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Design and optimization of stone columns under heavily loaded tanks: case study

H.S. Fard, M. Ayeldeen
Keller Grundbau GmbH-Middle East, Dubai, UAE

R. Thurner
Keller Grundläggning AB, Lindome, Sweden

ABSTRACT: In this study two alternative solutions, namely piling and stone columns, are evaluated and compared for foundations of heavily loaded oil storage tanks in eastern Egypt (with diameter up to 55 m, and load up to 330 kPa). After reviewing the soil condition and performing intensive preliminary analyses, stone columns were found to be suitable alternative, which is a cost-efficient solution with faster production speed, less material consumption, much less environmental impacts, and less manpower and equipment mobilization. In order to get more knowledge about the soil profile, five additional CPTs per tank were performed with average depth of 45 m. In order to optimize the design and utilize the stone columns' capacities, various column distribution and depth (short and long columns) were considered in a comprehensive study to comply with the allowable total and differential settlements at the tanks' centre as well as around the shells. A large variation in soil layering and profile was noticed and considered for long- and short-term behaviours. Regarding the load level and sensitivity of the superstructure (which restricted the allowable settlement) the analyses demanded very tight stone column grids -up to 1.2 m for some areas- with depth of up to 38 m which was a challenge for execution and required practical experience on site. This case study proves the capability of stone columns to fulfil tough design criteria and difficult soil condition, while still having economic and technical advantages.

1 INTRODUCTION

An international oil and gas consortium intended to develop a feedstock terminal in eastern Egypt, to include the services of storage, loading, unloading and transportation of refinery products from the Middle East to Europe.

The designated ground for this project were not capable enough to carry heavily loaded foundations and satisfy the project's requirements, therefore particular design solutions needed to be used to transfer the applied structural pressure to the ground in a safe way.

This paper describes and compares the alternative geotechnical solutions proposed for this project, and summarizes the selected technology and challenges encountered.

2 PROJECT'S SPECIFICATION

The project consisted of 8 oil flush tanks as shown in Figure 1, for which *Keller* as geotechnical specialized Contractor was deployed to propose, design and execute geotechnical solution(s) to transfer the tanks' loads to the ground in commercially and technically reasonable manner. Table 1 presents the given diameter and ground pressure of the tanks.

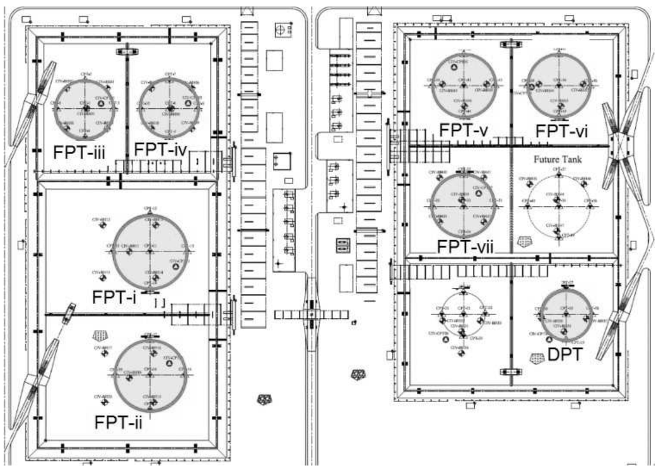

Figure 1. Layout of tanks in the scope of this project

Table 1. Specification of the oil storage tanks

Tank ID	Diameter (m)	Load* (kPa)
FPT-i	55	316
FPT-ii	51	282
FPT-iii	42	243
FPT-iv	42	243
FPT-v	46	271
FPT-vi	46	271
FPT-vii	46	271
DPT	38	250

* Applied pressure at tank bottom plate.

The maximum allowable settlements to be achieved in this project were as listed below:

- Max. settlement around the tank shell: 100 mm
- Max. differential settlement along the tank shell: 50 mm
- Max. differential settlement along the tank shell between 2 points 10 m apart: 13 mm
- Maximum differential settlement from the centre to the tank shell: 100 mm

The above requirements have to be sustained over a lifespan of 50 years.

2.1 *Subsoil condition*

A preliminary Soil Investigation had been done in the initial phases of the work even before the exact locations of the tanks and other structures were finalized, which included few boreholes in the tank area. Although the initial studies could give an indication about the soil profile, the geotechnical contractor decided to perform an additional and solution-oriented ground investigation (incl. 5 CPTUs per tank) in order to make sure that the designs fulfil the project's requirement and at same time saves costs and time for client.

