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Measurement results of instrumented full scale load tests of steel tanks supported by Rigid Inclusions

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ABSTRACT: This paper presents field measurements in terms of settlement and load distribution of a rigid inclusion (RI) foundation during the hydrotests of steel tanks. The idea of ground improvement with RI consists of transferring a significant part of the load into the columns and the other part into the surrounding soil. This load transfer permits to share the load from the structure to both elements at the level of the column head. The interactions between the surrounding soil, the rigid inclusions and the overlaying structure are an important assumption during design stage. For a biogas plant in Germany several high loaded steel tanks were placed on a RI system using the worldwide used CMC technique combined with a granular load transfer platform (LTP). Within the LTP several pressure cells were placed on top of the inclusions and on the compressible soil at the same level to validate the assumed load distribution ratio. The settlement of the tank was monitored along the ring beam. Further, inclinometers were placed inside the LTP to measure the evolution of settlement from the edge to the centre of the slab. During hydrotests the tanks were filled in several steps with water up to a final level of about 18.5 m. Finally, the measurements are compared with the analytical and numerical predictions during design stage.

KEYWORDS: rigid inclusions, CMC, field measurements, hydrotest, tank foundation.

1 INTRODUCTION

Industrial tanks are usually large and heavily loaded structures that are used for storing fluids or substrates. Given that tank storage structures are constructed using relatively thin walls, floors and roofs, unforeseen ground deformations can have undesired impacts on the performance of tanks.

Steel tanks of biogas plants are generally high and relatively simple structures. They are flexible and ductile. They can tolerate settlements without loss of structural integrity. These tolerable settlements, however, are not without limits. Excessive settlements may affect the serviceability of the tanks. Steel tanks are comparatively sensitive to edge failure and differential settlements around their shell.

In cases where predicted settlements are considered intolerable, the basis solution is usually an expensive and CO_2-consuming thick reinforced slab supported by deep piles. However, to optimise the structure in terms of concrete and steel savings, ground improvement methods are an appropriate solution. Several cases are shown by Yee & Varaksin (2007) and Hamidi & Varaksin (2017).

The rigid inclusion (RI) method is a well-established technique for soil reinforcement. Because of the higher stiffness the settlement reduction of RI is more efficient than with granular columns. This type of ground improvement will be assigned to class BII of the new Eurocode generation. The design and quality control presented in this paper corresponds to the guiding principles of the new Eurocode 7 Part 3 Chapter 12.

2 PROJECT OVERVIEW

2.1 *Project and Tank characteristics*

The biogas plant in lower Saxony, Germany, is one of the largest of its kind in Europe. It consists of five steel tanks, five concrete tanks and a 5,000 sqm hall for storing the biodegradable substrate before the fermentation process.

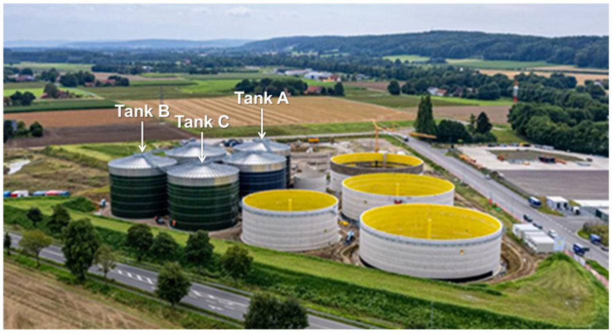

Figure 1. Project picture, before final installations.

Without any measures, the loads applied at the base of the tanks due to long-term fluid fill, combined with the high compressibility of the ground, would lead to settlements up to 25 - 45 cm and a potential of intolerable differential post-construction settlements along the tank shell. These differential settlements could cause disorders incompatible with the standard operation of the facility. To mitigate these geotechnical issues and homogenize the reaction of the soil, the RI solution using Controlled Modulus Columns (CMC) was selected instead of piling.

The focus of this paper are three instrumented steel tanks (tank A, B and C, see Figure 1) with equal dimensions of 24 m in diameter and a steel wall height of 19 m. These are fixed-roof tanks with an average ground pressure of about 185 kPa in service. The settlement criteria of each tank defined by the client was $s_{max} = 100$ mm and max. 1/100 of differential settlement.

