# Numerical Simulation of Liquefaction mitigation by using grout under existing building

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**Abstract.** Ground improvement using Jet grout columns is a well-known technique to mitigate liquefaction hazard in sand stratum under existing building. However, the performance of conventional jet grout reinforcement technique has not achieved the sufficient level yet in terms of reducing shear strains and excess pore water pressure generated within the liquefiable soil layer. Therefore, a new countermeasure method, using small diameter jet grout column with additional horizontal slab, is introduced to control the shear deformation and excess pore pressure more effectively. To determine the efficiency of the new countermeasure method, numerical studies on unimproved and improved ground were separately performed in this study. The effectiveness of jet grout column with horizontal slab was evaluated by comparing the changes in excess pore water pressure, acceleration as well as distribution of shear stress and shear strain in the liquefiable soil before and after improvement. The results showed that the new liquefaction mitigation method offers positive effect on control of excess pore water pressure and shear deformation.

**Keywords:** Liquefaction Prevention, Ground Improvement, Jet Grouting, Numerical Simulation

## 1 Introduction

After two devastating earthquakes occurring in 1964: Alaska and Niigata earthquakes, liquefaction has become a well-known disaster induced by earthquake due to its destructive effects to infrastructures and human lives. From that time, the negative effects of liquefaction are frequently encountered around the world. As liquefaction is one of the major problems that causes settlement, lateral spreading as well as lateral displacement in liquefiable soil during earthquakes, researches and efforts are emphasized on the necessity of soil remediation against liquefaction.

The mechanisms to improve liquefiable soil resistance against liquefaction are basically done by densifying the surrounding soil, reducing the generation of excess pore water pressure, decreasing the shear stress and shear strain. Several ground improvement techniques based on aforementioned mechanisms, such as gravel drain method, sand compaction pile method, deep mixing method and jet grouting method, have been developed for liquefaction mitigation. However, most of the commonly available ground improvement methods require the proposed area to be free from structures. And, methods that can be used under existing buildings are less readily available. Although permeation grouting and chemical grouting methods have been used at existing housing projects, they are not suitable to use in finer-grained soils due to the difficulty of the low hydraulic conductivity, as well as the high cost of this technology. In such case, shear reinforcement method, jet grouting is considered to be effective by reducing shear stress and shear strain in improved ground under existing structure (Baez, 1995).

In Japan, the grid type deep mixing method was developed for liquefaction mitigation since in 1990s, where the grid of stabilized column walls function has been used to restrict generation of excess pore pressure by confining the soil particle movement during earthquake, as shown in Fig.1.The effect of this improvement method was first evaluated in the Hyogoken-Nanbu earthquake in 1995. Subsequently, many numerical analyses, physical model tests and field tests have been conducted to investigate the behavior of the grid type, interaction between the improved ground and the surrounding ground and performance of ground improvement (e.g. Kitazume, 2009). According to good results from numerical analyses and filed tests, the grid form liquefaction mitigation technique has been frequently used in construction sites. As an example, this method was adopted to mitigate soil liquefaction damage in the land reclamation area, Urayasu, where residential houses were suffered severe damage due to liquefaction during the 2011 Tohoku earthquake. Past experiences show that liquefaction remediation using cement deep mixing grid-form reinforcement method can reduce liquefaction risk. Nevertheless, it is still unable to eliminate the risk completely because of its conventional design method. Moreover, jet grouting machines are very tremendous and difficult to deploy in city area.

