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EXPERIMENTAL STUDY ON MITIGATION OF LIQUEFACTION-INDUCED LATERAL DISPLACEMENT USING DEEP SOIL MIXING

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ABSTRACT

After 1990s' earthquakes in Japan, lateral flow of liquefiable slopes became a serious concern of engineers. Especially Kobe earthquake (1995) in which high subsidence of river levee as a result of liquefied sand lateral flow was observed, become a turning point in geotechnical engineering approach in dealing with this phenomena. From that time many different kinds of mitigation measures for preventing or at least controlling the extent of lateral flow have been proposed. Improving soil by deep mixing columns is one of the common methods of soil improvement that can also be used for controlling the consequences of liquefied sand flow. For analyzing the factors affecting the efficiency of this method, several shaking table tests have been done. This article is showing the effects of studied factors including columns pattern, the length and improvement ratio. Moreover the magnitude of flow inside and outside of improved area are scrutinized. Finally, based on experimental observations, behavior of liquefied sand in existence of deep mixed soil is modeled numerically.

INTRODUCTION

Liquefaction-induced damages become important when there is not enough land for people to construct their properties on stiff and reliable soils. After understanding the mechanism of liquefaction failure, engineers could find effective countermeasures for prevention of liquefaction. However, it does not mean that liquefaction can be prevented without considering how huge the affected area is, and how expensive retrofitting tasks can be. Liquefaction-induced lateral flow is one of large-scale dangerous consequences that can damage many other buried and surface important structures close to or on the liquefied slope. The knowledge of geotechnical engineering is enough to prevent this kind of flow but the economic issue scarcely allows expensive measures such as complete improvement of soil on a large scale. This point leads geotechnical engineers toward the so-called "performance based design" in geotechnical engineering. The essence of this idea lets geotechnical structures (in this research case, soil slopes) allow minor damages but no complete survival or complete stop of service is allowed after a big earthquake. In other words, and for this article in particular, liquefiable slopes are allowed to move to some extent but it should not flow significantly.

The 2011 gigantic earthquake in Japan also revealed another aspect of lateral flow of liquefiable slopes and river levees. Towhata et al. (2011) reported a huge number of river levees deformed in quite a short time (2115 damaged river levees). Figures 1 and 2 show significant distortion of Tone river levee as a result of liquefaction in underling soil. It is noteworthy here that the comprehensive investigation of the last author has shown that many of damages occurred even though the subsoil of river levees was not liquefiable. Hence the new controversial topic of liquefaction inside river levees rose. This huge number of damaged levees again leads us to the idea of performance based design in geotechnical engineering.

Conventionally, damage in river levees due to huge earthquakes has been accepted, because simultaneous great earthquake and flood has low probability, and it was supposed that damaged river levees can be restored rapidly within two weeks. The huge number of damaged levees in the past earthquake combined with many other social and technical problems has shown there are situations that restoring damaged river levees can extend much more than two weeks (Towhata et al. 2011). This suggests that by some extent of improving of slopes and river levees, which can decrease the lateral flow, such a hazardous situation as in previous earthquakes can be mitigated.

Fig. 1. Liquefaction-induced distortion of Tone river levee in Sawara (Towhata et. al 2011)

Fig. 2. Liquefied sand and sand ejection in front of distorted Tone river levee (Towhata et. al 2011)

Various methods of soil improvement have been proposed and used in practice so far to prevent lateral flow of liquefied soil. Sheetpile walls, sand compaction, soil grouting and columnar deep mixing are among very frequently used ones. Although it was believed historically that columnar deep mixing method is not effective in mitigation of liquefaction-induced damages (Koga et al. 1986), recent studies have shown this method can mitigate or at least delay commence of liquefaction because of constraining the surrounding sand (Yasuda et al. 2003, Tanaka et al. 2003).

To this regard, the present study was carried out to examine important factors that can affect performance of soil deep mixing in controlling the flow of liquefied slope. The pattern of mixed soil columns, length of improvement and its ratio (which is the number of columns in a specific area) are considered as the important factors. The pattern of mixed soil columns has a special advantage comparing with the other 2 factors because it does not increase the cost of construction if found to be effective. Recent studies have shown that change in pattern of deep mixed soil could have positive effects on remediation of displacement of quay walls subjected to liquefied soil pressure (see Bahmanpour 2009, Towhata et al. 2010 and, Derakhshani et al. 2011).

METHOD OF SHAKING TABLE TESTS

Figure 3 schematically shows the configuration of 1-G model tests. A soil box of 2.65m in length, 0.6m in height, and 0.4m in width was used for the models. At both ends of box 2.5cm-thick shock absorbers were installed to reduce the effects of rigid boundary. Toyoura sand with ρ_s=2.648, e_{max}=0.974 and e_{min}=0.605 was used for making the model ground. The bottom 13cm of ground which was considered to be unliquefiable was made by air pluviation method and then compacted to achieve 75% relative density. The upper layers were made by water pluviation method and constituted a 10% steep slope with a relative density of 40%. Ground water level was equal to the highest level of slope. It means the whole slope was submerged in water. For modeling the columnar deep mixed soil, cylindrical acryl columns were used. It was assumed that the bottom of the columns reached the unliquefiable soil layer, so the acryl cylinders were fixed at the bottom by screwing into an acryl plate. At the top also for keeping the distance between columns constant, acryl cylinders' tops were inserted into a plastic mold. Several number of pore water pressure transducers and accelerometers were installed inside the soil model. Moreover, the lateral displacement of soil was measured by means of vertical columns of colored sand close to the transparent acryl wall of the soil box. Several strain gauges were pasted on acryl cylinders to measure the bending moment produced by lateral flow of liquefied sand. The models were shaken by sinusoidal waves of 200Gal and after that 300Gal with frequency of 10Hz and duration of 12sec. Figure 4 shows the input accelerations. The direction of shaking was parallel to the slope.