Hydrotests were carried out up to full fluid hight of 18.5 m for two reasons: to check for leaks within the steel shell and to induce or preload the settlement before the final installation of the piping system. Thus, contrary to most structures whose actual performances under full loadings are only when the structure is put into service, the tanks are fully loaded with water before making the final connections of the piping system.

The hydrotest is a type of field zone test of the RI system and provides a unique opportunity to compare the design assumptions with the measurement results due to its clearly defined static load conditions.

2.2 *Ground Conditions*

The ground is dominated by alternating layers of high compressible alluvial loess (sa'cl'Si) and fluvial sands (siSa), which are underlaid by soft to stiff boulder clays with varying content of silt and clay. At depths of around 15-20 metres below ground surface, dense glacial sands and gravels with high bearing capacity were found as competent bearing layer.

Several Cone Penetrations tests (CPT) and Pressuremeter tests (PMT) were carried out under each tank. One representative soil profile for tank A is shown in the following Figure 2.

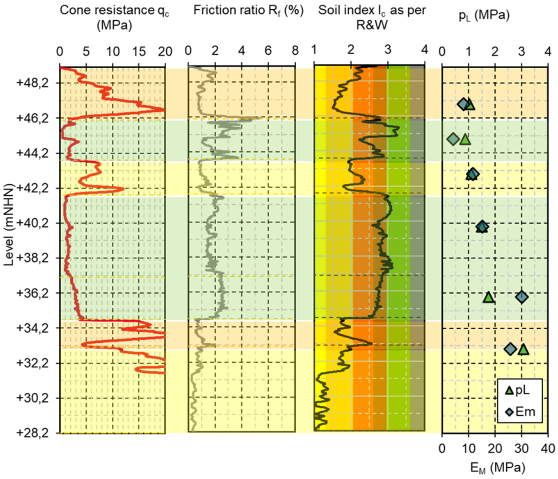

Figure 2. Soil profile for the edge of tank A (CPT and PMT 27).

2.3 *Ground Improvement works with CMC*

To mitigate the geotechnical issues and to homogenize the reaction of the soil, a rigid inclusion solution using Controlled Modulus Columns (CMC) was selected. This full displacement technology consists of a rigid inclusion network installed in the soil down to the load-bearing layer and disconnected from the above structure (often by the mean of a load transfer platform (LTP)): both inclusions and surrounding soil participate to the foundation system. Using CMC brings therefore similar effectiveness as full displacement piling, with the elegance of structural support on a shallow foundation.

On this project CMC elements with a diameter of 320 mm were arranged in a tight grid under the tanks. The length of the columns varies between 16 and 23.5 m. In total more than 55 km CMC were executed under the 10 tanks. The load transfer mechanism is ensured by the presence of a platform (LTP) under the structure made of compacted granular material. As LTP, a recycled crushed concrete was used with a thickness of 60 cm.

Figure 3. CMC execution for the tank foundation.

3 RESULTS OF THE HYDROTESTS

3.1 *Sequence of hydrostests and measurement technique*

Hydrostatic load tests were carried out about 4 months after completion of ground improvement works. Each tank was filled stepwise with about 1.5 m of water per day. After reaching the half filling level, the water level of 9 m was kept constant for 10 days before final filling was continued. The maximum height of water was maintained at 18.5 m for a minimum of 10 days depending on the leak-proof and sealing works at the shell.

The settlements of the tanks A, B and C were monitored along the ring beam during filling process. Further, tank A was equipped with additional measurement technique to get more information about settlement distribution and load sharing between columns and the soil. Two complementary measurement systems were used: the SAAV ShapeAccelArray inclinometer and Sisgeo earth pressure measurement cells.

The SAAV system is a flexible inclinometer array equipped with MEMS sensors in a distance of 0.5 m, providing high-resolution measurements. This technology enables continuous profiling of subsurface movements and ensures reliable long-term performance. It was placed within the LTP about 20 cm below the slab, see Figure 5 right. The Data was recorded at regular intervals and transmitted to a remote logging system.

Circular earth pressure cells were installed to quantify the vertical stresses (see Figure 5 left):

- on the CMC head in the centre of the tank
- on the soil between the column heads
- 20 cm below the slab and between the columns.