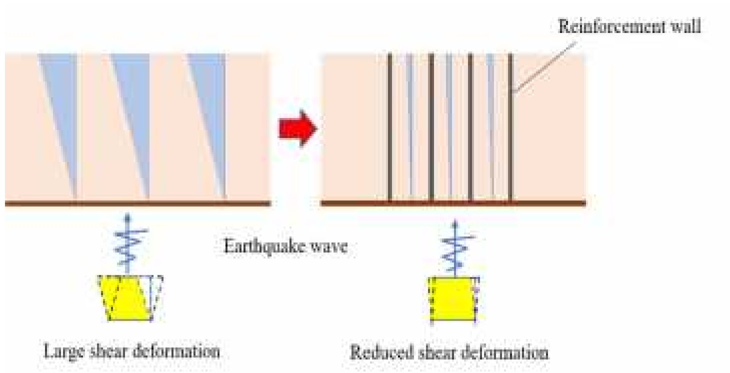


**Fig. 1.** Liquefaction mitigation mechanism of grid form wall

To overcome these problems, a new countermeasure method, using small diameter jet grout columns enhanced with the additional horizontal slab, is introduced. This method is instructive compared to the conventional approach because it uses closely-spaced jet grout wall (L/H= 0.2) to defend against liquefaction. In addition, the entire liquefaction prone layer is improved by confining with contiguous jet grout columns in both vertical and horizontal directions to restrain the shear deformation of structure during an earthquake. Based on the previous researches together with observations and experiences in the fields, it is observed that the increase in the improvement area ratio is particularly effective in increasing the potential of the improved ground for liquefaction mitigation (Namikawa et al., 2007). Furthermore, the outcomes of the results performed by research group of the Port and Airport Research Institute, indicated that the pore water pressure generation and seismic response of shear stress and shear strain distribution in a sand layer are highly influenced by grid spacing (Takahashi et al., 2006). This paper presents the findings of the effectiveness of closely-spaced jet grout wall with horizontal slab in reduction of liquefaction risk based on PLAXIS 2D numerical analyses, by comparing the changes in excess pore water pressure, acceleration as well as distribution of shear stress and shear strain in the liquefiable soil before and after improvement.

## 2 Numerical Modelling

In this study, numerical simulations, using PLAXIS two-dimensional software, were performed to measure the effect of jet grouting in liquefaction mitigation. In order to gauge the behavior and performance of high modulus Jet grout columns in liquefiable soil, numerical cases with and without soil improvement, were separately evaluated.

### 2.1 Geometry model and boundary conditions

As for soil profile used in numerical model, an idealized three layers of soil column was utilized. The water table was assumed to be coincident with the ground level. The effectiveness of ground improvement was measured at the 10-m-thick sand layer with $D_r$ = 50 %, which is overlying 25 m of clay. The underlain layer was assumed to be a bedrock where the earthquake data of the Loma Prieta earthquake (1989) was imposed with the maximum peak ground acceleration of 0.3 g. The aforementioned earthquake data was recorded at the outcrop of a rock formation and characterized by a magnitude Mw of 6.9. The history of acceleration time was depicted in Fig.2.

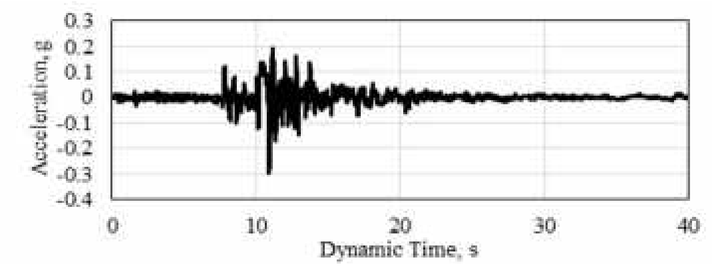

**Fig. 2.** Seismic Input motion applied in the Analyses

In this numerical analyses, 15 nodes triangular plain-strain elements were used to create a mesh distribution. Fine mesh option was used in the numerical analyses to meet the minimum required finite element length as suggested by Kuhlemyer and Lysmer (1973). The horizontal dimension of the soil profile was chosen to be large enough to minimize the boundary condition effect. Default fixities were applied for the static stages. In the dynamic phase, the vertical boundaries were modelled with tied-degree of freedom while compliance based was selected at the base as suggested in the site response and liquefaction evaluation by Brinkgreve (2015). To define the Rayleigh damping coefficients, damping ratios and related frequencies were considered based on the proposed method by Hudson et.al, 1994.

## 2.2 Parameters and constitutive models

In this study, an effective stress model of UBC3D-PLM was used to measure the development of excess pore water pressure and capture the onset of liquefaction in loose sand under dynamic loading. The liquefaction model, UBC3D-PLM, is a 3D generalized extension of the UBCSAND model and it was developed by Tsegaye (2010) and Petalas and Galavi (2012). In the model, the primary and secondary yield surfaces are utilized to account for the effect of soil densification and predict the smooth transition into the liquefaction state under undrained loading. Additionally, a soil densification rule, $f_{dens}$ , is implemented to better predict the evolution of pore pressures during cyclic loading.