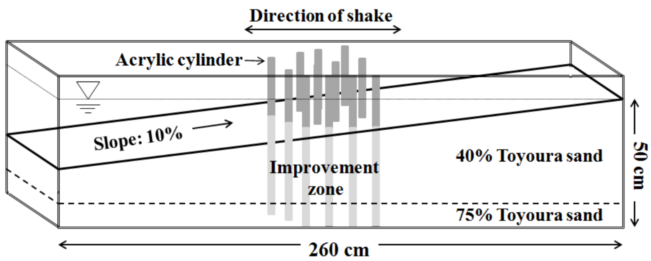


Fig. 3. Schematic configuration of model tests

Seven tests were conducted to evaluate the effects of length, ratio and pattern of improvement. Table 1 shows a summary of specifications of each test. Definition of regular and irregular patterns of improvement is shown in Fig. 5. The philosophy of the irregular pattern is that by using this pattern no straight path is available for sand to flow through the improvement area, so it is expected that this pattern can reduce the sand flow more effectively than the regular pattern in which still there are some paths for sand to pass through.

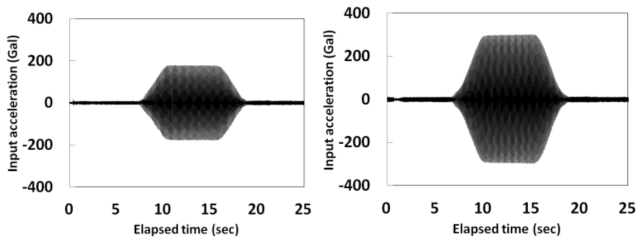


Fig. 4. Accelerations input to the models

Table 1. Summary of tested specifications

Test	Improvement pattern	Improvement ratio (%)	Improvement Length (cm)
1	No Improvement	0	0
2	Regular	25	63
3	Irregular	25	63
4	Regular	35	63
5	Irregular	35	63
6	Irregular	25	31.5
7	Irregular	35	31.5

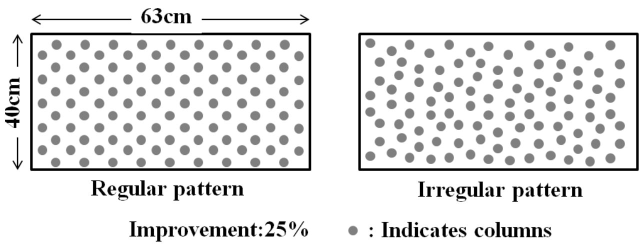


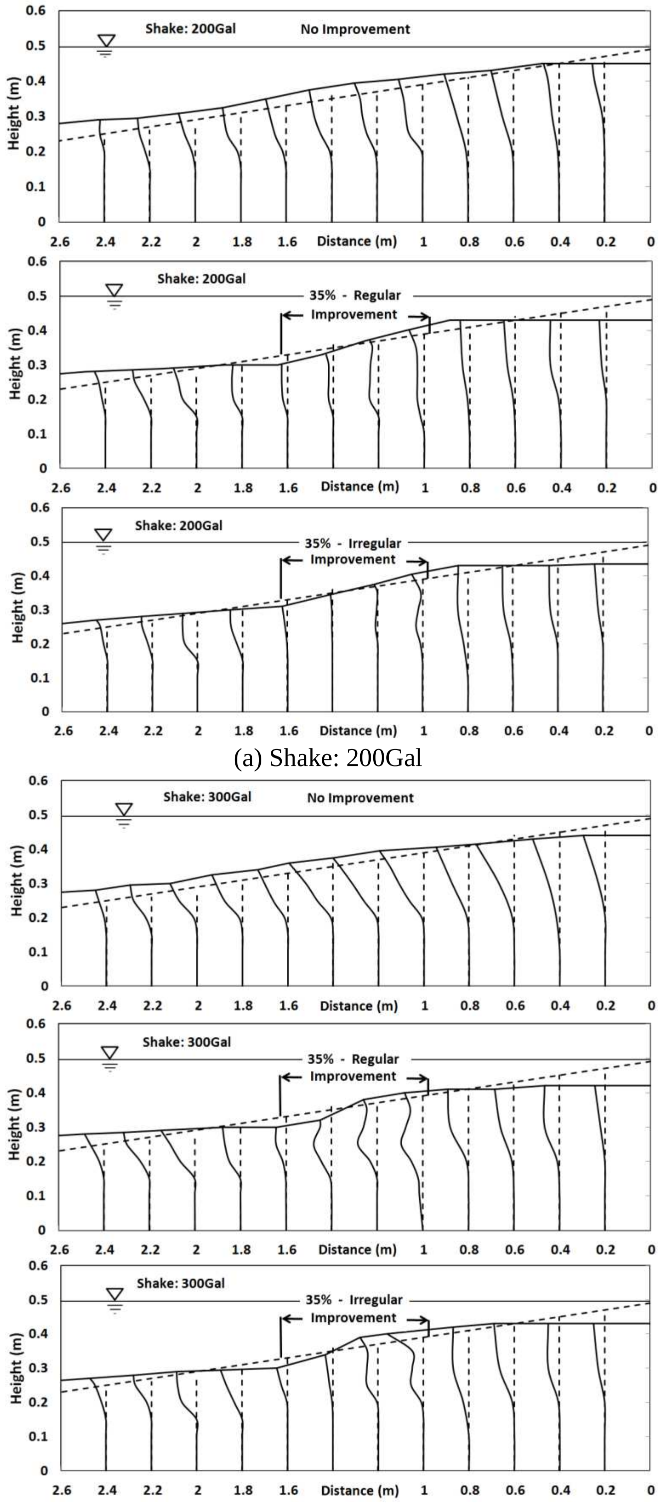
Fig. 5. Definition of regular and irregular improvement

The improvement ratio means the ratio of the cross section of column area over the total area of improvement zone. Width of improvement zone was constant in all cases and was governed by the width of the sand box which was 0.4m. However, the length of improvement zone was variable, which was either 63cm or 31.5cm in different cases.

