EFFECTIVENESS OF STONE COLUMNS AS COUNTERMEASURE FOR LIQUEFIABLE SANDY SOIL STRATUM WITH SILT INTRALAYERS

Roland Martin Simatupang*[1], Huei-Tsyr Chen[2], Chung-Jung Lee[2]

[1)]Department of Civil Engineering, Universitas Brawijaya
Jl. MT. Haryono 167 Malang, Indonesia;
[2)]Department of Civil Engineering, National Central University
Jhongda Rd. 300 Jhongli City Taoyuan County Taiwan

ABSTRAK

Numerical simulation was used to investigate effectiveness of stone column as countermeasure for liquefiable sandy soil stratum with silt intralayers. One finite element model of sand and two models for silt cases were subjected to two different stone column areas. The use of stone columns can delay and reduce the accumulation of excessive pore water pressure; although in some cases liquefaction still cannot be avoided. Stone column increases the stiffness of the sand area and able to reduces the ground settlement; however this benefit decreases as the more silt intralayers exist in the stratum.

Keywords: sandy stratum, silt, liquefaction, stone columns, finite element analysis

1. INTRODUCTION

Soil liquefaction can result in serious damage to the ground and the building such as sand boiling, lateral spreading, excessive settlement, tilting and overturning of structures. For a long time, many liquefaction-related studies mainly treated the ground as sandy ground; however, in reality there may be layers of silt or clay embedded in the sandy ground. In some earthquakes the failure of ground did not occur during the earthquake but after the earthquake stopped. The investigations on such a phenomenon showed that it may be due to the existence of a silt layer in the sandy ground where a water film develops at the bottom of the silt layer with high pore water pressure (Kokusho, 1999). This indicates that the sandy soil stratum with silt intralayers may become unstable even after the main shake, causing the sliding of slope.

Over the last years many countermeasures have been proposed to reduce the risk of liquefaction. Chen and Chen (2005) used effective-stress based nonlinear three-dimensional finite element method to investigate the efficiency of diaphragm wall as a countermeasure for liquefaction. It found the use of diaphragm wall will delay the build-up of excessive pore water pressure, but may not prevent a liquefiable soil stratum from liquefaction; however, the settlement is significantly reduced. On the other hand, the introduction of stone columns in the soil stratum have several benefits such as densification effect of surrounding non-cohesive soil because of the volume improvement due to general increase of permeability of the stratum, dissipation of excess pore water pressure and redistribution of earthquake-induced or pre-existing stress due to existences of the stiffer columns (Adalier et al. 2003). The purpose of this study is to gain a better understanding of the mechanism of stone columns as a countermeasure in a liquefiable sand-silt stratum.

2. METHOD OF ANALYSIS

For the numerical simulation the three-dimensional nonlinear effective stress finite element method was adopted (Jou, 2000). This method is developed on the basis of Biot theory for porous media. The nonlinear soil behavior was modeled using the Cap model with Mohr-Coulomb type failure line and the pore pressure model consistent with the Cap model was adopted (Pacheco,1989). The lateral boundaries can be modeled as either roller-type boundaries or absorbing boundaries, while the bottom bedrock is always fixed.

This method adopts the U-W form of equation of motion (Zienkiewicz and Shiomi, 1984) as follows:

$$\begin{bmatrix} m_{uu} & m_{uw} \\ m_{uw}^T & m_{ww} \end{bmatrix}\begin{Bmatrix} \ddot{\bar{u}} \\ \ddot{\bar{w}} \end{Bmatrix} + \begin{bmatrix} c_{uu} & c_{uw} \\ c_{uw} & c_{ww} \end{bmatrix}\begin{Bmatrix} \dot{\bar{u}} \\ \dot{\bar{w}} \end{Bmatrix} + \begin{bmatrix} k_{uu} & k_{uw} \\ k_{uw}^T & k_{ww} \end{bmatrix}\begin{Bmatrix} \bar{u} \\ \bar{w} \end{Bmatrix} = -\begin{bmatrix} m_{uu} & m_{uw} \\ m_{uw}^T & m_{ww} \end{bmatrix}\{J\}\ddot{\phi} \quad .(1)$$