Even though UBC3D-PLM is an advanced model, it is relatively simple to apply due to its reasonable number of parameters that can be extracted from laboratory or in situ tests. The input liquefaction parameters are derived based on the corrected clean sand equivalent SPT blow-count number $(N_1)_{60}$. However, the selection and calibration of parameters play a significant role to obtain reliable results. Hence, the calibrations for the parameters used in UBC3D-PLM model were conducted prior to the analysis. As depicted in Figure 3, the liquefaction parameters were calibrated by fitting with cyclic stress ratio curve reproduced by means of cyclic direct simple shear test implemented in soil test facility of PLAXIS 2D and the experimental data of cyclic loading test on Toyoura sand, DR=50% as published by Toki et al., (1985). The results show that the PLAXIS UBC3D-PLM model can give a good agreement with the experimental results and prove the liquefied state of the soil. The properties of soil parameters and numerical models for each soil layer are shown in Table 1.

However, the UBC3D-PLM model is not advisable to use in static analysis since the parameters used in model are designated to evaluate liquefaction in loose soils and suitable only for dynamic calculation (Plaxis 2D Material Models Manual, 2018). Therefore, Hardening soil model was used in initial static phase to generate the stress state correctly for liquefiable soil prior to the dynamic phase. Furthermore, Hardening soil model was also applied in clay layer to simulate the behavior of the stress dependent stiffness and cyclic subjected to earthquake loading. The underlain bed rock was modelled as Linear Elastic model. The properties of soil parameters used in Hardening soil model and Linear Elastic model were tabulated in Table 2 and 3.

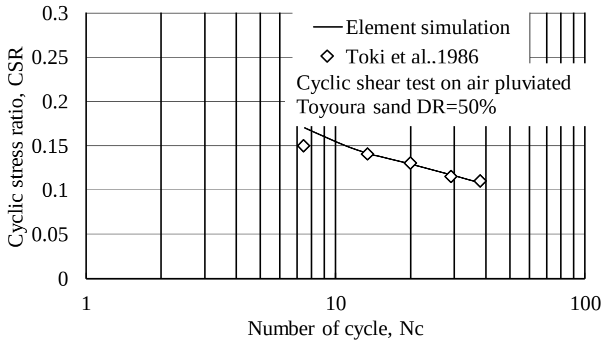


**Fig. 3.** CSR ratio obtained from numerical and experimental results

**Table 1.** Parameters of liquefiable soil used in the UBC3D- PLM model

| Parameter | Symbol | Value | Method/Formula |
|---|---|---|---|
| Peak friction angle | [illegible] | 35° | CD Test |
| Constant volume friction angle | [illegible] | 33° | CD Test |
| Elastic shear modulus number | [illegible] | 967.67 | $21.7 \times 20 \times (N_1)_{60}^{0.333}$ |
| Elastic bulk modulus number | [illegible] | 677.37 | $0.7 \times k_G^e$ |
| Plastic shear modulus number | [illegible] | 458.40 | $k_G^e \times (N_1)_{60}^2 \times 0.003 + 100$ |
| Elastic shear modulus index | [illegible] | 0.5 | default |
| Elastic bulk modulus index | [illegible] | 0.5 | default |
| Plastic shear modulus index | [illegible] | 0.4 | default |
| Failure ratio | [illegible] | 0.77 | $1.1 \times (N_1)_{60}^{-0.15}$ |
| Densification factor | [illegible] | 0.45 | Curve fitting |
| Post liquefaction factor | [illegible] | 0.02 | Curve fitting |
| Corrected standard penetration test | [illegible] | 11.1 | $DR^2/15^2$ |