EXPERIMENTAL RESULTS AND DISCUSSION

Effects of improvement pattern

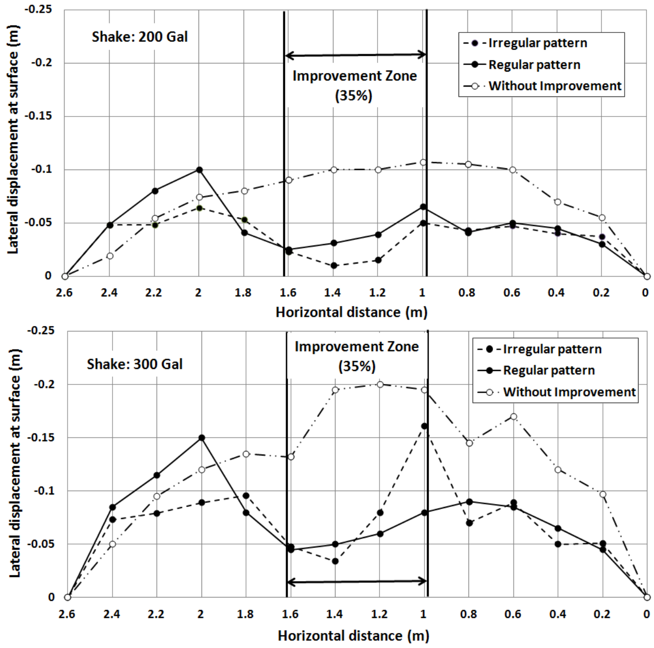
Tests 2, 3, 4 and 5 were conducted to study the effects of improvement patterns on slope flow. Fig. 6 indicates the slope flow after 200Gal and 300Gal shake of tests 4 and 5. Displacement of soil when there is no improvement is also shown in this figure.



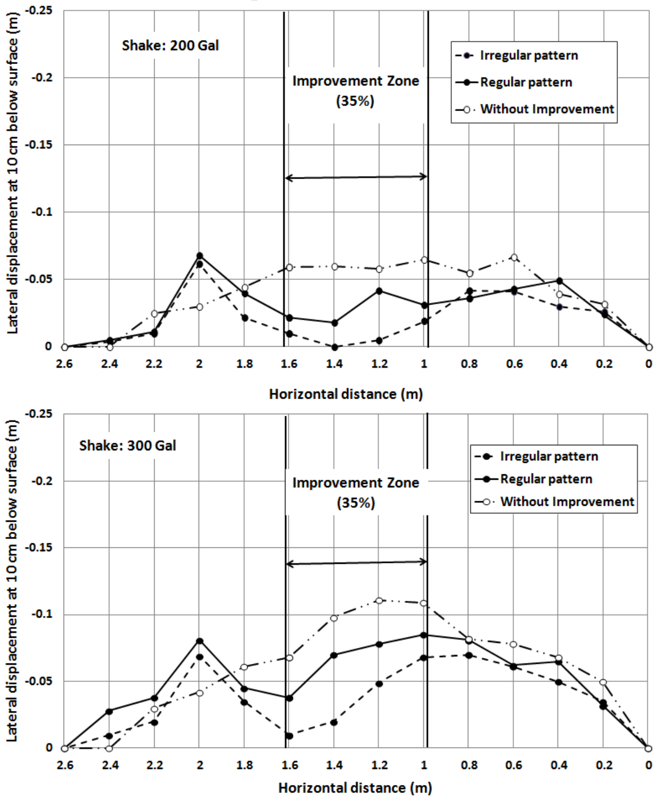
(a) Shake: 200Gal

(b) Shake: 300Gal

Fig. 6. Lateral flow of slope without improvement and tests 4 and 5 after 200Gal(a) and 300Gal(b) shakes



(a) Displacement at Surface



(b) Displacement at 10 cm below surface

Fig. 7. (a) Displacement at surface and (b) 10cm below surface of tests 4 and 5 after 200Gal and 300Gal shakes

Figure 7 shows the displacement at the surface and at 10 cm below the surface of these 3 tests more accurately. By comparing displacement of the 3 tests, and simultaneously looking at both Figs. 6 and 7, it is found that the columns may not necessarily reduce the lateral flow in the upstream unimproved area. In contrast, the change in pattern of improvement can effectively reduce displacement of sand inside the improvement zone. Although displacement at surface is not affected so much, displacement at 10 cm below the surface is apparently decreased (Fig.7). The irregular pattern of improvement blocks any straight path for liquefied sand to pass and reduces the displacement. Lateral flow in the downstream unimproved area is also reduced considerably. It may be expected that downstream also should show same behavior as upstream, but because in case of regular pattern, soil can pass the improvement zone easily and come to downstream, greater displacement of liquefied soil occurred.

Another important effect of change in pattern of improvement can be seen in Fig. 8. The pore water pressure transducers installed in the improvement zone shows that change in pattern of columns can lead to considerable decrease in excess pore water pressure in that zone. This observation is probably due to better constraining of soil by irregular pattern comparing with regular pattern. Consequently, degree of liquefaction is less in case of irregular pattern of improvement. This lower pore water pressure is consistent with the reduced displacement of liquefied zone in case of irregular pattern. In the case of no improvement, the reduced excess pore water pressure does not necessarily mean better situation because the shear deformation of soil was increased herein and the induced dilatancy reduced the excess pore water pressure.

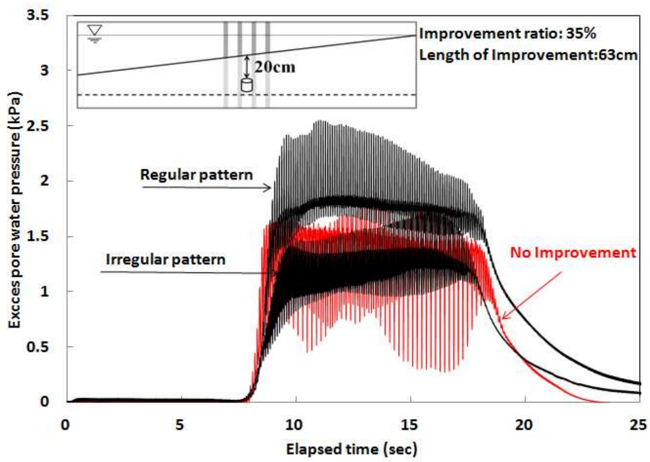


Fig. 8. Effect of improvement pattern on excess pore water pressure inside the improved zone

Figures 9 and 10 compare lateral flow and movement of surface of slopes for tests 2 and 3. This figure also shows that improvement reduced the extent of flow both in upstream and improvement zones, but no effect in the downstream section.

