Mitigation of liquefaction-induced ground displacement by using gravel and geosynthetics – validation by model experiment

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ABSTRACT: Earthquakes in liquefaction-prone areas are usually followed by the ground surface displacement due to liquefaction. This paper aims to study the influence of geosynthetics along with gravel usage on the liquefaction-induced ground displacement, both horizontal and vertical displacement using shaking table equipment. This influence is analyzed by measuring pore water pressures and soil deformation due to shaking process. The results of a series of 1-g shaking table tests which have been conducted are as follows: by using proposed mitigation, the horizontal displacement decreased up to 23%, and vertical displacement, which performed in two different initial relative densities, i.e., 50% and 90%, was reduced by 36% and 30%, respectively. Moreover, a differential settlement between loose sand and dense sand decreased as well, up to 38%.

Keywords: liquefaction, geosynthetics, gravel, shaking table test, ground displacement, horizontal displacement, vertical displacement

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). This phenomenon occurred because the liquefied layer is 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.

Ground displacement can be divided into two parts, namely horizontal displacement, and vertical displacement. Lateral spreading is the term used to refer to the development of horizontal ground displacement due to earthquake-induced liquefaction, in the case of even small free ground surface inclination (e.g., 1^{o}-3^{o}) or small topographic irregularities, e.g., river and lake banks (Valsamis et al. 2010). This phenomenon also occurs on mild slopes underlain by loose sands where a shallow water table is present. Such soil deposits are prone to excess pore water pressure generation, liquefaction and consequently lateral displacement during seismic excitations (Bartlett and Youd, 1992).

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 different density, ground differential settlement can take place and may cause damage to constructions 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 much 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) presented that significant volume changes occur only when there is liquefaction of sand. Otherwise, the settlement is very small. Correspondingly, Maharjan and Takahasihi (2013) 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) 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.

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), a combination of geosynthetics and gravel to restrain liquefaction in embankments, focused on the vertical displacement of the embankments. The result showed that the settlement of the embankments decreased by nearly 35% by using gravel and geosynthetics. They concluded that the use of geosynthetics sandwiched between gravel would 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), Morikawa et al. (2014), and Chang et al. (2014), and geosynthetics utilized reported by Vercuil et al. (1997), Boominathan and Hari (2002), and Noorzad and Amini (2014).

This paper highlights on studying the performance of the gravel along with geosynthetics to reduce liquefaction-induced ground displacement, both horizontal and vertical displacement, by a series of shaking table tests. The effectivity of gravel and geosynthetics was evaluated through the ground displacement occurred on the ground surface.

2. SHAKING TABLE TEST

The sand container was used has dimensions of 150 cm length, 75 cm width, and 75 cm height, and built from galvanized steel and acrylic/Plexiglas. The sand used in this research was silica sand No. 7. The remedial measures used were gravel and geosynthetics. Crushed stone No. 5 was used to form a model of a gravel layer of 6 cm thick. 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 Figure 1. In this series of tests, input harmonic wave used were as follows: frequency 5 Hz, a target maximum input acceleration of around 80 cm/s^2, and a shaking duration time of 15 seconds.

2.1. *Horizontal displacement test*

Figure 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% and a mildly sloping ground surface of around 4o.

Table 1. Properties of the materials used.

Properties:	Silica sand No. 7:	Crushed stone No. 5:
Density, ρ	2.66 g/cm^3	2.56 g/cm^3
Mean grain size, D_{50}	0.17 mm	3.55 mm
Relative density, *Dr*	50% ; 90%	
Model Geosynthetics:		
Tensile strength, T (ε=10%)	6.37 kN/m	
Tensile stiffness, *AE*	63.7 kN/m	

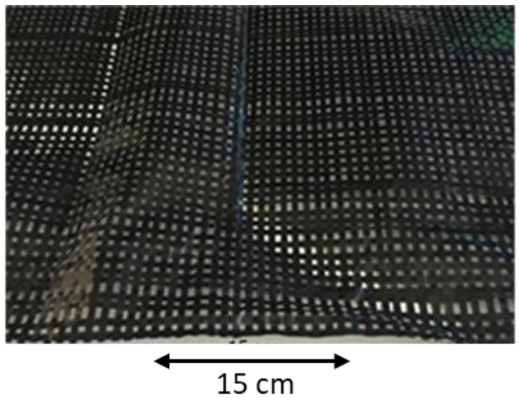

Figure 1. Photo of model geosynthetics used.

