3rd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering,
28-30 June 2012, Near East University, Nicosia, North Cyprus

Monitoring and numerical investigations of rigid inclusion reinforced concrete water tanks

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KEYWORDS: rigid inclusions, concrete water tank, monitoring, soft soil, numerical modelling

ABSTRACT: This paper describes experimental and numerical investigation of a rigid inclusions reinforced concrete water tank. This study was conducted in the French national research project, ASIRI, in order to improve the knowledge in this field. In-situ measurements show that the load is transferred to the rigid inclusions and settlements are reduced and stabilized. The numerical models are also developed to interpret these measurements. The numerical and experimental results are compared. This analysis contributes to understanding of the load transfer mechanisms granular earth-platforms with rigid inclusions.

1 INTRODUCTION

Soft soil improvement by rigid inclusions is common nowadays. However, some of the existing design methods do not take into account the complex behavior developed in these reinforced structures (Briançon et al., 2004). A French national research project (ASIRI) was thus launched to improve knowledge in this field and to draft a document constituting the guidelines for the design, construction and control of embankments and pavements on pile-reinforced soils. In this framework, a full-scale experiment was carried out (Briançon & Simon, 2012) and many real reinforced structures were monitored. Monitoring consists in the measurement of settlements and load transfer at the level of rigid inclusion head. The main interest of this study is to observe the influence of cycling loading on the differential settlement between rigid inclusions and the load transfer mechanisms.

2 SITE CONDITIONS

The water treatment plant of Pont-Audemer is projected to be built on a site where soft soils are present. Stratigraphy over the site of Pont-Audemer water treatment plant is composed of a loose superficial fill of sand about 6 meters thick, covering a layer of non-compressible clays. The ground water level is below the ground surface and is influenced by tides at certain times of the year. In order to decrease excessive settlements, the compressible soil can be replaced but the depth of the compressible soil makes this solution inadaptable for the project. Otherwise it can be bypassed with piles. Finally, the soft soil may be improved and reinforced. The soil replacement technique is not adapted to the project because of economical and ecological constraints. On the other hand, the solution with piles is less economic than the soil reinforcement and creates excessive bending moments on the slab foundation.

The soil reinforcement method with rigid inclusions was thus adopted for this project. The rigid inclusions pass through the compressible sand layer with a grid distribution of 3m x 3m. The diameter is 28 cm.

3 CONSTRUCTION DETAILS

3.1 Soft soil improvement

The design of rigid inclusion reinforced structures comprises two main elements; the rigid inclusions and the load transfer layer called earth-platform. The system can be considered like deep pile foundations with an earth platform between the structure and the foundation. The earth-platform can be made of gravel, ballast, lime-cement-soil, cement or another type cemented soil (Okyay & Dias, 2010). The load transfer mechanisms depend on the geometrical configuration of rigid inclusions and the mechanical characteristics of the earth-platform. Figure 2 shows the geometrical configuration of a rigid inclusion reinforced soil with a slab foundation.

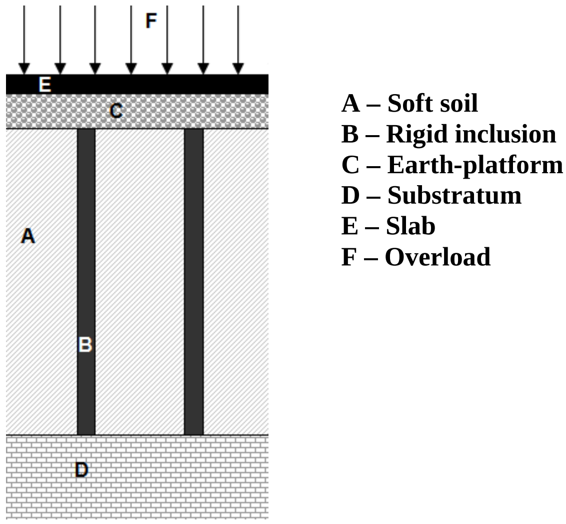
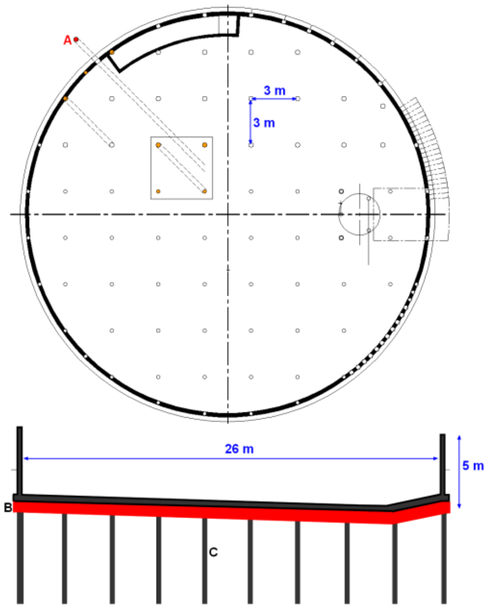


Figure 1. Soil reinforcement with rigid inclusions (Okyay, 2010).