Comparison of tests 2 and 3 in which improvement ratio is 25% indicates that change in pattern of improvement cannot reduce the magnitude of lateral flow in the upstream part that is outside of the improvement zone. Moreover, when the improvement ratio is 35% the change in pattern could reduce the magnitude of flow in downstream, but, when the improvement ratio is equal to 25%, such a reduction cannot be seen. The reason of this observation is probably that, when the improvement ratio is too low even by change in pattern of improvement, many easy paths would remain for liquefied sand to escape from the improvement zone (Fig. 5), and unlike 35% improvement ratio, for both cases of regular and irregular patterns of 25% improvement ratio, sand can flow from improvement zone to downstream. Unlike outside of the improvement zone, the pattern of improvement could have considerable effects on the lateral movement of soil inside of the improvement zone.

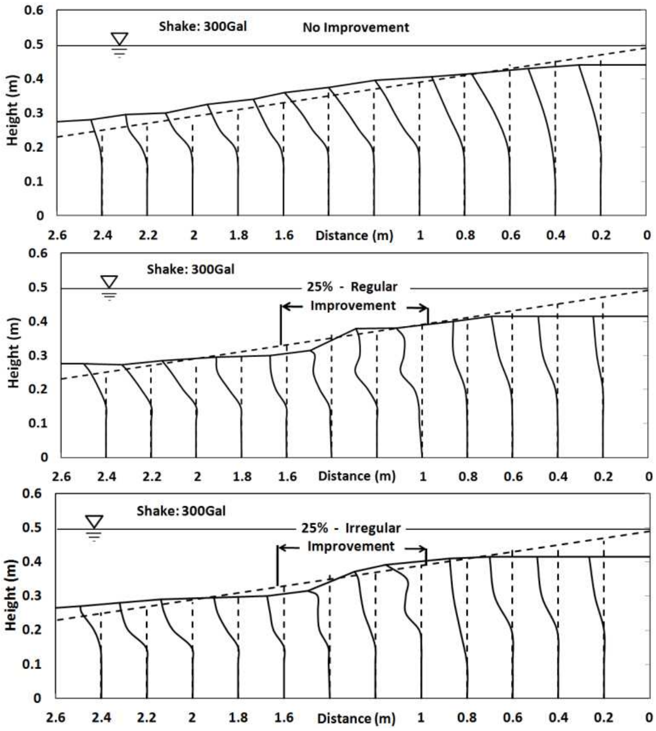


Fig. 9. Lateral flow of slope without improvement (upper) and tests 2 and 3 after 300Gal shake

Figures 9 and 10 indicate that only change in pattern of improvement columns without any change in ratio and length of improvement could reduce the magnitude of lateral flow substantially, especially below the surface (similar to the finding for 35% improvement ratio, reduction at surface is not considerable especially after 300Gal probably because of forming steep slope by 200Gal shake in the improved zone).

Effects of improvement ratio

Improvement ratio is increased by installing more acryl cylinders in the same area of improvement. Fig. 11 shows the lateral displacement at surface for 200gal and 300gal shake of tests 3 and 5. This figure apparently reveals that the lateral flow of liquefied sand is decreased by increasing the number of deep mixed columns in an specific area.

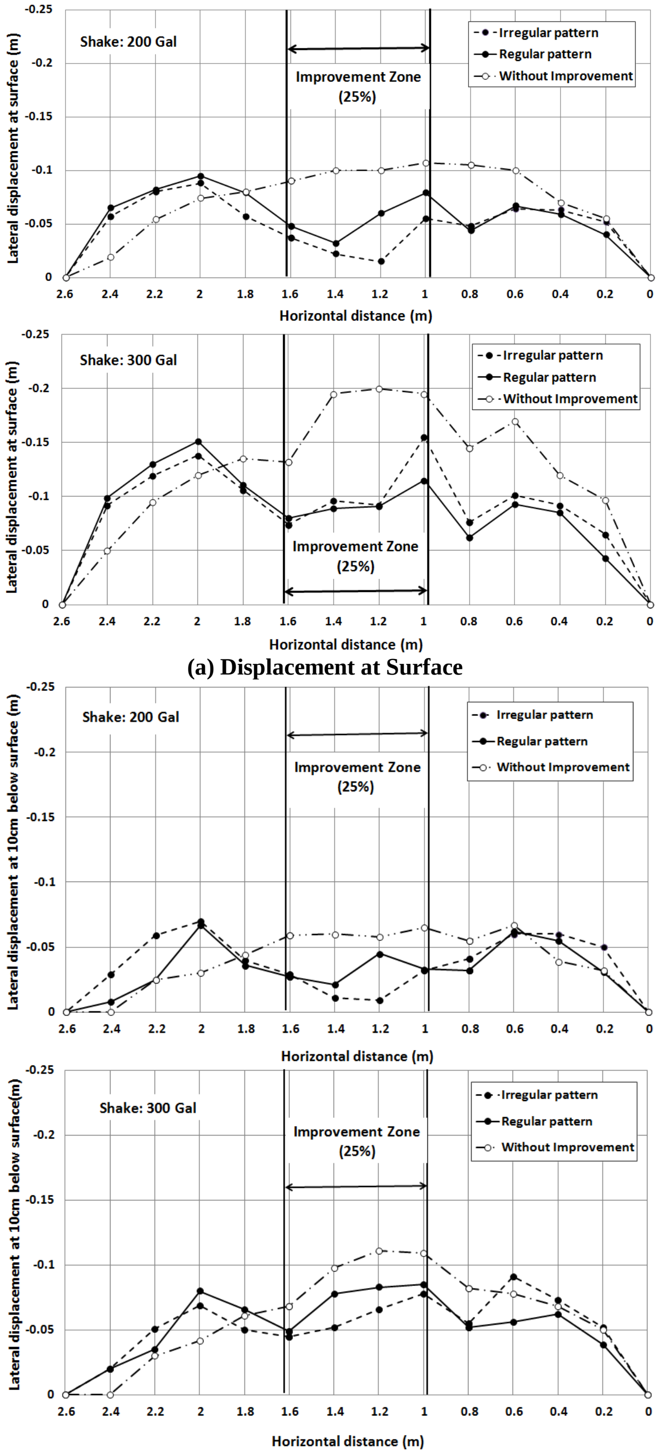


Fig. 10. (a) Displacement at surface and (b) 10cm below surface of tests 2 and 3 after 200Gal and 300Gal shakes

Recalling effects of pattern of improvement, it can be recognized that unlike pattern of columns, improvement ratio can have effects on both inside and outside of improvement zone especially on upstream, where no retrofitting effect of pattern was seen.

