MITIGATION OF LIQUEFACTION – INDUCED DIFFERENTIAL SETTLEMENT WITH DIFFERENT RELATIVE DENSITIES BY USING GRAVEL AND GEOSYNTHETICS-VALIDATION BY MODEL EXPERIMENT

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Earthquakes in liquefaction-prone areas are usually followed by the settlement of surface structures due to subsoil liquefaction. This paper aims to study the influence of geosynthetics along with gravel on the differential settlement of the soil with different initial relative densities using a shake table equipment. This influence is analyzed by means of measuring soil acceleration, pore water pressures and vertical soil deformation due to shaking process. Results of a series of 1-g shaking table tests which have been conducted in different initial relative densities which are 50% and 90% to evaluate the performance of proposed mitigation against settlement problem are presented. It is found that ground settlement reduced around 36% and 30% for initial relative density 50% and 90%, respectively. Moreover, differential settlement between liquefiable and non-liquefiable decreased as well, up to 38%.

***Keywords**: liquefaction, differential settlement, relative density, geosynthetics, gravel, shaking table test*

1. INTRODUCTION

Liquefaction is one of the phenomena which occur in the saturated loose sand layer during an earthquake. It takes place when the pore water pressure reaches a certain value which is close to the total stress of a soil. One of the consequences that can occur is structures built on top or within the liquefied ground may fail due to ground settlement.

Landfilled ground occasionally liquefies due to a large-scale earthquake and triggers deformations on the ground surface and undermine construction on it, for example, the road (Takahashi et. al., 2015)[1)]. This phenomenon occurred because the liquefied layer having low strength when shocked with large amplitude seismic waves, caused large movements to the road surface, and as a result, deformation of the road surface took place. Nevertheless, even though the road surface was composed of asphalt and roadbed and had high-strength if the ground under the road surface is liquefied, the strength (shear rigidity) of the road surface will be decreased and deformation will occur.

Furthermore, the extent of deformation is influenced by several factors, one of which is the relative density (*Dr*) of the ground. When earthquake-induced liquefaction occurs in the areas with dissimilar density, ground differential settlement can take place and may cause damage to construction built on it, such as the building tilted and roads become uneven/bumpy. Moreover, in the severe condition and significant differential settlement appears, this can lead to, for example, impassable roads. However, for the important roads, such as main roads, emergency evacuation routes, and roads connected to important facilities, it is necessary to ensure the accessibility of these vital roads during earthquakes. For that reason, it is necessary to restrain liquefaction-induced differential settlement by an economical method and simple to be implemented.

There are many research has been carried out to investigate the liquefaction phenomenon after the two main earthquakes in 1964, which are Niigata earthquake, Japan, and Alaska earthquake, United States, since the impact of liquefaction on the built environment was introduced to the geotechnical engineering community, in particular, related to the liquefaction-induced settlement. Ueng et al. (2010)[2] presented that significant volume changes occur only when there is liquefaction of sand, otherwise, the settlement is very small. Correspondingly, Maharjan and Takahasihi (2013)[3] reported the results of dynamic centrifugal tests conducted to investigate the liquefaction mechanism in non-homogeneous soil deposits. In the following year, Maharjan and Takahashi (2014)[4] conducted a study of the liquefaction-induced deformation of earthen embankments on non-homogeneous soil deposits and found that the embankment resting on non-homogeneous soil deposits suffer more damage compared to the uniform sand foundation of same relative density. Harmoniously, Zeybek and Madabhushi (2017)[5] presented a study of the influence of air injection on the liquefaction-induced deformation mechanisms beneath shallow foundations.

