Experimental study on effects of underground columnar improvement on seismic behaviour of quay wall subjected to liquefaction

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ABSTRACT
There are various mitigation methods to reduce the structural damage caused by liquefaction. In order to keep the performance of quay wall structures, deep mixing can be utilized as a useful soil improvement method to decrease the residual deformations. Recently, columnar type of deep mixing is expected to be more economical than overall grouting or that of square grid. Effect of soil stabilization pattern, area and position (where the underground columns are placed) is evaluated in this research. By conducting model shaking table tests, features of quay wall behaviour were evaluated based on two different improvement patterns: normal (regular) and irregular. Efficiency of the normal pattern and irregular pattern as well as its area and position are compared with respect to unimproved case. It is inferred that, in soil improvement design, selection of irregular pattern with an appropriate placement area and position can make the seismic behaviour of the structure better.

1 INTRODUCTION

Waterfront structures that are located on loose sandy subsoil are susceptible to large ground displacement due to extensive liquefaction. In order to prevent large deformation of such geotechnical structures and keep their serviceability, several methods of soil improvement measures have been performed. One suitable liquefaction mitigation method is soil stabilization by means of deep mixing which is carried out by mixing sand with cement-like materials. By developing bonding among sand grains and preventing negative dilatancy of particle displacement, liquefaction resistance of sand is improved (Towhata 2008).

In contrast to different types of deep mixing like overall or square grid grouting, the columnar type was considered less effective than others in liquefaction mitigation in spite of its lower installation cost (Koga et al. 1986). However, more recent shaking model tests by Yasuda et al. (2003) and Tanaka et al. (2003) indicate that columns are able to constrain shear deformation of soil and hence mitigate the onset of liquefaction.

As noted above, construction of underground deep mixed columns can be proposed as one cost effective approach among existing configurations (Figure 1). More efficient application of this method will be possible by evaluating the effective parameters such as pore water pressure and quay wall displacement.

This paper aims to study the reduction of quay wall displacement when it is subjected to lateral flow of liquefied backfill sand where underground grouted columns are installed. The geometry of columns positions is considered supposing that an irregular installation of columns may result in better mitigation than conventional regular (square) configuration of columns.

2 1-G SHAKING TABLE EXPERIMENTS

In total, five models were prepared and ten experiments were performed on a group of 93 columns, sheet-pile quay wall and anchor wall. The main objective of this series of 1g shaking table model tests was to investigate the improvement in quay wall behaviour. Configurations of the models were identical except the pattern, area and position of improvement measures.

Figure 1. Columnar deep mixing method

2.1 Law of Similitude

Better simulation of the site condition is achieved by following similitude rules in model experiments such as 1g shaking table and Ng centrifuge tests. So, appropriate use of these rules is important.

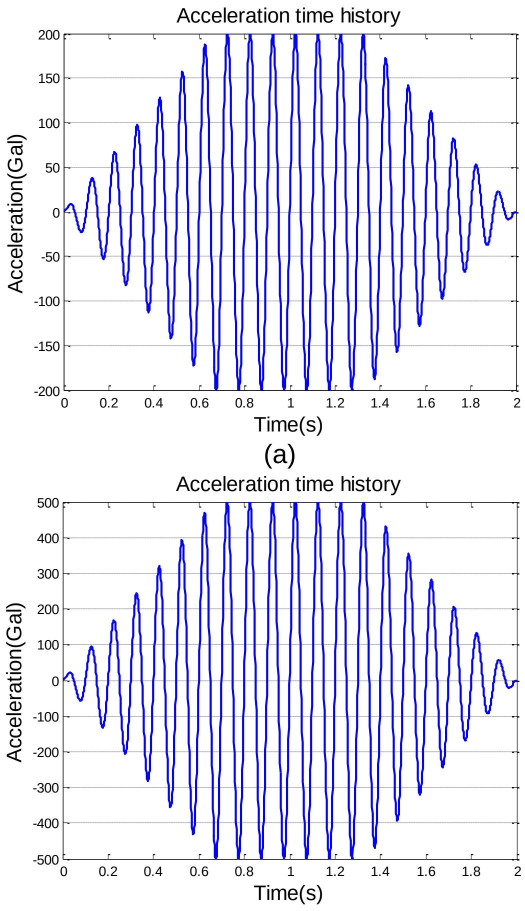
Various items like geometry, frequency, etc. are related by such rules between models and prototypes. A procedure for simulation of soil-structure-fluid system in shaking table tests is proposed by Iai (1989). Table 1 provides information about the utilized values and scales in this series of tests.

