The use of hydro test results for design of steel tanks on stone column improved ground - a case history

L'emploi des résultats des essais hydrauliques dans l'étude des réservoirs en acier sur le sol amélioré par colonnes de pierre – histoire de cas

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ABSTRACT: This paper describes hydro tests performed on five large storage tanks (80.000 m^3 each) located at the Sisak Oil Terminal, Croatia. Because of its small stiffness and low water permeability, foundation soil for each tank was improved with 660 stone columns. In order to reduce the risk of accidents, such as fire, breach or leak, a crude oil storage tank requires stringent security measures. In the case of the Sisak tanks, the hydro tests were conducted as part of technical monitoring to determine a set of documented and interconnected activities which would provide proof of proper functioning of all elements of a tank structure. In case of critical deviations from the operation expected, such activities ensure that such deviations are removed or corrected on time by taking necessary measures approved by experts. Under a procedure for the hydro tests, the phases of tank and bund filling were defined and each phase was followed by visual inspection and measurements of settlements and deformations of the steel structure. Design directions for future foundation and hydro tests of tanks were made accordingly.

RÉSUMÉ : Les essais hydrauliques conduits sur cinq réservoirs de grande taille (chacun de 80,000 m3) situés dans le Terminal pétrolier de Sisak en Croatie, sont décrits dans l'ouvrage. Compte tenu de petite rigidité et perméabilité à l'eau peu importante, le sol de fondation pour chaque réservoir a été amélioré avec 660 colonnes de pierre. Les mesures très rigoureuses doivent être prises pour les réservoirs à pétrole brut afin de réduire le risque d'accidents tels que feu, rupture ou fuite de pétrole. Dans le cas des réservoirs de Sisak, les essais hydrauliques ont été conduits dans le cadre de la surveillance technique dont le but était de définir une série des activités bien documentées et interconnectées visées à prouver le fonctionnement impeccable de tous les éléments structurels du réservoir. Dans le cas d'une déviation critique par rapport au fonctionnement normal, ces activités permettent l'élimination ou la correction prompte de ces déviations en prenant les mesures appropriées approuvées par les experts. Dans la procédure pour les essais hydrauliques, les phases de remplissage du réservoir et de la cuvette de rétention ont été définies, et chaque phase a été suivie par une inspection visuelle et par mesurage du tassement et des déformations de la construction en acier. Les instructions d'études sont fournies pour les essais hydrauliques et les essais des fondations futurs.

KEYWORDS: steel tank, stone columns, hydro test, monitoring, settlement

1 INTRODUCTION

During the years 2010 and 2011, five new crude oil storage tanks were built at the Sisak Oil Terminal.

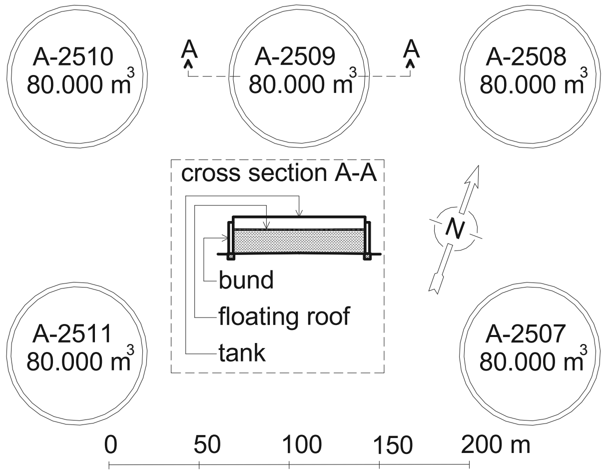

Figure 1. The layout plan of the tanks

All the tanks are of the same size and have an identical steel structure with a floating roof and steel bund wall designed in accordance with API 650. The diameter of the tanks and bunds is 73,2 m and 78,2 m respectively. The tanks have 80.000 m^3 in volume and their total and overflow height is 20,6 m and 19,5 m respectively (Figure 1.).

Foundation soil is horizontally stratified and, therefore, the soil under all the tanks is of almost the same properties. Because of its small stiffness and low water permeability, the foundation soil for each tank was improved with hundreds of stone columns, which is a technology applied in similar cases of soil improvement (Raju et al 2004, Ambily and Gandhi 2004).

In order to prevent industrial accidents, viz. fire, breach or leak of a tank, etc. to happen, a crude oil storage tank requires special safety measures. For this reason, all tank development stages such as ground investigations, design, construction, hydro tests and exploitation, were strictly controlled according to a highly elaborated plan as laid down in API 653 and EN 14015.