Among the variety of liquefaction countermeasure methods proposed, the use of gravel, geosynthetics, or geosynthetics in conjunction with gravel attracted some attention due to their effectiveness and relatively low cost. This method is thought to be a good technique to mitigate liquefiable soil problems. As presented by Murakami et al. (2010)[6], a combination of geosynthetics and gravel in order to restrain liquefaction in embankments, focused on the vertical displacement of the embankments. The result showed that the settlement of the embankments decreased nearly 35% by using gravel and geosynthetics. They concluded that the use of geosynthetics sandwiched between gravel will have high resistance against bending deformation due to the overburden load of the embankment. Even though this method does not overcome the occurrence of liquefaction completely, it does alleviate the excessive deformation such as settlement and lateral movement. Accordingly, some other research also showed a corresponding results, for example by use gravel presented by Orense et al. (2003)[7], Morikawa et al. (2014) [8], and Chang et al. (2014) [9], and geosynthetics utilized reported by Vercuil et al. (1997) [10], Boominathan and Hari (2002) [11], and Noorzad and Amini (2014) [12].

This paper highlights on studying the performance of the gravel along with geosynthetics to reduce liquefaction-induced differential settlement by a series of shaking table tests. To study the effectiveness of the proposed mitigation method, a control of, an unreinforced model was also tested. The effectiveness of the gravel and geosynthetics was evaluated through the settlement occurred on the ground surface.

2. GROUND DISPLACEMENT TESTS

The sand container used has dimensions of 150 cm length, 75 cm width, and 75 cm height and built from galvanized steel and acrylic/Plexiglas. The sand layer in the sandbox was divided into 2 parts, which are non –liquefiable, composed of dense sand with a relative density (*Dr*) 90%, and liquefiable sand, composed of loose sand with *Dr* around 50%. The sand that was used in this research was silica sand No. 7. The remedial measures used in this study were gravel and geosynthetics. Crushed stone No. 5 was used to form a model of a gravel layer of 6 cm thick. This type of crushed stone is widely used as gravel in modeling tests. Furthermore, a sheet of model geosynthetics made of polyethylene placed at the bottom of the gravel layer was utilized. Properties of the materials used (silica sand No. 7, crushed stone No. 5, and geosynthetics) in this series of tests can be seen in **Table 1**. A photograph of the model geosynthetics used is shown in **Fig. 1**.

In this series of tests, input harmonic wave used were as follows: frequency 5 Hz, a target maximum input acceleration of around 50 gal, and a shaking duration time 15 seconds.

Table 1 Properties of the test material.

Properties:	**Silica sand #7:**	**Crushed stone #5:**
Density, ρ	2.66 g/cm^3	2.56 g/cm^3
Mean grain size, D_{50}	0.17 mm	3.55 mm
Coefficient of permeability, k	4.79x10^{-3} cm/s	9x10 cm/s
Relative density, Dr	50% and 90%	
Model Geosynthetics:		
Thickness	0.05 mm	
Tensile strength, T (ε=10%)	6.0 kN/m	
Tensile stiffness, AE	60.0 kN/m	

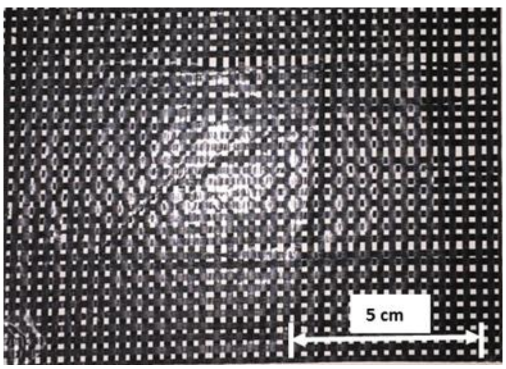

Fig. 1 Photo of model geosynthetics used.

Fig. 2 shows the plan view and the cross section of the unreinforced model (case 1), reinforced with gravel (case 2) and gravel accompanied by geosynthetics (case 3) along with the layout of accelerometers, water pressure meters, and displacement meters. The ground in the model composed of a liquefiable sand layer with a relative density around 50%, non-liquefiable part with relative density 90% in dense condition, and dry sand on the ground surface.

3. RESULTS AND DISCUSSIONS

A summary of the main data measured during the shaking table test such as excess pore water pressure, acceleration, and settlement of ground surface is presented and discussed.

