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LONG TERM GEODETIC MONITORING OF THE DEFORMATION OF A LIQUID STORAGE TANK FOUNDED ON PILES

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Abstract

A large storage tank capable of storing 12,000 t of liquid ammonia has been operating at the industrial area of the city of Thessaloniki since 1983. The tank is founded on 112 long bored piles. Due to the type of the stored material, any damages on the construction would cause exceptionally catastrophic consequences. To prevent this possibility, geodetic measurements were used for monitoring the settlements of the structure. These measurements included high precision leveling and started just after the completion of the structure. New periods of measurements were repeatedly made on a permanent base until today. The recorded values of deformation gave important information about the pile group settlement distribution of the tank with time and tank loading history. Finally, a comparison of the behavior of the tank to the behavior of similar structures was done and the corresponding conclusions were derived.

1. Introduction

Monitoring of the behaviour of large technical structures has been a reality for the last few decades. Deformations that occur may cause severe damages to structures or even loss of life and injury to people. These deformations may be attributed to several reasons, such as incomplete investigation of foundation soil properties, improper construction of the foundation system, insufficient knowledge of the operating conditions, earthquakes etc. In all cases, the continuous monitoring of the behaviour of the structure can detect deformations and displacements authenticating study and construction theories and proving the safety of the operation of the technical work. So, the observations and recordings of deformation donnot present only scientific interest for the geotechnical engineers, but they are also indications of the long-term behaviour of the construction (Badellas and Savvaidis, 1990).

In this paper, the deformation observations of a heavy storage tank for storing 15,000 t of liquid ammonia founded on a large group of bored piles are presented. The tank is located at the industrial area of Thessaloniki, about 10 Km SW of the city center and near to the seaside (fig.1). Due to the type of material stored, any damage to the construction would cause exceptionally catastrophic consequences and the prevention of leakage is of paramount importance.

The complex consists of an internal steel tank protected by an independent cylindrical shell of a 280 mm thick circular, prestressed concrete wall. The concrete shell has 37.60 m external diameter, it is 31.60 m high and it is covered by a dome type fixed prestressed roof. The superstructure is founded on a 800 mm thick circular concrete raft, 1.30 m above the ground surface, which is supported by 112 bored piles (fig.2). The dead weight of the whole structure is approximately 7,000 t (Pitilakis et al., 1985).