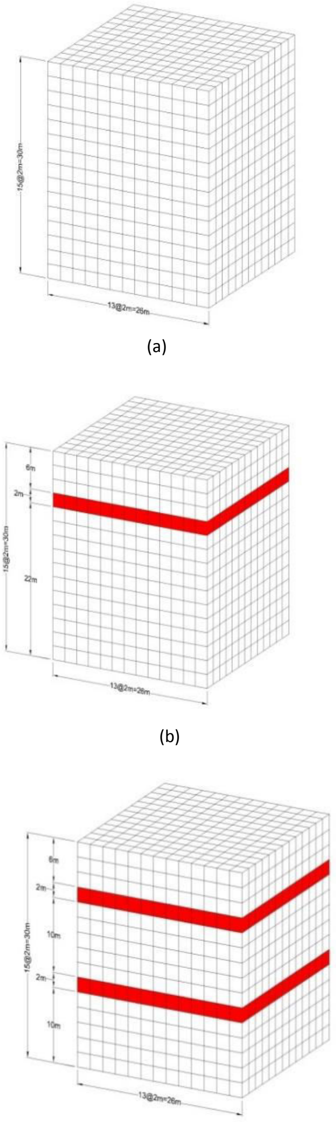
where $\bar{u}$ is the displacement of soil particle and $\bar{w}$ is the displacement of water relative to soil particle. The vector {J} is made up of 1's and 0's to account for the desired of input motion. $\ddot{\phi}$ is the input motion specified at the bedrock of soil stratum.

2.1 MODEL DESCRIPTION

This study used three basic models denoted as Sand, Silt 1 and Silt 2 as shown in **Fig. 1**, with the same dimension of 26 m x 26 m x 30 m (length x width x depth). For each model, two models with stone columns were also constructed, denoted as Stone 1 (16 stone columns or 9.5% area of treatment) and Stone 2 (36 stone columns or 21,3% area of treatment). The stone columns have size of 2 m x 2 m extending from the surface to the bottom.

Fig. 2 shows the top view of the layout of the stone columns. For the sake of discussion, these models are denoted as Sand model, Sand-Stone 1 model, Sand-Stone 2 model, Silt 1 model, Silt 1-Stone 1 model, Silt 1-Stone 2 model, Silt 2 model, Silt 2-Stone 1 model and Silt 2-Stone 2 model. Detailed parametric values for all models can be seen in the thesis by Simatupang (2011).

A real earthquake motion recorded in 1999 ChiChi earthquake at Chiayi station (Chiayi input motion) was used for this 3D simulation study. Before the simulation, from the selected earthquake the maximum acceleration of all components was selected and normalized to 0.2g; thereafter, the same scaling factor was applied to the motions of the other two directions. These three scaled component of motions were then used as the input motions for the simulation.

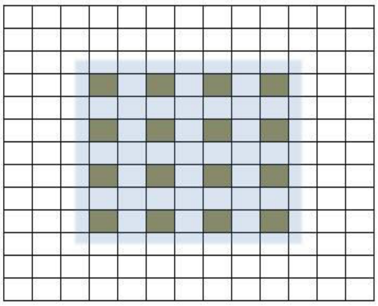


(a)

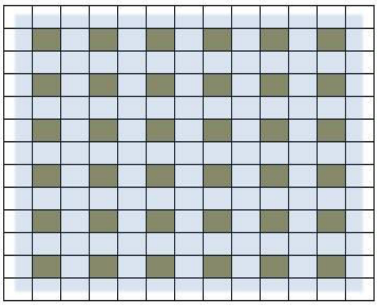
(b)

(c)

Fig. 1. Finite element models: (a) Sand model, (b) Silt 1 model, (c) Silt 2 model



(a)



(b)

Fig. 2. Layout of stone columns (top view): (a) Stone 1, (b) Stone 2

It should be mentioned that the validity of the proposed analysis was checked by comparing with the results of centrifugal test. The simulation results shows the same trend as the experimental results and the agreement is acceptable (Chen et al., 2011).