Table 1. 1-G Similitude between field and test

N= 20	Model/ Prototype	Prototype	Model
Scale	1/N	1	0.05
Pile diameter	1/N	52 cm	2.6 cm
Frequency	$N^{0.75}$	1 Hz	10 Hz
Relative density	-	60%	40%
Acceleration	1	200&500 Gal	200&500 Gal
Flexural rigidity (EI)	$N^{4.5}$	0.36 MNm^2	45.19 Nm^2

2.2 Model Configuration and Material Properties

The models consist of a quay wall, anchor wall, underground columns and surrounding saturated soil. Figure 2 shows the cross sectional view of the model. An aluminum plate with 51cm height, 40cm width and thickness of 3mm was used as a quay wall. The columns were made of hollow PVC pipes of 50cm in length with the inner diameter of 20mm and 3mm thickness; so, the outer diameter was 26mm. Pipes were fixed by means of two plates at top and bottom. In addition a thin gravelly layer was put over the top plate to improve the fixity. Also, 10cm of soil at the bottom was compacted to achieve the relative density of 85% as well as in the passive part in front of the wall.



(a)

(b)

Figure 3. Loading: (a) 200 Gal max. amplitude & (b) 500 Gal max. amplitude

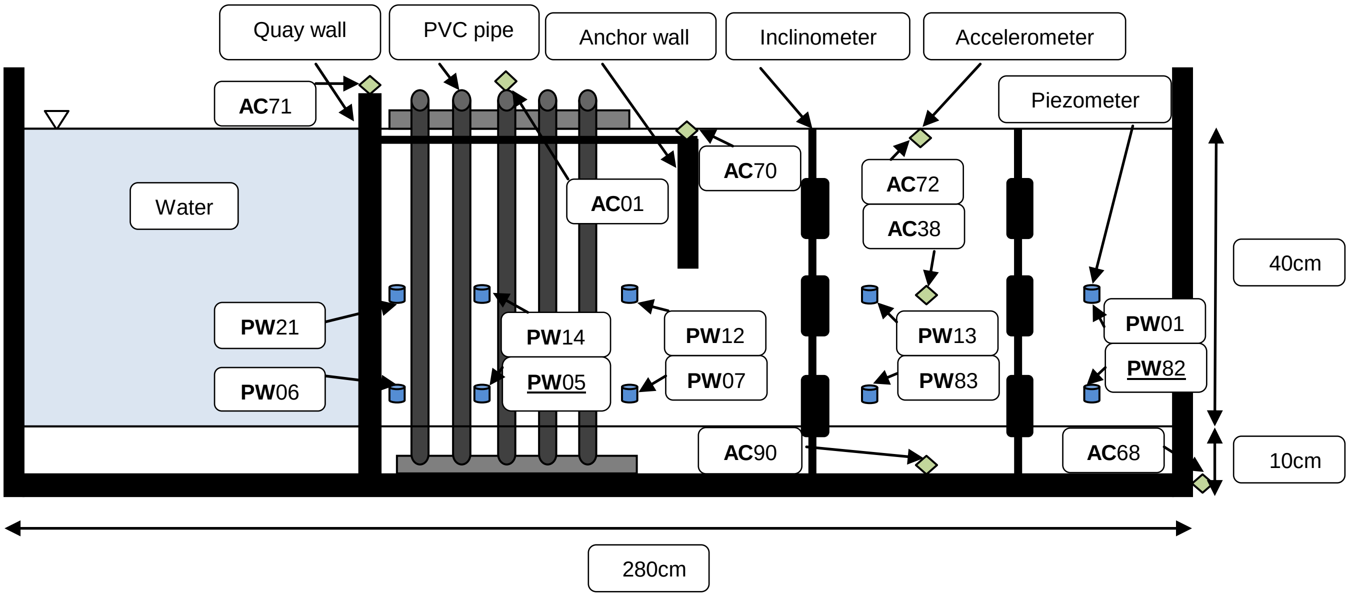


Figure 2. Configuration of model tests

Toyoura sand was used in models. The important properties of this sand are presented in Table 2. The relative density of the sand in experiments was kept at 40% (γ = 14.2kN/m^3) by using water sedimentation method. A designated amount of sand was poured into a specific water depth in this method. It was found that 10cm depth of water was appropriate for each step of sand pouring (Bahmanpour 2009).

This low relative density was employed to cancel the effects of low effective stress level on dilatancy and liquefaction resistance of sand.

Table 2. Important properties of Toyoura sand

G_s (g/cm^3)	e_{min}	e_{max}	D_{50} (mm)
2.648	0.605	0.974	0.21

2.3 Loading

