doi:10.1680/ecsmge.60678

Institution of Civil Engineers
publishing

Load-settlement behaviour of three pile groups: a case study

Le comportement de trois groupes de pieux vissés : étude d’un cas réel

P.O. Van Impe*[1,2], W.F. Van Impe[1,2] , A. Manzotti[2] and L. Seminck[3]

[1] Ghent University, Ghent, Belgium
[2] AGE Consultants bvba, Ghent, Belgium
[3] GFS Industries NV, Belgium
** Corresponding Author*

ABSTRACT The paper presents the case study on the construction of three 48m diameter steel tanks, each founded on a group of 422 displacement cast in-situ piles. The three tanks are close enough to each other to induce interaction. The movements of the tank foundations have been monitored during the hydro-testing of the steel tanks, and during the subsequent working stage of the tanks. The bearing layer for the pile group is a 5 m thick stiff sand layer at a depth of about 20m, overlain by a very heterogeneous soft fill containing sand pockets, and underlain by a very thick slightly overconsolidated clay. The authors present some short and long term settlement prediction for the tanks, based on soil parameters derived from CPT on site, and compare this to the measured settlements. The initially derived soil parameters are re-evaluated in order to predict the long term settlement for the full life span of the construction.

RÉSUMÉ Cette contribution décrit le cas réel de trois groupes de pieux servant comme fondations de trois réservoirs de combustibles; chaque réservoir, en acier, se trouvant fondé sur 422 pieux vissés avec refoulement. Les trois réservoirs se trouvent en proximité l’un de l’autre et peuvent donc être considéré se comportant en interaction majeure. Les déformations en trois axes ont été mesurées pendant les épreuves hydraulique de chaque réservoir et en plus durant l’exploitation des réservoirs remplis de combustibles. La couche résistante des groupes de pieux a une épaisseur de 5m de sable très rigide, à une profondeur de 20m, recouverte par de multiples couches ou lentilles minces et très hétérogènes jusqu’à la surface du terrain naturel. Le sol en dessous de la couche portante peut être considéré comme une argile légèrement sur-consolidée sur une épaisseur d’environ 100m. On présente ici la comparaison entre les résultats d’analyse de prédiction des tassements immédiats et à long terme, pour les trois réservoirs en interaction, partant de l’interprétation de multiples essais de pénétration en profondeur d’un côté, et les mesures en fonction du temps de ces tassements des trois réservoirs de l’autre côté. Les estimations des paramètres de rigidité des diverses couches ont été ré-analysées utilisant cette banque de données des tassements mesurés afin de pouvoir prévoir avec plus de confidence les tassements à très long terme.

1 INTRODUCTION

The three tanks (each 33.000 m³) are steel structures of 48m in diameter and a height of 19m. Figure 1 shows the relative location of the tanks on the site in Ostend, Belgium.

The tanks are positioned in a triangular arrangement at an interdistance (centre-to-centre) of about 65m. (Tanks 1 and 3 are slightly further apart, see figure 1). They are founded on a 48.8m diameter, 60cm thick reinforced concrete slab, supported by 422 displacement screw piles.

The 460mm diameter displacement screw piles of the Omega type are placed at an interdistance of 2.2 m (centre-to-centre) and reach to a depth of 21.5m. They are designed to each take a maximum design load of 960 kN, including some 180 kN negative skin friction.

We refer to Van Impe et al. (2013), and the discussion by Fellenius (2014), for more details on the design and related pile testing. Both papers also present some initial settlement predictions.

2 SOIL CONDITIONS AT THE SITE

2.1 *Soil layering from CPT*

The area where the tanks are located has been excavated and hydraulically refilled over several decades before reaching the today's level. This has resulted in a very heterogeneous fill of about 20m, consisting of a very soft clayey/silty material containing sandy lenses. The location and thickness of these lenses vary considerably across the site.

At the base of this fill, at the level −20m, we encounter a very dense tertiary sand layer with a very consistent thickness of about 5m. This layer is the main foundation layer : the piles are installed to about 1.5m into the sand.