On the basis of in situ and laboratory tests, a numerical model was created in Plaxis, and all phases of hydrostatic tests were checked before testing.

2 DESIGN REQUIREMENTS

In the near vicinity of the new tanks, three 80.000 m^3 tanks with floating roofs were installed 30 years ago. During the hydro test performed on one of them, the yielding of foundation soil occurred, which caused tank shell deformations. Such deformations affected normal operation of the floating roof and consequently made the use of the tank impossible. The case described above has not been fully documented, but this is the reason why the investor imposed strict requirements for tank behaviour.

Based on the documented cases of soil yielding during tank foundation works (Bell & Iwakiri, 1980) criteria for design, construction and use of tanks have been established.

Criteria for maximum total and differential settlement of tanks were determined according to Marr, et al. (1982), API-650 and API-653. Allowable differential settlements are the maximum allowable design limits for deformation of the tank after allowance has been made for construction tolerances. These comprise combinations of: (a) tilt of the tank; (b) tank floor settlement along a radial line from the perimeter to the tank centre; and (c) settlement around the perimeter of the tank.

Foundation and foundation soil are subjected to the highest load during hydro tests when a tank is filled with water having a density of 1 t/m^3. Later, during tank use, loads on foundations and foundation soil are lower by about 15 % because the tanks are filled with crude oil having a density of 0,85 t/m^3.

3 OVERVIEW OF GROUND INVESTIGATION WORKS

At the site, 45 geotechnical boreholes were drilled of which three were 70 m deep. In addition to the boreholes, 18 CPTU tests were also carried out. From the boreholes, undisturbed soil samples were continually taken or SPTs performed. A piezometer was installed in one borehole and a level of ground water monitored over a number of years. Soil classification tests as well as strength, stiffness and water permeability tests were carried out in a laboratory. The investigations showed that the soil is horizontally stratified.

4 DESCRIPTION OF FOUNDATION

The foundation soil was improved with hundreds of stone columns. After the soil had been prepared in this way, the tank shell and bund wall were installed on rigid reinforced concrete ring while the tank bottom was placed directly on the bedding prepared.

4.1 *Soil improvement*

As the foundation soil is horizontally stratified, the soil under all the tanks has almost the same properties. Because of its small stiffness and low water permeability, the foundation soil for each tank was improved with about 660 stone columns.

The depth of the improved soil was approximately 18 m. The spacing between stone columns varied depending on their location on the layout plan. Considering that tank structure is susceptible to planar tilt settlement and non-planar settlement, stone columns were spaced more closely on the perimeter below the foundation ring and centre to achieve stronger effect of improvement.

The quality of improvement was checked by CPTU and SASW tests and geodetic surveys carried out in control fields before and after soil improvement. In addition, the data relating to the installation of stone columns were analyzed. Among other things, the volume of the gravel pressed into foundation soil was determined. For each tank, it was found to be about 3% of the volume of the foundation soil improved. As geodetic surveys showed negligible soil upheave (a few millimetres), it can be considered that all the stone pressed into the soil increased directly its density, i.e. soil compaction.

4.2 *Concrete ring foundation*

The shells of both the tanks and bund walls were mounted directly on a rigid reinforced-concrete foundation ring of rectangular cross-section b/h=350/(260-370) cm, with a central drainage gutter having a width b=60 cm and variable height h=40–80 cm. Outside and inside ring diameters are D_{out}=79,00 m and D_{in}=72,00 m respectively.

4.3 *Bedding of steel tank bottom*

The bottoms of the steel tanks were mounted directly on the multi-layer bedding prepared as described below.

The foundation soil was levelled and a layer of gravel of grain size 0-64mm was placed. The layer had 70 cm in thickness. To prevent soil pollution in case of tank leak, a HDPE geomembrane was installed in the bedding. The geomembrane was placed between a geosynthetic clay liner and clean sand to protect it from damage. Above the geomembrane, cathodic protection was installed. Additional reinforcement of the soil below the tanks was achieved by placing sand in geocells of 20 cm in height.

5 GEOTECHNICAL DESIGN ANALYSIS

On the basis of in situ and laboratory tests, an axisymmetric numerical model was created in Plaxis 2D-V8. The material behaviour is represented by the Hardening Soil model.

In a numerical analysis, soil materials of five types were used and their description and some properties are shown in Table 1. The analysis included tank installation stages, hydro tests and tank exploitation.