As shown in Figure 3, all experiments were performed in two steps of maximum amplitudes of horizontal input motion including 200 and 500cm/s^2 in the longitudinal direction. The duration of shaking was 2 seconds consisting of constant harmonic motion and two tapering parts in the beginning and the end. The applied frequency for shaking was 10Hz. According to similitude rule this is equivalent to 1Hz in the field.

2.4 Experimental Program

Table 3 lists the summary of the experiments in which the effect of the improvement type was investigated. As shown, the first model was made without improvement and the second and third ones contain normal (regular) and irregular improvement patterns. Two other models were prepared by improving half of the area between quay wall and anchor wall irregularly; the column group is positioned near the quay wall and near the anchor wall in “Test 4” and “Test 5” respectively. It should be noted that considering the improvement ratio greater than 35% does not further mitigate the liquefaction problem (Towhata et al. 2010), improvement area ratio is selected to be 25% in all models.

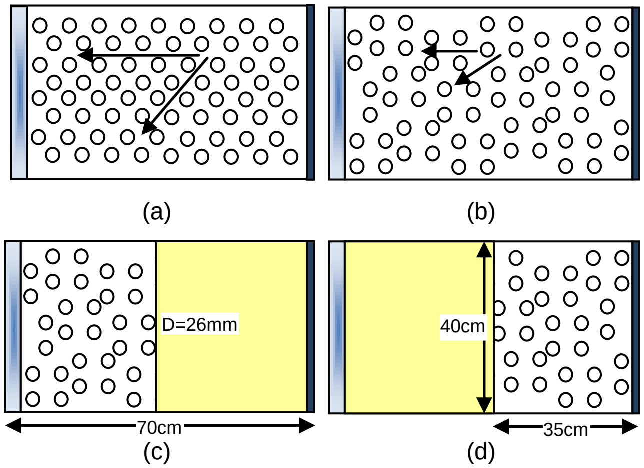
Note that the normal pattern is a regular triangular placement of parallel column rows. The irregular pattern is described as the positioning of quadruple column groups next to each other. They are arranged in a way that the edge of one group is placed in line with centerline of the adjacent groups.

Figure 4 displays the schematic plan views of different patterns, area and places of columns groups. In each plan view the quay wall is located in the left and the anchor wall is in the right side.

The arrows drawn among the columns are indicating possible passages of sand movement. Free flow of sand between columns of normal positioning is shown in part (a) of Figure 4. On the contrary, columns act as barriers in front of sand flow in irregular pattern as depicted in Figure 4(b).