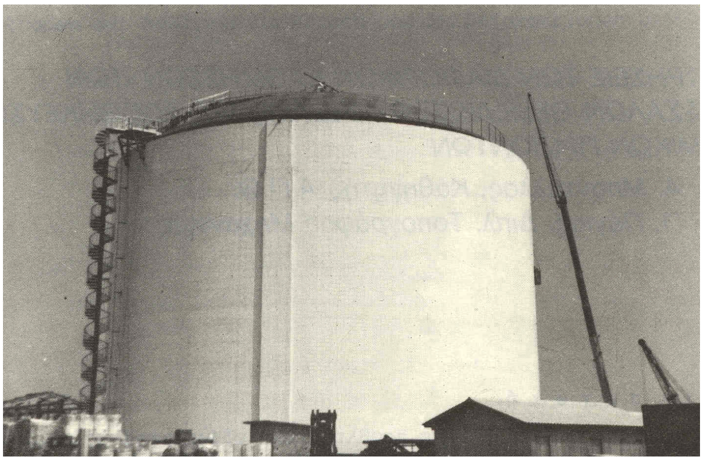

Fig. 1. The liquid ammonia tank at the industrial area of Thessaloniki

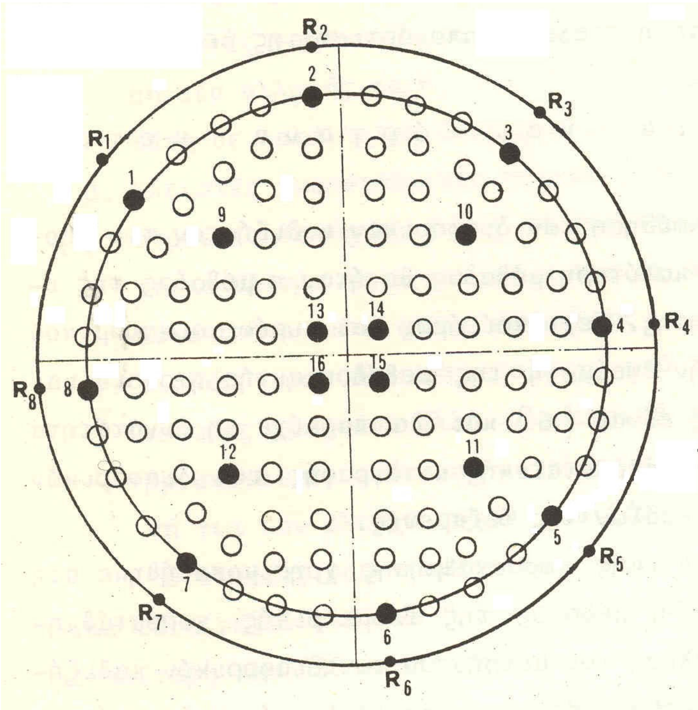

Fig. 2. Layout of the group of piles (black dots show piles with benchmarks for settlement monitoring)

Numerous articles have been published about piles during the last years and several design methods have been proposed, based on theoretical considerations or results from model tests but knowledge about the bearing capacity and settlements of pile groups is still rather limited. This is due to lack of data from full-scale field tests. So, any case history related to pile foundation settlements offers useful information on the understanding of the real mechanism and the role of the factors affecting pile group behaviour (Badellas et al., 1988, Savvaidis and Ifadis, 2001).

The construction of the tank started in June, 1982 and was completed in about 11 months. The monitoring of piles settlement and slab deformation started just after the completion of the structure in June, 1983 and has been continued for 20 years, last epoch of measurements being in January, 2003. In this sense, the liquid ammonia tank is probably the longest monitored for deformations construction in the Hellenic area.

2. Foundations consideration and design

Storage tanks are relatively flexible structures and they can tolerate greater settlements than other engineering structures. However, there is a limit to the settlements expected to be taken without distress. The most important undesirable effects of settlements to avoid in designing tank foundations are as follows:

- Overall settlement of the tank.
- Differential settlement across the diameter, which may overstress internal piping connections.
- Differential settlement along the periphery, which may overstress the superstructure.
- Differential settlement between the tank and the external connection pipework.

Due to the fact that the deposit of weak soils was found very deep and foundation conditions could not be effectively improved by strengthening techniques such as replacement with engineering fills, vibration, compaction, stone columns, line columns etc., a piled foundation system was the only viable foundation solution. Furthermore, the loading conditions, the existence of soft clayey strata and the available large amount of surrounding plant were the main reasons for the decision to avoid the displacement piles and to choose the rotary, cast in place, large bored piles with bentonite slurry as the most efficient pile type.
Finally the pictured in fig. 2 group of 112 piles was designed and constructed. Each pile has a diameter of 1.00 m and it is 42 m long. Taking into account the interaction between piles in a semi-infinite mass, the mean total settlement of the group was evaluated equal to 14.7 cm by applying Poulos method for piles group settlement computation (Poulos, 1979).

