

Field measurements of the settlements induced by preloading and vertical drains on a clayey deposit

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Abstract – The paper describes the results of an almost two-year long monitoring period of the field performance of the foundation soils of two tanks founded on a clay soil deposit improved using the technique of preloading and vertical drains. During the preloading period settlements were monitored measuring the vertical displacements of settlement platforms by topographic survey. During the hydraulic leakage tests of the tanks their settlements were measured using a level probe along a flexible pipe placed in a shallow excavation under each tank. The measurement results are discussed showing their usefulness in the application of the Asaoka procedure for settlements prediction. Despite the significant influence of the lithological and mechanical heterogeneity of the foundation soils, absolute and differential settlements of the tanks, as well as angular distortions, resulted consistent with allowable limits envisaging a satisfactory performance of the tanks.

I. INTRODUCTION

The use of the observational approach in geotechnical engineering projects allows savings in cost or programme [1]. Accordingly, it was widely adopted with reference to full-scale geotechnical systems or reduced-scale physical models, to monitor or predict the static [e.g. 2-4] and the seismic [e.g. 5-7] performance.

In this framework, the paper describes the results of an almost two-year long monitoring period of the field performance of the foundation soils of two large steel tanks (diameter of 19 m and height of 15.6 m) founded on a medium to stiff clayey and silty soil deposit improved using the technique of preloading associated with 20 m long prefabricated vertical drains.

Figure 1 shows the plan view of the construction site together with some relevant sections describing the main preloading embankment ($H = 9.2$ m) and the placement of the two tanks whose foundation consist of a reinforced concrete ring filled with compacted sand.

In-situ investigations, including boreholes, cone penetration tests and dissipation tests, and laboratory tests were carried out to define the geotechnical profile of the construction site and the mechanical properties of the foundation soils of the two tanks. Furthermore, an extensive field monitoring of the site was carried out

during the preloading period and during the hydraulic leakage test of the tanks.

A detailed description of the geotechnical characterization and of the work sequence is provided in [8]. In the present paper some of the measurement results are presented highlighting the significant influence of the lithological and mechanical heterogeneity of the foundation soils on the tanks settlement response.

The monitoring results are discussed showing their usefulness in the application of the Asaoka procedure for settlements prediction and in the detection of possible occurrence of serviceability limit states of the tanks during their service life.

II. MONITORING DURING THE PRELOADING PERIOD

During the preloading period and the preloading embankment removal settlements were monitored measuring, by topographic survey, the vertical displacements of 20 settlement platforms (*SP* in Fig. 1). Measurements started some days before the beginning of the embankment construction ($t = 0$) and were taken about every 3 days for a period of 284 days, until the embankment was removed. Figure 2 a,b and 3a show the time-settlement curves observed at the platforms in the areas where the two tanks had to be built and in the centre of the main preloading embankment. The curves exhibit the typical concave shape in the first 98 days (embankment construction) and then become convex during the preloading period. A sudden increment of settlements was measured at about 144 days from the beginning of the embankment construction, due to the achievement of the full saturation in the drainage system [8]. Differences in the values of final settlements are apparent depending on the location of the settlement plates. Maximum settlements under the embankment were in the range 36-39 cm and, as expected, occurred along the longitudinal axis (*SP8*, *SP12*, *SP18*); points located north of this axis (i.e. *SP5* and *SP17*) showed a stiffer response than the corresponding points located south of the axis (i.e. *SP7* and *SP19*), with differences in measured settlements of about 6.6 cm between *SP5* and *SP7* and of about 7 cm between *SP17* and *SP19*. This result may be ascribed to the lithological and mechanical heterogeneity of the soil deposit.