Table 3. List of shaking table model tests

Test ID.	Dr (%)	Freq. (Hz)	Acc. Amp. (Gal)	Remarks
Test 1	40	10	200 & 500	Without Improvement
Test 2	40	10	200 & 500	Normal Improvement
Test 3	40	10	200 & 500	Irregular Improvement
Test 4	40	10	200 & 500	Irregular Improvement Near Quay Wall
Test 5	40	10	200 & 500	Irregular Improvement Near Anchor Wall



(a) (b)
(c) (d)

Figure 4. Plan views of improvement patterns: (a) Normal, (b) Irregular, (c) Irregular pattern near quay wall, (d) Irregular pattern near anchor wall

3 MEASUREMENTS AND DATA PROCESSING

All the models were instrumented with various sensors such as accelerometers and pore water pressure transducers (see Figure 2 for details). Many strain gauges were pasted on the sheet-pile quay wall to measure bending strain and laser transducer was used for displacement measurement. In this section, some primary output data from a shaking table test are presented.

3.1 Acceleration

In Figure 5, acceleration time histories of irregular improvement case with 200cm/s^2 shaking is illustrated. Acceleration amplitude inside the soil is decreased from bottom of the soil to its surface as a result of excess pore water pressure built-up and consequent liquefaction.

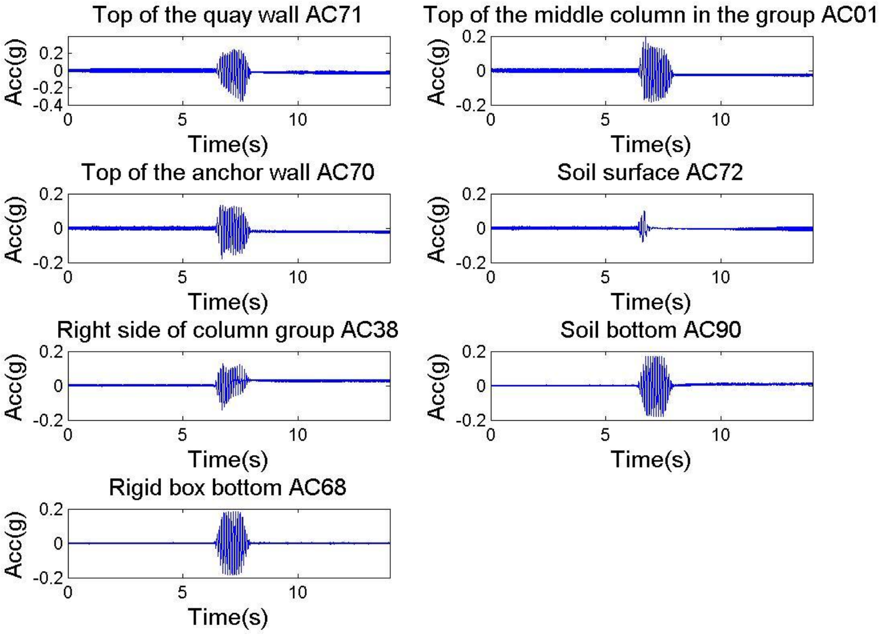


Figure 5. Time history of acceleration response (irregular improvement – 200 Gal)

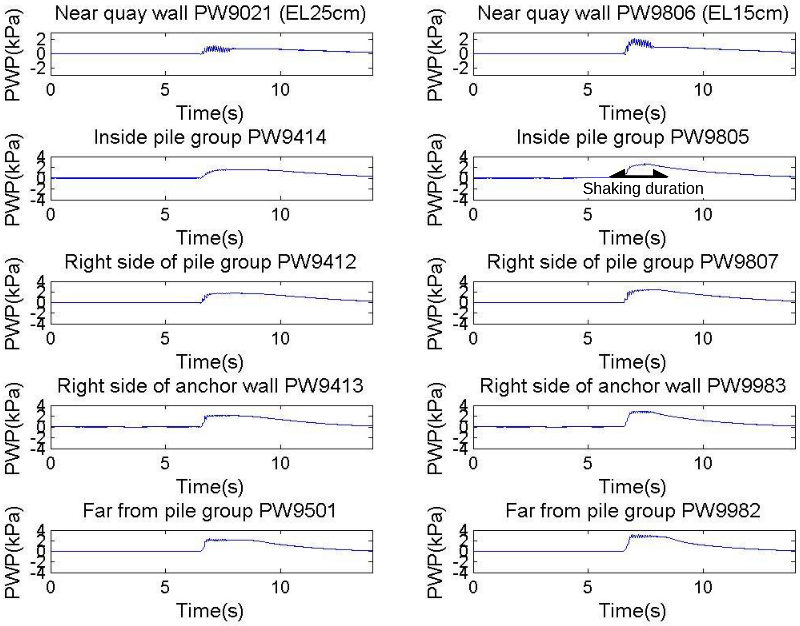


Figure 6. Time history of pore water pressure (irregular improvement – 200 Gal)