The ground basically consisted of several layers of silty and gravelly sands and silty clays with various properties and thicknesses. The layers were highly varying even under a single tank.

Table 2 presents the average properties and depths of layers for the tank area, however, all observed fluctuations in properties and depths were considered very precisely in design and calculations.

Table 2. Average and simplified soil profile of the project

Depth* (m)	Soil type	Properties
0.0 - 0.5	Fill (gravel)	E = 75 MPa
0.5 - 10	Silty sand	E = 15 - 25 MPa
10 - 19	Gravelly sand	E = 40 - 60 MPa
		OCR = 1 - 1.8
19 - 21	Silty clay	Cc = 0.35
		Cr = 0.050
21 - 24	Gravelly sand	E = 40 - 60 MPa
		OCR > 3
24 - 28	Silty clay	Cc = 0.21
		Cr = 0.045
28 - 35	Silty sand	E = 20 - 35 MPa
35 - 50	Various silty and clayed layers	

* From the working platform

No bedrock was observed in the geotechnical investigations up to the full studied depth (max.: -50 m).

3 GEOTECHNICAL SOLUTIONS

3.1 *Initial solution*

Initially CFA or bored piles were recommended as the only feasible methods to achieve the requirements of heavily loaded and large tank foundations.

Regarding the soil condition the piles were considered friction piles with almost no contribution of end bearing resistance to the pile capacity. The piles rested in either limited thickness of the sand formations or in the stiff clay.

According to the project's primary designs, the pile lengths were ranging from 39 to 46 m for different tanks, with diameters of 0.8, 1.0 and 1.2 m and centre to centre spacing of 2.5 times the diameter (i.e. 1.92, 2.50 and 3.00 m).

3.2 *Keller's alternative solution*

After *Keller* joined the project as geotechnical specialist and reviewed the site conditions and constraints, proposed a Ground Improvement Technique as an alternative cost and time efficient solution to piling, namely *Vibro Replacement Method*, as described in Section 4 of this paper. This method requires mobilization of less manpower and equipment, consumes no cement and no steel and caused much less environmental impacts compared to piling solutions. *Keller*'s proposal was studied by client and consultant and found a technically and commercially reasonable and safe solution which was finally approved and executed.

However needless to say that not always and under every circumstances piling can be replaced by ground improvement methods. Decision on applicability and type of ground improvement requires vast and related knowledge and experience.

4 VIBRO-REPLACEMENT METHOD

Vibro Replacement Method is a ground improvement technique invented in 1950s, and later modified and customised by geotechnical specialists. This technique could also attract considerable attention in the researches for different conditions and applications (Greenwood 1970, and 1976, Gruber 1994, Kirsch 2004, Kirsch & Kirsch 2010, Nahrgang 1976, Priebe 1976, 1988, 1995, and 2003, Sondermann & Kirsch 2009, Sondermann & Wehr 2004, van Impe 2001, Wehr 1999, 2005, and 2007, Wehr et al. 2008, etc.). Nowadays this technique is considered as a reliable and well-established ground improvement method by many standards and guidelines worldwide.

4.1 *Function and execution*

The technology is used to treat clays, silts and mixed stratified soils and improve their load bearing and settlement characteristics by installing pile-like vibratory compacted stone columns into the ground using a depth vibrator to the design depths. Stone is introduced either down the side (top feed method) or from the tip of the vibrator (bottom feed method) and is compacted bottom-up in controlled stages.

The stone columns reinforce soft soil, accelerate drainage and mitigates liquefaction due to a seismic event. Typical applications for stone columns include settlement and stability improvement below embankments and stockpiles, foundations for all type of building especially warehousing and industrial buildings, wind turbines and liquid storage tanks.

4.2 *Design and calculation*

The most widely used method to design stone columns is introduced by Priebe (1976). The method uses the unit cell concept describing the stress situation of an infinite grid pattern of stone columns loaded with the vertical stress σ via a rigid foundation raft. The deformation of the stone column is approximated by the cylindrical cavity expansion method for describing the pressure meter deformations. Later Priebe (1976, 1988, 1995, 2003) modified and customized his design method. Kirsch & Kirsch (2010) also summarized this method backed up with recommendations and practical examples.