3. NUMERICAL RESULTS AND DISCUSSIONS

3.1 Excessive Pore Water Pressure

Fig. 3 depicts the variations of Excess Pore Water Pressure (EPWP) ratio at different depths for Sand model, Sand-Stone 1 model and Sand-Stone 2 model subjected to Chiayi input motions. Despite the use of stone columns, the soil from the surface to the depth of 9 m still liquefies; however, the duration of soil in the liquefaction state is shorter as compared with that of Sand model. For the liquefied layers, the EPWP ratio gradually increases to reach a value of 1 within 10 seconds for Sand model, while the EPWP ratio remains small in the first 10 seconds, and suddenly increases to reach the value of 1 which occurs later than that of Sand model for the cases with stone columns. Fig. 4 depicts the profile of EPWP at different time for all cases of Sand model. It can be seen that the use of stone columns is to delay the build-up of EPWP; however the increase in the area of replacement does not help reduce the EPWP ratios. In addition, the reduction in EPWP ratio is more pronounced as the depth increases.

Fig. 5 depicts the variation of EPWP ratio at different depths for the cases of Silt 1 model. At the depth of 1 m and 5 m, the soil of Silt 1 model liquefies, while this is not the case for Silt 1-Stone 1 and Silt 1-Stone 2 models. At the depth of 7 m which is inside the silt layer, all models are liquefied; however the soil of Silt 1-Stone 2 model only liquefies for very short duration. At the depth of 9 m which is the location of water film, the use of stone columns does not reduce the EPWP rations significantly. **Fig. 6** shows the profile of EPWP at different time for all cases of Silt 1 model.

The variations of EPWP at different depths for the cases of Silt 2 model are presented in **Fig. 7**. Except for the depths of 7 m and 9 m, the use of column stones leads to the reduction in EPWP so that the soils at the depths of 1 m and 5 m, which liquefy in the Sand model and Silt 1 model, did not liquefy. Similar to Silt 1 model, all cases were also liquefied inside the silt layer (7 m); however unlike the previous models, in this case this layer has slightly higher EPWP ratio, as compared with Silt 2 model; yet the dissipation of EPWP is faster in the cases with stone columns at this depth. At the depth of 9 m, liquefaction still occurs for both models using stone columns for short duration.

Fig. 8 shows the profile of EPWP at different time for all cases of Silt 2 model. In addition, the use of stone columns changes the pattern of EPWP pile between the two silt layers and the drastic variations between the top and the bottom of silt layer, as observed in Silt 2 model, disappear.

The zigzag pattern appears for all cases with stone columns as the depth increases, where it is more pronounced in the Silt 2 than the other two models. This is probably due to the fact that the stone columns have much higher shear wave velocity and therefore the waves in soil surrounded by stone columns bounces back and forth. From the references reviewed, nor results at deeper locations have been presented; thus, such a phenomenon needs the experimental validation.

3.2 Surface Settlement

Depicted in Fig. 9 is the settlement for all cases of Sand model. The maximum settlement of Sand model is 85 cm. For Sand-Stone 1 model the maximum settlement reduces to 65 cm, with percentage of reduction being 23.5%. For Sand-Stone 2 model the maximum settlement reduces to 48 cm depth, with percentage of reduction being 43.5%. This shows that the stone columns work properly in reducing the settlement of the ground. From the discussions in previous section, the use of stone columns can delay the accumulation of EPWP and reduce the magnitude of EPWP not significantly; the reduction in the settlement may be due to the increase in rigidity of the stratum due to the replacement of liquefiable ground by stone columns. Thus, the use of large number of stone columns can effectively reduce the settlement of the ground.

Fig. 10 depicts the settlement for all cases of Silt 1 model. The maximum settlement of Silt 1 model is 55 cm which is smaller than that of Sand model. As described in previous section, this reduction in settlement is due to the existence of silt layer; this less permeable layer leads to the higher pore water pressure beneath it, known as water film, and the high pore water pressures push the layer above it to significantly reduce the surface settlement.