**Table 2.** Parameters used in Hardening soil model

| Parameter | Symbol | (Unit) | Clay | Sand |
|---|---|---|---|---|
| Unit weight | $\gamma_{sat}$ | (kN/m$^3$) | 18 | 20 |
| Effective cohesion | [illegible] | (kN/m$^2$) | 13 | 0 |
| Effective friction angle | [illegible] | (°) | 22 | 35 |
| Dilatancy angle | $\Psi$ | (°) | - | 1 |

| | | | | |
|---|---|---|---|---|
| Secant Modulus | [illegible] | (kN/m$^2$) | 5436 | 20,380 |
| Tangent stiffness for primary oedometer loading | [illegible] | (kN/m$^2$) | 5436 | 20,380 |
| Unloading/ reloading stiffness | [illegible] | (kN/m$^2$) | 16,310 | 61,130 |
| Power of stress-level decency | m | | 0.8 | 0.5 |

**Table 1.** Parameters of bedrock used in Linear Elastic model

| Parameter | Symbol | (Unit) | Values |
|---|---|---|---|
| Unit weight | $\gamma_{sat}$ | (kN/m$^3$) | 22 |
| Young's modulus | E | (MN/m$^2$) | 6,000 |
| Poisson's ratio | $\upsilon$ | | 0.2 |

On the other hand, the 0.6 m diameter of jet grout columns (10 m long) with closely grid spacing (L/H = 0.2) were installed for improved ground case. Moreover, 1 m thickness of horizontal slabs were added at every 1 m interval as shown in Fig.4. The loose sand layer was improved in both vertical and horizontal directions to restrain the shear deformation during the earthquake. Mohr-Coulomb model was applied in jet grout columns modelling. Elasticity modulus, Poisson's ratio and Undrained shear strength of the columns were selected as 1000 MPa, 0.2 and 1 MPa, respectively.

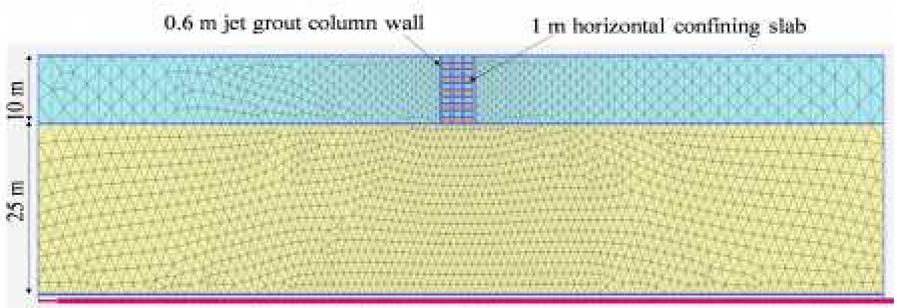


**Fig. 4.** Finite element model of the improved case

# 3 Result and discussion

The aim of the study is to evaluate the effect of liquefaction mitigation by using closely spaced jet grout columns with the horizontal slab in liquefiable ground. Thus, numerical cases of soil improvement with and without were separately measured. The analysis results were evaluated based on the effect of jet-grout columns on the distribution excess pore water pressure ratio, acceleration, shear stress and shear strain in the liquefiable soil layer.

### 3.1 Excess pore water pressure ratio

Excess pore water pressure ratio is an indicator of liquefaction occurrence, which can be calculated by means of the ratio of the excess pore water pressure and initial effective vertical stress at the depth. In the UBC3D – PLM model, the excess pore water pressure ratio was measured by vertical effective stress at the end of the dynamic calculation and initial effective vertical stress prior to the dynamic stage **(**Brinkgreve, 2015)**.** The corresponding layer can be determined as a complete liquefied layer when the excess pore water pressure ratio is 1. The comparison results of excess pore water pressure distribution with dynamic time at different depths for unimproved and improved cases were stated in Fig. 5. Based on the comparison results, it can be observed that, the proposed liquefaction countermeasure method is effective in excess pore water pressure control. Because the excess pore water pressure ratio in the improved ground case did not increased into 1.0 until the end of the seismic loading. On the other hand, Liquefaction occurred in the original unimproved case, where, excess pore water pressure ratio is increased into 1.0 after the dynamic time 13 s.