3. Measurement of settlements

In order to monitor the vertical deformation of the tank, 8 benchmarks (R1, R2, …, R8) were established around the circular slab periphery and 16 benchmarks (P1, P2, …, P16) were installed on the upper free part of certain piles (fig.2). The benchmarks can be divided into three groups: P1, P2, P3, P4, P5, P6, P7, and P8 located on piles at the external periphery of the slab, P9, P10, P11, and P12 located on piles at an intermediate periphery and P13, P14, P15, and P16 located at the central piles.
High precision geodetic levelling was used for the determination of the possible settlements of the benchmarks with time and load. Three reference elevation points were established at distances of 50, 400 and 1500 m from the tank respectively. The measurements were carried out at first with a Zeiss Jena Ni 2 automatic level and then with a Topcon automatic level, both with optical micrometers. In each epoch, the same leveling network consisting of the reference and the control points was measured. The network was then adjusted (Savvaidis, 1995). In this way, the elevation of the control points was computed for each epoch. The vertical movement of the benchmarks could then be computed by comparing their elevations between epochs.
Observations started during the water loading test of the tank in June 1983. The tank was gradually filled with 15,000 t of water in about 11 days. The water was kept there for a week and then it was slowly removed within a period of 8 days (fig. 3).

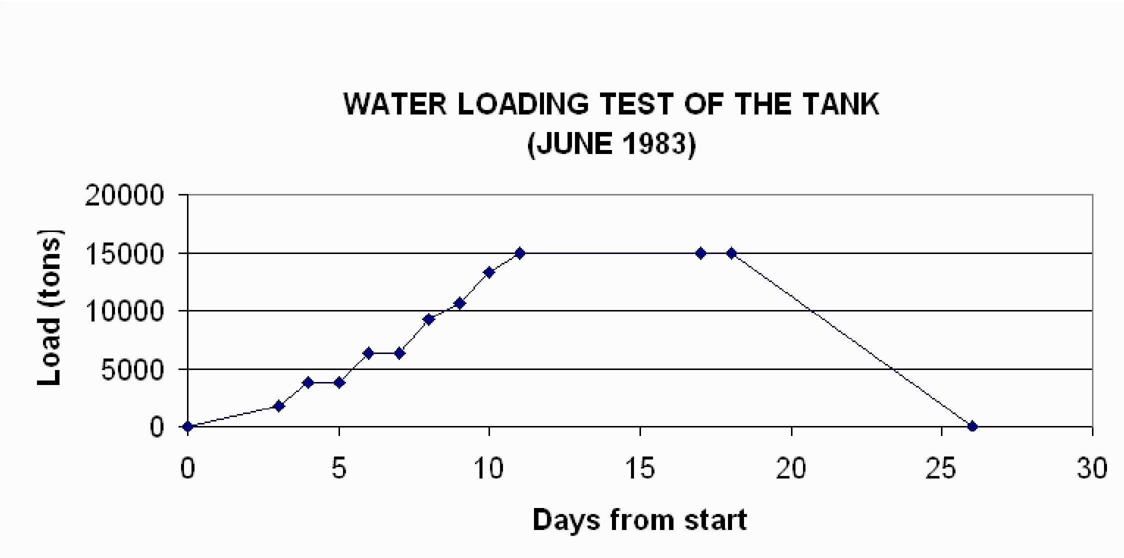

Fig. 3. The water loading test of the liquid ammonia tank in June, 1983

The vertical displacements of the pile benchmarks during the test loading measurements can be seen in figs. 4 (all piles) and fig. 5 (piles 7, 11, 16). Furthermore, the total deformation of the slab according to the settlement of the piles under maximum load can be seen in fig.6.