The earth pressure cells are constructed from two stainless steel plates, welded together around their pheriphery. The anular space between these plates is filled under vacuum by deaired oil. The pressure pad is connected by means of a stainless steel tube to the transducer forming a closed hydraulic system. An electrical signal proportional to the applied pressure may be remotely read on a variety of portable readout units or dataloggers. The cells were positioned at strategic depths mentioned above and recorded the stress evolution during the hydro test.

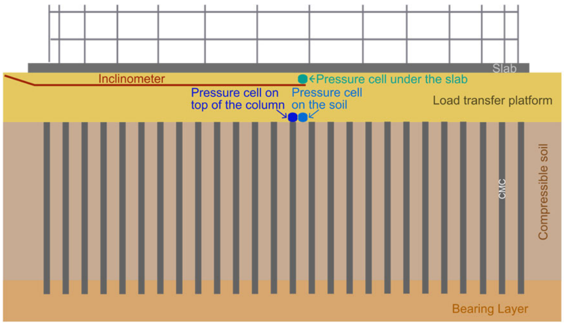

Figure 4. Cross-section of the equipped tank A

Figure 5. Circular pressure cells (D = 30 cm) placed on CMC (left) and Inclinometer installation in the LTP (right)

3.2 *Settlements during loading*

Each tank was equipped with six settlement sensors at the tank shell to detect any potential tilting of the tanks. The final settlement around the tank shell during the hydrotest is shown in Figure 6. The measured settlement (s_{edge}) for tank A, tank B and tank C ranged from 18 - 26 mm, 16 - 29 mm and 11 - 30 mm respectively.

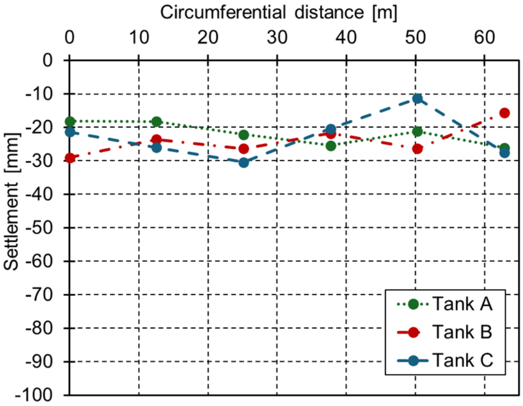

Figure 6. Final settlements after full loading with 18.5 m water, measured at edge of tank A, B and C.

The mean settlement (s_{edge}) is 22 mm for tank A, 24 mm for tank B and 23 mm for tank C. The maximum differential settlement around the tank shell was found at tank C which was 16 mm between 2 adjacent measured points over a distance of 12.6 m. This is equivalent to 1/800 which satisfied the requirements of 1/100.

Due to the additional measurements tank A will be focused in this paper. The edge settlement of tank A as a function of the filling process is shown in Figure 7. The settlements occur immediately with the several load steps without significant long-term settlement. This is because the CMC are anchored in a coarse-grained bearing layer. Only a very small part of the settlement occurs after 2-3 days due to consolidation of the soft soils on the top.

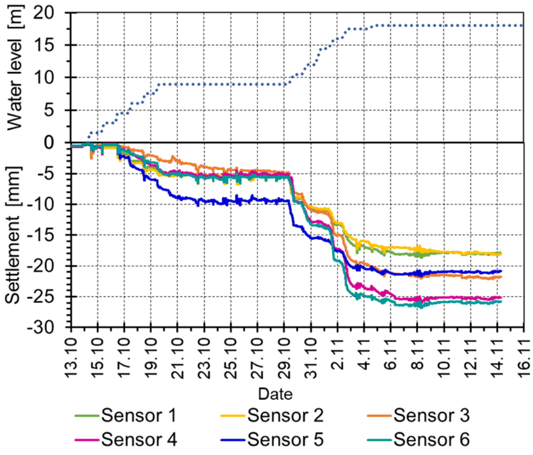

Figure 7. Edge settlement of tank A during hydrotest.

The inclinometer recording gives a settlement analysis of the cross-section. The sag of the slab can be visualised. This data was also monitored over the entire filling process.

Figure 11 shows the differential settlement along the radius. The coloured lines show the settlement behaviour at different points (each half meter) of the inclinometer.