The overload is transferred onto the head of the rigid inclusions and the soft soil. The residual load on the soft soil is also retrieved by rigid inclusions by negative friction forces along them.

3.2 Tank construction

Concrete tanks in water treatment plants are used to store liquids like dirty and cleaned water. All liquid tanks are designed as crack free structures to eliminate any leakage. The settlements are also limited (generally 2 cm for a global settlement). The storage tank of Pont-Audemer water plant is about 26 m of diameter a 5 m of height. It is subjected to cyclic loading during its service time. The surcharge loading is about 50 kPa when the tank is filled. Figure 2 shows the plan view of the structure as well as the final view.



A - Reference point
B - Earth-platform
C - Rigid inclusions

Figure 2. Plan and final views of the structure

4 INSTRUMENTATION

The instrumentation is focused on two major zones under the slab. The first one located under the centre of the tank and the second one located under the perimeter of the tank.

4.1 Settlement measurement

Settlement of soft soil and inclusion head are measured with pressure transmitters for level measurement (T). The sensors are interconnected by means of a pressure line, an air compensation line and a digital data cable. The elevation changes of the individual sensors in the system are then derived from the liquid pressure. This is done by comparing the liquid pressure at each sensor with the pressure at the reference sensor located outside the embankment. Sensor T1 is located outside the construction and serves as reference. Sensors T2 and T6 are located on the inclusion head respectively under the center of the tank and under its perimeter. Sensors T3, T4 and T5 are located on the soft soil between two diagonal adjacent inclusions under the center of the tank. Sensors T7, T8 and T9 are also located between two diagonal adjacent inclusions but under the perimeter of the tank (Figure 3).

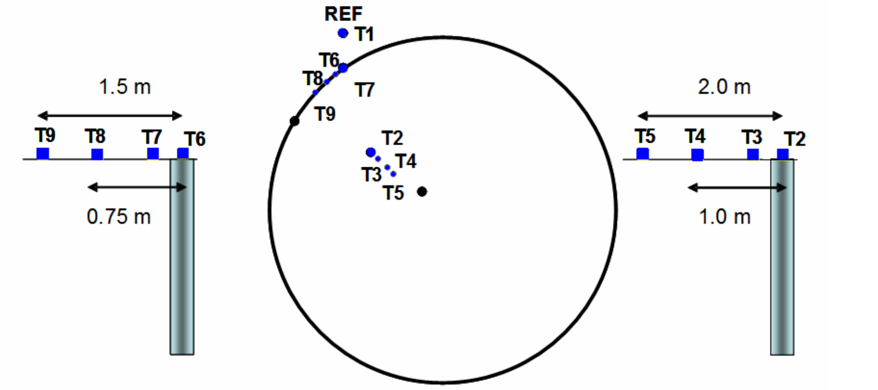


Figure 3. Location of settlement sensors

4.2 Stress measurement

Two earth pressures cells are located in each monitored areas to measure the load transfer:

- one on a inclusion head,
- one on the soft soil between two diagonal adjacent inclusions.

Figure 4 shows the location and the notation of these sensors. They are set up inside a sanded trench in the traffic platform.

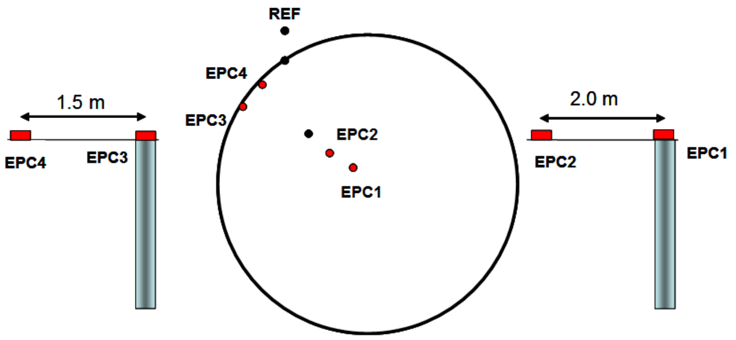


Figure 4. Location of earth pressures cells

All sensors are connected to a data logger recording measures every 4 hours.

5 RESULTS OF MEASUREMENT

Stress values have been measured since the beginning of the construction of the water concrete tank and during more than one year after the construction. During this period, three tests of loading-unloading cycles have been applied. The stress distribution on the inclusions and the soil is presented at Figure 5. This load transfer is greater under the centre of the water concrete tank than under its perimeter when the tank is filled.

