MITIGATION OF LIQUEFACTION HAZARDS USING GEOSYNTHETIC DRAINS

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ABSTRACT
The use of vertical drains to improve the performance of potentially liquefiable soil has been developed over the last two decades. Practices in this area leans heavily towards the use of gravel drains and stone columns. More recently, vertical geosynthetic drains have been used for liquefaction mitigation work, as they have naturally large discharge capacities than their counterpart gravel drains or stone columns. The objective of this research is directed to investigate, experimentally, the efficiency of geosynthetic drains on liquefaction mitigation. Special attention is paid to the mitigative effects of using geosynthetic drains on the stability of underground tank. Shaking table apparatus in Ain Shams university was developed and employed to perform the desired study. Extensive studies have been carried out on experimental model (underground tank) to investigate the effect of many parameters such as drain length, spacing ratio between drains, inclination angle of drains and factor of safety against uplift on the liquefaction potential of liquefiable sandy soil. Generally using experimentally geosynthetic drains proved to mitigate liquefaction effect on the underground tank stability. On the other hand, it can compete with gravel drains in terms of reliability and economy where noise and vibration are not allowed.

RÉSUMÉ
L'utilisation des drains verticaux d'améliorer l'exécution de la terre potentiellement liquéfiable a été développée pendant les deux dernières décennies. Les pratiques dans ce secteur se penchent fortement vers l'utilisation des drains de gravier et des colonnes en pierre. Plus récemment, des drains geosynthetic verticaux ont été employés pour le travail de réduction de liquéfaction, car ils ont des capacités naturellement grandes de décharge que leur gravier de contreparties s'écoule ou les colonnes en pierre. L'objectif de cette recherche est dirigé étudier, expérimentalement, l'efficacité des drains geosynthetic sur la réduction de liquéfaction. Une particulière attention est prêtée aux effets atténuants d'employer les drains geosynthetic sur la stabilité du réservoir souterrain. La secousse de l'appareillage de table de Ain Shams université a été développée et utilisée pour réaliser l'étude désirée. Des essais ont été effectués sur le modèle expérimental (réservoir souterrain) pour étudier l'effet de beaucoup de paramètres tels que la longueur de drain, rapport d'espacement entre les drains, angle de l'installation des drains, et facteur de sûreté contre le soulèvement sur le potentiel de liquéfaction du sol arénacé liquéfiable. Employer généralement les drains expérimentalement geosynthetic s'est avéré atténuer l'effet de liquéfaction sur la stabilité souterraine de réservoir. D'autre part, il peut concurrencer des drains de gravier en termes de fiabilité et économie où on ne permet pas le bruit et la vibration.

1. INTRODUCTION

Damages due to floatation of underground tanks were recorded in many historical earthquakes around the world. During earthquake when tanks embedded in liquefied soil, mobilization of additional high water pressure may produce additional uplift force. Floatation of underground tank will occur, if the tank was empty and the total uplift forces exceed the gravity weight of the tank itself (Koseki et al., 1997, Kamal El Dine, 2004).

Drainage is one attractive option for liquefaction mitigation, especially when used in conjunction with densification techniques. The fundamental principle of vertical drains is to allow fast dissipation for pore pressure during earthquake loading, thus preventing the development of large excess pore pressures leading to liquefaction. Performance assessments for these systems require the estimation of vertical drain spacing such that a maximum threshold level of excess pore pressure ratio does not exceeded certain values (Pestana et al., 2001; Sesov et al., 2001).

Large capacity prefabricated drains are an alternative to gravel drains or stone columns for liquefaction mitigation. These drains consist of corrugated, plastic pipe with open slots, and can range in size from 75 to 150 mm in diameter. Filter fabric is placed around the pipe to prevent the migration of fines into the pipe. The perforated plastic pipe provides a larger discharge capacity than gravel drains, which makes it more effective to dissipate excess pore water pressure. Prefabricated drains are installed either statically or dynamically, with conventional drilling equipment. They are carried within a steel casing which is driven into the soil to the desired depth of treatment. At this point the casing is removed, leaving the drain in place. Because no mixing occurs, prefabricated drains can reliably provide the desired drain permeability. When driven dynamically, prefabricated drains also provide some densification to the surrounding soil. When driven statically, the drains can be installed beneath existing structures, which represents one of the only cost-effective means to remediate liquefiable soils at developed sites

(Pestana et al., 2001; Rollins et al., 2003; Chang et al., 2003, Kamal El Dine, 2004).