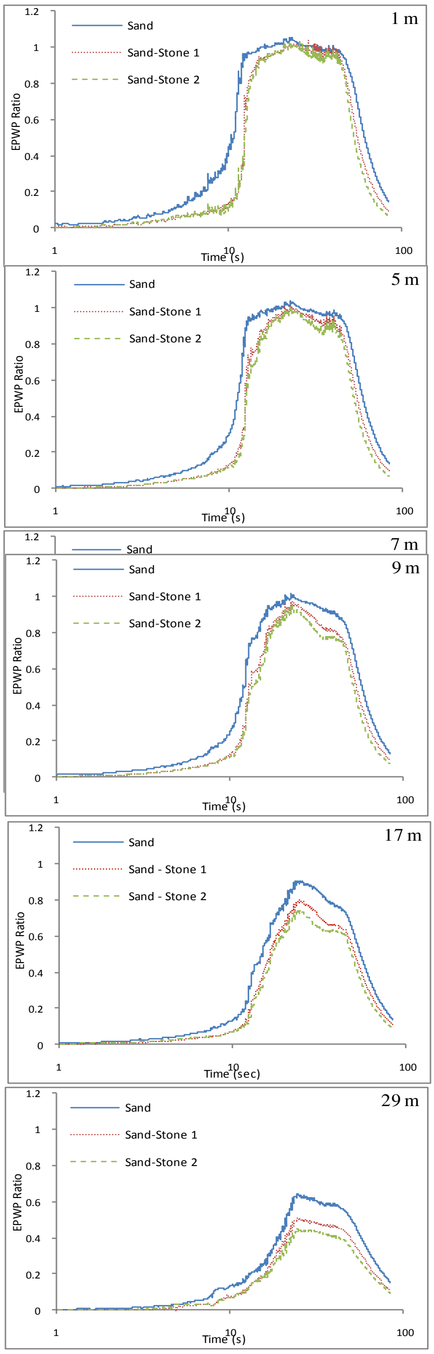


Fig. 3. Time history of EPWP ratios at different depths for Sand model with and without stone columns