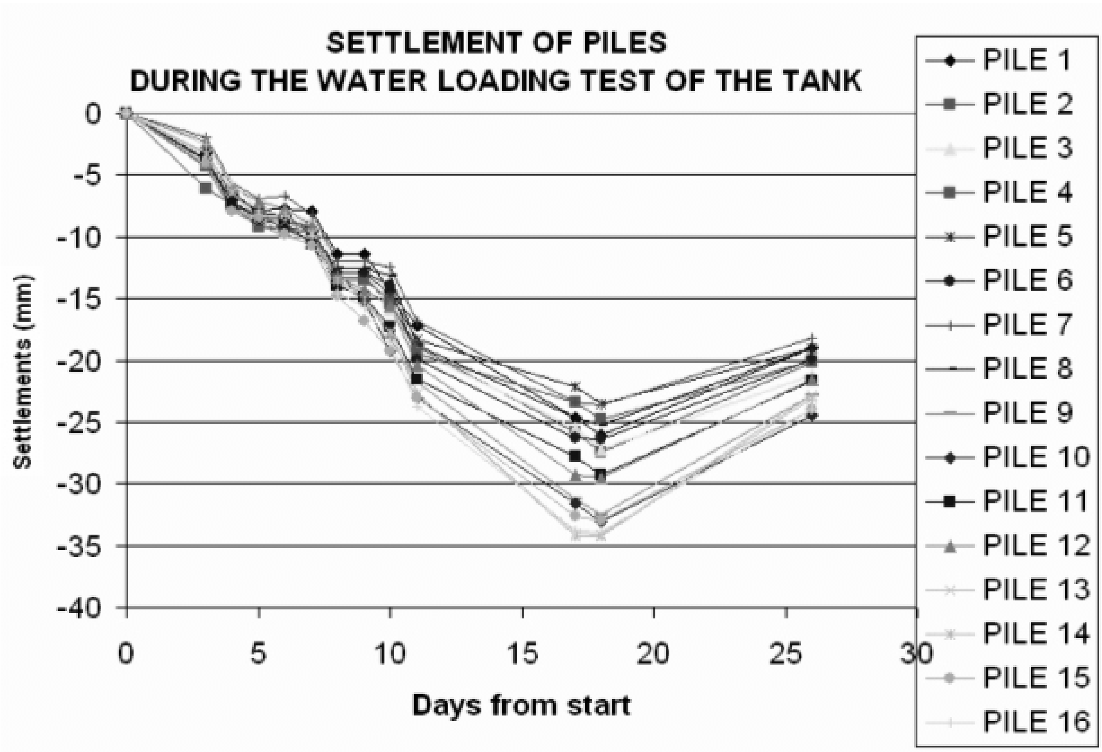

Fig. 4. Settlements of all piles during the water loading test of the tank in June, 1983