This paper presents the efficiency of using geosynthetic drains on the mitigation of liquefaction hazards. Experimental shaking table tests performed to investigate the mitigative effects of using geosynthetic drains on the stability of underground tank model embedded in loose saturated sand. Several tests were performed in order to find out optimal and economical spacing between vertical drains, inclination angle and effective length of the drains, for the pore water pressure dissipation and achieving stability of the underground tank.

2. RESEARCH BACKGROUND

-Pestana et al. (1997) developed a finite element code, referred to finite earthquake drain (FEQ), to analyze pore pressure generation and dissipation with vertical drains and considering non-linear discharge capacity of prefabricated drains. Analytical study was developed by the same authors in (2001) using FEQ drain code for evaluation prefabricated drains. The results suggesting that prefabricated drains can be reasonably well described by the "perfect drain" analyses.
-Sesov et al. (2001) used a series of shaking table tests to investigate the efficiency of new type of artificial drains and gravel drains on the dissipation of pore water pressure. Results show that gravel drains has less influence on dissipation than the artificial drains and the artificial drains is closer to the so called "perfect drain".
-Rollins et al. (2003) used blast loading to test prefabricated drains installed in liquefiable soil. It was recorded that the presence of this type of drain has significantly increased the rate of excess pore water pressure dissipation and settlements were decreased by 40% to 80 % less than those non-treated areas.
-Chang et al. (2003) used full-scale liquefaction tests to evaluate the effectiveness of prefabricated drains in terms of generated excess pore pressure ratio and liquefaction induced settlement.. Specimen constructed with a full size single drain, results indicated that prefabricated drain can significantly reduce excess pore pressure ratio and liquefaction induced settlement.

3. EXPERIMENTAL WORK

3.1 Test Equipment

Testing equipments consists of shaking table and a large soil sample container (1.10x1.10m) and 0.7m height manufactured with special requirements for the research purposes. The shaking table was fabricated in An Shams university by Abdel-Motaal in (1995). The used shaking table utilizes a single horizontal translation degree of freedom through sinusoidal harmonic motion. Angular velocity (ω = 2.17 cycle/sec) was assigned for the applied harmonic motion. Base acceleration of 0.125g was selected for the research purpose.

As a function of dynamic loading, the pore water pressure of the liquefiable sand may increase and it is preferable to record its time history, especially its peak values. Experimentally, this was done using piezometers connected to the soil sample container, by means of three metal perforated pipes (P1, P2 and P3). As shown in Figure 1, the initial total thickness of the sand deposition is 0.40m and the metal pipes were fixed at three predetermined levels (0.05m, 0.20m and 0.35m, measured from the base level). Also two additional piezometers (P4) and (P5), leveled with (P2), were installed underneath the used experimental model (underground tank) and between geosynthetic drains to record the pore water pressure at these locations. These piezometers (P4) and (P5) leveled with piezometer (P2) to facilitate the comparison.

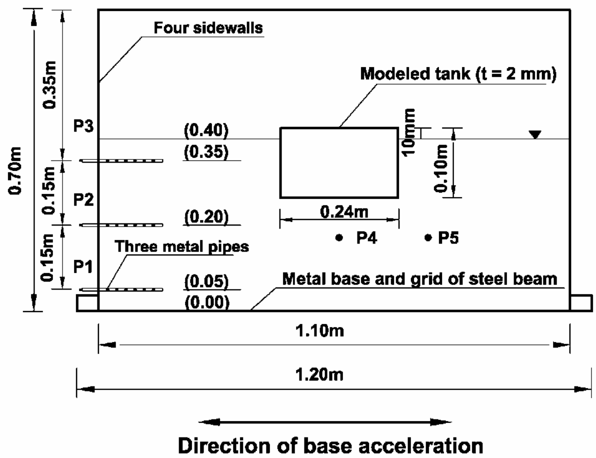

Figure 1. Shaking table test model of underground tank

3.2 Soil Properties

The selected soil sample is medium to fine siliceous sand and can be classified as poorly-grade sand (SP) according to the unified soil classification system (USCS). The physical properties of the used sand are summarized in Table 1.

Table 1. Properties of tested sand

Property	Value
G_S	2.69
γdry_{max} (t /m³)	1.75
γdry_{min} (t /m³)	1.44
D_{50} (mm)	0.26
D_{10} (mm)	0.16

3.3 Underground Tank Model

The modeled tank consists of metal container having 0.24 m diameter, 0.1m height and 2mm wall thickness. This tank was embedded in the sand with 0.09m. To adapt the factor of safety against uplift, predetermined additional weight (uniform stress) was added inside the container.