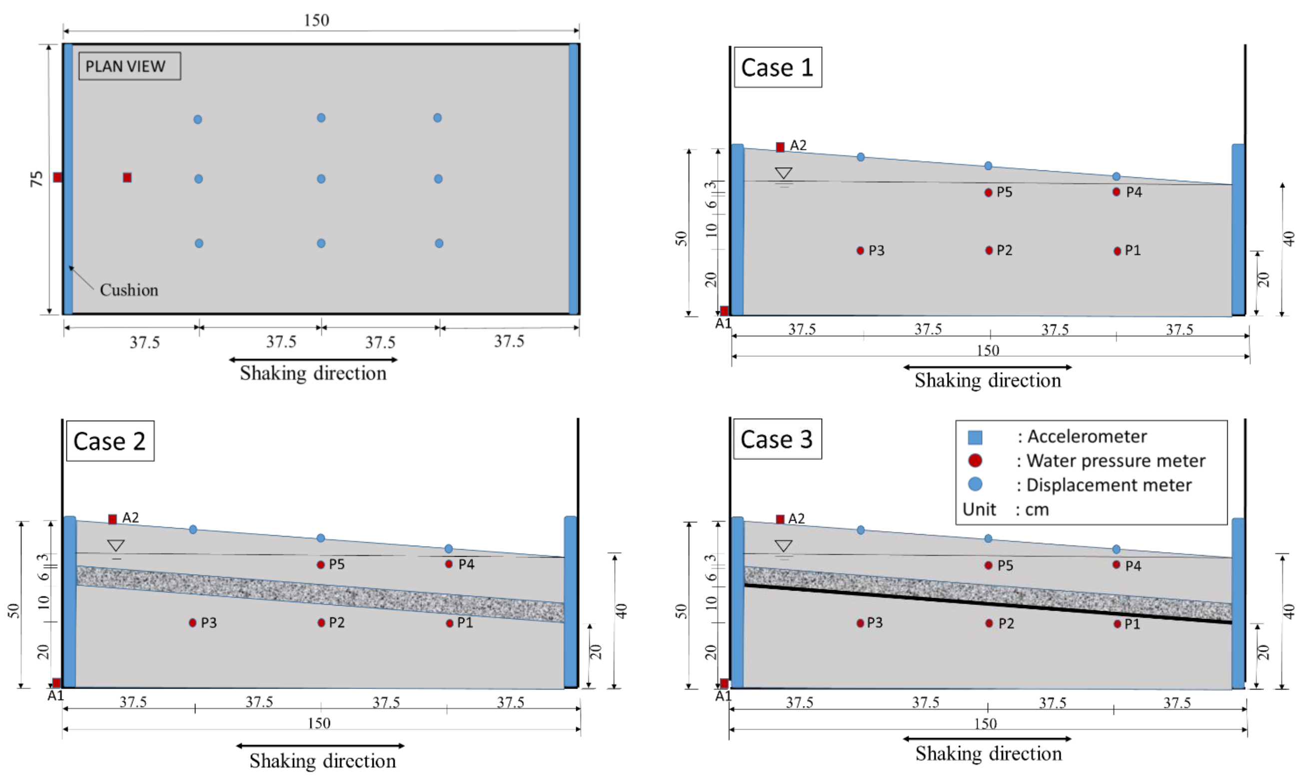

Figure 2. Plan view and cross-section of the sand container in horizontal displacement measurement.

2.2. *Vertical displacement test*

The same sand container as the previous experiment was used, but in this test, the sand divided into two parts, firstly, non-liquefiable part, which composed of dense sand with relative density around 90%, and secondly liquefiable part, composed of loose sand with a relative density of 50%. Also, the flat ground surface was applied. Figure 3 displays the top view and side view of the shaking table tests to measure the settlement for 3 cases; no countermeasure (Case 1), gravel only (Case 2), and gravel in conjunction with geosynthetics (Case 3).