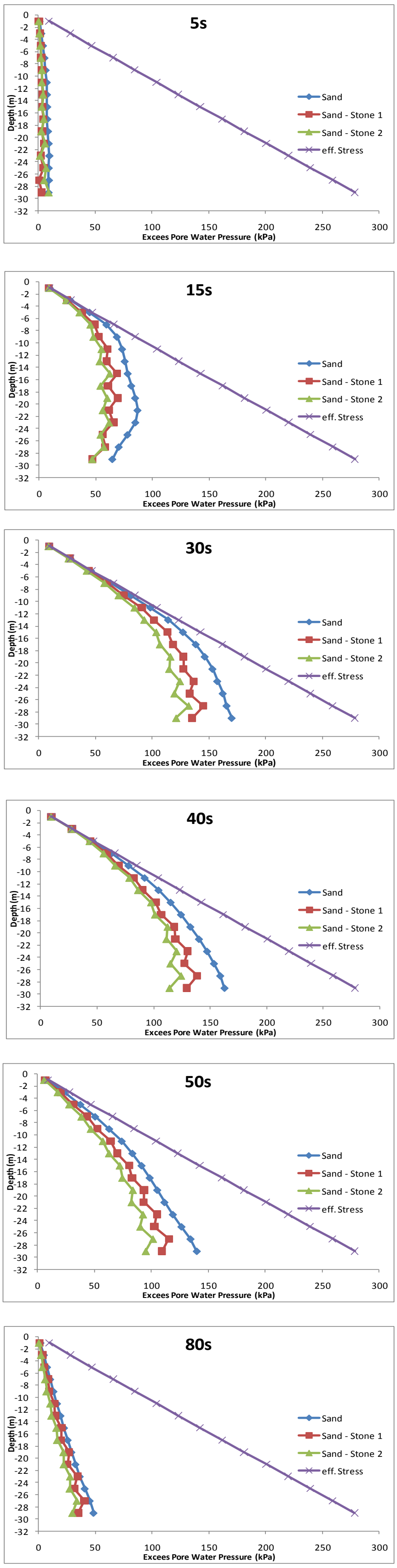


Fig. 4. EPWP profile at different time for Sand

model with and without stone columns

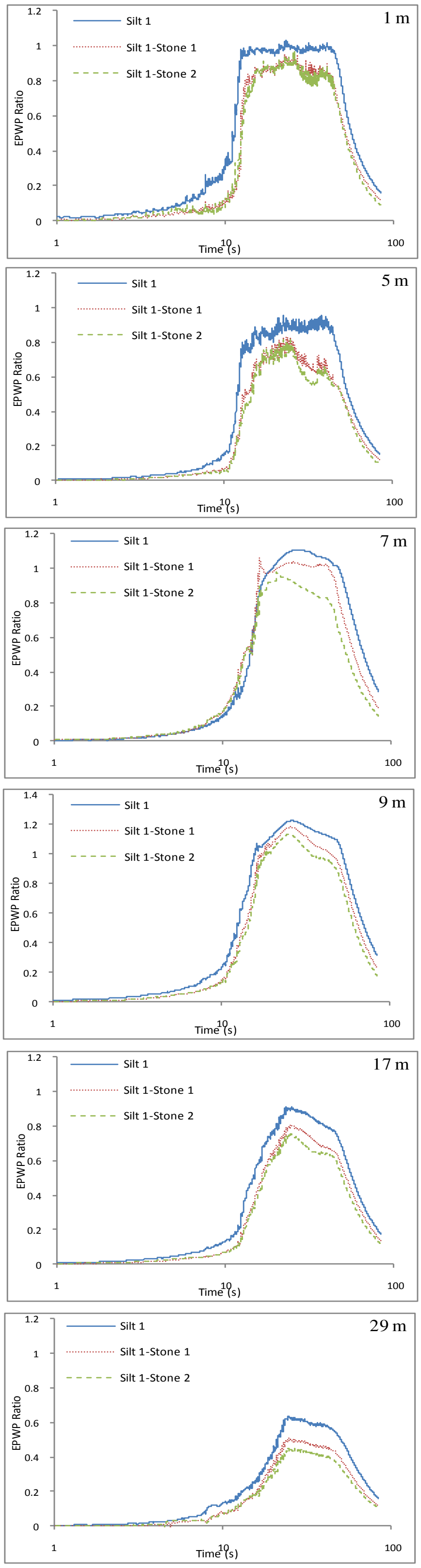


Fig. 5. Time history of EPWP ratios at different depths for Silt 1 model with and without stone columns

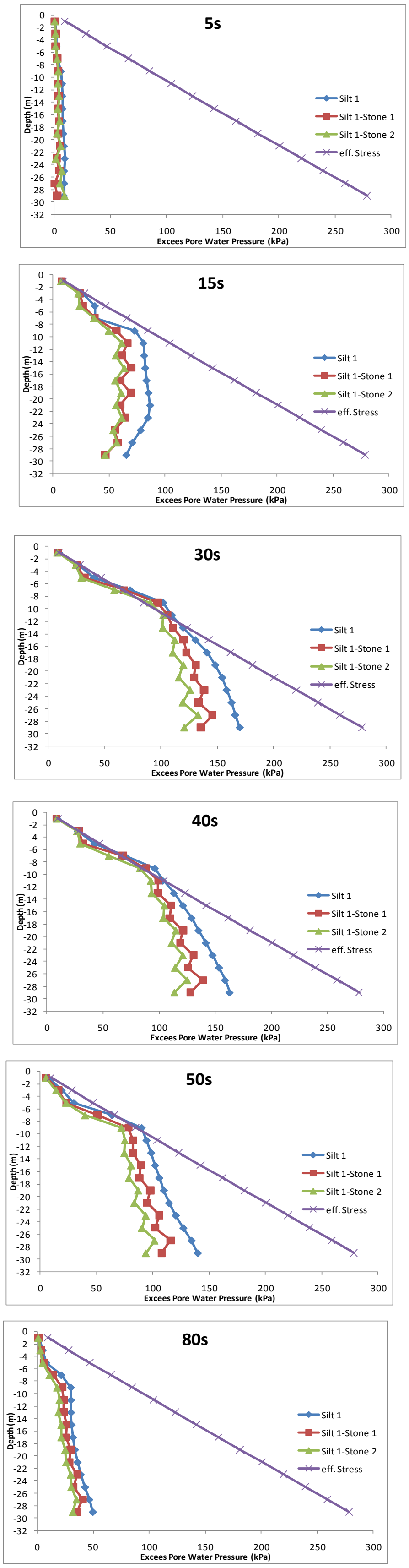


Fig. 6. EPWP profile at different time for Silt 1 model with and without stone columns