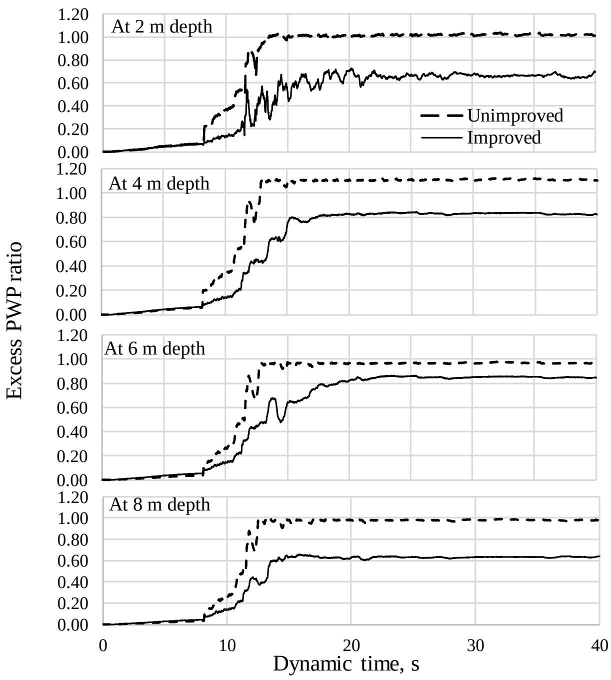


**Fig. 5.** Comparison result of PWP ratio measured from unimproved and improved cases

### 3.2 Acceleration

Acceleration time histories of the unimproved case and improved case at different depths were described in Fig.6. Some noticeable differences in the behavior were identified when the acceleration time histories of the unimproved and improved cases were compared. The peak accelerations recorded at the surface of improved case and unimproved case are 0.24 and 0.18 g, respectively. Besides, soil acceleration attenuation behaviors occurred in all acceleration time histories measured at different depths of the unimproved case. That is, the soil acceleration appeared to decrease upon the onset of liquefaction (around dynamic time at 13 s) due to the reduction of soil strength and stiffness, and increase in hysteretic damping. However, there was no trace of acceleration decreasing due to liquefaction encountered in improved case. In other words, the newly proposed liquefaction countermeasure method can control the soil stiffness reduction against seismic loading.

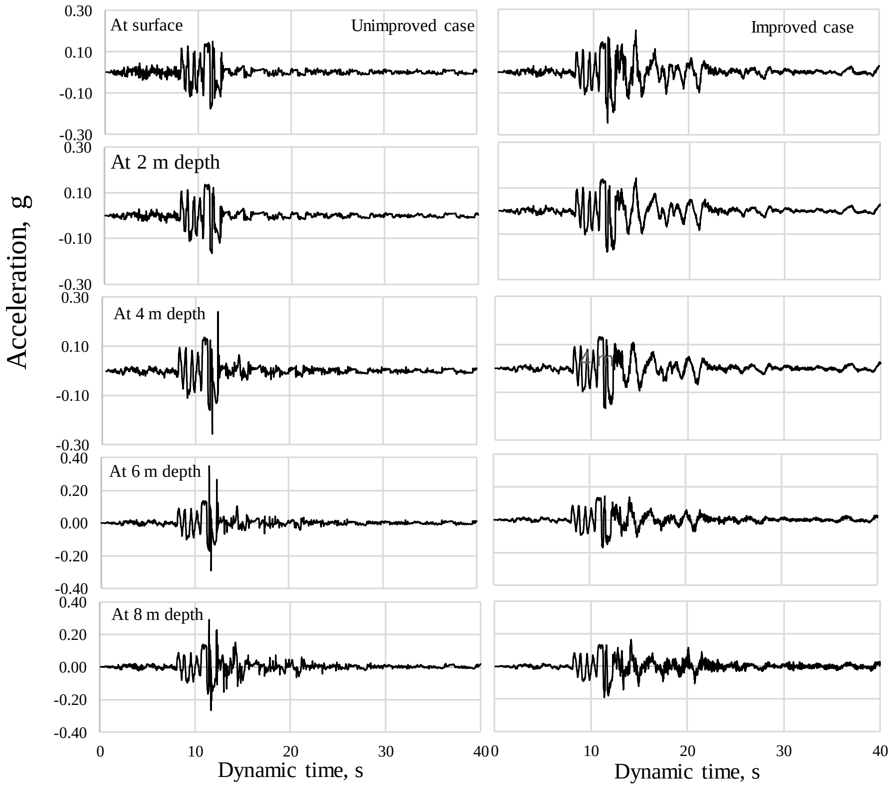


**Fig. 6.** Acceleration time histories measured from unimproved and improved cases

### 3.3 Shear stress and shear strain distribution

In order to investigate the improvement effect of the proposed liquefaction countermeasure method, the response of shear stress and shear strain of the liquefiable soil inside the grid form were evaluated. Fig.7 shows the results of shear stress distributed in unimproved and improved cases. Like in acceleration time histories, a similar characteristic of liquefaction identification was observed in unimproved case.