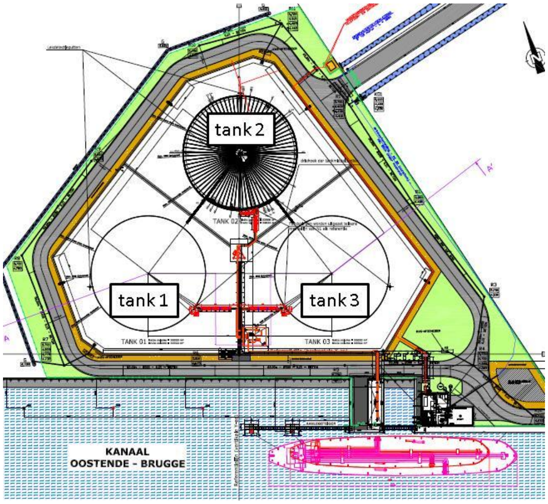

Figure 1: Overview of the site and location of the three tanks at Ostend, Belgium

This layer is underlain by a silty clay of the Tielt formation ("Kortemark"). Geological data suggests that this layer reaches down to the level of −45m (20-25m thick).

This silty clay layer is itself underlain by a very large overconsolidated clay layer (Kortrijk formation), reaching depths of 170 m.

A large number of CPT tests have been performed across the site, confirming the heterogeneity of the fill and the quite regular location and thickness of the tertiary sand. Unfortunately, none of the CPTs reach more than 10m into the Kortemark silty clay layer, making it impossible to determine its thickness. There is also no data available on the thick OC clay layer of the Kortrijk formation. Figure 2 represents a typical CPT result on the site (in the case of this example, close to tank 3).

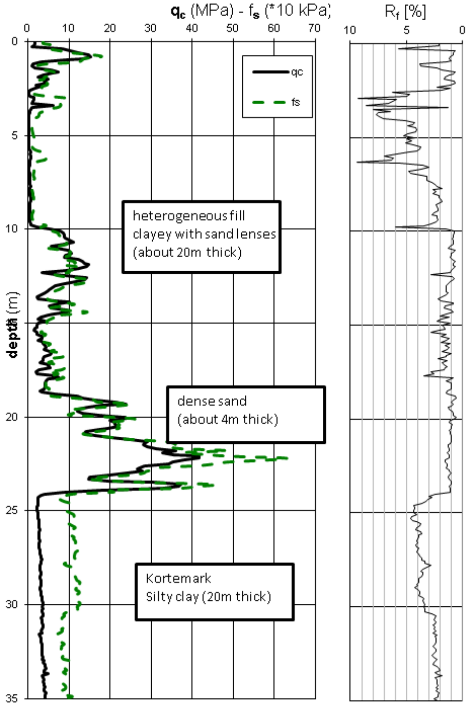

Figure 2: Typical CPT profile in the area of the tanks

2.2 *Settlement estimation*

An initial settlement estimation was done for a single loaded tank using the method of the equivalent raft. Soil parameters for this method were obtained by interpreting the CPT given in figure 2.

The method predicted 32 mm of immediate settlement and 81 mm of additional consolidation settlement. This was done assuming certain compressibility parameters of the layers below level −35m for which we did not have any data. Of the above settlement values, about 50% is located in these layers. So the prediction is very much depending on the actual compressibility of the unknown layers. For this reason, settlement monitoring of the tanks was deemed to be essential.

3 OBSERVED SETTLEMENT BEHAVIOUR

3.1 *Monitoring*

Each tank is being monitored on 16 points along its perimeter. This was initially done both at the level of the tank and the level of the concrete slab. This has allowed to get information about the deformation of the asphalt stress-distribution layer between the tank and the concrete slab. Currently, during the operational phase, monitoring is limited to the tank.

The settlement measurements along the perimeter are analysed and result in an average settlement (average of the 16 points), a best fit plane, the size and direction of the rotation of the tank (tilt), out-of-plane settlements (deviation from the best fit plane) and out-of-plane deflections (distortion). During the operational phase, movements of the foundation slab is estimated based on the movements of the tank and the estimated deformations of the asphalt interlayer.

3.2 *Tank settlement and rotation during hydro-test*

As part of the quality control, a hydro-test was performed on all tanks in the spring of 2013. During this test, all tanks were filled with water to a height of 18m. The filling of each tank took about 3 days.

Figure 3 shows the filling sequence of each tank and its settlement response at the level of the tank bottom. As mentioned before, the tank settlement is the combination of the settlement of the foundation (raft and pile group) and the compression of the asphalt layer. The latter was established to be about 3mm, so the settlement of the foundation is 20 to 21mm under a load of 180 kPa.

As each tank was tested separately (with only a small overlap between the testing of tank 1 and tank 2) and for a very short period, the impact of the load is presumably limited to the immediate response of the stiff sand layer in which the pile group is resting and the upper part of the underlying silt clay layer.