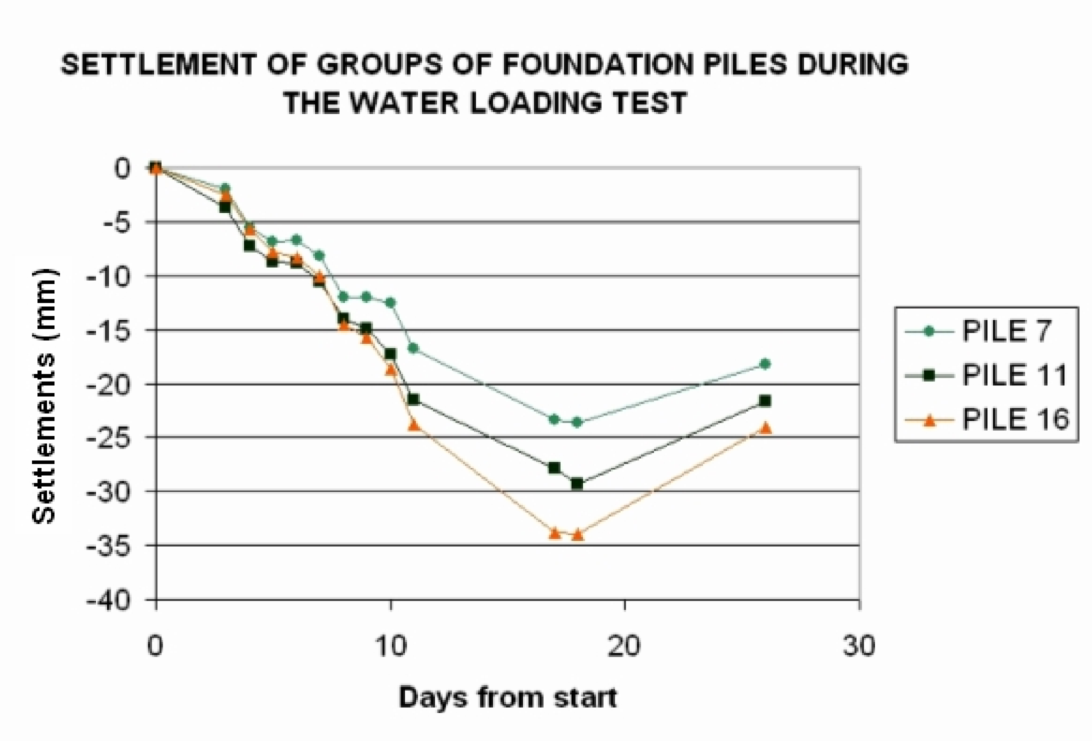

Fig. 5. Settlement of pile 7 (external periphery of slab), 11 (intermediate periphery), and 16 (center of slab)

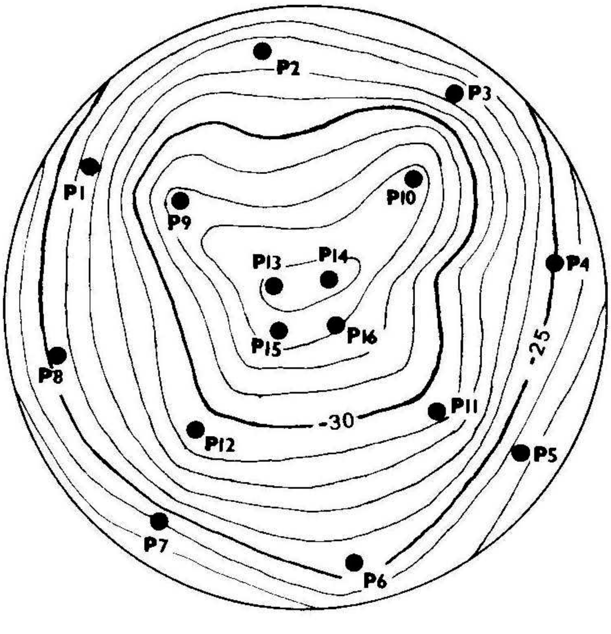

Fig. 6. Lines of equal vertical displacement of piles under maximum load during the water loading test of the tank

Monitoring of the liquid ammonia storage tank has continued since the first loading test on a periodic base. A total of 50 epochs of measurements was performed until January, 2003. Figs. 7 and 8 show the total loading history of the tank and the mean settlement of benchmarks R1, R2, … , R8 (established around the circular slab periphery) for each epoch respectively.

As it can be seen from the above figures, the vertical displacements of pile benchmarks generally follow the loading and unloading of the tank. During the water loading test, the maximum settlements of the slab occurred at central piles P13, P14, P15, and P16 with a mean value of approximately 35 mm. The settlements observed were smaller with increasing distance from the center of the circular slab. The maximum settlement observed during the period 1983 – 2003 equals to 63 mm. In the last three years the observations resulted into no significant vertical displacements.