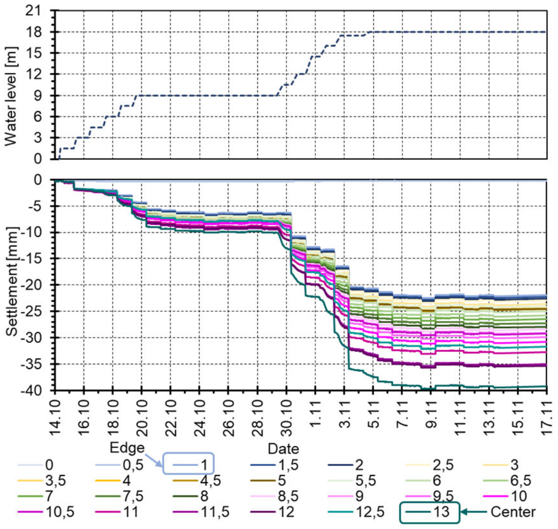

Figure 8. Final settlement of inclinometer with an interval of 0.5 m.

The initial point “0” is the reference of the inclinometer one meter outside the slab. Point “1” shows the deformation directly under the edge at the tank shell and Point “13” is in the middle of the tank.

The centre settlements are larger than those at the edge of the tank. There is a final sag of about 19 mm from edge to centre. The resulting settlement in the centre after full loading is 39 mm, which means a typical settlement ratio of $s_{centre}/s_{edge} = 1.9$ for that tank geometry and shallow foundation load distribution.

The settlement on defined load stages is shown in Figure 9 as a cross-section.

- 14.10.: one day before filling
- 18.10.: shortly after reaching 30 % fluid hight
- 20.10.: shortly after reaching 50 % fluid hight
- 29.10.: after 10 days of 50 % fluid hight
- 05.11.: shortly after reaching 100 % fluid hight
- 16.11.: after 10 days of 100 % loading

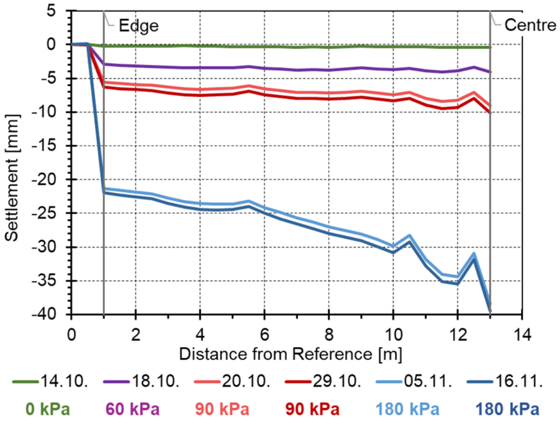

Figure 9. Cross-section settlement from edge to centre of the slab.

After 10 days of a constant loading, the settlement has only increased by approx. 1 mm, so the CMC eliminated a potential consolidation settlement or creep of the fine-grained compressible soils.

3.3 *Stresses on the CMC and on the soil*

The pressure cells in the centre of the tank were installed directly under the slab, on the CMC and at the same height on the soil between the columns. In this way, the load distribution ratio between the column and the soil can be evaluated.

The Figure 10 shows the measurement results regarding the load sharing. There is an expected stress concentration on the column head in every loading stage. After full filling the measured stress on the head is close to 4,000 kPa. However, on the soil between the columns the stress is only 50 kPa.

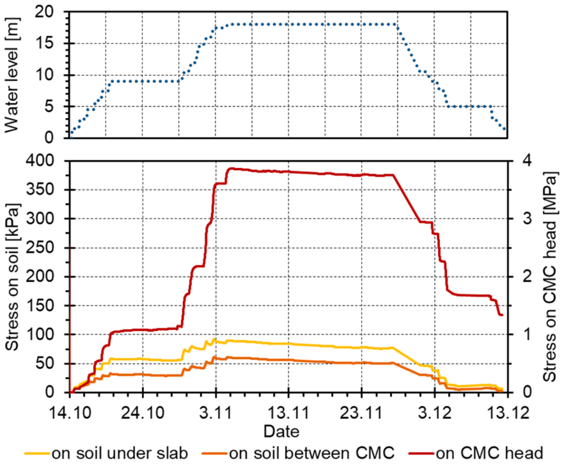

Figure 10. Measured vertical stress under the slab, on the soil between the CMC and on top on the CMC

The Figure 11 verify the load conservation idea, which states that the sum of the load on the ground of the unit cell and the load on the column must correspond to the total load from the water filling. The measurements can even verify the load conservation equation for high loading stages.