Significant stress degradation has occurred upon the onset of liquefaction at dynamic time 13 s and then vanish until the earthquake ends. Nevertheless, the aforementioned stress degradation due to liquefaction was not observed in the improved case.
Fig.8 depicts the comparison results of the shear strain variations with depth after the earthquake measured from unimproved and improved cases. As seen from figure, the shear strains tend to increase linearly with depth from the ground surface in both unimproved and improved cases. However, the range of shear strain distribution from the ground surface to the depth is wide as approximately 0.01 % to 3.5 % in the unimproved case. In contrast, the slightly distribution of shear strain along the entire depth was observed in improved case. It can be determined that the loose soil layer was effectively controlled from shear deformation during the earthquake as the vertical and horizontal reinforcement. Moreover, the effect of liquefaction mitigation due to soil improvement method, the comparison results of the relationships of shear stress & shear strain and shear stress & vertical effective stress relationships at different depths were described in Fig.9. Significant reduction of shear stress was not observed compared to the shear strain. Fig. 9 (b) shows the vertical effective stress at measured depth is gradually reducing to zero as per increasing of excess pore water with dynamic time in unimproved case. However, the behavior of vertical effective stress reductions was not found since excess pore water was effectively controlled by the improved method. Generally, it can be said that excess pore water pressure and shear strain in the liquefiable soil was effectively restricted by jet grout columns with horizontal slab soil improvement method.