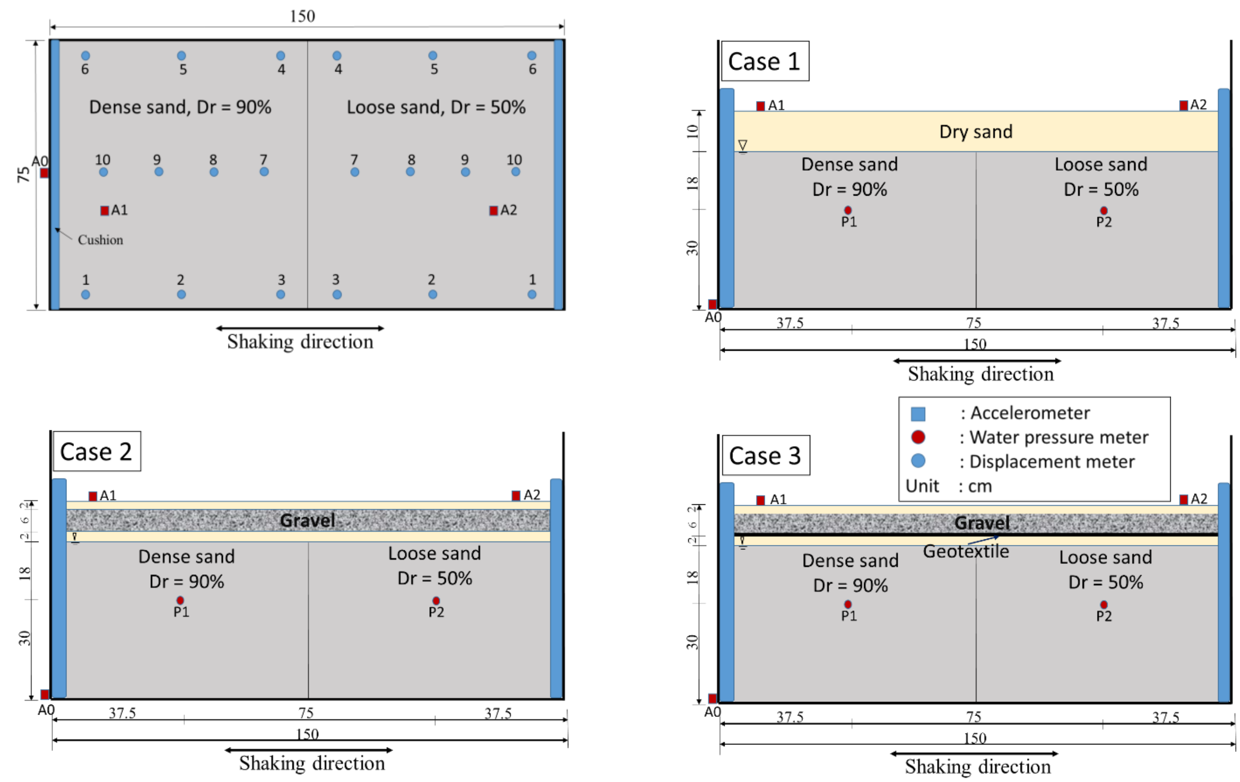

Figure 3. Plan view and cross-section of the sand container in vertical displacement measurement.

3. RESULTS AND DISCUSSIONS

A summary of the main data measured during the shaking table test such as pore water pressure and ground displacement are presented and discussed.

3.1. *Horizontal displacement test*

3.1.1. *Pore water pressure*

Pore water pressure was observed by installing five pore water pressure transducers at two different levels. P1, P2, and P3 were located below the gravel layer around 20 cm from the bottom of the sand container, while P4 and P5 were sited above the gravel layer about 37 cm from the bottom of the sand container. Excess pore water pressure measured were converted to pore water pressure ratio by dividing excess pore water pressure with initial vertical effective stress (σ_v'). Pore water pressure ratio time histories (represented by P1, P2, and P3) are shown in Figure 4.

As can be seen in this figure, particularly for P1, the use of gravel and geosynthetics (Case 3) has decreased the pore water pressure ratio around 20%, from 1 into 0.8, compared to no countermeasure model (Case 1). Furthermore, for P2 and P3, although the decrease in pore water pressure is not as significant as P1, it appears that by using proposed mitigation, the pore water pressure can be dissipated more quickly.

