results of dilatometer DMT7 and piezocone CPTu7. Settlement evaluation for embankment P-10m was based instead on tests DMT14s and CPTu14s. An example of the DMT profiles obtained in the area is shown in Figure 4. The upper sand layer is clearly visible.

The three preload embankments were monitored with settlement plates, plus horizontal and vertical inclinometers. In Figure 5 the instrumentation outlay for embankment P10m is illustrated. The arrangement for the other embankments was very similar.

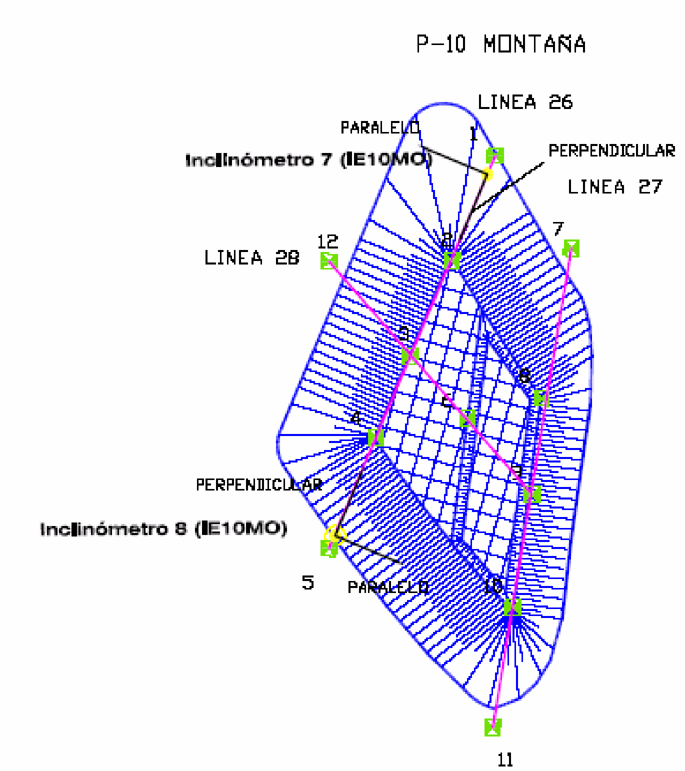

Figure 5. Instrumentation outlay for embankment P10m

3.2 *Case study 2*

This is a permanent embankment, 12 m high, 80 m wide and 190 m long, located on the main axis of the motorway. Construction started in April 2005 and, while not yet finished, had attained a height of 4.5 m at the time of writing. Embankment is being monitored using settlement plates, horizontal and vertical inclinometers and an extensometer.

Soil investigation at the embankment location initially included two dilatometers (DMT4 and DMT5). They revealed softer than average silt layers. As a consequence of the large embankment load, the dilatometer settlement evaluation indicated an average of 2.5 m of long term settlement. The extra volume of material required to compensate such settlement was not negligible, and it seemed convenient to confirm the dilatometric results by performing another sounding. Test repeatability was good and the prediction of large settlements was confirmed. It is noteworthy that the accompanying piezocone (CPTu4) would have not given enough indication of such a large deformability.

An example DMT profile at this case is shown in figure 6. The very soft layers below the upper sands are clearly visible.

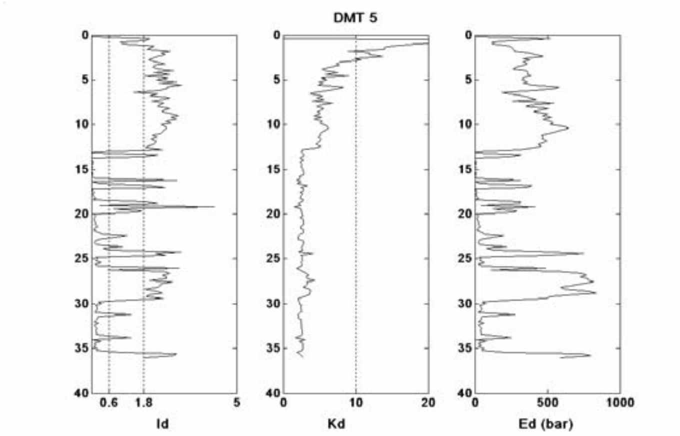

Figure 6. Typical DMT profile at Case 2 location

3.3 *Case study 3*

The third case study corresponds to an area where the upper sand layer had been replaced by uncontrolled fills. Both rotary drilling and in-situ tests detected the presence of the fills, whose thickness varied between 4 and 8 m.

The piezocone and dilatometer results in that layer were unreliable, erratic and frequently lacking pressure readings (Figure 7).