3.4 Geosynthetic Drains

The used geosynthetic drains were fabricated of fine plastic mesh having the shape of perforated plastic pipe (5mm in diameter) warped with geotextile (filter fabric) to prevent the migration of fines into the pipe. The geotextile is a nonwoven polypropylene. product commercially known as Du Pont Typar 3267.

3.5 Drains Arrangement

In this study, drains aligned along the outside perimeters of the tank, as shown in Figure 2. To enhance the behavior of this arrangement, studies have been carried out using inclined drains to minimize the horizontal drainage path between drains.

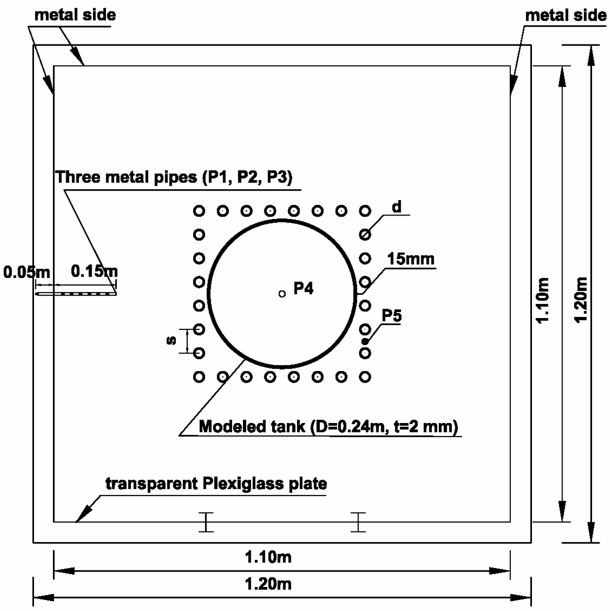

Figure 2. Drain arrangement around the outside perimeter of underground tank model

3.6 Test Program

A series of tests were performed on the prepared saturated sand at 55% initial relative density. A special pneumatic system was created at the bottom of the sand container. It consists of a grid of hollow steel pipes (1.00x1.00m), connected to a compressor for air pressure supply. The prepared sand density in the container was checked to satisfy the required relative density.
To establish the effect of using geosynthetic drains, series of tests have been carried out with and without geosynthetic drains. In every test, the soil was subjected to horizontal continuous cyclic shear motion having a base acceleration 0.125g and was imposed for 60 seconds time period. The underground tank model was placed at its right position and according to the desired factor of safety against uplift. Geosynthetic drains were installed according to the desired length, spacing ratio and inclination angle. The developed of excess water head and excess pore water pressure ratio were recorded in every cycle using digital camera. Also both final free surface settlement and final vertical movement of tank were monitoring under the effect of the studied parameters.

The testing program of this study consists of two test categories:
Category I consists of three tests, which were performed to study the dynamic behavior of underground tank installed on liquefiable sandy soil without geosynthetic drains. Tests were performed using different values of initial factor of safety against uplift pressure (Fu=1.2, 1.4, and 1.6). These tests were considered as datum tests.
Category II contains twenty-two tests to study the effect of soil improvement, using geosynthetic drains, on the uplift stability of the underground tank model during cyclic shear loading. Through this category, the following parameters have been studied:
Spacing ratio between drains (s/d): Different spacing ratios (s/d) were investigated. These different ratios are (s/d = 3.5, 5 and 7), where “s” is the spacing between drains and “d” is the diameter of drains. Therefore, the numbers of installed drains are 32, 24 and 16 for s/d = 3.5, 5 and 7 along tank perimeter, respectively.
Drain length (L): Drains were installed using 0.15 and 0.30m length. Test results were compared with the case of no drains installation (i.e., drain length = zero).
Inclination angle (α): This parameter has been investigated as the drain inclination angle on drain system reflects the capability to permit rapidly water pressure dissipation. Inclination angles($\alpha=0^0$, $15^0$and 30^0) are used, where α is measured with vertical direction.
Factor of safety against uplift pressure (Fu): Tests have been carried out considering different levels of safety factors (Fu = 1.2, 1.4 and 1.6).