(1) Excess pore water pressure

Pore water pressures were observed by installing two pore water pressure transducers at 30 cm from the bottom of the sandbox, both for the loose sand part and dense sand part. Excess pore water pressure measured were converted to excess pore water pressure ratio by dividing excess pore water pressure with initial vertical effective stress (σ_v'). Excess pore water pressure ratio time histories are shown in **Fig. 3**.

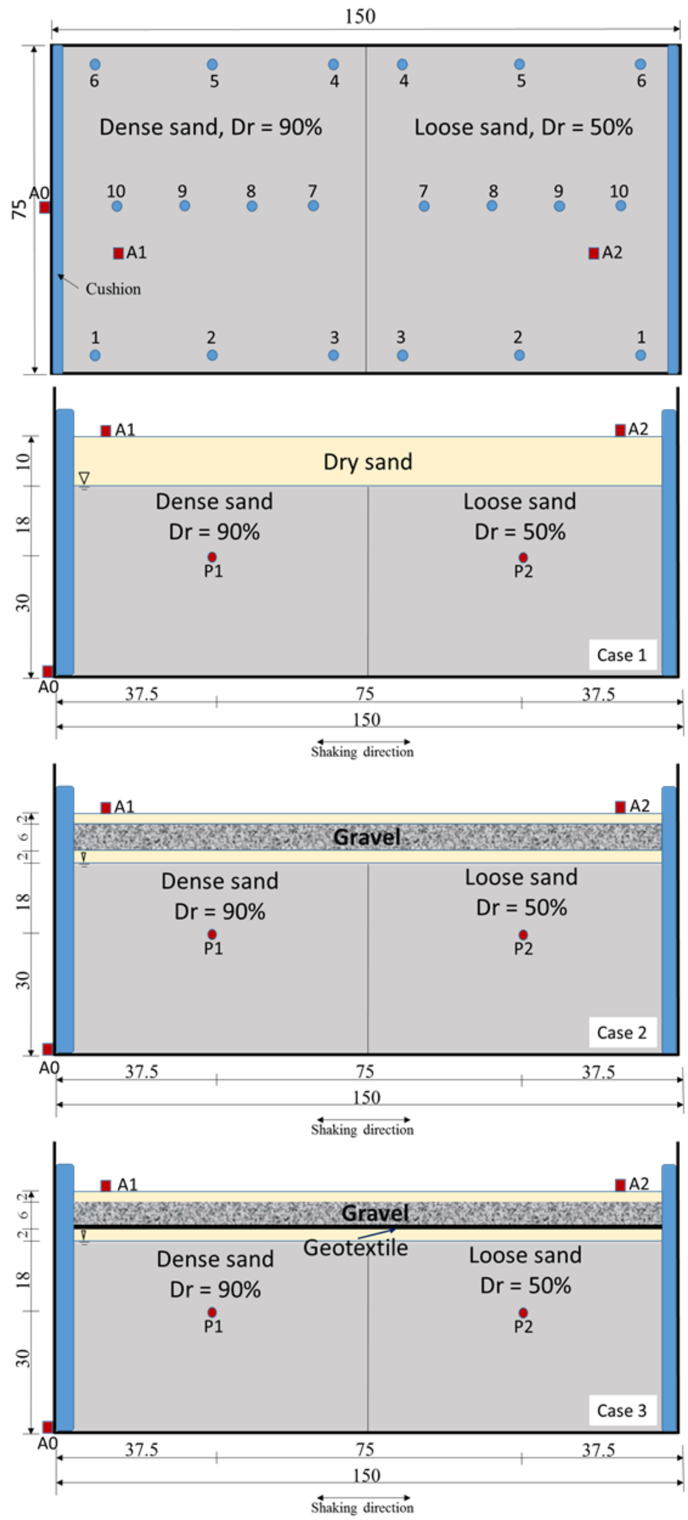

Fig. 2 Plan view and cross-section of the sandbox instrumentation.