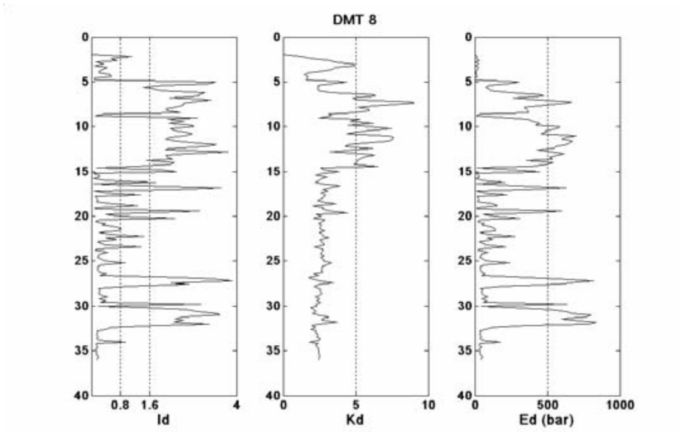

Figure 7. Typical DMT results at case 3 location. Estimated fill thickness at this point: 6 m.

A large culvert box structure is planned in the area, and preloading was necessary to ensure acceptable settlements. A preloading embankment, 11 m high, 17 m wide and of 120 m long, was constructed in 10 weeks.

As shown in Figure 8, the preload embankment was monitored using settlement plates, horizontal and vertical inclinometers and an extensometer. However, this extensometer was only operative for a month, since it was damaged early after the start of construction operations.

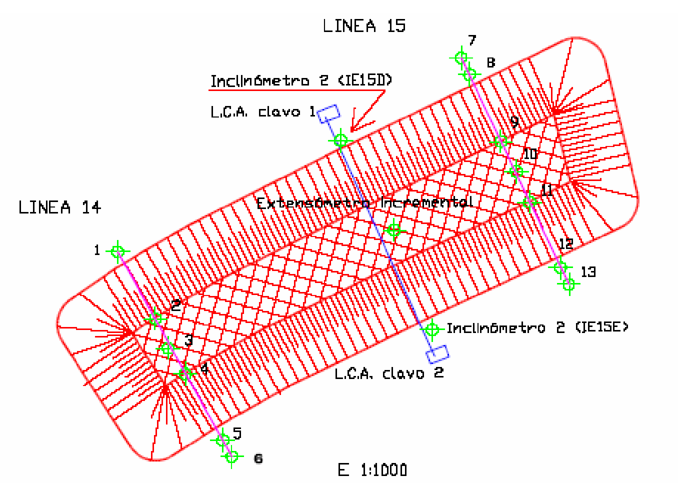

Figure 8. Instrumentation outlay for Case 3. LCA indicates an horizontal inclinometer. Numbers 1 to 13 indicate settlement plates.

4 RESULTS

4.1 *Case study 1*

In Figure 9 the settlement evolution predicted along the centerline of embankment P10 is compared with the settlement measured by a plate located there. Initially, the computations had assumed a very fast construction, i.e. quasi-instantaneous load application. In practice, it took over two months for the embankment to reach its maximum height of about 12 m. When the real load history is taken into account the predicted settlement agreed very well with the measured settlement.

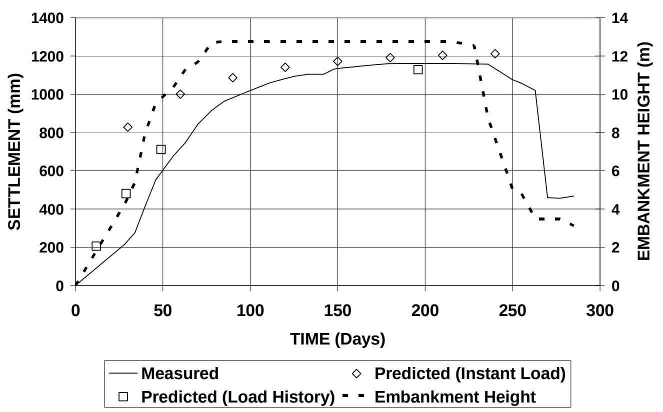

Figure 9. Time-history of embankment loading, measured and predicted settlements for P10 (Case 1).

The settlement seemed to stabilize after 150 days. The final consolidation settlement value measured has an excellent agreement with that predicted with the DMT. Similar results were obtained with the other two nearby embankments, P10m and P10s as shown in Figure 10.