This observation suggests that mechanical parameters of improvement area are more important than its geometrical properties (because, unless an specific improvement ratio is not reached, change in geometrical parameters (pattern) has no effect). However, change in pattern of improvement, does not increase the expenses of the project while increase in improvement ratio is increase the cost of improvement.

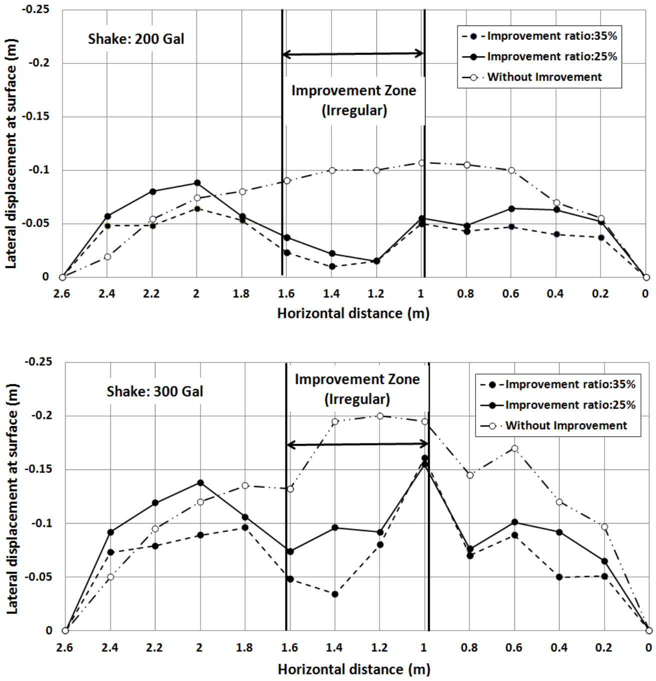


Fig. 11. Displacement at surface of tests 3 and 5 after 200Gal (upper) and 300Gal (lower) shakes

Figure 12 shows lateral displacement at surface of tests 6 and 7. By increasing improvement ratio from 25% to 35% the lateral flow of liquefied sand is decreased. However, when compared with the results of tests 3 and 5 in which the length of improvement area was twice greater, the reduction of lateral flow is less significant. That is probably because of shorter distance that liquefied sand needs to pass to escape from the improvement zone. In other words, although routes for liquefied sand flow become narrower by increasing the improvement ratio, they are not long enough, and liquefied sand could pass it during the shaking. Effects of length of improvement zone is discussed in more detail in the next section.

Figure 13 compares the excess pore water pressure induced in the improvement zone in case of improvement ratio of 25% and 35%. It is recognized that increase in improvement ratio slightly decreased the excess pore water pressure. Recalling the effects of pattern of improvement on excess pore water pressure, the amount of decrease resulted from the change of pattern is considerably higher than decrease, resulted from change in improvement ratio. This observation suggests that pattern of improvement is the predominant factor in liquefaction onset delay.

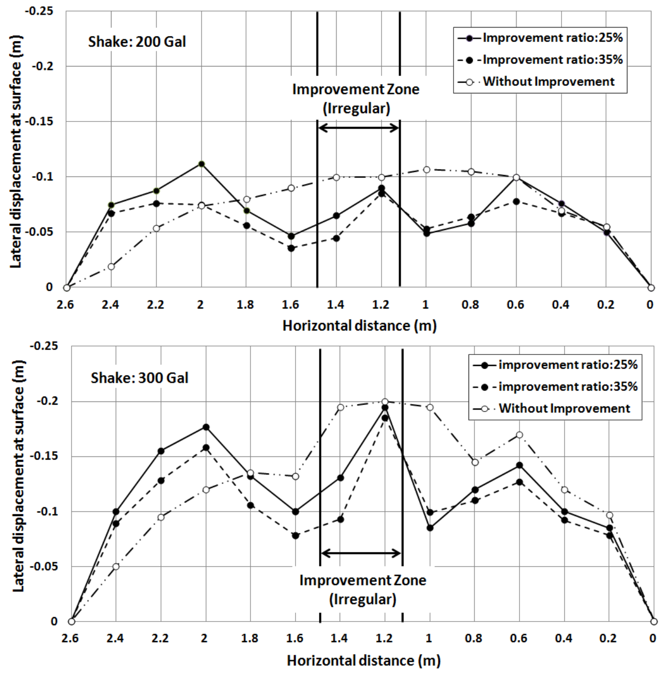


Fig.12. Displacement at surface of tests 6 and 7 after 200Gal (upper) and 300Gal (lower) shakes

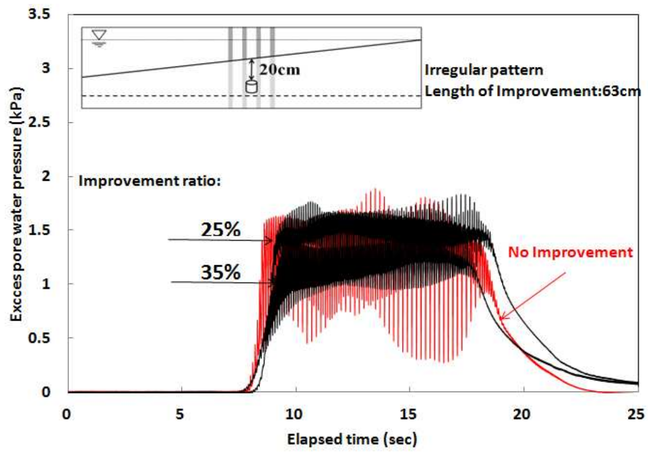


Fig. 13. Effect of improvement ratio on excess pore water pressure inside the improved zone

Effects of length of improvement

Length of improvement zone and improvement ratio are two important properties. After increasing the length of improvement, stiffer improvement zone can resist liquefied sand flow. Fig. 14 shows the lateral displacement of slope after 200Gal and 300Gal shakes. The improvement zone is either 63cm or 31.5cm in length with 35% improvement ratio. It can be seen that the magnitude of lateral flow is reduced both inside and outside of the improvement zone by increasing the length of improvement. This is because the distance that should be passed by liquefied sand is increased by increasing the length of improvement and consequently less amount of liquefied sand can pass through the improvement zone. Recalling the effects of improvement ratio, when the improvement ratio was increased in shorter length of improvement, the amount of lateral flow reduction was less than flow in the case of longer length of improvement.