3.2 Excess Pore Water Pressure

The pore water pressure (PWP) transducers were installed at different locations inside soil to record the time history of excess pore water pressure. An example of these data from irregular improvement case with 200cm/s^2 shaking is presented in Figure 6. PWP records show that high excess PWP developed in the early stage of shaking and was maintained during shaking.

3.3 Displacement and Bending Moment of Quay Wall

The present study employed a sheet pile as the quay wall. To measure the displacement at the wall top, a laser transducer and image processing were used. The data received by the transducer was checked by processing of the photos of the experiment and then, displacement was confirmed.

Figure 7 shows the laser transducer data of near anchor wall irregular improvement case with 200cm/s^2 shaking. Figure 8 demonstrates the pictures of quay wall deformed laterally together with the liquefied backfill before and after shakings.

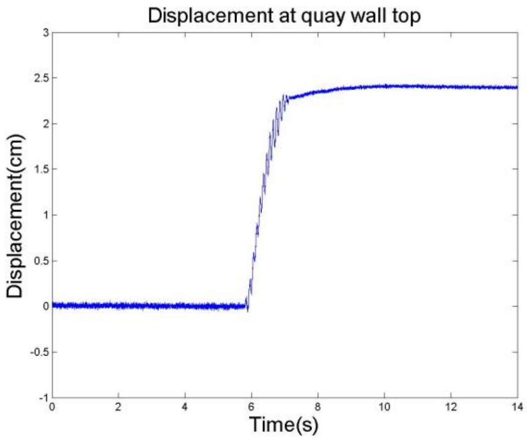


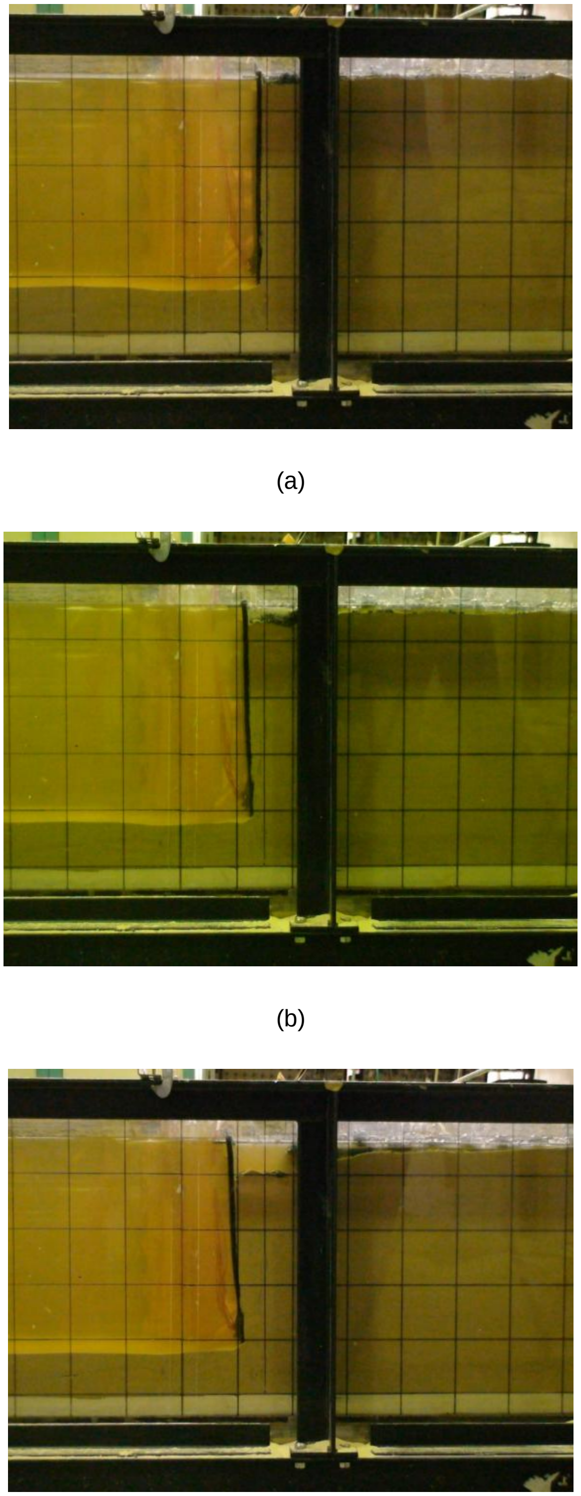
Figure 7. Displacement time history at quay wall top (near anchor wall irregular improvement - 200 Gal)