It can be noticed that the response of each tank is very similar, indicating that the stiff sand layer indeed exhibits very similar behaviour across the site.

The tilt of the tanks during this procedure was obviously limited (2-3mm) as there was no real interaction between the tanks.

Analysing the response of the separate tanks under hydro-test loading allows to estimate the immediate compressibility parameters of the sublayers. Using a simplified 3D elastic model (Boussinesq stress distribution, SteinP 3DT program by Geologismiki), we get a value of 200 MPa for the sand layer and 230 MPa for the underlying silty clay. The same value was assumed for the thick OC clay layer, although the impact of the hydrotest of a single tank probably does not reach deep enough to be significantly impacted by this layer.

At the end of the hydro-test, after fully emptying the tanks, the residual average deformation was about 8mm for all tanks. This value is a combination of the average settlement of the foundation (about 3mm) and a plastic deformation of the asphalt layer (about 5mm).

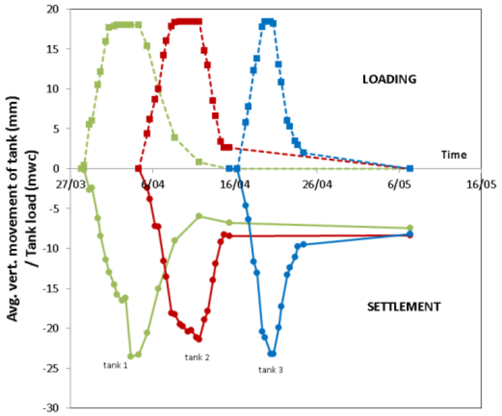

Figure 3: Average settlement of the tank during hydrotest

3.3 *Tank settlement and rotation during operation*

The tanks have been in operation since July 15th 2013. In a timeframe of 6 months, all tanks have been filled with diesel, increasing the load on the foundation to 145 kPa. The filling of each tank took about 2 months.

A first measurement of the settlements occurred right after the filling of tank 3 had been complete (January 2014). A second measurement campaign was organised 8 months later.

Figure 4 shows the loading sequence of the tanks and the average settlement as a function of time. The additional average settlement during the operational phase at this point has reached values of 34 to 40mm.

This average settlement is obviously higher than the one during the hydrotest. There is the increased stress field -- as now all tanks are loaded at the same time -- and we have the onset of consolidation.

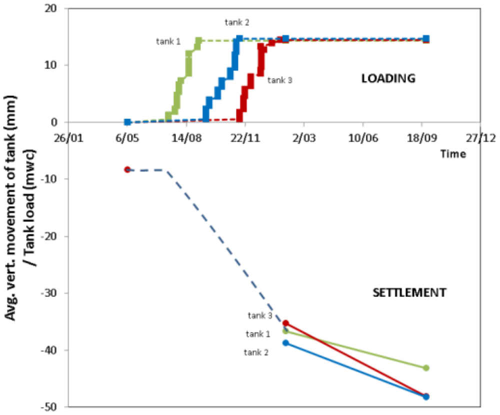

Figure 4: Average settlement of the tank during operation

Figure 5 shows the vertical deviation from the average value for each measurement point. Points with negative values (outside the smaller circle) indicate points which have settled more than the average. The shape of the curves therefore indicate the size and the direction of the tilt of the tanks. These values have been presented separately in figure 6. The tilt is the largest for tank 3 where we get a value of about 20mm.