Table 1. A description of stratified foundation soil

Layer	*depth [m]*	*description*
(1)	approx 0 –6	Surface layer of stiff clay k=0,0002[m/day]; E_{oed}^{ref}=9,4[MPa]; E_{ur}^{ref}=30[MPa]; p^{ref}=100[kPa]; m=0,409
(2)	approx 6 –13	Layer of soft clay k=0,0002[m/day]; E_{oed}^{ref}=7,8[MPa]; E_{ur}^{ref}=23,4[MPa]; p^{ref}=100[kPa]; m=0,376
(3)	approx 13 –20	Sand with silt and clay k=0,02[m/day]; E_{oed}^{ref}=16[MPa]; E_{ur}^{ref}=50[MPa]; p^{ref}=100[kPa]; m=0,5 Soil below the tanks was improved with stone columns as designed k=1[m/day]; E_{oed}^{ref}=35[MPa]; E_{ur}^{ref}=90[MPa]; p^{ref}=100[kPa]; m=0
(4)	approx 20 –70	Alternating layers of clay and sand with silt k=0,0002[m/day]; E_{oed}^{ref}=10[MPa]; E_{ur}^{ref}=40[MPa]; p^{ref}=100[kPa]; m=0,376

k - permeability; E_{oed}^{ref} reference edometric modulus at reference stress p^{ref}; $E_{oed} = E_{oed}^{ref}(\sigma/p^{ref})^m$ edometric modulus; E_{ur}^{ref}= unload/reload modulus

6 HYDRO TEST

6.1 *Introduction*

In the case of the Sisak tanks, hydro tests were conducted as part of technical monitoring to determine a set of documented and interconnected activities which would provide proof of proper behaviour of all elements of a tank structure.

In case of malfunction or critical deviations from the expected behaviour, such activities would ensure that these deviations are removed or corrected on time by taking necessary measures approved by experts.

Under a procedure for a hydro test, the phases of tank and bund filling and emptying were defined; after each phase had been completed, visual inspection and measurements of settlements and deformations of the steel structure were made. The next phase of the hydro test could begin only after the analysis of the results of measurements obtained from a previous one had been made.

Monitoring of each tank settlement involved geodetic surveys and measurement of settlements by a horizontal inclinometer. The geodetic surveys included 24 points on the outside perimeter of the foundation and one point on each of six manholes allowing access to horizontal inclinometer pipes (HI). Settlement measurements were made in three 100-m long pipes running below the tank centre and horizontally declined by 60°. The manholes were located eight meters outside of the foundation perimeter.

A monitoring programme was planned and carried out in a similar manner as described in the paper by Berardi and Lancellotta (2002).

6.2 *Hydro test results*

By way of illustration, the results of settlements obtained from the hydro test carried out on Tank A-2507 are given. Figure 2 shows time history of tank and bund filling and emptying together with the graphs showing averaged settlements of HI pipes at manholes HI, points on the foundation perimeter and centre.

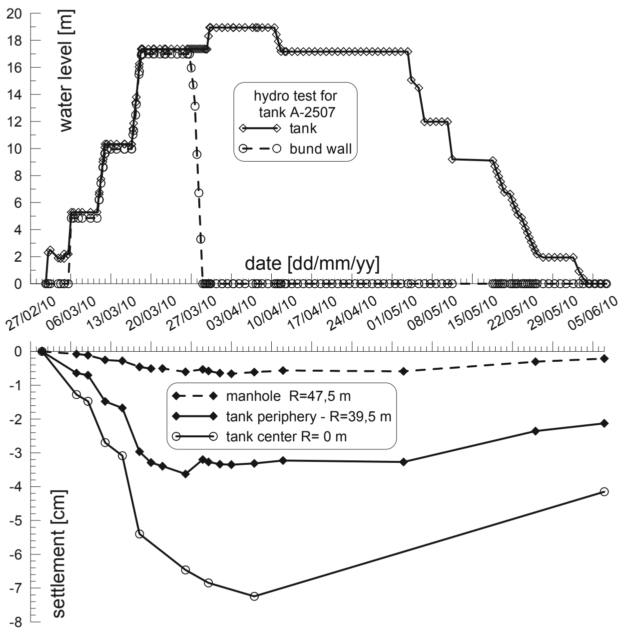

Figure 2 Time history of the hydro test performed on Tank A-2507

According to settlement criteria (Marr et al 1982), the design defined allowable total and differential settlements for different settlement patterns. Thus, during the hydro test, the allowable total settlement of the tank perimeter and tank centre were 15 cm and 31 cm respectively. In a calculation, they were estimated to be 11 cm and 19,5 cm respectively. However, the results of measurement obtained for such settlements as shown on the graph were 3,6 cm and 7,2 cm respectively.