In order to measure bending moment, quay wall was instrumented with several strain gauges. The strain data were then converted into bending moment using calibration factors.

In Figure 9, a sample primary set of recorded bending moment time histories is depicted. It is measured at different elevations from the quay wall top and related to irregular improvement case with 200cm/s^2 loading.

4 OBSERVATIONS AND DISCUSSIONS

Based on the results which are briefly described above, changes in values of various parameters are summarized and compared in different model conditions.



(a)

(b)

(c)

Figure 8. Model ground: (a) before shaking, (b) after 200 Gal & (c) after 500 Gal

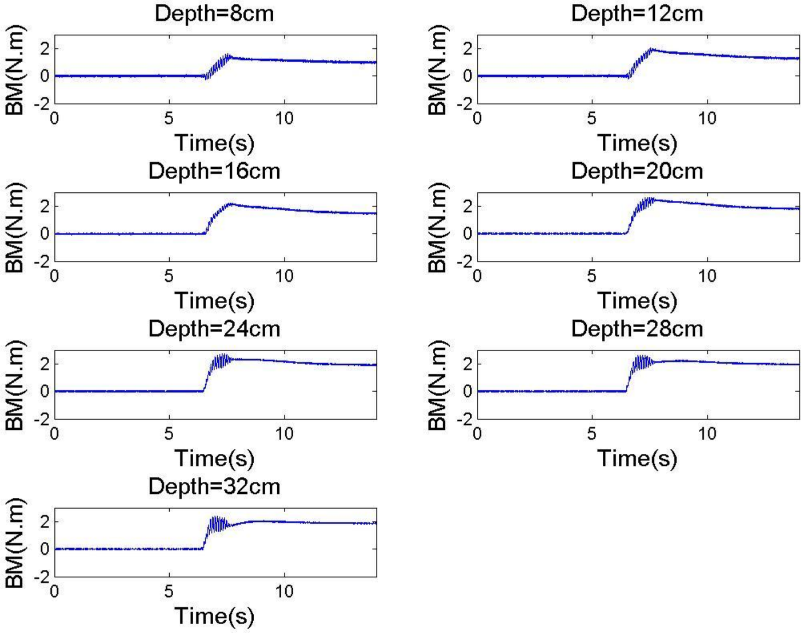


Figure 9. Time history of quay wall bending moment measured from wall top (irregular improvement – 200 Gal)

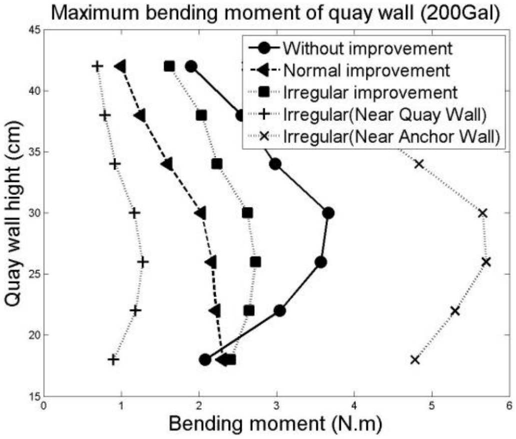


Figure 10. Profile of quay wall maximum bending moment (200 Gal shaking)