4. TEST RESULTS AND ANALYSIS

4.1 Test Results Presentation

Considering the mobility of the water pressure as a result of dynamic excitation and the associated instability of the underground tank, the following have been assigned:
-The water pressure time history and the pore water pressure ratio (r_u) for the five piezometers.
-Final settlement of the liquefiable sand deposition and the vertical movement of the tank, are presented in a set of curves with the different studied parameters.

4.2 Category I (underground tank without geosynthetic drains)

Tests were performed to study the dynamic behavior of underground tank installed on liquefiable sandy soil without geosynthetic drains, at different values of initial factor of safety against uplift pressure (Fu=1.2, 1.4, and 1.6). These tests are considered as datum tests.

4.2.1 Excess water head and excess pore water pressure ratio (r_u)

-Excess water head reached its peak values after nearly twenty cycles for piezometers (P1 and P2) and after nearly twenty five cycles for (P3) as shown in Figure 3.
-Pore water pressure ratio (r_u) begins to drop at the bottom soil layer that settles firstly, before the top layers and top layers experienced high values of water pressure for relatively long period, as shown in Figure 4.
-The three piezometers (P1, P2, and P3) were installed at the sides of shaking table pin sufficiently away from the influence tank weight. As results, the comparison of the recorded excess water head was concentrated on piezometers P2 and P4.
-Figure 5 and 6 show a comparison between records of piezometers P2 and P4, for different safety factors. It can be established that increasing the safety factor against uplift decreases liquefaction potential for the underneath soil (that directly installed under tank base). This notice can be clarified as increasing tank weight cause a considerable increases in the values of the effective stress, for the underneath soil layers and consequently decreasing water pressure ratio and liquefaction potential.

4.2.2 Free surface settlement and vertical movement of tank

Figure 7 and 8, show considerable reduction in values of free surface settlement and tank movement, as a result of increasing the safety (Fu). This is believed to be due to the balance between the gravity weight of tank and the total uplift pressure induced during cyclic loading.

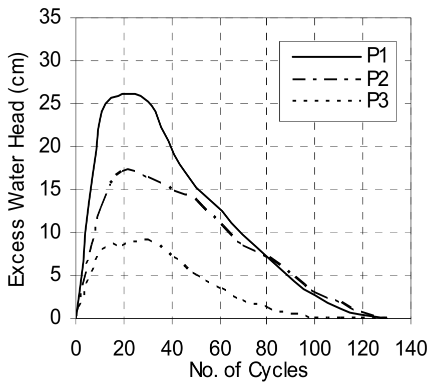

Figure 3. Excess water head and number of cycles relationship, a_{max} = 0.125g, Fu = 1.2 (without geosynthetic drains)

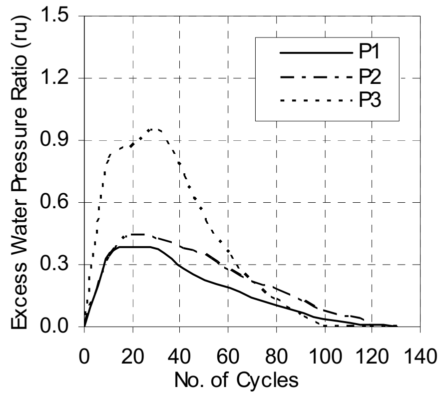

Figure 4. Excess water pressure ratio(r_u) and number of cycles relationship, a_{max} = 0.125g, Fu=1.2 (without geosynthetic drains)

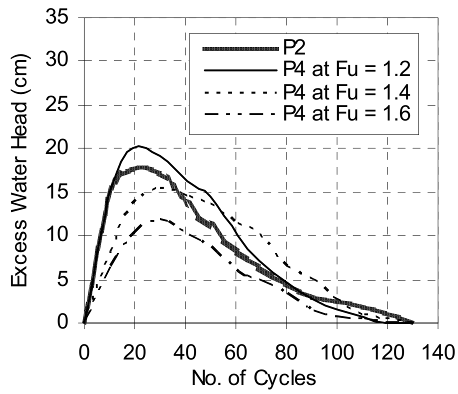

Figure 5. Excess water head and number of cycles relationship, a_{max} = 0.125g (without geosynthetic drains)