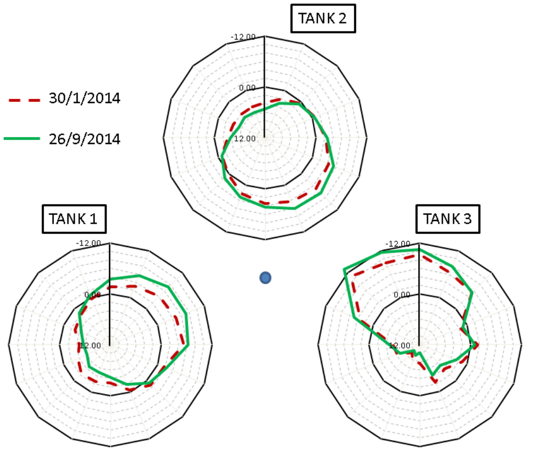

Figure 5: Vertical deviation from average settlement (mm) during operation

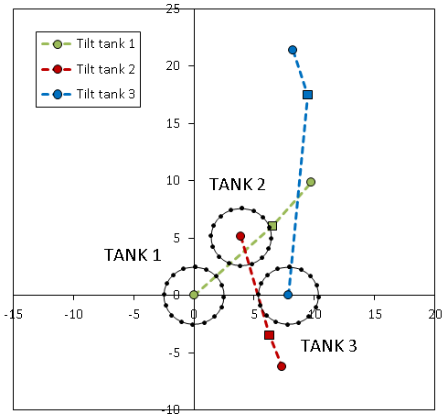

Figure 6: Direction and size (mm) of tilt of the tanks during operation

An increased value of the tilt compared to the situation of the hydrotest is also to be expected due to the interaction of the different loads.

Although the average settlement for all tanks is very similar, there is a significant difference in the size and direction of the tilt. Both tank 1 and 2 exhibit a 12-13mm tilt (0.00026 m/m) towards the central area in-between the tanks, i.e. the centre of the stress field, while tank 3 tilts almost directly north for about 20 mm (0.0004 m/m).

Additionally, tanks 1 and 2 exhibit nearly perfectly planar tilt while tank 3 is clearly slightly distorted. This could be due to local subsoil heterogeneities below tank 3.

The values of average settlement, tilt and distortion are still far below critical values.

4 ANALYSIS OF THE TIME SETTLEMENT BEHAVIOUR

The settlement of the full pile group is only marginally influenced by the fill material. The important characteristics are those from the dense sand layer, the silty clay and, in the long term, the thick OC clay layer.

As mentioned, the data on the two latter are very limited. In this respect, authors have attempted to analyse the current settlement data in order to predict the long term behaviour of the construction.

Based on the analysis of the CPT data, following data on the constrained modulus were derived (Robertson 2010)

Table 1: Deformation parameters from CPT

layer	M (constrained modulus)
sand	170-209 MPa
silty clay	27 + 2*(z-24) MPa between -24m and-44m

Based on these compressibility parameters – combined with the immediate compressibility parameters derived from the fast hydrotest, a single value of the consolidation coefficient c_v for the silty clay was calculated to obtain the best fit between prediction and measurement. Fitting was done on the values of the average settlement.

The prediction was done using a simplified 3D elastic stress model (again using the SteinP 3DT program). The model takes into account the slight variation in thickness of the sand layer below the different pile groups (slightly lower thickness below tank 3).

The ultimate average settlement for the tanks ranges from 87 to 90 mm (See figure 7). The centres of the tank sill settle 132 to 136mm The long-term tilt ranges from 19 to 21 mm.

As the actual size of the consolidating layer is unknown, fitting was done on the basis of the combined c_v/d^2 parameter (where d is the drainage path length).

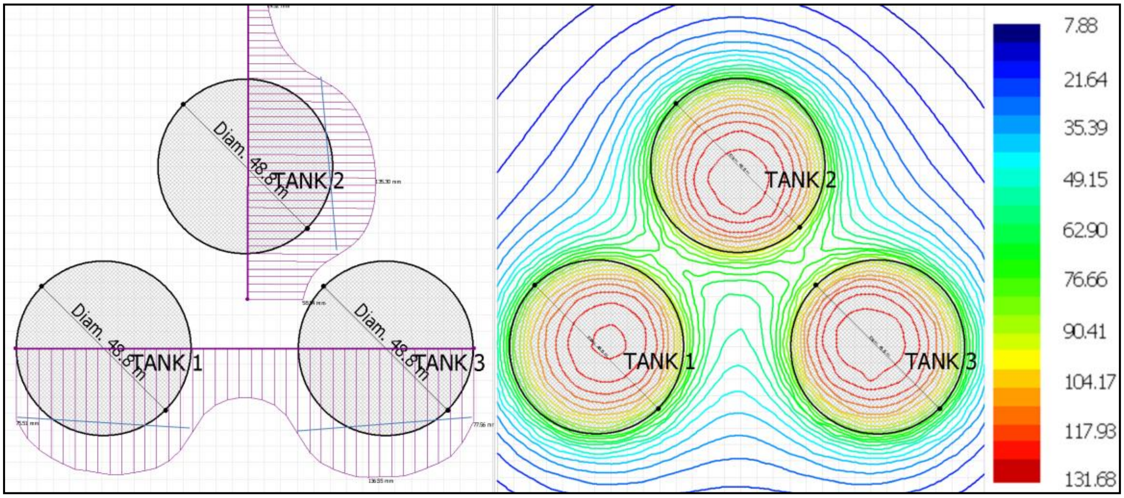

Figure 7: Simplified settlement analysis of the tanks under operational load

This leads to a value of the time factor c_v/d^2 of 0.0022 month^{-1}. The results of the fitting are presented in figures 8 and 9, which show the predicted versus measured values for respectively the average settlement and tilting of the tanks. The time range which is presented is approximately 20 years.