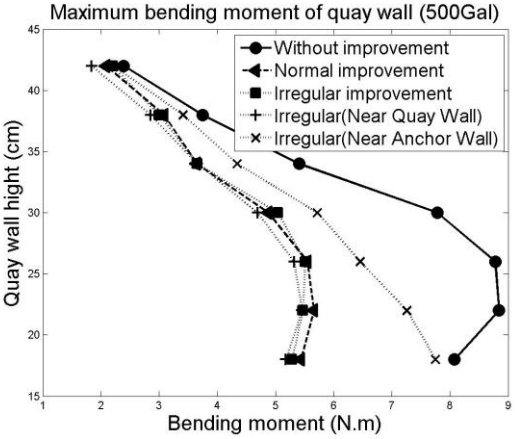


Figure 11. Profile of quay wall maximum bending moment (500 Gal shaking)

Profiles of the maximum bending moments during experiments recorded by seven pairs of strain gauges pasted along the center line of the quay wall are illustrated in Figures 10 and 11. The figures are showing the values including the cyclic component. As shown, the largest bending moment was recorded near the mid height of the quay wall. Due to effect of existing columns in improved tests, the quay wall bending moment is generally decreased (Derakhshani et al. 2010).

However, for the irregular improvement near anchor wall, higher values can be seen in bending moment profiles.

Note that mitigation effect of improvement is partially because the anchorage was stabilized by the columnar soil improvement. Another reason is the stabilization of the backfill that exerts directly earth pressure on the quay wall. This suggests that the lack of improvement measure immediately behind the quay wall increases the bending values in the irregular improvement near anchor wall case.

Figure 12 shows the excess pore water pressure ratio at the end of shaking in all experiments. In order to obtain this figure, pore water pressure inside the column group in depth of 35cm (data of transducer “pw05”) was divided by the initial effective stress($\sigma_{v0}' = 3.1$kPa).

As demonstrated, irregular pattern condition has the higher pore water pressure than normal pattern condition and the normal configuration has more pore water pressure than the case without improvement. Also, semi irregular cases are placed in between.

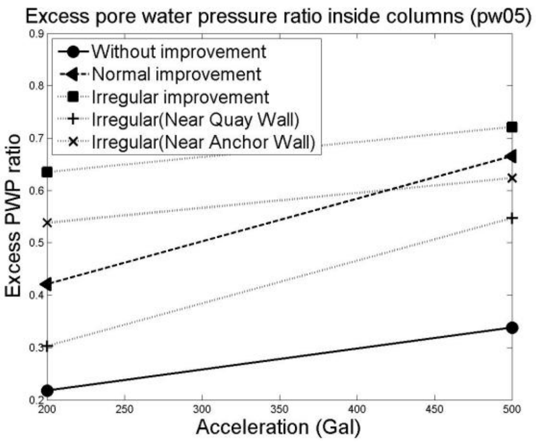


Figure 12. Pore water pressure ratio inside columns

Figure 13 illustrates the normalized pore water pressure ratio. This ratio was calculated by dividing the pore water pressure inside the improved part by the measured pressure outside and far from the columns (pw05/pw82). The generated pore water pressure inside columns is generally lower than outside as indicated by the ratio less than unity. In the case without improvement, large deformation is associated with lower pore pressure because of positive dilatancy. Moreover, in the improved cases pore pressure inside columns is high, because soil shear deformation is small.