5 GROUND IMPROVEMENT SOLUTION PROPOSED FOR THE STUDIED PROJECT

5.1 *Design*

In cooperation with a local and competent designer, different stone column patterns were designed and calculated using *Keller*'s in-house software KID (based on Priebe method), GGU-SETTLE and PLAXIS programs (see Figs. 2, 3 and 4) taking the diameter of the tanks, applied ground pressure, settlement requirements and subsoil conditions into account. Therefore, different column lengths and spacing were designed for different tanks as well as for central, peripheral and outer areas of each tank. Figure 5 shows stone column designs of 2 tanks as examples.

5.2 *Execution and challenges*

In this project the stone columns were executed using top feed method with vibrators type S300 manufactured by *KGS* a subsidiary of *Keller*. The design diameter of columns was 1 m, however the executed diameter can vary depending on the ground layers. For softer layers larger diameter is expected.

The most challenging part of the project was the length of stone columns which was max. 38 m from the working platform (touching the world record for Vibro Replacement Method) and the very tight spacing between columns (min. 1.2 m). These challenges and difficulties could be overcome using right technology, powerful equipment and experienced manpower. Execution of stone columns in this project is shown in Figure 6.

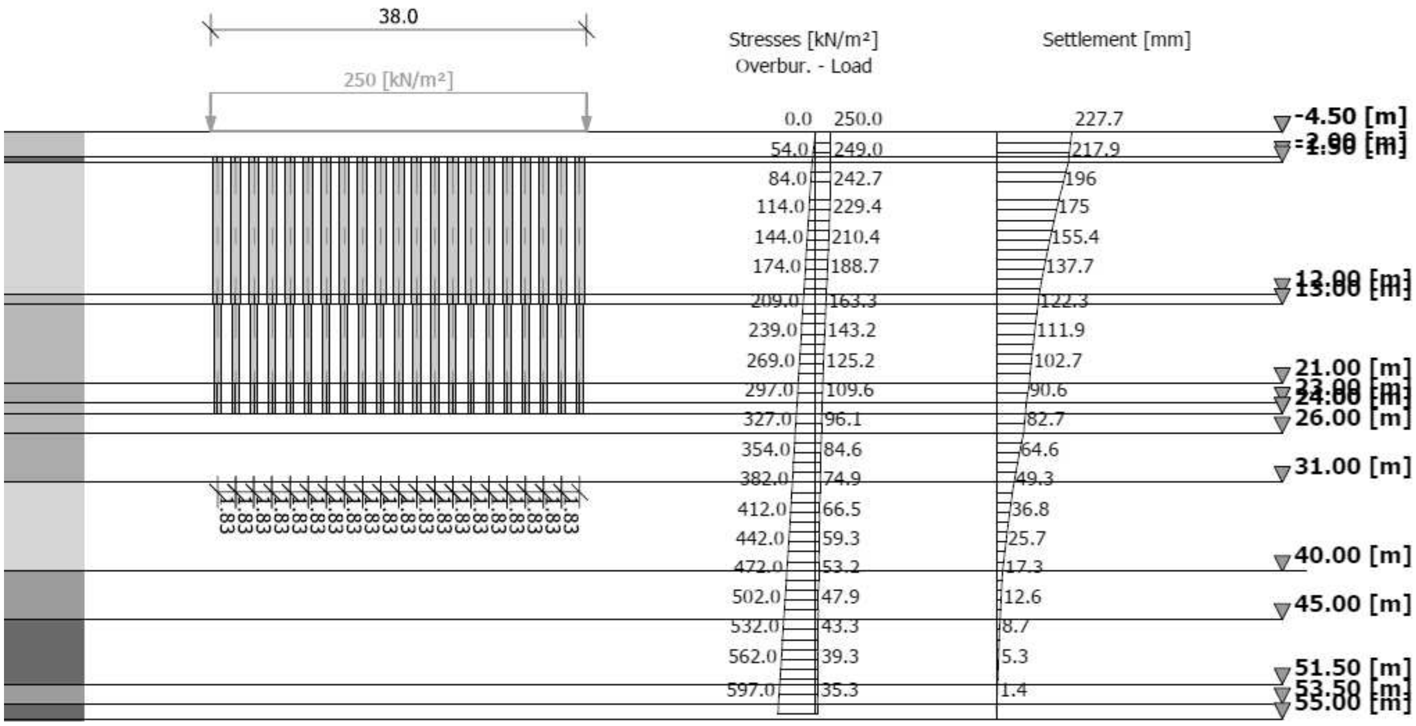

Figure 2. KID (Keller Improvement Designer) calculations

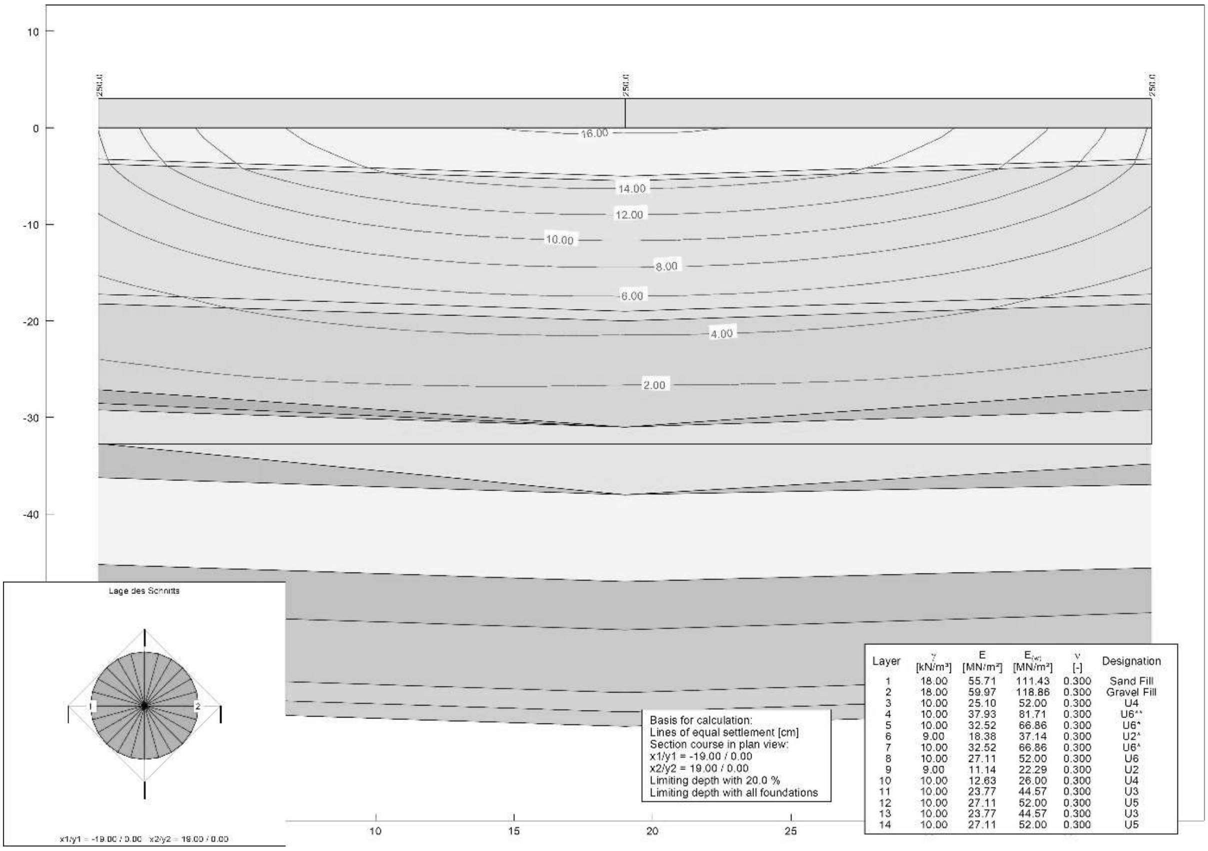

Figure 3. GGU-SETTLE calculations

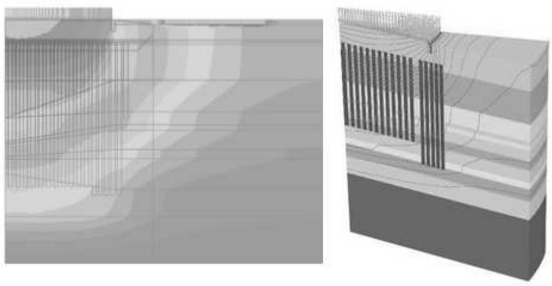