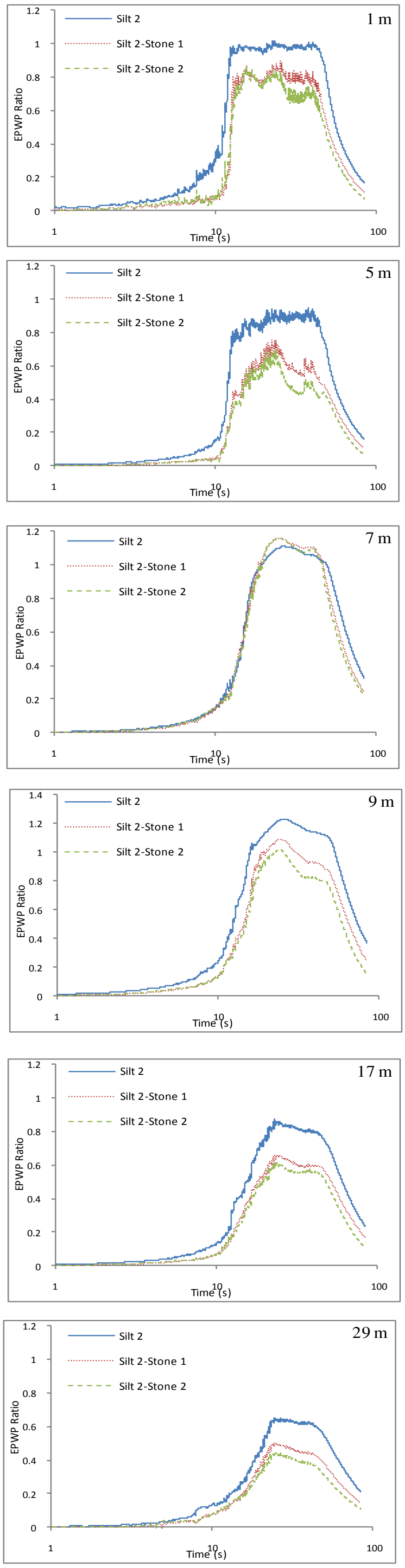
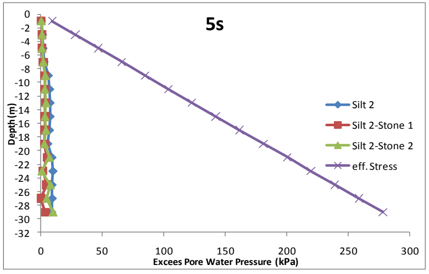
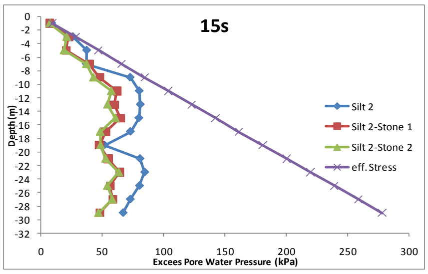
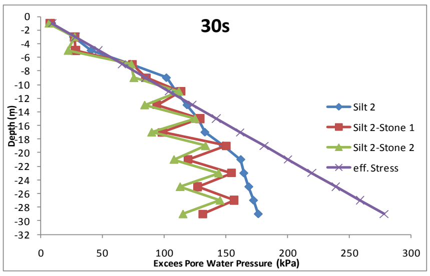
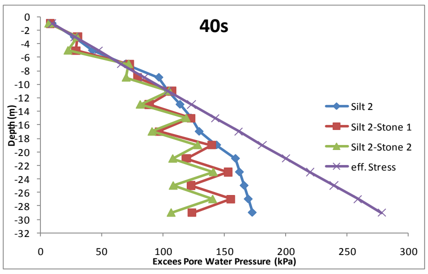


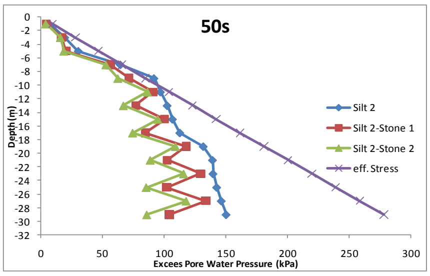
Fig. 7. Time history of EPWP ratios at different depths for Silt 2 model with and without stone columns











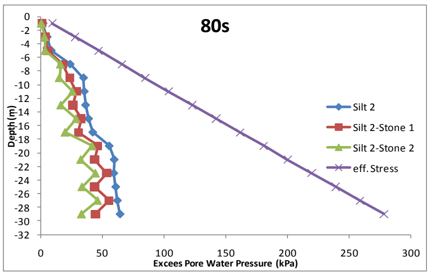


Fig. 8. EPWP profile at different time for Silt 2 model with and without stone columns

However the percentage or reduction decreases for Silt 1-Stone 1 model and Silt1-Stone2 model, which are 9.1% and 30.9%, respectively. Because of the existence of one silt layer, the use of stone columns in reducing the ground settlement is less effective, as compares with Sand model.