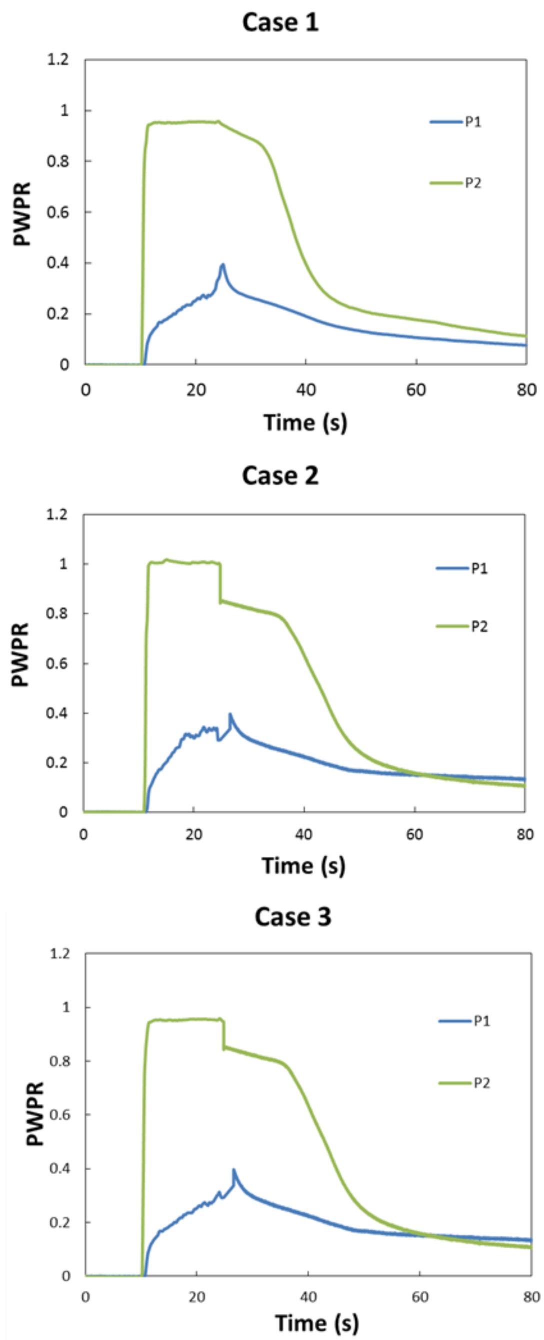

Fig. 3 Pore water pressure ratio time histories.

As can be seen in **Fig. 3**, the pore water pressure ratio in dense sand part (P1) show almost similar results for all three cases. This is possible due to the dense sand conditions which there is no liquefaction occurred. Furthermore, although pore water pressure ratio in the loose sand (P2) show relatively comparable values, it can be seen a slightly lower water pressure ratio in Case 3 compared to Case 1 and 2. According to the figure, it is also observed that in Case 2 and Case 3, pore water pressure dissipated faster than Case 1 which thought due to the high permeability of the improved layer.

(2) Acceleration

Fig. 4 shows horizontal acceleration time histories. As can be seen, accelerations that measured at the bottom of the sandbox (A0) resulted in similar values. It also can be observed, accelerometers that placed on the loose sand (A2) resulted in almost analogous amounts as well. In contrary, acceleration obtained in the dense sand (A1) shows a significant difference for three cases which the minimum acceleration measured in Case 3. The reasons for this result might be due to the acceleration propagated over the dense sand was less compared in the loose sand condition. This is resulted in no liquefaction occurred. In contrary, in loose sand zone, liquefaction occurred and cause stronger acceleration amplification. In addition, Dense state of sand, particularly improved with gravel and geosynthetics which perform identically to a rigid board with high permeability, on the one hand, could decrease water pressures, and on the other hand, could increase the density of the sand under the reinforcement layer during shaking. As a result, as can be observed from **Fig. 3**, in Case 3, pore water pressure ratio decreased and dissipated faster compared to Case 1 and 2 which reduced the liquefaction occurrence and cause lower acceleration propagation in Case 3 compared to Case 1 and 2 as shown on **Fig. 4**.

(3) Settlement

The settlement was measured through ten points on the ground surface for each sand condition by using displacement meter.