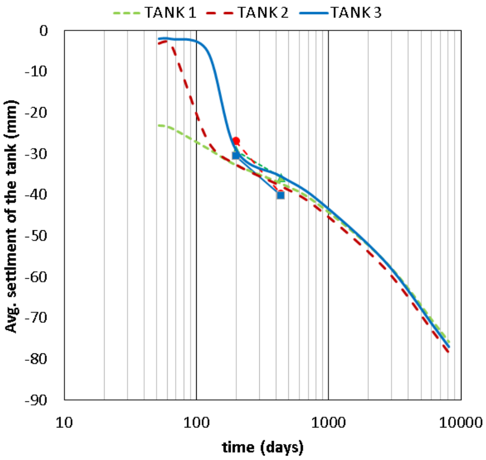

Figure 8: Predicted (lines) versus measured (dots) average settlement of the tank under operational load

The prediction at this point clearly underestimates the amount of tilt which is occurring, especially for tank 3. This could be due to the existence of some stiffness heterogeneity in the region of this tank, which – as mentioned above – could also be responsible for the distortion (non-planar tilt).

Further modelling would require additional soil data to increase the accuracy of the soil model and higher-level software capable of taking into account complex soil layering.

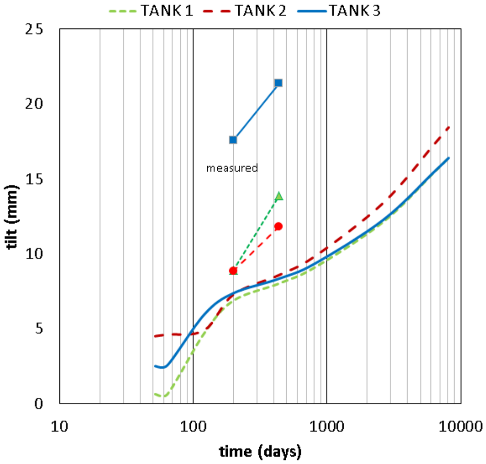

Figure 9: Predicted (lines) versus measured (dots) tilt of the tanks under operational load

5 CONCLUSIONS

The paper presents some monitoring data on the settlement of three large pile groups which function as tank foundations. The three groups are close enough to each other to interact.

This interaction is clear from the data as the combined loading of the three groups gives rise to larger settlements than those measured during the separate loading of the tanks during hydro-testing. Moreover, a significant tilting of the tanks occurs.

Due to the large scale of the combined constructions, the influence depth is considerably larger then the extent of the soil investigation. The tanks are underlain by very thick sandy clay and OC clay layers, which will govern the long term settlements. Authors have made an attempt to analyse the data obtained during the hydrotest and the current operational stage to make an educated guess on compressibility and consolidation coefficients. The obtained values lie within the normal range for these type of soils, and allow further extrapolation of the current measurements.

Additional measurement campaigns will be planned to allow further optimization of the model.

REFERENCES

Fellenius, B.H. 2014. Discussion on : an instrumented screw pile load test and connected pile group load-settlement behaviour by Van Impe et al 2013. *Journal of Geo-Engineering Sciences* **1**(2), 101-108.

Robertson, P.K. 2010. Soil behaviour type from the CPT: an update. Proceedings International Symposium on Cone Penetration Testing CPT 10.

Van Impe, P.O., Van Impe, W.F. & Seminck, L. 2013. Discussion of an instrumented screw pile load test and connected pile group load-settlement behaviour. *Journal of Geo-Engineering Sciences* **1**(1), 13-36.

Van Impe, W.F. et al. 1988. Prediction of the single pile bearing capacity in granular soils our of CPT results. *Proceedings of the First International Symposium on Penetration Testing* (specialty session), ISBN 90-6191-803-0.

Van Impe, W.F. et al. 1988. End and shaft bearing capacity of piles evaluated separately out of static pile loading test results. *Proceedings of the First International Geotechnical Seminar Deep Foundations on Bored and Auger Piles*, 489-498, CRC Press / Balkema.