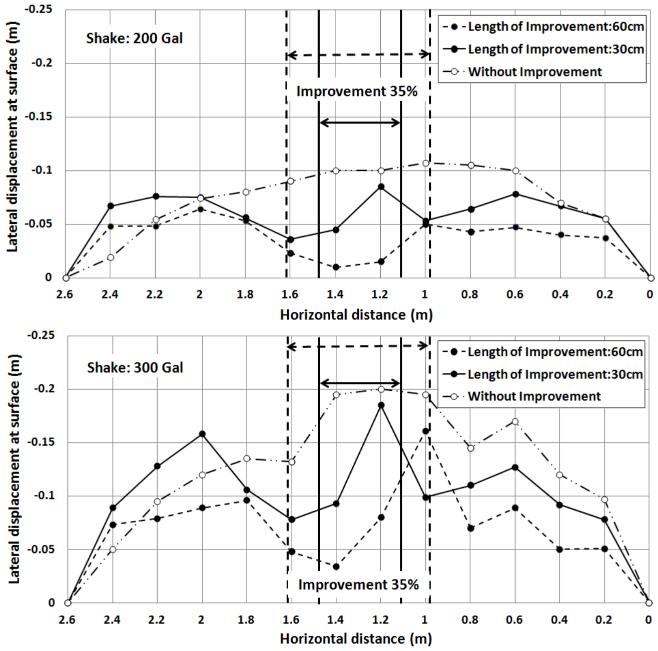


Fig.14. Displacement at surface of tests 6 and 7 after 200Gal (upper) and 300Gal (lower) shakes

In case of effects on pore water pressure, increasing in length of improvement leads to decrease in excess pore water pressure in the improvement area (Fig. 15). Amount of reduction is considerably greater than effect of improvement ratio, but close to the effect of pattern. It can be due to scale of improvement that outside improvement zone pore water pressure could affect inside part. However, the effect of improvement on reduction of pore water pressure is decreased near the edge of the improved area.

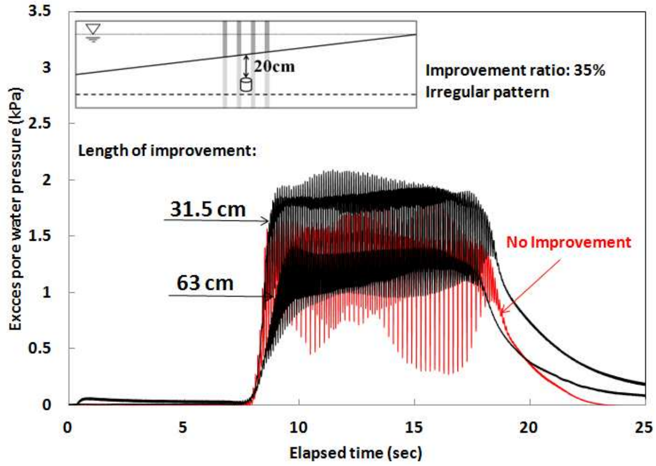


Fig. 15. Effect of length of improvement on excess pore water pressure inside the improved zone

NUMERICAL ANALYSIS

Original theory of lateral displacement of liquefied slope

Towhata et al. (1999) developed a new method of analysis for calculation of liquefaction-induced lateral displacement of slopes. The method is based on the minimum potential energy principle. Although explanation of details of solution is out of scope of this article, the precise demonstration of the method can be found in Towhata et. al (1999) and Kogai et. al (2000). Herein just the important features of the method is described briefly:

1. Liquefied soil in slope moves laterally similar to sine function in vertical direction, increasing from zero at the bottom and maximum displacement at top.
2. Maximum possible displacement of slope is calculated based on minimum potential energy principle, so maximum possible displacement happens when the overall potential energy reaches its minimum value.
3. Constant volume deformation is assumed in the solution. By this assumption the vertical displacement can be calculated if the horizontal displacement is known.
4. The liquefied sand is modeled as a viscous liquid. Time history of displacement can be calculated by assuming the liquefied sand as Newtonian or Bingham fluid.

Modeling of deep mixed soil as an embedded wall

The original solution was developed for such embedded walls as sheetpile and compacted soil. Here for modeling the deep mixed soil as an embedded wall, the improvement zone parameters are identified as parameters of a homogenous compacted soil wall (which was considered as a shear beam in the original solution). As experimental models have shown, the mechanical parameters of deep mixed soil are the governing parameters of its behavior. Moreover, since the liquefied soil is assumed not to bear any moment or shear force and in real deep mixed soil shear deformation is predominant, the whole improvement zone is modeled as a shear beam. Before demonstrating how improvement zone is idealized as a shear beam, original solution for compacted soil which was also treated as shear beam needs to be explained briefly. For details, see Kogai et al. (2000).