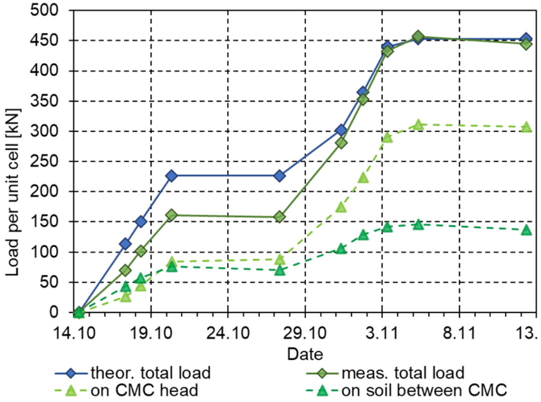

Figure 11. Load conservation in the unit cell

Reaching the half filling height of 9 m, only 34 % of the total load is carried by the CMC, but also the load conversation is not satisfied. The efficiency of the CMC increases with higher loads respective the water level. This fact may indicate that at a certain stress level, the maximum allowable stress on the natural soil is reached and any further increase in load is carried by the columns due to the high bearing capacity in this case. This is a good feature of the adaptive system of rigid inclusions and LTP. After reaching the full filling, about 60 % of the total load is on the CMC head and the load conservation is satisfied: The sum of measured the load on the soil and the measured load on the column correspond to the total load applied by water.

3.4 *Swelling during unloading*

This section provides an analysis of the unloading during emptying the tank. Figure 12 illustrates the heave at the edge and at the centre during unloading obtained from the inclinometer.

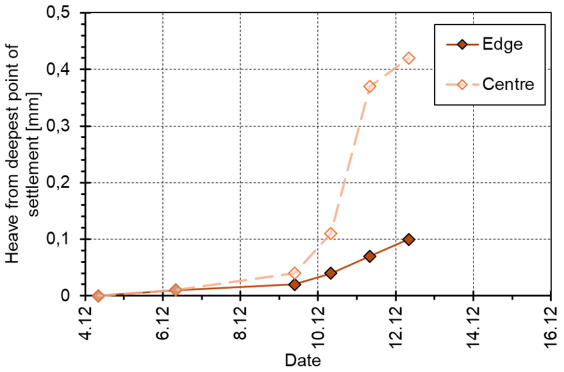

Figure 12. Heave from deepest point of settlement during unloading process

The measured heave is generally very small, in the range of less than one mm. This shows the settlements during loading were almost plastic deformations. Thus, it is expected that Re-loading during service of the tanks will not cause any significant further settlement.

4 COMPARISION OF THE MEASUREMENT RESULTS WITH PREDICTIONS

To design the mesh of columns under the uniformly distributed load of the tanks and to determine the interaction effects between the RI and the structure, unit cell calculations were done comprising the single column and its surrounding soil. These calculations can be used in particular to model the rigid inclusion behaviour in the centre of the tanks, because there is no effect of load dissipation in the ground.

4.1 *Semi-empirical mobilisation laws of Frank and Zhao*

To characterize the soil-structure interaction in a soil reinforced by columns, several authors have proposed load transfer curves that are based on different approaches. However, the final design of rigid inclusions for a slab-on-grade is not signicantly impacted by the curve model (Burtin & Racinais 2024). In Germany, the load transfer curves by Frank & Zhao (1982) and Bohn & Vogt (2018) are widely used.

Frank & Zhao (1982) proposed two semi-empirical laws for mobilization of skin friction along the column and for end-bearing at the tip of the column. This model is based on pressuremeter data. The skin friction mobilization law is defined according to the relationship between the shear stress τ and the relative displacement s_s (between the rigid inclusion and the soil around the shaft of the column). This law depends directly on the limit value of skin friction $q_{s,ult}$ which could be correlated from the limit pressure p_L according to Eurocode 7-2 Appendix E or NF-P 94-262 (2012). The end-bearing mobilization law is defined according to the relationship between the stress at the column toe q_b and the vertical displacement at the inclusion tip s_b in the bearing layer. The end-bearing resistance $q_{b,ult}$ could be also correlated from the limit pressure p_L.