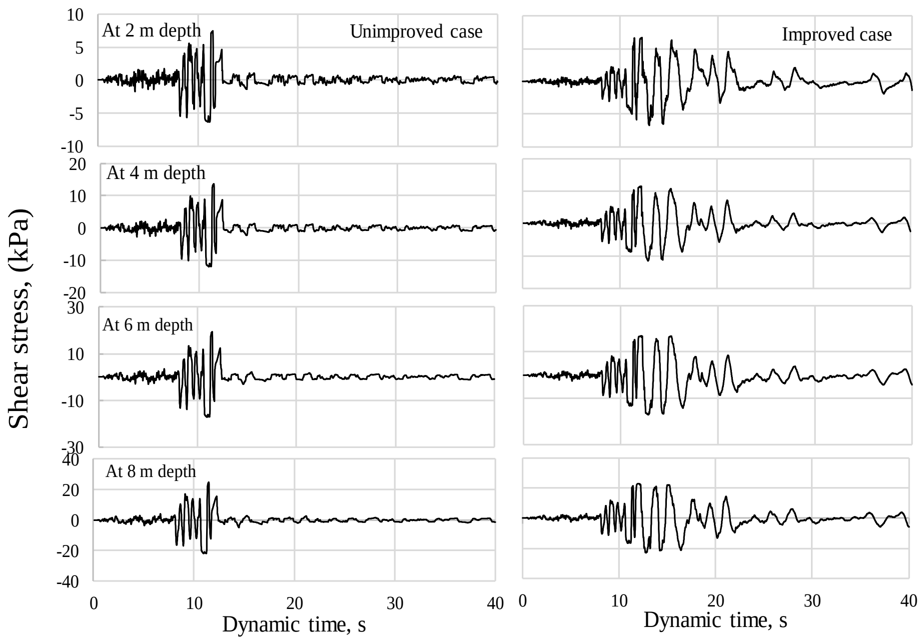

**Fig. 7.** Distribution of Shear stress in unimproved and improved cases

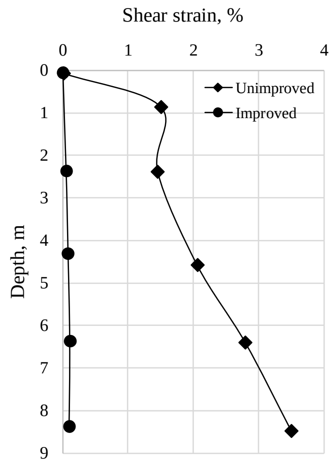


**Fig. 8.** Distribution of shear strain in unimproved and improved cases with depth

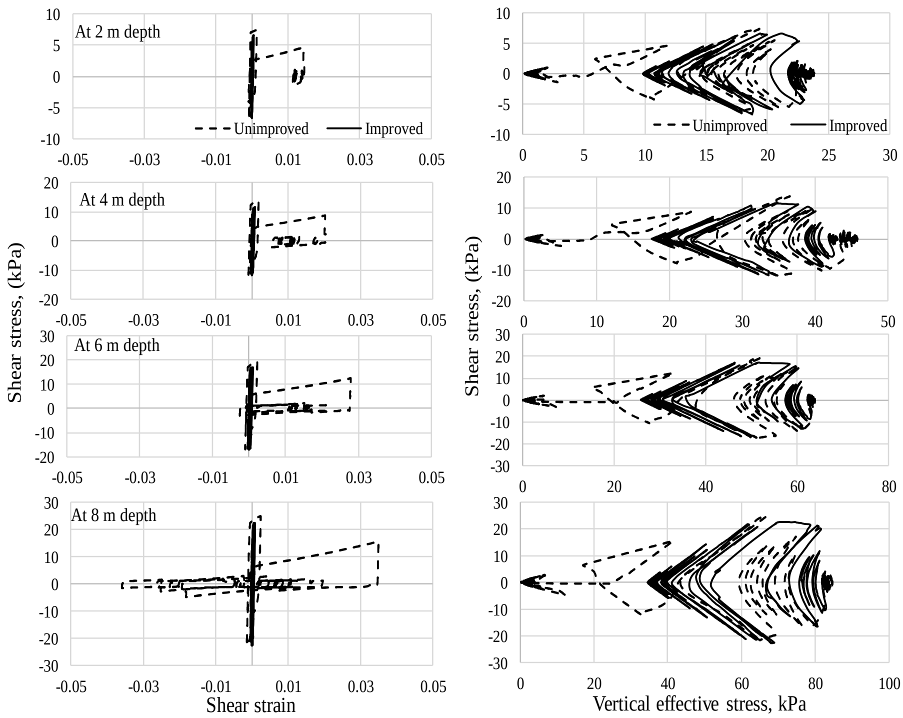

**Fig. 9.** Variation of shear stress and strain in unimproved and improved soil (a) shear stress and shear strain relationship (b) shear stress and vertical effective stress relationship

## 4 Conclusion

Numerical simulations for unimproved and improved ground conditions were conducted to assess the effectiveness of the liquefaction mitigation. As an initial assessment for liquefaction prevention, the study on the effectiveness of the close spacing of jet grout contiguous columns with horizontal confining method was performed. The following findings were deduced based on the comparison results of unimproved and improved cases.

1. Liquefaction did not take place in the improved case since the excess pore water pressure ratio did not reach to 1.0. On the other hand, Liquefaction was found to occur in original unimproved case, where, excess pore water pressure ratio is increased to 1.0 after the dynamic time 13 s.
2. Regarding the soil acceleration, acceleration attenuation due to soil strength and stiffness reduction did not occur in the improved case, while significant decrease in acceleration was observed upon the onset of liquefaction in unimproved case.
3. Based on the shear stress distribution, the characteristics of shear stress degradation was not observed in improved ground case, whereas the occurrence of significant stress reduction took place in the unimproved case.
4. Shear strain variations with depth were observed in both unimproved and improved cases. However, the range of shear strain distribution from the ground surface to the depth of interest is obviously larger in unimproved case compared to improved case. Thus, the close spacing of jet grout contiguous columns with horizontal slab can effectively control the shear deformation of improved ground layer during the earthquake.
5. If vertical effective stress is concerned, the effect of liquefaction mitigation can be clearly seen in improved ground case. Because, the vertical effective stress at measured depth was gradually reducing to zero as the excess pore water pressure increasing with dynamic time in unimproved case. Nonetheless, this behavior did not exhibit in improved case since the excess pore water pressure was effectively controlled by the jet grout column with horizontal slab liquefaction mitigation method.

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