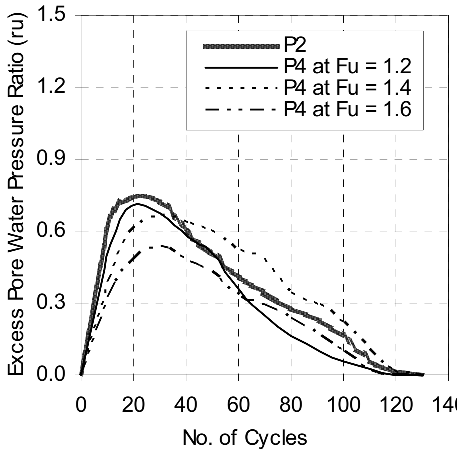

Figure 6. Excess water pressure ratio(r_u) and number of cycles relationship, a_{max} = 0.125g (without geosynthetic drains)

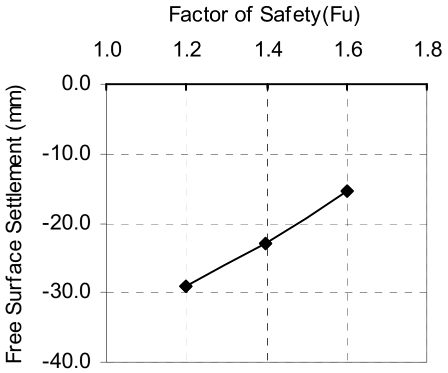

Figure 7. Free surface settlement and factor of safety (Fu) relationship, a_{max} = 0.125g (without geosynthetic drains)

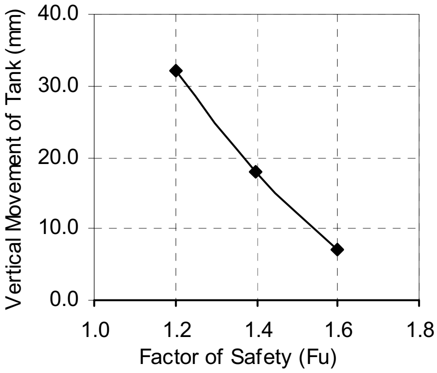

Figure 8. Vertical movement of tank and factor of safety (Fu) relationship, a_{max} = 0.125g (without geosynthetic drains)

4.3 Category II (underground tank with geosynthetic drains)

Tests were performed to study the effect of soil improvement, using geosynthetic drains, on the uplift stability of studied underground tank during cyclic shear loading. The investigation was extended to comprise different conditions such as, spacing ratio between drains, drains length, inclination angle of drains and initial factor of safety against uplift.

4.3.1 Excess water head and excess pore water pressure ratio (r_u)

- Figure 9 and 10 show that both excess water head and excess pore water pressure ratios are inversely proportional to spacing ratio (s/d). It can be clarified as decreasing drain spacing enables the dissipation of water pressure to take place rapidly.
- Drain efficiency is directly proportional to its length. These results can be clearly obtained through comparing test result with the second category test results (no soil treatment which means L = 0).
- It is obvious that the efficiency of the geosynthetic drains, as a mitigation technique, increases with the increasing of drain inclination angle, due to minimizing the horizontal drainage path between drains.
-As shown in Figure 11 and 12, it is clear that the number of cycles required to dissipate the excess water head depends on drainage path. It means that increasing the inclination angle will decrease the drainage path between opposite drains and hence improve the drainage system efficiency.
-Test results show that 15^0 inclination angle may be considered as the optimum inclination angle, from drainage point of view. This can be clarified as increasing the inclination angle above certain limit may not dissipate water pressure rapidly, at zones outside drain perimeter.
-Finally the effect of factor of safety against uplift has no noticeable change can be observed for the trend of excess water pressure. Results is expected as changing the factor of safety is not a treatment technique.

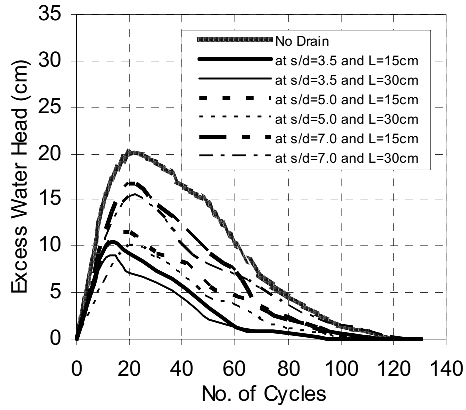

Figure 9. Excess water head and number of cycles relationship, a_{max} = 0.125g, Fu = 1.2, $\alpha = 0^0$