Table 2 displays the settlement obtained through ten points on the ground surface for three conditions of the test. Generally speaking, based on the settlement amount that presents in this table, the settlement has decreased in various value by the presence of improved layer, both in dense and loose conditions.

In order to simplify understanding, the settlements measured are averaged as shown in **Fig. 5**. It can be observed that based on the average values of the settlement measured, the presence of the proposed mitigation could reduce vertical displacement in varying amounts. By use gravel only, the settlement was decreased around 19% for the loose condition, and reach approximately 33% for the dense condition. Moreover, by use gravel along with geosynthetics, the result obtained much better for the loose condition, up to around 36%, while for the dense condition settlement gained almost equal to case 2, around 30%.

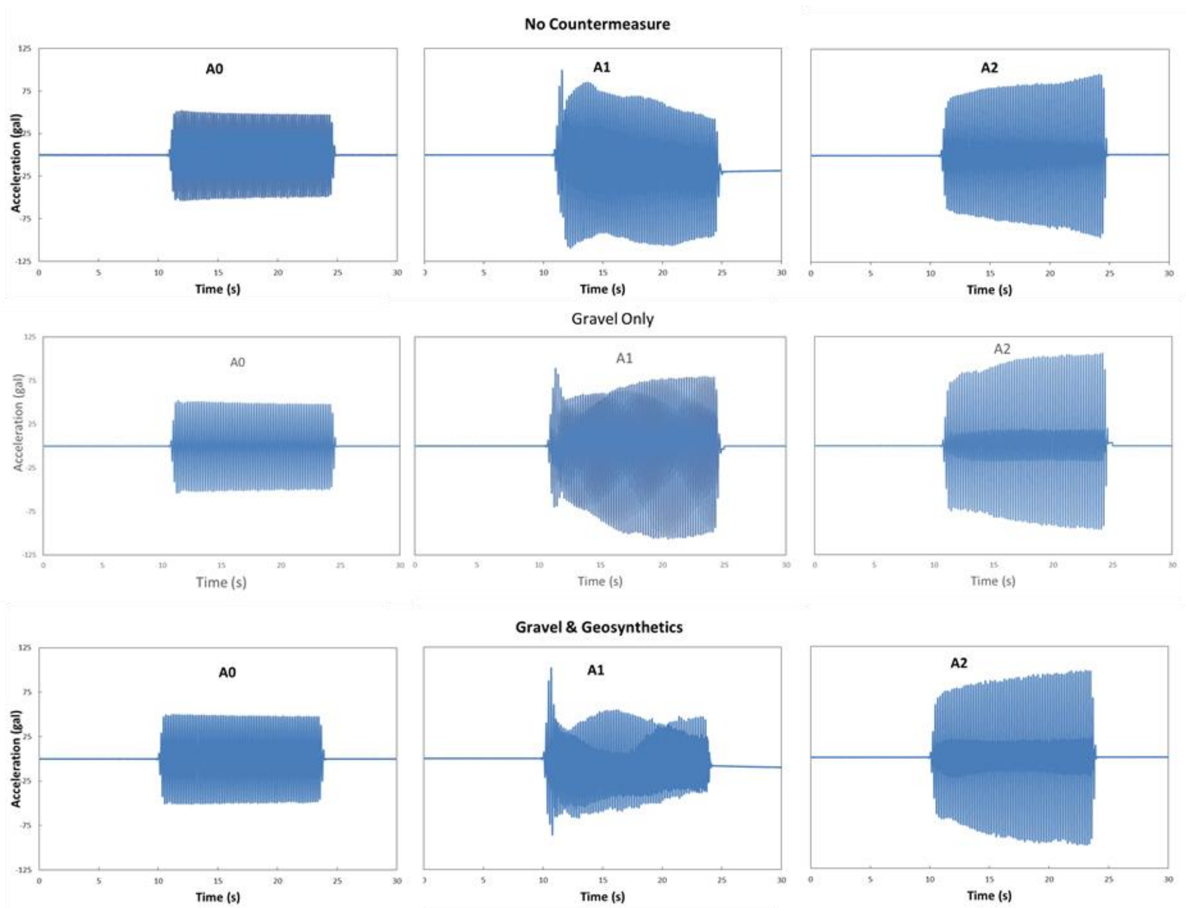

Fig. 4 Acceleration time histories.