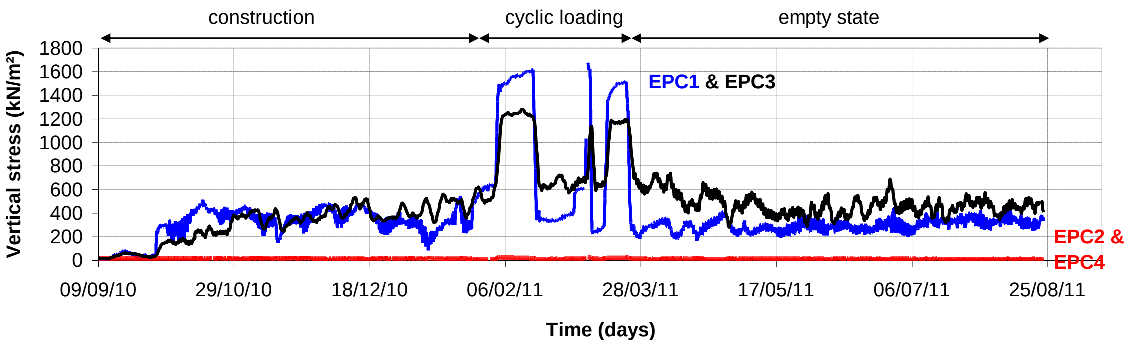


Figure 5. Stress distribution at inclusion head and soil

Measures of settlement have been initialized after the construction of the water tank. Figure 6 shows the measured settlements under the center of the tank. Rigid inclusions and soil settle at the first stage of filling-emptying. The settlement of the rigid inclusion is greater than settlement measured on the soft soil. Measurement highlights that the soil settles uniformly. After the first stage of cyclic loading, the settlement is stabilized and for the next cycles, the settlement value remains constant. These observations on the settlement show that as the rigid inclusions are not anchored in the substratum, they can penetrate in the substratum under loading.

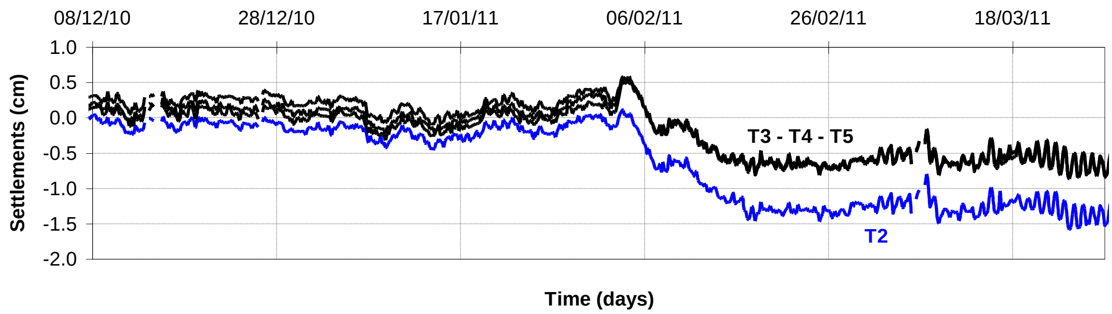


Figure 6. Settlement under the centre of the water concrete tank

The sensor T6 located on a pile under the tank perimeter has been damaged during the set up thus the only measures under the tank perimeter are those of sensors located on the soft soil. We notice that the soil under the perimeter of the water concrete tank raises up (+ 0.5 cm) while the soil under the centre of the water concrete tank settles (- 0.5 cm).

6 NUMERICAL INVESTIGATIONS

In order to estimate the settlement at the centre of the tank and the maximum stress on rigid inclusions a cell of rigid inclusion is simulated by an axisymetrical model. Settlements and stresses were computed using the FEM software Plaxis^{2D} axisymmetrical model of the unit cell. Soils and rigid inclusion properties are summarized on Figure 7. An interface element is placed between rigid inclusion and soil layers.