In the original solution, compacted sand was idealized as a shear beam. For the case where distortion is small and in the linear elastic zone (Fig. 17 right), the strain energy of beam can be derived by integration of $G_s L_s (d\rho/dz)^2/2$ from the bottom to top of the beam. G_s represents the shear modulus of compacted sand, L_s width of the wall and ρ displacement of the beam. Solving based on the minimum energy principle takes into account the strain energy of the beam. By considering volume consistency between beam deformation and soil movement, the following equation is derived:

$$\zeta = \frac{\pi}{2H}\left\{\left[ET\frac{dF}{dx}\right]_{x^-}^{x^+} + \left[\frac{2PH}{\pi} + \frac{4\gamma H}{\pi^2}\left(H\frac{dF}{dx} + bF\right)\right]_{x^-}^{x^+}\right\} \quad (1)$$

$$\left[ET\frac{dF}{dx}\right]_{x^-}^{x^+} + \left[\frac{2PH}{\pi} + \frac{2}{\pi}\left(1-\frac{2}{\pi}\right)\gamma H^2 + \frac{4\gamma H}{\pi^2}\left(H\frac{dF}{dx} + bF\right)\right]_{x^-}^{x^+} - \frac{12 L_s G_s}{\pi^2 H}F = 0 \quad (2)$$

where ζ stands for the net earth pressure acting on the wall, H is the height of liquefied sand, E the Young's modulus of unliquefiable layer at the surface and T, the thickness of that layer, F horizontal surface deformation of sand, P, surcharge applied at surface, γ, unit weight of liquefied sand and b is representing the change of thickness of liquefied layer in X direction. Fig. 16 shows different parameters of equation more clearly.

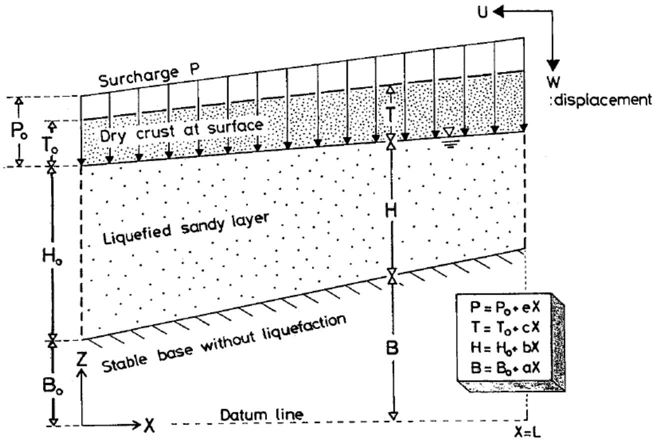


Fig.16. Parameters of soil slope (Towhata et. al 1999)

When the case is out of linear elastic range of distortion then using residual shear stress, τ_r, is more reasonable (Fig. 17 left). Then equation 2 changes to:

$$\left[ET\frac{dF}{dx}\right]_{x^-}^{x^+} + \left[\frac{2PH}{\pi} + \frac{2}{\pi}\left(1-\frac{2}{\pi}\right)\gamma H^2 + \frac{4\gamma H}{\pi^2}\left(H\frac{dF}{dx} + bF\right)\right]_{x^-}^{x^+} - L_s\tau_r = 0 \quad (3)$$

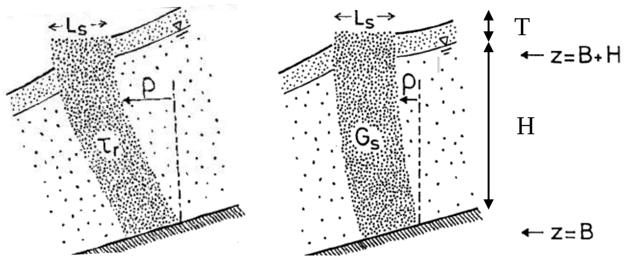


Fig.17. Schematic illustration of shear beam in elastic zone(right)-after yielding point (left) (Kogai et. al 2000)

For idealizing the improvement zone as a shear beam, displacement at top of each acryl column is assumed to be equal to the displacement at top of representing shear beam. Supposing that the total force applied from soil to the acryl columns is equal to F_t, and that this force is distributed equally between the columns, each column is bearing a force equal to F_t/N, where N is the number of acryl columns. This force can produce top displacement, w_l, equal to $F_t L^3/8EIN$ in each pile, where E is the Young modulus of each column, I is the moment inertia of the column and L is the length of columns. It is noteworthy here to mention by idealizing the improvement zone like a shear beam as in Fig. 17, the liquefied sand is supposed that cannot pass the improvement zone. This simplifying assumption is far from the real behavior and interaction of liquefied soil and improvement zone. The important point in the idealization is that the real Young modulus of acryl should not be used in this equation. To make this point clear, it should be noticed that liquefied sand can pass through the improvement zone. In contrast, by idealizing it as a shear beam it is assumed that the openings between columns are blocked. For considering this point, reduced values of Young modulus for acryl should be used. The following calculations use E of columns equal to 20.6 MPa, although the real E of acryl is 2940 MPa. This is because trial and errors indicated this value of E gives reasonable agreement between calculation and experiment. Note that the real values of E for prototype situations have to be studied in future.

Now, it is time to idealize the improved zone as a shear beam. For a shear beam with the same dimensions as improvement zone the displacement at top resulted from the force of F_t is equal to $F_t L/2G_{eq}AB$, where A and B are width and length of improvement and L is the height of beam. Making displacement at top of a column equal to displacement at top of shear beam, the equivalent shear modulus of shear beam can be calculated as: $G_{equ}=4EIN/ABL^2$. This equivalent shear modulus is replaced with G_s in Eq. 2. It is noteworthy that pattern of improvement is not tentatively considered in this idealization of improvement zone to a shear beam.

Here an example calculation of G_{eq} for the case of 35% improvement ratio and 63cm length of improvement is presented:

Acryl columns properties and improvement zone of 35% Improvement ratio and 63cm Length :
$E=20.6MPa$ $I=1.46\times10^{-8}m^4$ $L(average)=0.4m$ $A=0.39m$ $B=0.63m$ $N_{35\%}=144$

$G_{eq}=4EIN/ABL^2$
$G_{eq}=4\times20.6\times1.46\times10^{-8}\times144/(0.39\times0.63\times0.4^2)=4.4KN/m^2$

The same solution is repeated for other cases. By doing so, the equivalent shear modulus of each improvement area is selected as follows:

$$G_{eq}\ (35\%\text{-}63cm)=G_{eq}(35\%\text{-}31.5cm)=4.4KN/m^2$$
$$G_{eq}\ (25\%\text{-}63cm)=G_{eq}(25\%\text{-}31.5cm)=3.2KN/m^2$$

This idealization method is examined against experimental observations. Since the numerical calculation gives the ultimate displacement of slope, the experimental results of 300Gal shake which are supposed to achieve the ultimate displacement are studied. Moreover, since current solution focuses on displacement of sand outside the improved area, the lateral displacement of sand inside the improvement zone is not included in comparisons.