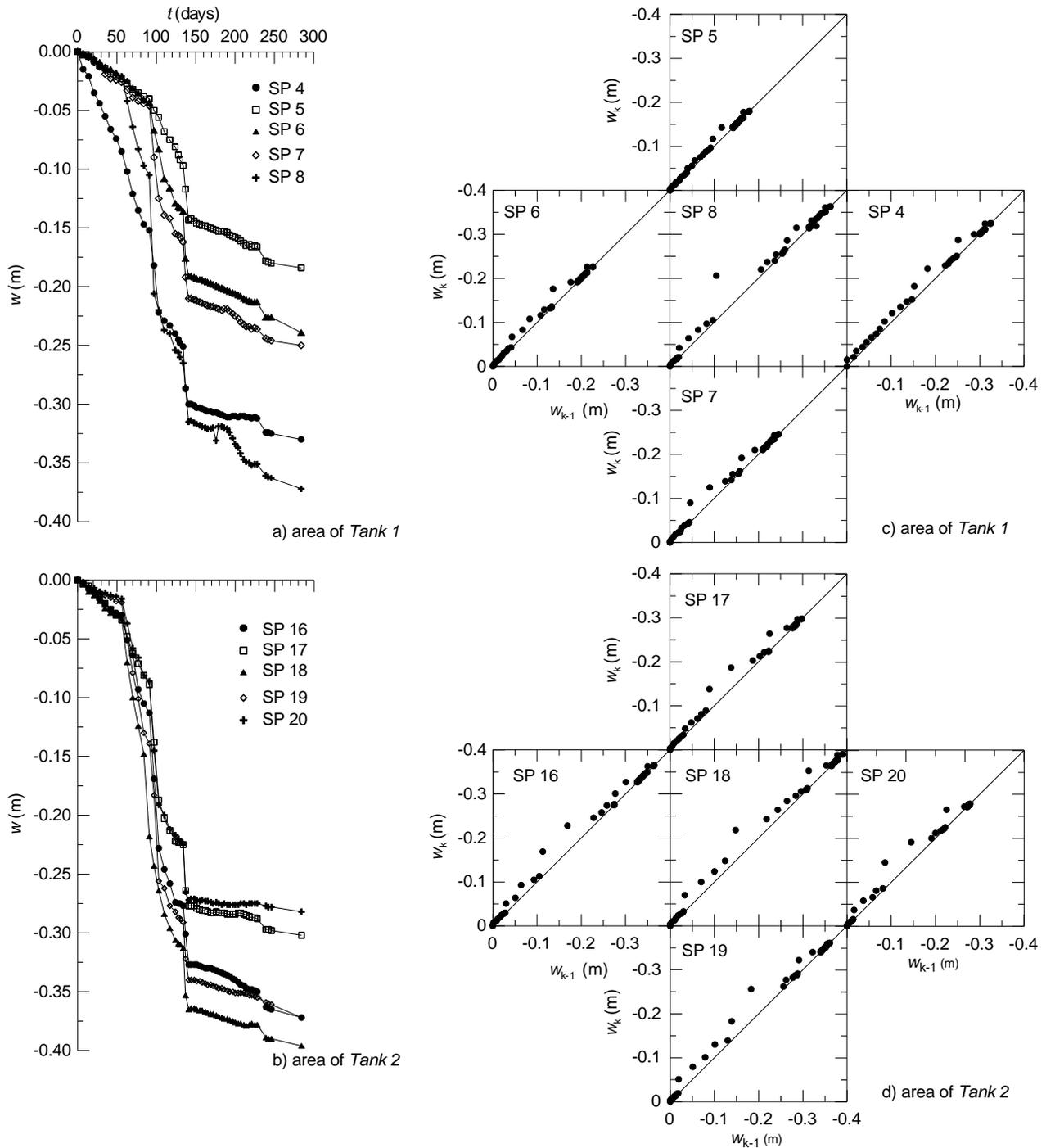


Fig. 2. Preloading period: settlement time-histories (a,b) and Asaoka plots (c,d) observed at the platforms in the areas where the tanks had to be built.

During the emptying phase a significant fraction of the settlements was recovered. Maximum settlements w_{\max} under the centre of the tanks are about 6-7.5 cm. Figure 4 c,d displays the Asaoka's plots for the settlement measurements carried out at the centre and at one of the tank edges: points in the plots exhibit, especially for the case of *Tank 1*, a trend to align along the bisector. At the

edges of the two tanks the settlement variation, due to filling and emptying, resulted always less than 3 cm, consistently with the prescribed design limit. This confirmed the effectiveness of the improvement technique adopted at the site and allows predicting a satisfactory performance of the tanks.