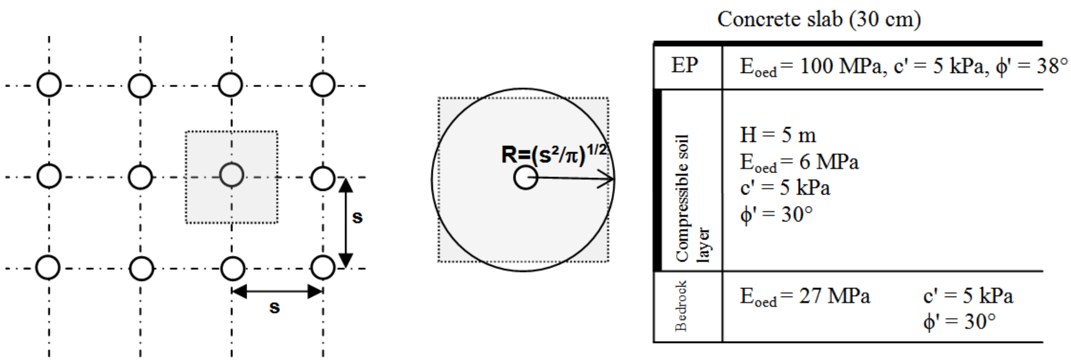
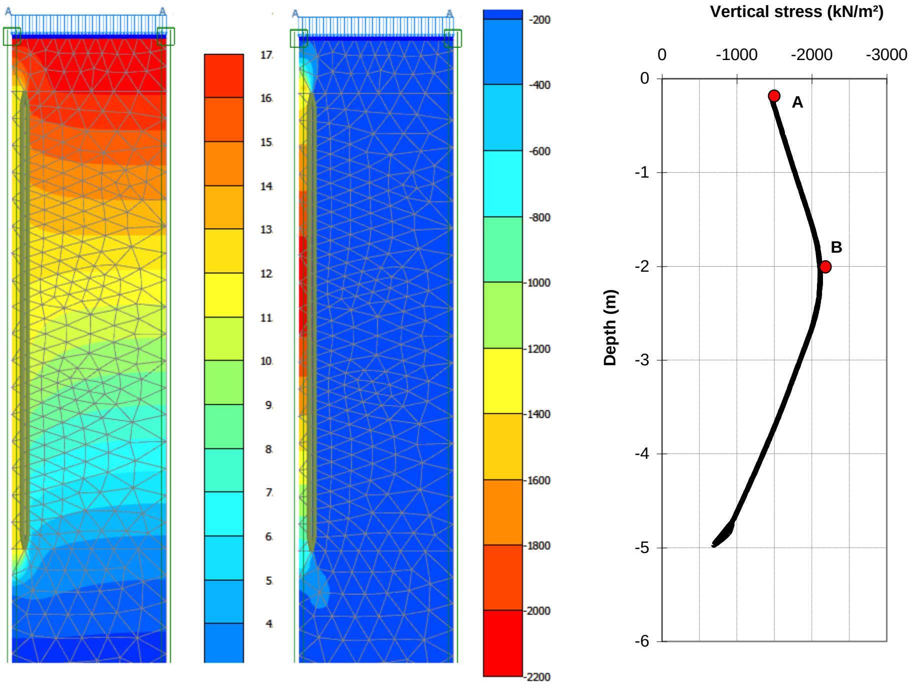


Figure 7. Characteristics of the soil layers and geometry used in the FEM Analysis

The axisymmetrical calculation results are shown graphically on Figure 8. Based on this model, the settlement at the centre of the tank is about 17 mm. The maximum vertical stress in the rigid inclusion is 2120 kN/m².

The results of numerical calculations are in concordance with in-situ measurements. At the end of the simulation with 50 kPa of surcharge loading, a vertical stress of 1500 kN/m² is obtained at the head of the rigid inclusion (Figure 8c, point A). The in-situ measurement at inclusion head varies between 1400 and 1600 kN/m². The vertical stress in the rigid inclusion increases gradually in depth by negative skin friction. The skin friction between soil and rigid inclusion is involved in the load transfer mechanisms. The maximum value of the vertical stress is 2120 kPa at 2 m of depth where neutral point is situated (Figure 8c, point B).



a) Vertical displacements (mm) b) Vertical stress (kN/m²) c) Vertical stress in the rigid inclusion (kN/m²)

Figure 8. Vertical displacements and stresses after loading

7. CONCLUSION

The performed in-situ measurements and numerical investigations contribute to the current knowledge about load transfer mechanisms with rigid inclusion reinforced structures. This analysis shows that the soil reinforcement with rigid inclusions reduces the settlements and homogenizes differential displacements under slab foundations. The load transfer mechanisms develop in the earth-platform and the stresses are redistributed onto the rigid inclusions by arching effect. Besides the transfer mechanisms in the earth-platform, the residual load on the soft soil pass on rigid inclusions by negative skin friction. This transfer also contributes to the settlement reduction on surface. The stress value on the rigid inclusion increases at depth. The results for the cyclic loading tests show that the loading-unloading cycles do not influence the load transfer. The results from the in-situ measurements provide a database for numerical modeling and analytical studies. The use of cemented-soil earth-platform and the reinforcement of the earth-platform by geosynthetic material will be investigated.

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