Figure 3 shows total settlements of the tank perimeter for the two representative phases of the hydro tests in which the largest settlements occurred at the highest loads. In the third phase, i.e. when the tank was emptied, permanent (plastic) deformations occurred.

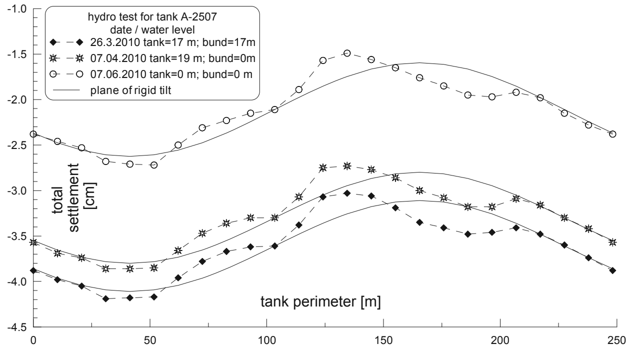

Figure 3 Total settlements of the tank perimeter occurred during the hydro test on Tank A-2507

Figure 4 illustrates the two phases in which the largest differential settlements of tank perimeter at the highest load occurred as well as the phase following tank emptying in which permanent (plastic) deformations occurred.

Design allowable differential settlements for the cases of planar tilt settlement and non-planar differential settlement was 44 cm and 0,8 cm respectively. The planar tilt settlement and non-planar differential settlement obtained by calculation were 1,3 cm and 0,34 cm respectively. The results of measurement obtained for such settlements were 1,0 cm and 0,32 cm respectively.

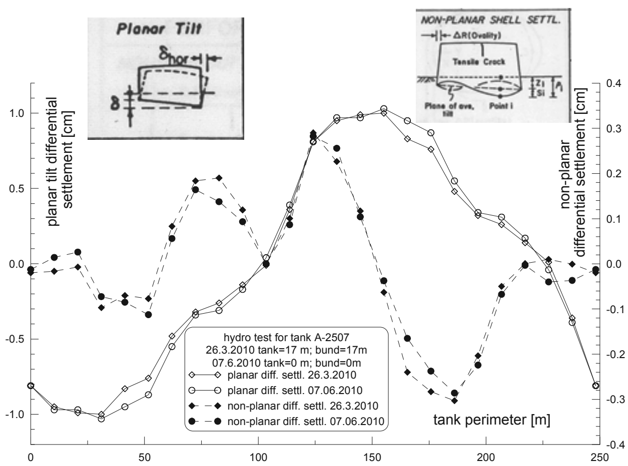

Figure 4 Differential settlements at the perimeter of Tank A-2507

Figure 5 shows total settlements for the three representative phases of the hydro test measured by horizontal inclinometer.

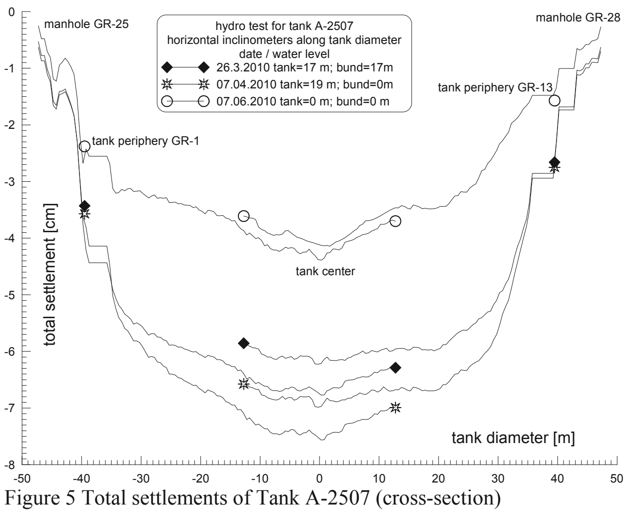

Figure 5 Total settlements of Tank A-2507 (cross-section)

7 CONCLUSIONS

Soil improvement described in this paper involved stone columns installed below each tank. The gravel material pressed into the soft soil is equivalent to a layer of about 30 cm in thickness. Since the geodetic surveys showed negligible soil upheaval (a few millimetres), it can be concluded that the soil improvement prevented equivalent settlement of 30 cm.

The hydro test showed, as demonstrated in the case of Tank A-2507, that total settlements are relatively small, i.e. smaller than estimated by calculation (Figure 6).