Table 2 Settlement measured through ground surface

Point No.	Settlement measured (cm)					
	Case 1		Case 2		Case 3	
	Loose	Dense	Loose	Dense	Loose	Dense
1	2.39	1.06	2.19	0.48	1.46	0.47
2	2.08	0.37	2.18	0.83	1.5	0.9
3	1.91	0.52	1.7	0.75	1.68	0.56
4	2.78	0.31	2.21	0.16	1.28	0.11
5	2.14	0.54	1.39	0.12	1.84	0.28
6	2.43	0.57	1.42	0.09	1.33	0.15
7	2.73	1.41	1.72	0.24	0.95	0.46
8	1.15	0.21	0.31	0.41	1.16	0.6
9	1.59	0.35	1.35	0.18	1.07	0.3
10	1.69	0.21	2.39	0.48	1.05	0.1
Average	**2.09**	**0.56**	**1.69**	**0.37**	**1.33**	**0.39**

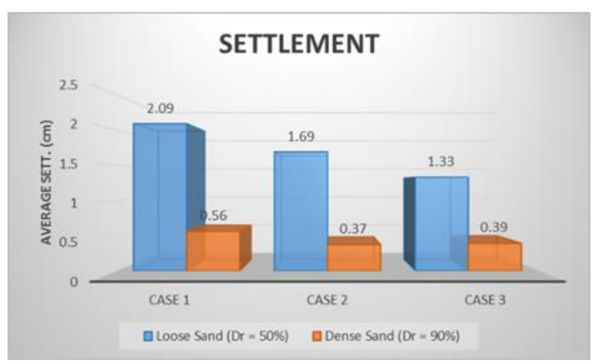

Fig. 5 Averaged Settlement.

Furthermore, the differential settlement between non-liquefiable and liquefiable sand in every model were compared. For no countermeasure model, the settlement difference was 1.53 cm, while for gravel only improvement the result was 1.32 cm, and model reinforced with gravel and geosynthetics resulted in 0.94 cm of differential settlement. According to this, the proposed mitigation could reduce the differential settlement between dense and loose sands around 38%.

The coherence of the gravel layer with its high permeability and high tensile strength provided by geosynthetics were considered as the main reason for this good result. Since the tension generated in the geosynthetics restrain the deformation of the gravel layer and integrally perform like a rigid plate with high permeability, this reinforcement could reduce the liquefaction-induced vertical displacement that occurred on the ground surface. However, the vertical displacement gained in non-liquefiable sand showed lower compared to the loose sand condition. It might be due to in dense sand, a void ratio of the ground is lower than loose sand.

4. CONCLUSIONS

The effectiveness of gravel along with geosynthetics remediation to restrain the liquefaction-induced vertical displacement of liquefiable soils had been measured by conducting a series of shaking table tests. According to the results acquired from the tests carried out, the following conclusions are obtained. It is found that the use of gravel and geosynthetics effectively reduce the vertical displacement of liquefiable ground due to the permeability of the gravel and tension strength of the geosynthetics. The conjunction of these two reinforcing materials resulted in a permeable layer which behaves like a rigid plate.

The results showed that by using this proposed mitigation, the settlement of the ground surface decreased around 36% in the liquefiable zone and up to 30% in the non-liquefiable zone. It is also observed that the differential settlement between liquefiable sand and non-liquefiable in the same condition decreased about 38%, from 1.53 cm in no countermeasure condition into 0.94 cm when model improved with gravel and geosynthetics. In the future, gravel in conjunction with geosynthetics could be recommended and becomes an established liquefaction countermeasure mitigation due to its effectivity in order to reduce the liquefaction-induced ground surface vertical displacement.

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