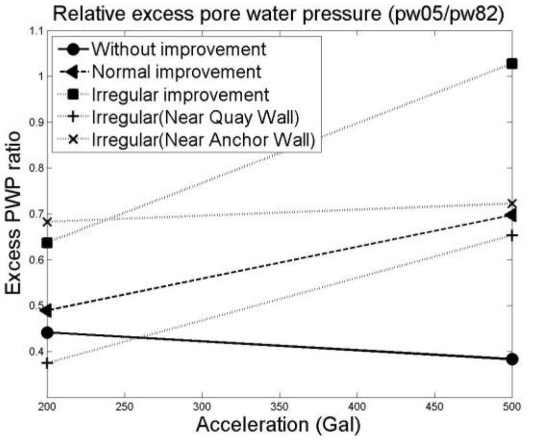


Figure 13. Relative excess pore water pressure ratio

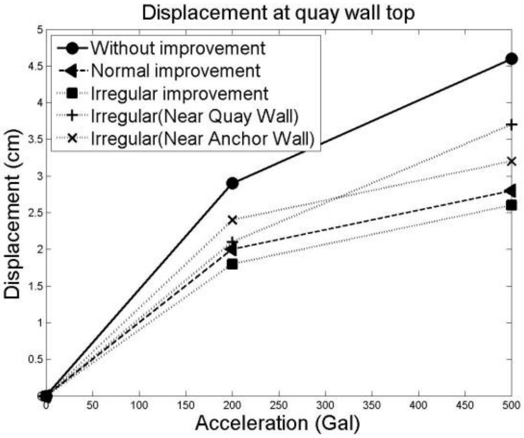


Figure 14. Displacement of quay wall top

The performance of a quay wall structure is most reasonably evaluated by its lateral residual deformation. This important criterion is plotted in Figure 14. It presents that the displacement of the wall top is reduced by using the normal pattern of stabilization and further reduced by the irregular positioning. This is seen for both shaking steps of 200 and 500cm/s^2. As shown, moreover, two cases of semi irregular improvement are in between normal and without improvement lines.

Finally, the relationship between the pore water pressure and the quay wall displacement is illustrated in Figure 15. It shows the relationship between these two major parameters.

It is concluded that using the deep mixed columns in liquefiable soil behind the quay wall results in generation of higher pore water pressure, but less wall top lateral displacement. Considering the displayed lines for each pair of experiments, gradual change of these parameters can be seen from the points without improvement to those of irregular pattern.

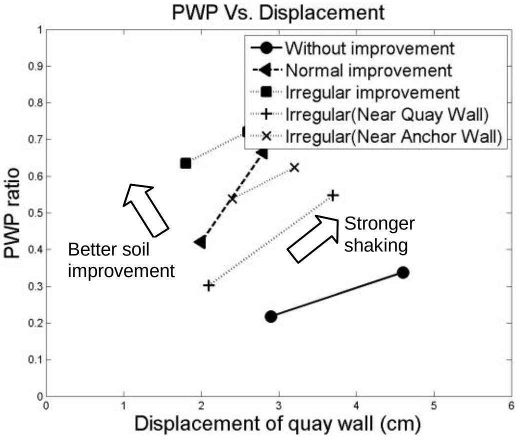


Figure 15. Pore water pressure versus quay wall displacement

5 CONCLUSIONS

Results of a series of shaking table tests on columnar deep mixing soil stabilization in ground models subjected to liquefaction presented in this paper. Conclusions from this study are summarized as follows:

1. The maximum bending moment in the quay wall is generally decreased by using variety of improvements. Among them, the irregular configuration near anchor wall shows relatively higher maximum bending moment. This may be because of far position of stabilized area measured from the quay wall structure.
2. Excess pore water pressure ratio is lower when there is no improvement. The relative excess pore water pressure ratio (ratio of excess pore water pressure inside columns to outside and far from them) is mostly less than one. A special care should be taken of pore pressure development when the mitigative effect is evaluated. This is because pore water pressure is possibly made lower by both large deformation and positive dilatancy of sand.
3. Displacement of the quay wall top was reduced by using normal improvement pattern and further decreased by utilizing irregular pattern. Due to irregular placement, some columns are working as barriers in front of sand flow while travelling via passages between columns. Comparatively, sand can flow among columns that are placed with normal pattern without any obstruction.
4. Although the wall displacement in models with irregular placement of columns near quay/anchor wall is more than other improved cases, it is not so high regarding the use of half of improvable area between quay wall and anchor wall. Considering other mentioned parameters such as bending moment and excess pore water pressure, irregular stabilization in half of area can be an economical choice in construction or rehabilitation against liquefaction.

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