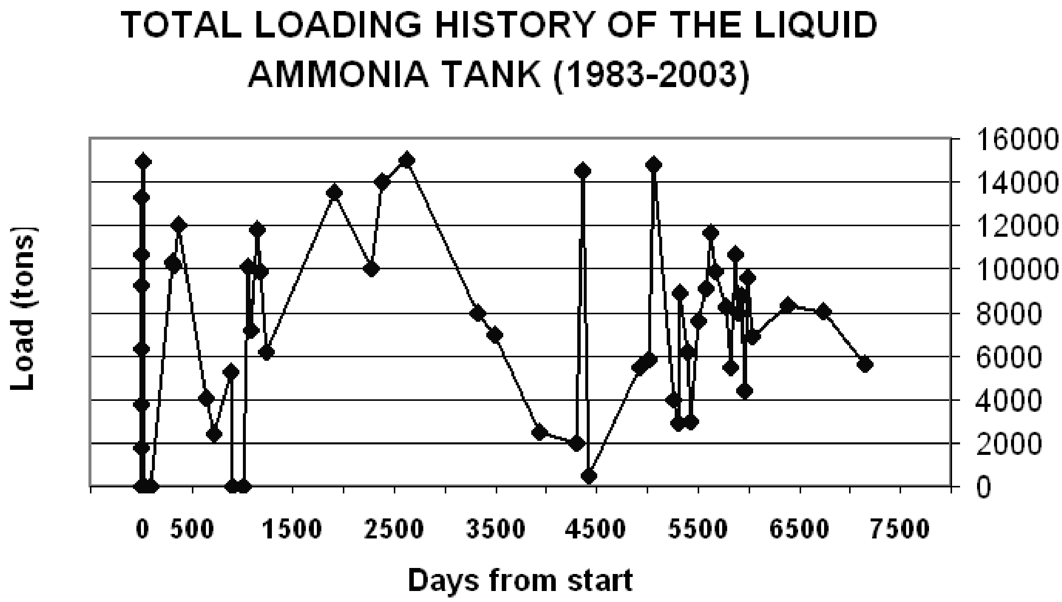

Fig. 7. Total loading history of the liquid ammonia storage tank (1983 – 2003)

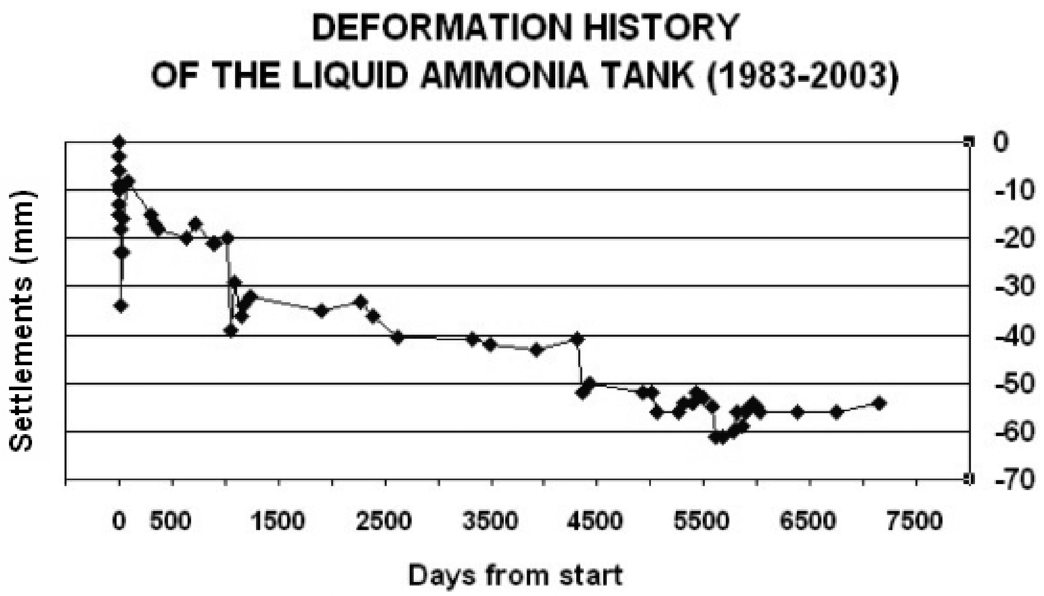

Fig. 8. Mean settlements of benchmarks R1, R2, … , R8 for each epoch (1983 – 2003)

4. A survey of similar structures

Some other structures where similar construction techniques were used are:

- A heavy storage tank capable of storing 50,000 t of sugar (Savvaidis and Ifadis, 2002). It was constructed in the installations of the Hellenic Sugar Industry S.A. at Plati, about 50 Km from the City of Thessaloniki. The tank, which is the largest structure of this category in Europe, is founded on 124 long bored piles (fig. 9). The design and construction of its foundation system is very similar to that used in the liquid ammonia storage tank under consideration in this paper. Geodetic measurements were used for monitoring the displacements of the structure both in the vertical and the horizontal sense for a period of one year (1995 -96) after the completion of technical works. In this structure, too, the maximum vertical displacement occurred at the central piles, with settlements getting smaller values when moving to the periphery of the tank. There was no indication of horizontal deformation.
- A heavy storage tank capable of storing 40,000 t of sugar at Forlipopoli, Italy (Bakavelou et al., 1997). The circular concrete raft is founded on 396 piles. It is a structure identical to the one at Plati. Both horizontal and vertical deformation monitoring of the tank have been carried out. The observed vertical displacements obtained maximum values again at the central piles of the foundation system. Also, horizontal deformations were detected at the lower part of the circular, prestressed concrete wall of the cylindrical shell of the tank.

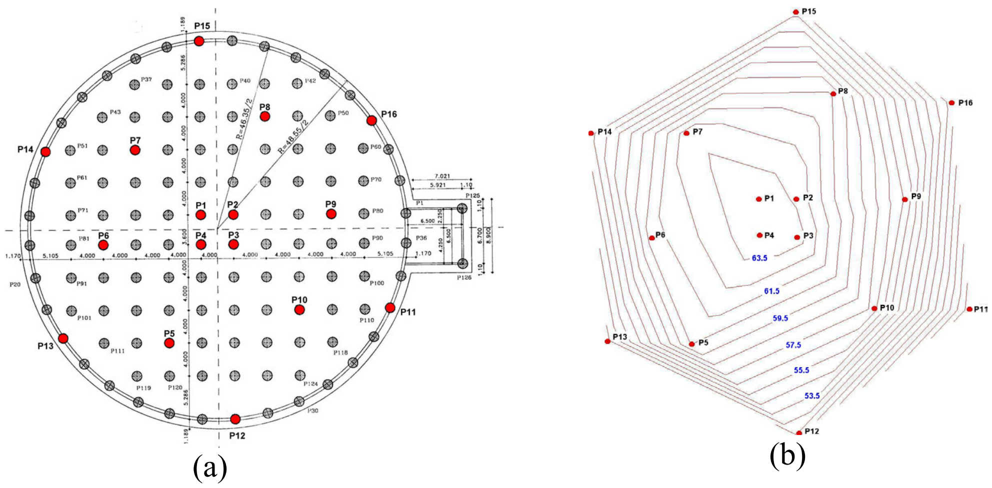

Fig. 9. Layout of foundation piles (a) and measured vertical displacements (b) of the 50,000 t sugar storage tank at Plati

5. Conclusion

In this paper, the recorded values of the actual deformations of a storage tank capable of storing up to 15,000 t of liquid ammonia were presented for a period of 20 years (1983 – 2003). From the results of the measurements and the analysis of displacements following conclusions could be drawn:

1. During the first loading of the tank with 15,000 t of water, the mean value of the observed settlement was equal to the 18% of the predicted mean final settlement. After water removal the mean remaining settlement was 9% of the final predicted value. The differential settlements between the center of the foundation slab and the peripheral points were fractions of the overall slab settlement, quite close to the ratio estimated in the computations.

2. The differential settlements between successive peripheral control points, which may be attributed to soil profile variability and to small differentiations in pile construction, were kept less than several mm.
3. Up to date the observed settlements seem to be the 43% of the computed as final settlements.
4. There has been an indication of stabilization of the settlements in the last three years.
5. The model of vertical deformation of the liquid ammonia storage tank in Thessaloniki was very similar to the behaviour observed in the other two tank structures mentioned above (the sugar storage tank at Plati, Hellas and the sugar storage tank in Forlipopoli, Italy).

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