The mobilization curves of skin friction and tip resistance are determined according to the model shown in Figure 13 as a function of the pressuremeter modulus E_M. The values for the coefficients m_q and m_τ depend on the soil type.

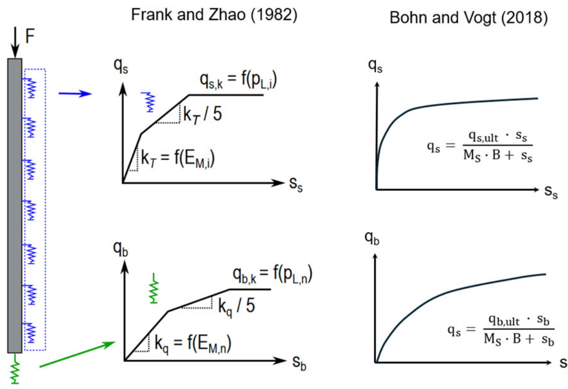

Figure 13. Mobilisation laws for RI. Left: Frank and Zhao (1982), Right: Hyperbolic approach by Bohn and Vogt (2018)

Bohn & Vogt (2018) proposed two main load transfer curves with cubic root and hyberbolic shape. The figure presents the empirical hyperbolic law, which can be used in absence of pressuremeter parameters.

The parameters M_s and M_b are the result of an empirical study of several load tests and are defined for all inclusion installations and soil types.

4.2 *Analytical Prediction*

The RI design with LTP under the tanks was based on the analytical model MV2 described in the ASIRI recommendations. It is a two-phase model which examines the interaction between the domain of inclusions and the surrounding soil in a unit cell. The calculation is iterative. The first iteration assumes a distribution of the load between the two domains, which enables to assess the settlements directly below the slab in each domain. In the following iterations the load distribution is varied to reach the equality of the settlements directly below the slab. The two domains are linked by load transfer curves according to section 4.1.

The further model parameters are given in Table 1.

Table 1. Parameters of the analytical model

	E_{oed} (MPa)	c' (kPa)	φ' (°)	γ/ γ' (kN/m³)	q_s (kPa)	q_b (kPa)
LTP	100	0	42	18/10		
Sand I	13,4	0	37,5	20/10	24	
Loess	5,9	10	30	19/10	17	
Sand II	17,9	0	37,5	20/10	39	
Boulder clay I	18,9	10	35	19/10	60	
Boulder clay II	26,2	10	35	20/10	80	
Gravel	100	0	40	20/10	200	5.000

The results of the analytical and numerical unit cell calculation for the final load of 185 kPa ground pressure are as follows and shown in Figure 14 for tank A:

1. distribution of settlements within the soil and the RI (left),
2. distribution of the axial load in the RI (right).

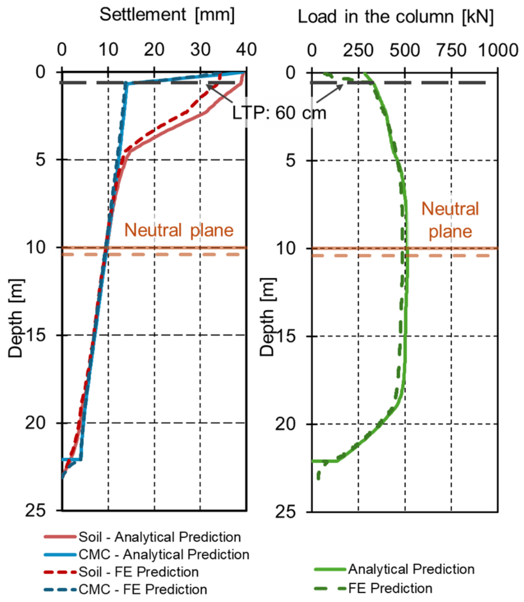

Figure 14. Results of unit cell calculation for tank A (full loading = 185 kPa) using the load transfer curves by Frank & Zhao (1982) and with FE modelling

For a total load of 185 kPa, the analytical calculated settlement of the slab was 40 mm and the FE calculation gave 34 mm. The load at the column head is calculated with 312 kN (58 % of the total load within the unit cell), what means a stress of 3,900 kPa. The result is a punching of the column head about 25 mm into the LTP, what means more than 50 % of the total predicted settlement of 39 mm. The most part of soil deformations takes part in the alluvial loess layer. Up to 10 m deep the deformation of the surrounding soil is predicted larger than the column settlement, which results in negative skin friction. The maximum the load in the CMC is calculated with 500 kN in the neutral plane, which is nearly the total load of the unit cell. Below the neutral plane positive skin fiction is activated and the load within the column decreases.