Figure 18 compares calculation with the results observed in experiment with improvement zone of 63cm and 25% improvement ratio and irregular pattern of improvement. The results of numerical calculation is in reasonable agreement with the experiment. However, numerical analysis is predicting less displacement in the upstream section and slightly greater displacement in the downstream part. This inconsistency can be due to the fact that calculations assume no sand flow through the improvement zone. This probably leads to underestimation of displacement of sand.

Figure 19 compares results from test 5 with numerical analysis. In this experiment that had improvement ratio equal to 35% and 63cm length of improvement, the upstream zone behavior of sand shows quite good agreement between reality and prediction. However, in the downstream part, relatively big difference observed between experiment results and numerical calculations. In this case improvement ratio was increased comparing with previous calculation. Therefore, it is reasonable to expect lower amount of liquefied sand pass through the improvement zone, and consequently better agreement in the upstream section is seen. However, in the downstream part, although good agreement can be seen immediately after the improvement zone, in the middle part of downstream, because of some unknown reasons prediction is showing greater displacements than reality.

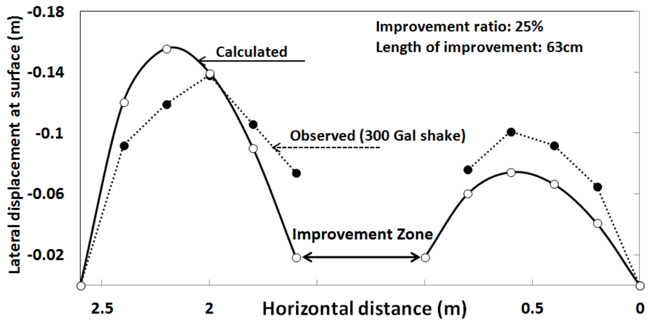


Fig.18. Lateral displacement at surface, Calculated vs. Observed-test 3

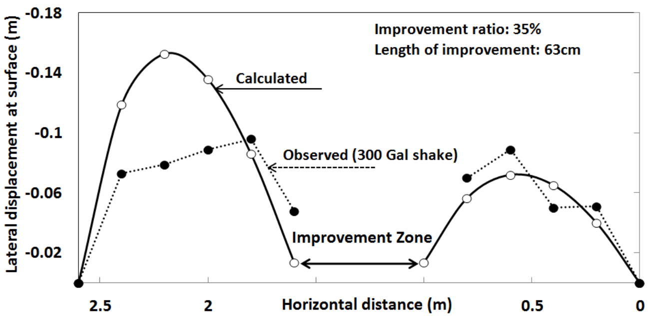


Fig.19. Lateral displacement at surface, Calculated vs. Observed-test 5

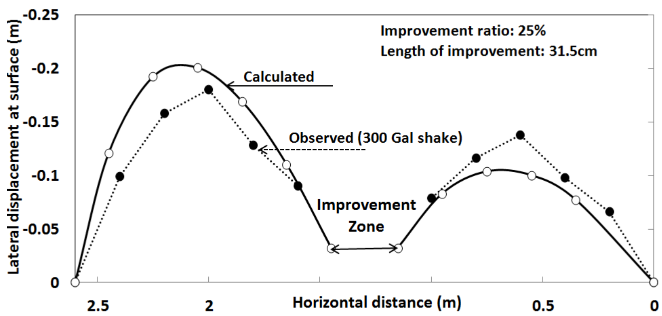


Fig.20. Lateral displacement at surface, Calculated vs. Observed-test 6

Figure 20 shows comparison between the results of test 6 and its representing numerical analysis. The calculation predicted the behavior of sand in an acceptably good manner. Again it is seen that displacement in the upstream is slightly more than prediction, and on the other hand displacement of downstream is slightly less than prediction. This observation is same and consistent with the other two previous predictions, and regards to relatively high volume of flow of liquefied sand into improvement zone in upstream and less volume of flow from improvement zone into the downstream part.

Numerical calculation and experimental results of test number 7 is shown in Fig.21. Same observations as previous comparisons are predominant. The experimental and numerical results are reasonably close to each other. However, the calculated displacement in the upstream region is less than reality while that in the downstream part is greater than reality probably because the described modeling is not good enough.

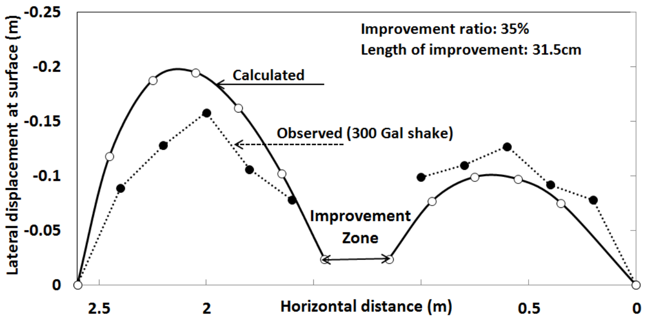


Fig.21. Lateral displacement at surface, Calculated vs. Observed-test 7

SUMMARY AND CONCLUSION

Several 1-g shaking table experiments were conducted to study a number of important factors that can affect behavior and efficiency of columnar soil deep mixing that mitigates the lateral flow of liquefied slopes. The main conclusions of this study are as follows:

1- It was observed that change of column configuration decreases the magnitude of lateral flow reasonably, especially inside the improvement zone and the downstream part of slope. However, the improvement ratio was not high enough, liquefied soil could find some routes to flow through the improvement zone and consequently efficiency of mitigation was decreased. Moreover, change in pattern of columns could decrease excess pore water pressure inside the improvement area.

2- Increase in improvement ratio reduces the lateral displacement. However, it is found that improvement ratio does not have considerable effect on excess pore water pressure inside improvement zone.

3- Length of improvement also found to be effective on magnitude of lateral flow. Increase in length of improvement also reduced lateral displacement of liquefied sand. Moreover, it reduces excess pore water pressure inside the improvement zone.

4- The experiments were modeled by a numerical method. For that purpose, the columnar deep mixing zone was idealized as a shear beam. By some simplifying assumptions, the model could predict the experiments reasonably.

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