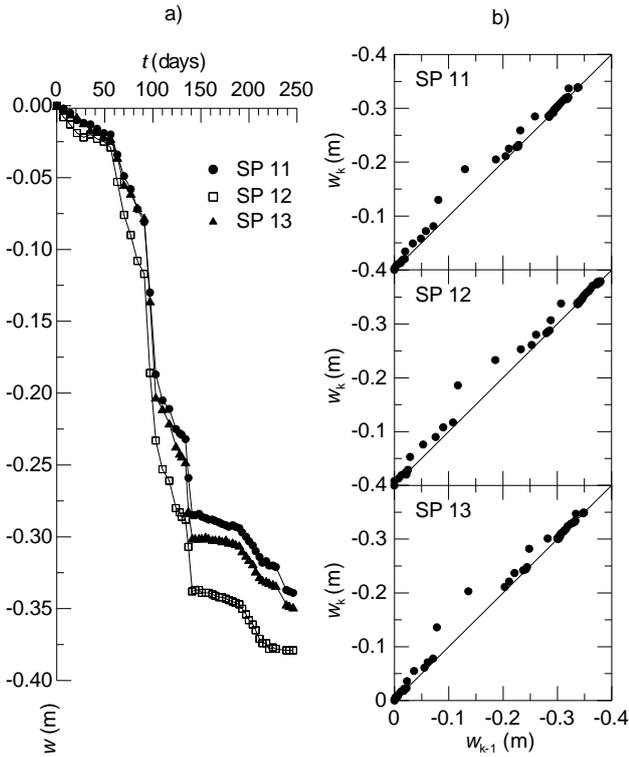


Fig. 3. Preloading period: settlement time-histories (a) and Asaoka plots (b) at the centre of the embankment.

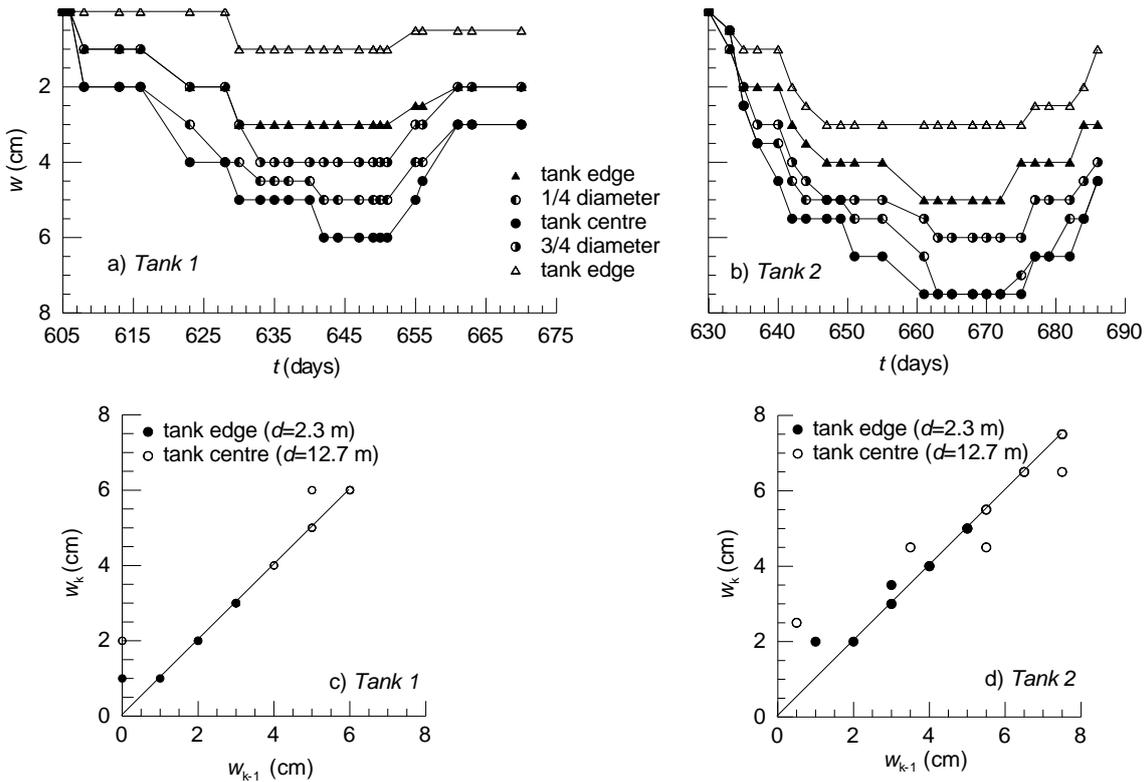


Fig. 4. Hydraulic tests of the tanks: a,b) settlement time-histories; c,d) Asaoka plots.