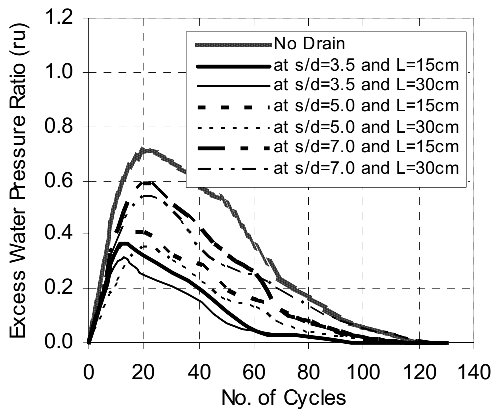

Figure 10. Excess water pressure ratio(r_u) and number of cycles relationship, a_{max} = 0.125g, Fu = 1.2, $\alpha = 0^0$

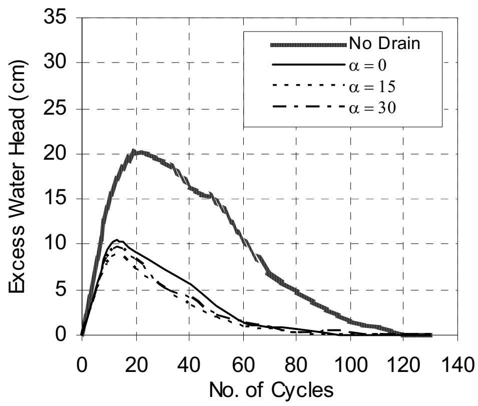

Figure 11. Excess water head and number of cycles relationship, a_{max} = 0.125g, Fu = 1.2, s/d = 3.5, L = 0.15m

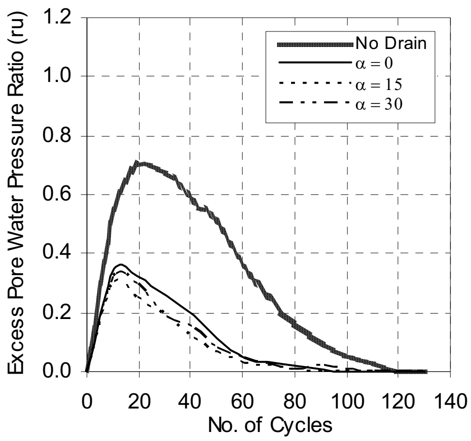

Figure 12. Excess water pressure ratio(r_u) and number of cycles relationship, a_{max} = 0.125g, Fu = 1.2 s/d = 3.5, L = 0.15m

4.3.2 Free surface settlement and vertical movement of tank

-As shown in Figure 13 through Figure 16, it is clear that the spacing ratio is directly proportional to both free surface settlement, and vertical movement of tank. Also, it can be established that, the obtained results using (s/d) = 3.5 are nearly equal to that obtained using (s/d) = 5. Therefore (s/d) = 5 may be considered as the optimal and economical spacing ratio, in this case study.

-Also, it is clear that the length of drains is inversely proportional to both free surface settlement and vertical movement of tank, as shown in Figure 17 and 18. Referring to these figures, it can be established that 0.20 m drain length may be considered as the optimal and economical value, in the domain of this scaled model.

-Considering both free surface settlement, and vertical movement of tank, it is clear that the inclination angle of drains is inversely proportional, as shown in Figures 19 and 20. According to study results this feature for remediation may be considered as a benefit technique for existing structures.

-So the existence of geosynthetic drains, as a countermeasure against liquefaction hazards, plays an important role in minimizing each of free surface settlement, and vertical movement of tank values without the need of increasing the factor of safety Fu at higher values, as shown in Figure 21 and 22.

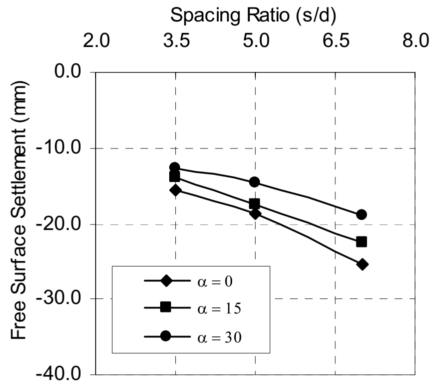

Figure 13. Free surface settlement and spacing ratio (s/d) relationship, a_{max} = 0.125g, d = 5 mm, L = 0.15m, Fu = 1.2