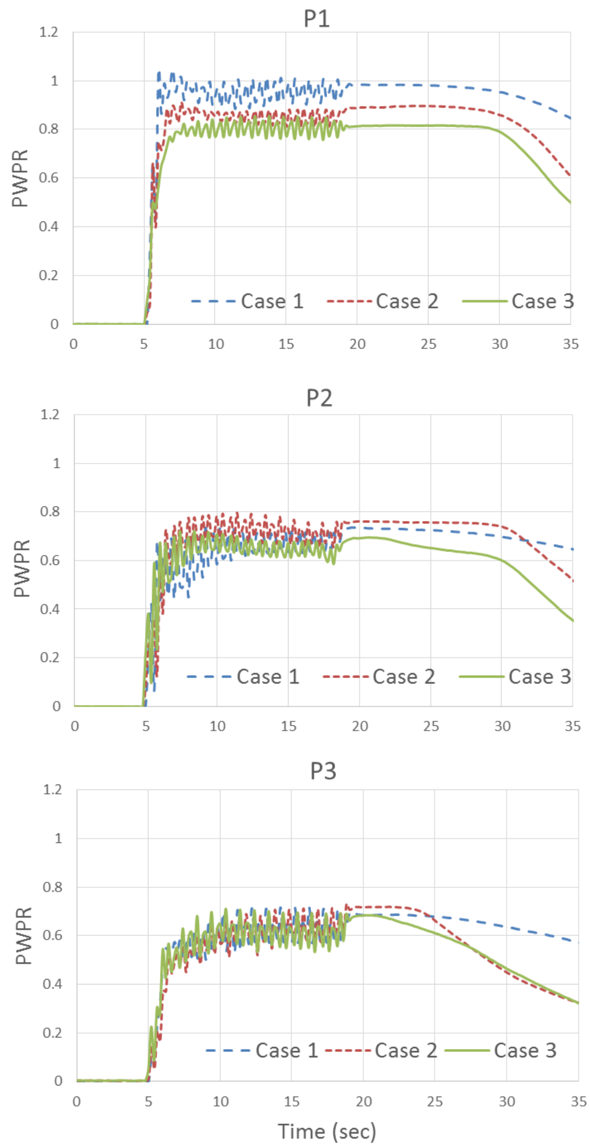

Figure 4. Pore water pressure time histories.

Generally speaking, based on the results, the presence of gravel and geosynthetics have reduced pore water pressure and speed up the process of pore water pressure dissipation which is thought because of its high permeability. As a result, reduction in pore water pressure will decrease liquefaction potential of the ground.

3.1.2. *Lateral spreading*

Lateral spreading was measured through nine points on the ground surface. In order to simplify understanding, the lateral displacements measured are averaged as shown in Figure 5. It can be observed that the presence of the proposed mitigation measures could reduce lateral displacement in various levels, based on the average values of the lateral displacement measured. In Case 2, the deformation was lowered around 0.2 cm, from 5.64 cm in Case 1 into 5.44 cm in Case 2. The better result was obtained in Case 3, where the deformation was reduced up to 1.3 cm, or around 23%, compared to Case 1.

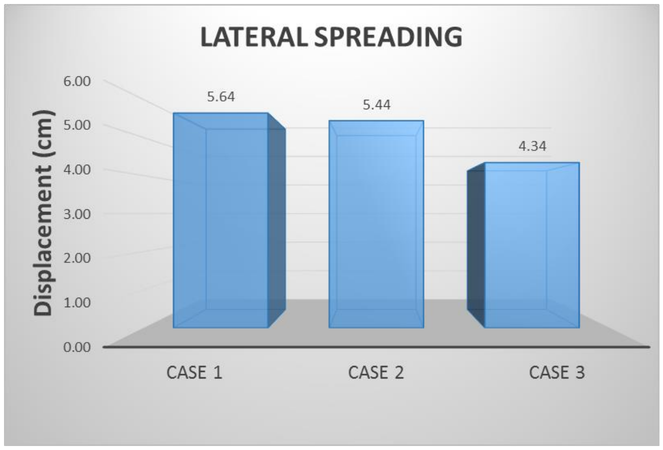

Figure 5. Averaged lateral spreading.

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 behaves like a board, this reinforcement could reduce the liquefaction-induced lateral deformation that occurred on the ground surface.

3.2. *Vertical displacement test*

3.2.1. *Pore water pressure*

Pore water pressure was observed by installing two pore water pressure transducers at 30 cm from the bottom of the sand container, both for the loose sand part and dense sand part. Pore water pressure ratio time histories of vertical displacement experiments are shown in Figure 6.