In Figure 5 the settlement profiles are shown in a normalized diagram where the settlement w and the radial distance r are divided by the settlement w_{max} and by the tank radius R , respectively. Both tank foundations exhibit the classical dish-shaped settlement profile with larger values near the centre and settlements that decrease smoothly toward the edges.

Despite the symmetry in the tank structures and in the applied load, settlement profiles are not symmetric; again, a stiffer response of the northern area of the tank foundation can be attributed to the lithological and mechanical heterogeneity of the alluvial deposit.

The effect of the soil heterogeneity on settlement response becomes apparent by comparing the profiles of measured settlements with the profile shapes (shaded area in Fig. 5) suggested by D’Orazio and Duncan [8] for tanks overlying homogeneous soil deposits.

IV. CHECKING SERVICEABILITY LIMIT STATES OF THE TANKS

As it is usual in the case of dish-shaped settlement profiles [9,10], the possible occurrence of a serviceability limit state of the tank bottom has been checked referring to threshold values δ_{lim} of the differential settlement δ_R between the centre and the edge of the tank and to threshold value β_{lim} , of the angular distortion [8, 9].

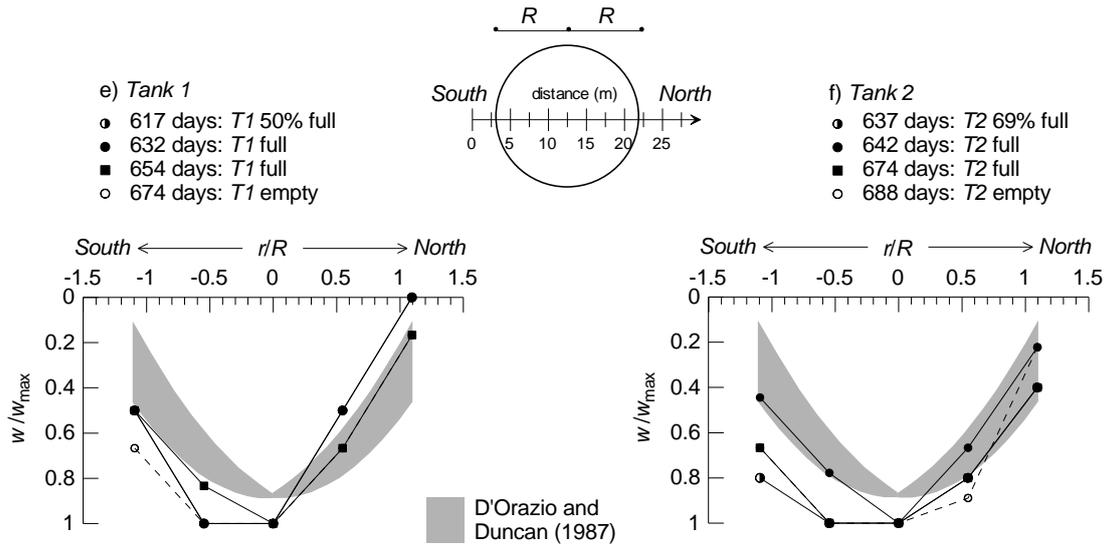


Fig. 5. Hydraulic tests of the tanks: settlement profiles.