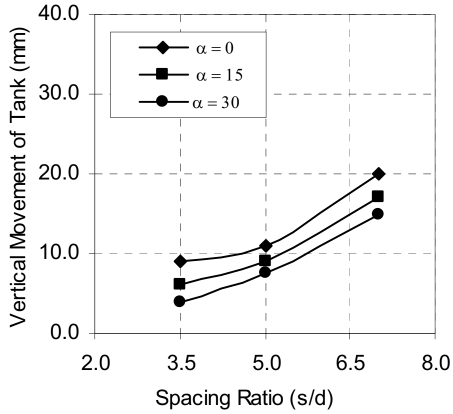

Figure 14. Vertical movement of tank and spacing ratio (s/d) relationship, a_{max} = 0.125g, d = 5mm, L = 0.15m, Fu = 1.2

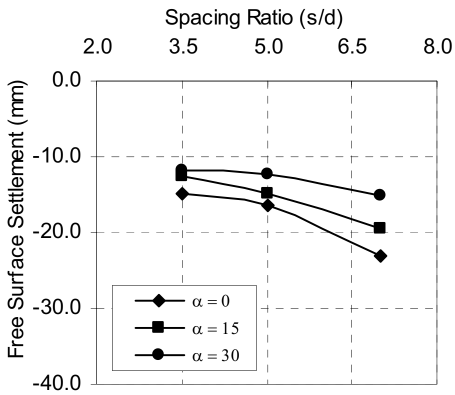

Figure 15. Free surface settlement and spacing ratio (s/d) relationship, a_{max} = 0.125g, d = 5 mm, L = 0.30m, Fu = 1.2

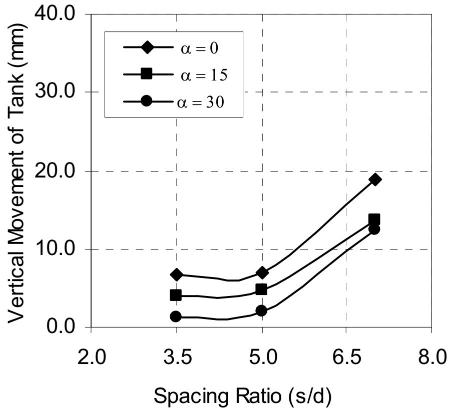

Figure 16. Vertical movement of tank and spacing ratio (s/d) relationship, a_{max} = 0.125g, d = 5mm, L = 0.30m, Fu = 1.2

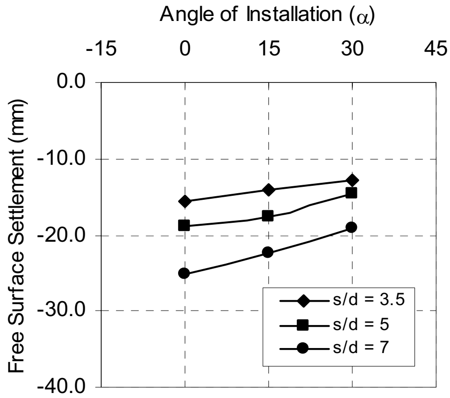

Figure 19. Free surface settlement and angle of installation (α) relationship, a_{max} = 0.125g, d = 5 mm, L = 0.15m, Fu = 1.2

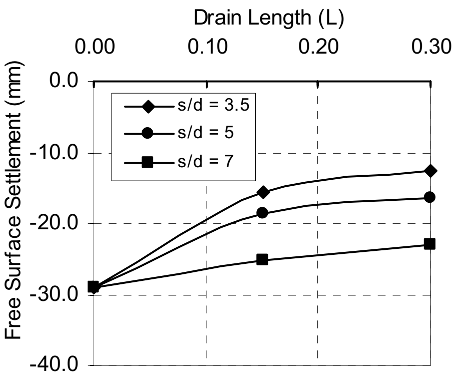

Figure 17. Free surface settlement and drain length (L) relationship, a_{max} = 0.125g, d = 5 mm, $\alpha = 0^0$, Fu = 1.2

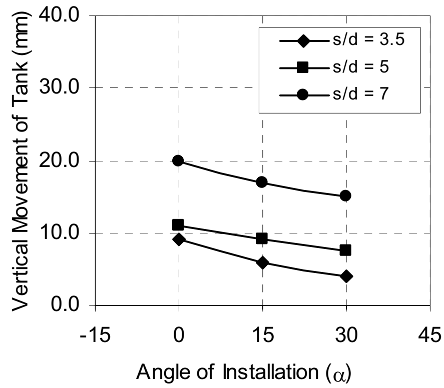

Figure 20. Vertical movement of tank and angle of installation (α) relationship, a_{max} = 0.125g, d = 5 mm, L = 0.15m, Fu = 1.2