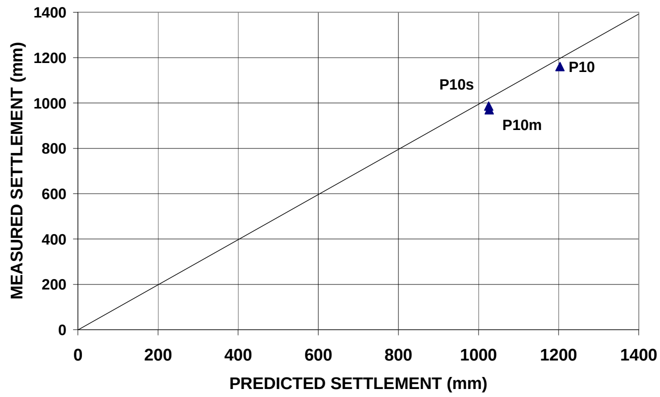

Figure 10. Predicted vs measured settlement at the end of consolidation at embankment centerline

4.2 *Case study 2*

As explained above, this embankment has not yet reached its design height. In Figure 11 the load history is plotted alongside the measured settlement at a plate located at the embankment centerline. The figure includes the measured settlement at the top of a nearby extensometer and the DMT-predicted settlement history. The prediction was obtained taking into account the load history of the embankment.

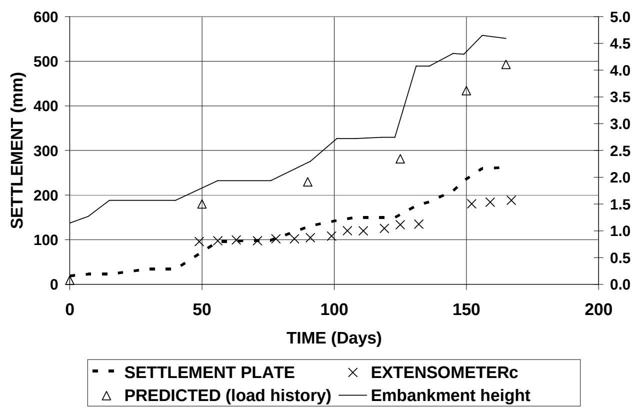

Figure 11: Time history of loading, measured and predicted settlements for Case 2.

It is fairly clear that the settlement prediction here obtained is too conservative, nearly double of that measured by the settlement plates. Some insight into the sources of this error might be obtained by looking in more detail at the DMT prediction.

Such a detail is provided, in principle, by the extensometric readings. In fact, the extensometric readings available in this case pose some problems of their own, like their late start or their divergence from the plate readings, visible in Figure 11. Notwithstanding these difficulties a comparison is attempted in Figure 12 for the settlements measured as a response to the loading step of approximately 1.5 m made 125 days after the construction started.

The comparison shows that there are two main causes for the divergence between measured and predicted settlements. The first is the greater depth of the upper rigid layer at the extensometer location:

BACK

16 m vs 12 m for the assumed profile. The second cause is the larger settlements predicted for the deeper clayey layers. It remains yet to be seen if the prediction error is due here to a DMT-based underestimate of the operative drained moduli or to a CPTu-based overestimate of the settlement rate.

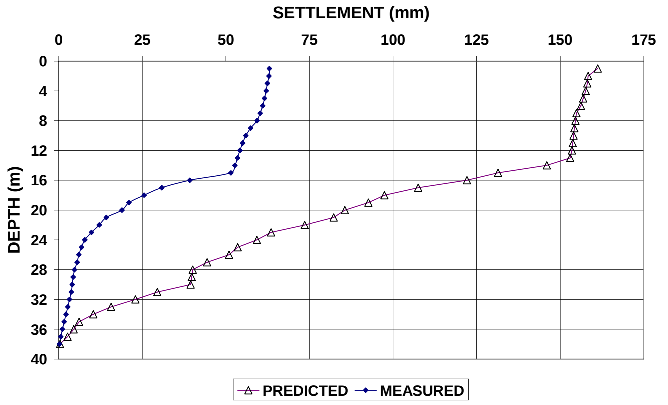

Figure 12. Settlement vs depth distributions predicted and measured in case 2. Prediction made by DMT-CPTu method for a load step of 1.5 m at 125 days.

4.3 *Case study 3*

In this case, as in case 1, the preload history is complete. Figure 13 shows that both load and settlements were almost level for a period of nearly 100 days. The figure presents measurements obtained with different instruments: two different settlement plates, an horizontal inclinometer (LCA in Figure 8) and an extensometer. There are important variations in the measurements of the to different instruments. This may be partly attributed to the different thickness of fills present alongside the embankment.