Figure 4. PLAXIS 2D and 3D calculations

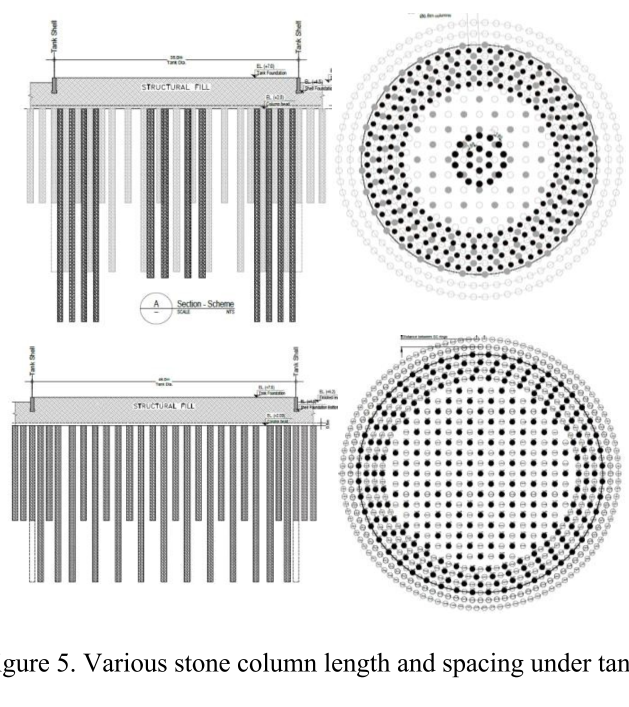

Figure 5. Various stone column length and spacing under tanks

Figure 6. Stone column installation Table

5.3 *Quality control*

To control the post treatment quality of the ground 3 tests were conducted; Plate Load Test (PLT), Zone Load Test (ZLT) and Hydro-Test.

One PLT per 100 columns was performed with loading plate diameter of 0.75 m to back-calculate the actual stiffness of executed columns based on the observed settlements. The actual stiffness was compared with the design value. Moreover at least one ZLT per tank was also carried out over a group of 4 stone columns (using a 3×3 m reinforced concrete footing) to evaluate the overall performance of delivered ground replacement and to verify the bearing capacity of composite stone columns and their surrounding soil. The maximum applied load was 1.5 times the working load of the tanks.

Results of both PLT and ZLT proved that the executed columns have achieved the required quality as considered in the design for the top part. For deeper layers the Production Protocols the stone columns including ground resistance (indicated by Amperes recorded automatically during the execution) and amount of stone fed into the ground vs. depth showed that the stone columns have been installed in line with the design assumptions. Therefore, the project's requirements can be satisfied with the implemented ground improvement technique. As examples results of PLT and ZLT on tank FPT-i are presented in Tables 3 and 4. The results demonstrated that the requirements have been fully achieved.