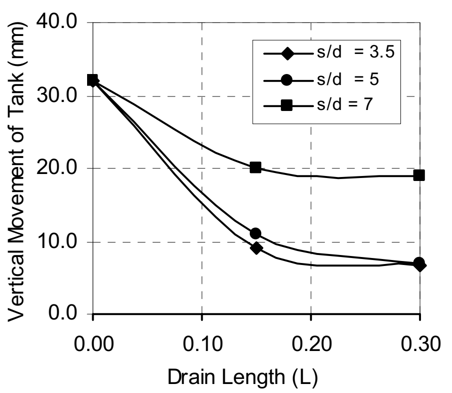

Figure 18. Vertical movement of tank and drain length (L) relationship, a_{max} = 0.125g, d = 5 mm, $\alpha = 0^0$, Fu = 1.2

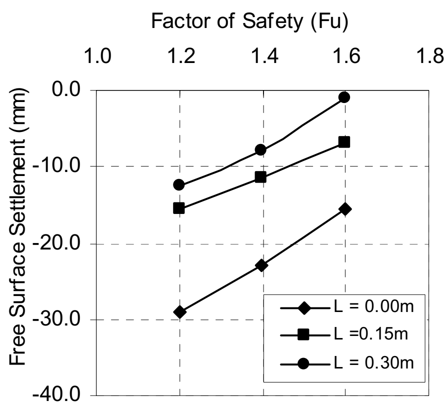

Figure 21. Free surface settlement and factor of safety (Fu) relationship, a_{max} = 0.125g, d = 5 mm, $\alpha = 0^0$, s/d = 3.5

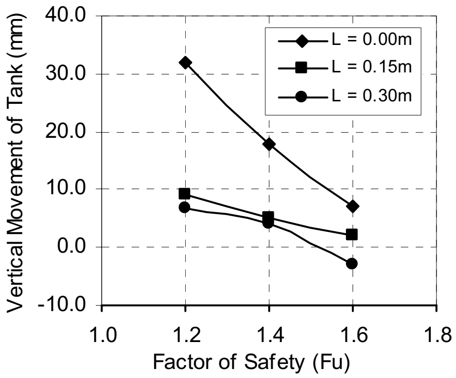

Figure 22. Vertical movement of tank and factor of safety (Fu) relationship, a_{max} = 0.125g, d = 5 mm, $\alpha = 0^0$, s/d = 3.5

5. CONCLUSIONS

A study was performed by series of shaking table tests on experimental model (underground tank) in loose, saturated sand, with and without geosynthetic drains. Qualitatively results are based on the findings of this investigation, and limited to the materials under study. The analysis are developed and discussed throughout this paper has given the possibility to draw out some conclusions, as follow:

-Excess pore water pressure ratio (r_u) begins to drop at the bottom soil layer that settles firstly, before the top layers. It was also found that pore water pressure ratio (r_u) at top layers will experience high values for a relatively longer period than the bottom layer.

-Spacing ratio between geosynthetic drains has significant effects on the liquefaction remediation works, as it decreases the lateral drainage path of water towards the drains.

-The efficiency of the investigated geosynthetic drains increases with the increasing of drain length, as a result of increasing drain media.

-One of geosynthetic drains advantage; it can be installed at various angles, in contrast to gravel drains that are usually installed vertically. It was found that the efficiency of the geosynthetic drains as mitigation technique increasing with the increasing of angle of inclination of drains. This could be due to minimizing the horizontal drainage path between drains. According to study results, this feature for remediation may be considered as a benefit technique for existing structures.

In this study according to the experimental model size the optimum spacing ratio between drains (s/d) and drain length (L) were found to be 5 and 0.20m respectively. Beside inclination angle (α) of geosynthetic drain 15^0 was found to be better than 30^0 from drainage point of view.

-Increasing the factor of safety has a significant effect on minimizing liquefaction hazards, where increasing the safety factor may lead to balance the gravity weight of tank with the total uplift pressure that induced during cyclic loading. However, this solution is not economic and has no effect on the trend of the excess water pressure curves.

-The existence of geosynthetic drains, as a countermeasure against liquefaction hazards, plays an important role in minimizing the excess water head. Also minimizing each of free surface settlement and vertical movement of tank without the need of increasing the factor of safety (Fu) at higher values.

6. ACKNOWLEDGMENT

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