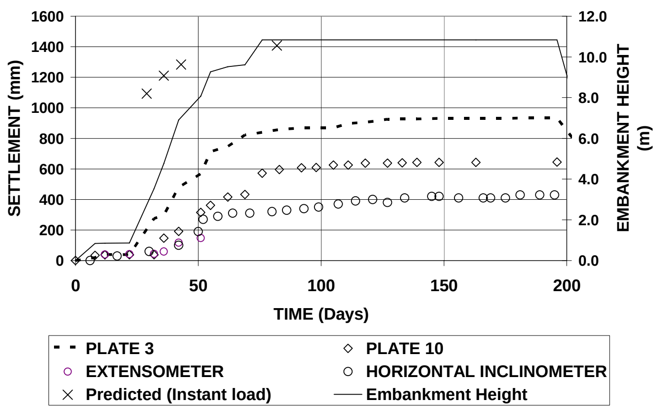

Figure 13. Time-history of embankment loading, measured and predicted settlements for Case 2.

However variable the fill thickness was, it is clear that a large part of the discrepancy between measures and prediction may be attributed to the conservative characterization of the fill at the design stage. The poor results of the DMT measurements in the fill were compensated with a very conservative estimate of the fill operative modulus. This is clear in Figure 14, where the 5 upper meters of fill contribute almost half of the surface settlement.

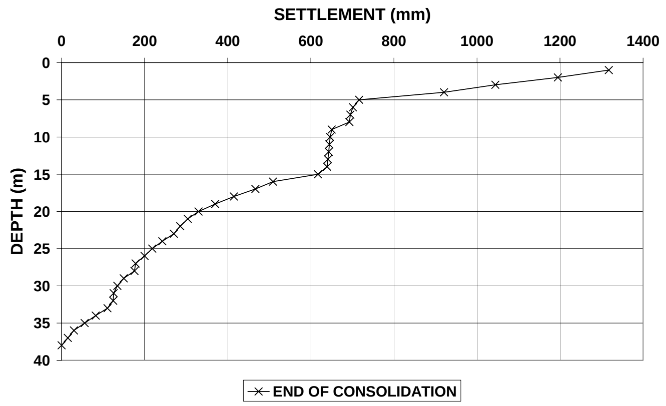

Figure 14. Depth distribution of the predicted consolidation settlement for Case 3.

As shown in figure 13, the extensometer present in this case failed quickly, only after nearly 50 days of embankment construction. At that stage the accumulated settlement measured by the instrument is shown in figure 15.

The extensometer readings do not suggest there is a fundamental change in stiffness between made ground and soil as assumed in design. If this error is removed from the DMT-prediction shown in Figure 14, the final settlement value estimated would have compared much better with the settlement plate measurements (600 to 900 mm, Figure 13).

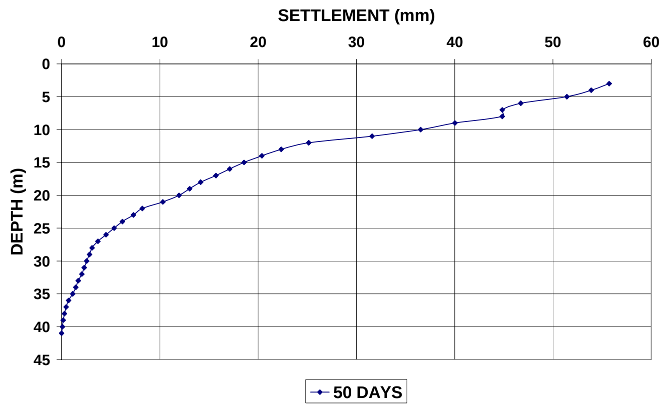

Figure 15. Last valid reading of the extensometer in Case 3.

4.4 *Other aspects*

None of the previous cases had included piezometers within the monitoring measurements. That decision was partly based on the generally poor performance of these instruments on the Llobregat delta area. In fact, measurements taken with vibrating wire piezometers in other embankments of the project were always unable to register any excess porepressure.

5 SUMMARY AND CONCLUSIONS

This paper has presented results from several embankment loads on a deltaic area where large settlements have been measured. These measurements have been compared with settlement predictions

BACK

made with DMT and CPTu. Three cases were presented.

In the first case consolidation is complete and the ground profile is regular and did not include any large pockets of very soft mud or made ground. The end of consolidation DMT-predicted settlement fits almost perfectly with the measurements. The CPTu-based prediction of consolidation is acceptable.

In the second case the ground profile is more varied, due to the presence of pockets of very soft mud. The settlement prediction seems over conservative. Since consolidation is not yet complete, it is not possible to determine if the measured settlements will continue to increase until they more closely match the DMT or CPTu predictions.

The emplacement of the third case is full of fill of varying thickness. The preload embankment completed its settlement, attaining a lower final settlement than that predicted with the "in situ" probes. The prediction error can be mostly attributed to an incorrect characterization of the fill, partly due to failing "in situ" measurements.

In balance, it may be said that the combination DMT-CPTu has proved itself a very useful instrument for settlement prediction in this deltaic area.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the permission of AENA to use the data presented in this work.

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BACK