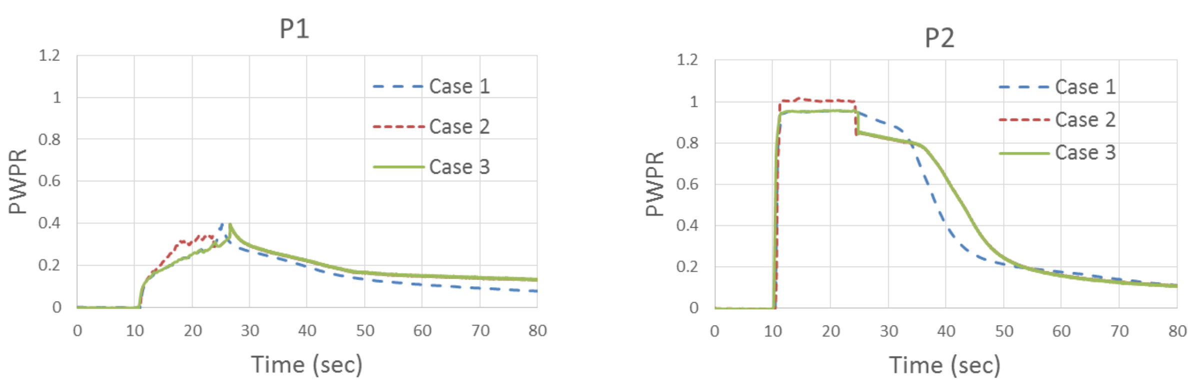

Figure 6. Pore water pressure time histories in settlement test.

As can be seen in Figure 6, the maximum pore water pressure ratio in the dense sand part, P1, is low, around 0.4 and almost similar for all cases. This condition indicates that there is no liquefaction occurred in the dense sand zone. Furthermore, the maximum pore water pressure in the loose sand zone, P2, is higher than P1, around 1 for Cases 1 and 2. This result signifies that liquefaction occurred. Although pore water pressure ratio shows 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, immediately after the shaking process stops; pore water pressure dissipated faster than Case 1, which thought due to the high permeability of the proposed mitigation layer.

3.2.2. *Settlement*

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

The settlements measured are averaged as shown in Figure 7. 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 different degrees for every case. In Case 2, compared to Case 1, the settlement was decreased by around 0.4 cm for the loose condition, and reach 0.19 cm for the dense condition. Moreover, in Case 3, by use gravel along with geosynthetics, the result obtained is more significant. For the loose condition, the settlement lowered up to 0.76 cm, around 36% compared to Case 1, while for the dense condition settlement gained almost equal to case 2, decreased about 0.17cm.

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%, as shown in Figure 8.

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 the dense sand, a void ratio of the ground is lower than loose sand.

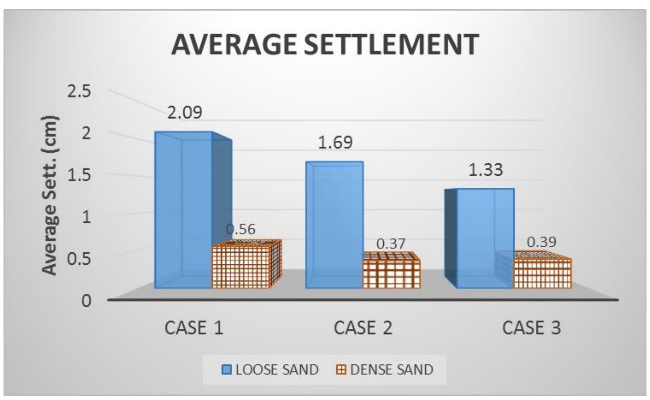

Figure 7. Average settlement.

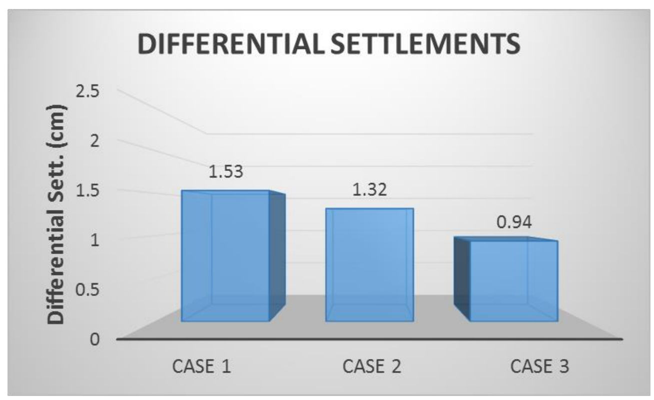

Figure 8. Differential settlements

4. CONCLUSIONS

The effectiveness of gravel along with geosynthetics remediation to restrain the liquefaction-induced ground 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 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, lateral displacement measured was decreased up to 23%. Furthermore, the settlement of the ground surface decreased by around 36% in the liquefiable zone and up to 30% in the non-liquefiable zone. Additionally, 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 to reduce the liquefaction-induced ground surface displacement.

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