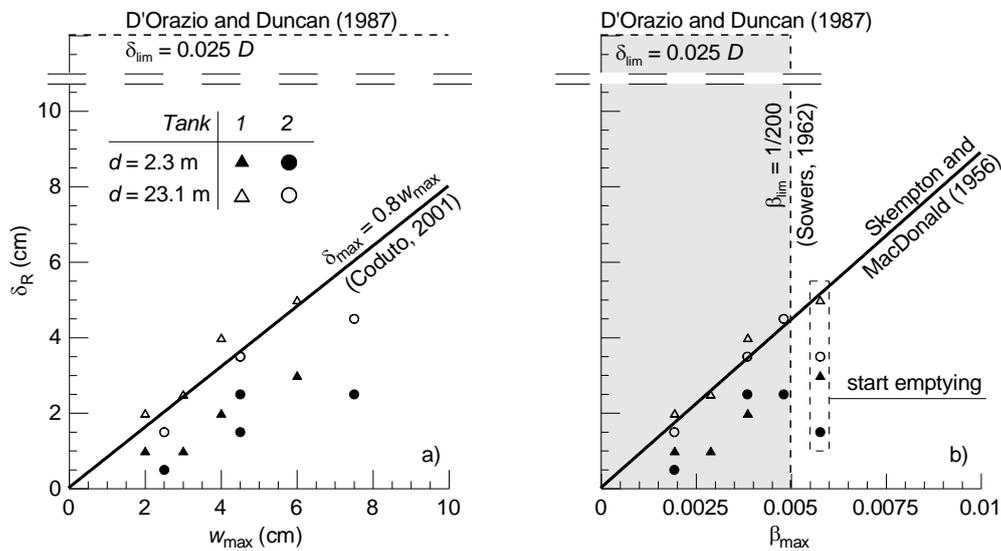


Fig. 6. Checking serviceability limit state of the tanks bottom.

In Figure 6a the differential settlements δ_R , computed at both edges ($d = 2.3$ m, $d = 23.1$ m) of the tanks (Fig. 5), are plotted against the maximum absolute settlement w_{max} measured, at different dates, at the centre of the tanks.

It can be observed that, despite the considerable values of the maximum settlement measured at the tank centre ($w_{max} = 2 \div 7.5$ cm) and the rigid rotation ($\alpha_o = 0.5 \div 1\%$), the differential settlements δ_R are always in the range 3-5 cm and, thus, are much smaller than the threshold value $\delta_{lim} = 47.5$ cm that can be estimated according to the recommendation by D'Orazio and Duncan [9] for steel tanks of diameter D : $\delta_{lim} = 0.025 \cdot D$. Furthermore, for

most of the data plotted in Figure 6a, the design δ - w_{max} relationship proposed by Coduto [11] represents a conservative upper-bound.

In Figure 6b the values of δ_R are plotted versus the maximum value of the angular distortion β_{max} computed, along the north-south axis of the two tanks, from settlement measurements [8].

Despite β_{max} increases with δ_R , its values resulted generally lower than the threshold limit $\beta_{lim} = 1/200$ suggested by Sowers [12]. Moreover, for most of the data in Figure 6b the empirical relationship $\delta = 350 \cdot \beta$ proposed by Skempton and MacDonald [13] for buildings

is approximately an upper bound.

All the computed data are within the shaded area in Figure 6b delimited by the thresholds limits, δ_{lim} and β_{lim} , suggested by D’Orazio and Duncan [9] and by Sowers [12], respectively. The only exception is represented by the measurements carried out at the start of tank emptying which exceed the limit $\beta_{lim} = 1/200$; however, no damage was observed in the tank steel structure and in the piping connections during and after the hydraulic leakage tests. Thus, it is confirmed that the recommended criteria to check the occurrence of a serviceability limit state should be based on maximum and differential settlements rather than on angular distortions.

For the considered case study, despite the lithological and mechanical heterogeneity of the foundation soils significantly affected the tanks settlement response, maximum absolute settlements and angular distortions resulted consistent with allowable limits.

V. CONCLUDING REMARKS

In the paper a well-documented case history concerning the improvement of the foundation soil of two large tanks through the method of preloading and prefabricated vertical drains is described.

Data of the observed behaviour during the preloading period and the hydraulic leakage tests of the tanks were collected during an almost two-year long monitoring period.

In situ settlement measurements confirmed the effectiveness of the technique adopted in the project even if pointed out that the lithological and mechanical heterogeneity of the foundation soil deposit significantly affects the tanks settlement response.

Differential settlements and angular distortions were compared with expected profile shapes for tanks overlying homogeneous compressible soil layers. A general fair agreement was observed even if the heterogeneity of the soil deposit affects the tanks response.

Absolute and differential settlements, as well as angular distortions, resulted consistent with allowable limits envisaging a satisfactory performance of the tanks under service conditions.

Accordingly, the large set of measurements collected during field monitoring will allow a suitable numerical modelling with the final aim to calibrate a predictive tool for the behaviour of the tanks under service conditions and of future installations at the site.

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