At the time of this writing the Hydro Tests on tanks are still ongoing, therefore no result can be provided.

Table 3. Results of 4 PLTs on tank FPT-i

Stiffness of stone columns back-calculated from PLT results		Stiffness considered in design
Young modulus (MPa)	Constrained modulus (MPa)	Constrained modulus (MPa)
148	192	100
240	313	100
285	370	100
233	302	100

Table 4. Results of 3 ZLTs on tank FPT-i

Applied stress (kPa)	Observed settlements ZLT-1 (mm)	ZLT-2 (mm)	ZLT-3 (mm)	Expected settlement* (mm)
118.5	1.4	1.9	1.1	4.90
237.0	3.2	3.7	1.8	9.80
355.5	5.7	5.6	2.6	14.75
474.0	10.5	10.6	4.4	19.65

6 CONCLUSION

Reviewing the above case history illustrates that ground improvement with Vibro Replacement Method is a technically reliable replacement for piling which reduces the project's costs and duration.

This method can be successfully applied even under heavily loaded foundations and in differently stratified grounds. However, depending on the site-specific situations, not always piling can be replaced by ground improvement methods.

Stone columns can be extended to 38 m deep or even beyond if the treatment against short- and long-term settlements or liquefaction is necessary. And if the design demands the spacing between columns can be tightened to 1.2 m.

In order to optimize the design and consequently the costs, stone columns can be installed with different lengths and patterns even under one construction, providing that very precise and solution-oriented ground investigation is available.

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