For the purpose of comparing actual settlements with those given in behaviour criteria, the settlements of the tank bottoms are shown so that displacements corresponding to a rigid body rotation are given separately from displacements resulting from non-planar differential settlement. Figure 3 illustrates that the bedding was mostly displaced as a rigid body, while non-planar differential settlement was slight. For this reason, it is sure to say that maximum values of the settlements and their shapes are within the values required by the relevant standard (Figure 4).

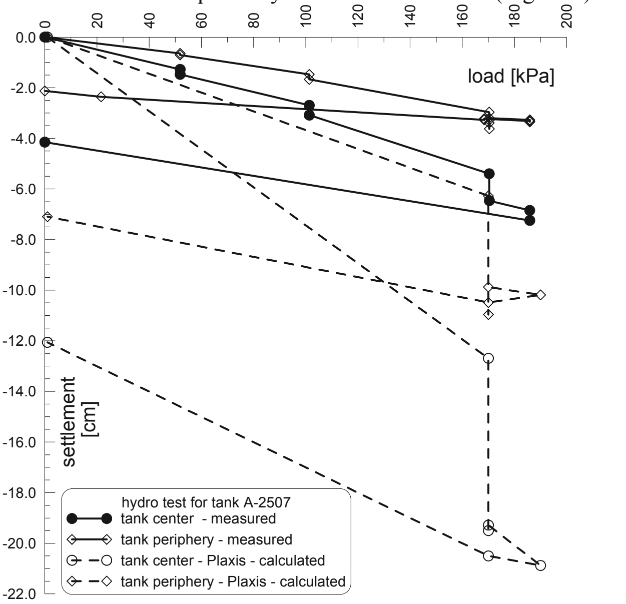

Figure 6. A comparison of measured and calculated results of settlements obtained from the hydro test on Tank A-2507.

It was found that the settlements, after the tank had been emptied, were smaller although they had the same shape. This proves that the deformations after tank emptying are mostly elastic (Figure 4). As tank loads by crude oil are less than those by water, it is expected that subsequent displacements at operating load will be less than those recorded in hydro tests, and that no further non-planar differential settlement of the tank bedding will occur. The same goes for the other four tanks (Figure 7). The diagram of the settlements of all five tanks shows that such settlements are about the same when the tanks are subjected to the same load. As this is normally expected in the case of horizontally stratified soil, this is proof of proper and correct measurement of displacement.

As seen in Figure 6, the settlements obtained by calculation were significantly greater than those measured. An explanation for different values of settlements should be thoroughly investigated in further numerical analysis which will take into consideration the fact that columns and soil act together as recommended in Ambily and Gandhi (2004).

In the case of the Sisak tanks, the hydro tests proved correct functioning of the floating roofs, watertightness of the shells and bottoms, and rigidity of the foundation structure for all tanks.

The strictly applied procedures regarding soil investigation, design, hydro test and exploitation ensured safety in execution and further use. Considering the safety risks and loss of investment in case of non-allowable differential settlements of the soil, it is clearly understandable, yet in some cases disregarded, why such procedures must be applied.

The data collected about the behaviour of the tanks during the hydro tests were well documented and could be used to improve design of tanks.

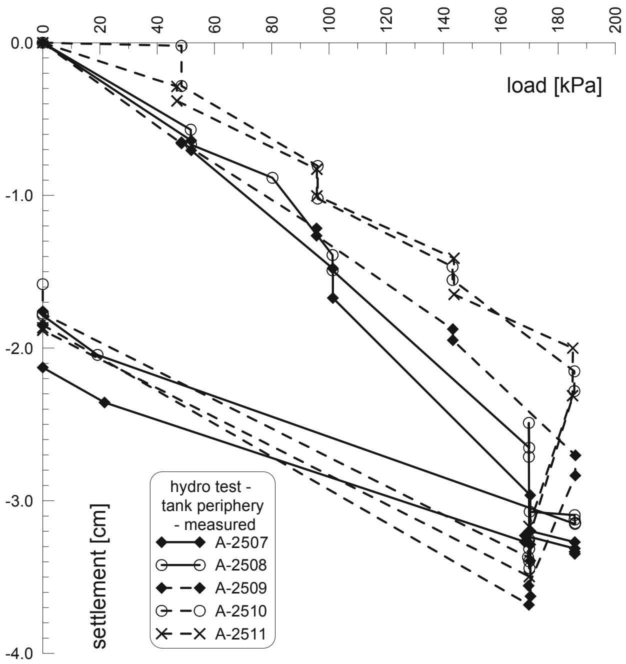

Figure 7. Total settlements of tank perimeters during hydro tests performed on all five tanks

8 ACKNOWLEDGEMENTS

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