4.3 *Comparison with measurements*

Unit cell calculations were carried out representing the centre of the tank. The predicted settlement for tank A, tank B and tank C are summarized in Table 2.

Table 2. Predicted and measured settlements of full loading (18.5 m water)

	Tank A	Tank B	Tank C
Predicted settlement (analytical)	39	43	43
Predicted settlement (FE)	34	-	-
measured at the edge s_{edge} (mean values)	22	24	23
measured in the centre s_{centre}	39	46*)	45*)

*) estimated from measurements on the slab after emptying the tank

The measured settlement in the middle of the slab can be compared with the calculated settlement using the methodology of a unit cell described above for different stages during filling process. Figure 15 shows the modelled and measured settlements in the inner area of the slab (inner diameter of 3 m).

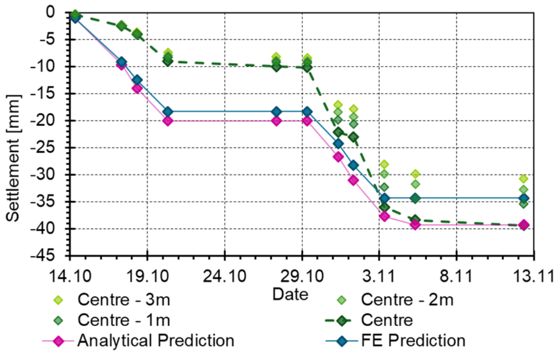

Figure 15. Measurement vs. Settlement predictions of tank A.

The predicted settlement based on analytical and numerical calculations of the unit cell model show good agreement with the measured values in the centre of the slab, especially for high loading. At a lower filling level (from 0 to 9 m water level), the calculation provides a larger settlement than observed in the field.

It can be also seen in Figure 16, that the measured stresses are lower than the calculated values for a fluid hight up to 9 m. Maybe because the applied load was too low to activate the boundary between pressure cell and column head.

The beneficial properties of the adaptive system consisting of rigid inclusions and LTP have already been illustrated in Figure 11. It shows that after complete filling, about 60 % of the total load is on the CMC head, which corresponds well with the predicted values, see Figure 16.

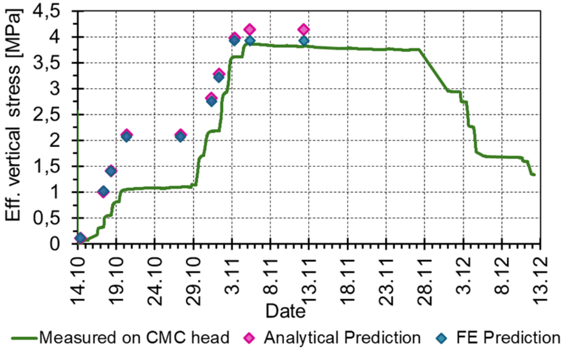

Figure 16. Measured vs. predicted vertical stress on top of the CMC

5 CONCLUSION

Heavy loaded steel tanks on compressible ground conditions can be founded on shallow foundations after ground improvement with rigid inclusions. Due to accurate soil parameters from the Pressuremeter test, it was possible to implement an efficient ground improvement solution using Controlled Modulus Columns (CMC). Compared to a conventional pile foundation, concrete and steel reinforcement in the slab could be saved.

The analytical and numerical calculations with the simple model of the unit cell show good agreement with the measured values in the centre of the circular slab, for both: the settlements and the load distribution between the columns and the surrounding soil.

An accurate determination of the load distribution is an important part of the RI design, for example to determine the interaction mechanisms with the slab in terms of bending moments and resulting tension stresses.

Observations of the behaviour of tanks during hydrostatic load test provide a basis for the expected performance of tanks during service. The tanks of this case study will be in service for the next 30 years. Further measurements will be published on following papers.

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