The settlement for all cases of Silt 2 model is depicted in **Fig. 11**. The maximum settlement of Silt 2 model is 37 cm which is smaller than that of Silt 1 model. The presence of second impermeable silt layer makes the settlement of general stratum become lower due to the high pore water pressures beneath the silt layers. Similar to the Silt 1 cases, the percentage of reduction also decreases for the Silt 2-Stone 1 model and Silt 2-Stone 2 model, which are 2.7% and 16.2%, respectively.

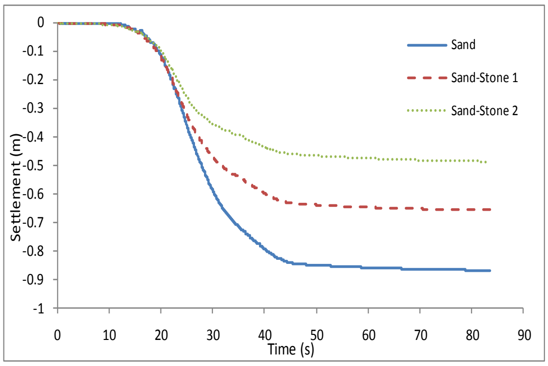


Fig. 9. Time history of Settlement for model with and without stone columns for Sand Model

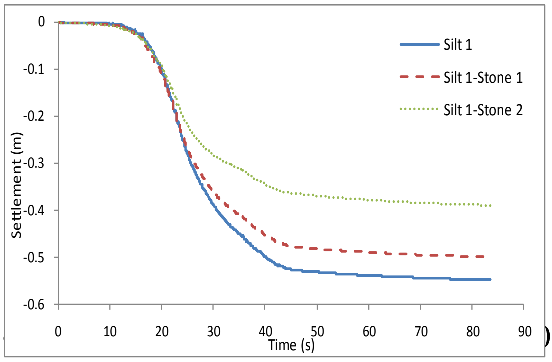


Fig. 10. Time history of Settlement for model with and without stone columns for Silt 1 model

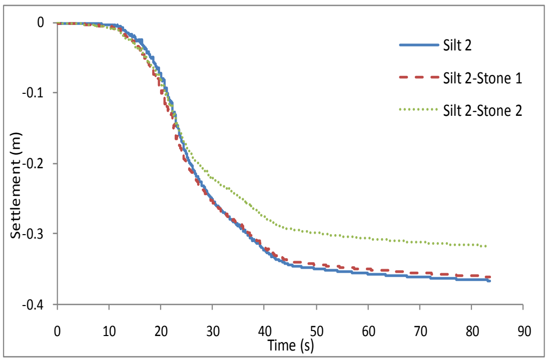


Fig. 11. Time history of Settlement for model with and without stone columns for Silt 2 model

4. CONCLUSIONS

Using stone columns as liquefaction countermeasure can delay the accumulation of excessive pore water pressure and reduce the excessive pore water pressure development. Although in some cases the use of stone columns cannot prevent the soil from liquefaction, the duration of state of liquefaction can be reduced. From this study, however, the use of replacement area of 21.3 % does not show much benefit over the use of replacement area of 9.5%, except for few cases. Furthermore, the stone columns can help reduce the EPWP build-up at the bottom of the silt layer where the stone columns also work as the drainage.

The existence of impermeable silt layers leads to the reduction in the surface settlement due to the high pore water pressures beneath the silt layers. The reduction in settlement by using stone columns is due to the fact that replacing the liquefiable soil by stone columns increases the rigidity of the ground; however, the use of stone columns for reducing the settlement is effective for Sand model and become less effective as the number of silt intralayers increases.

5. REFERENCES

Adalier, K., Elgamal A-W., Meneses J., Baez J.I. (2003), “Stone Columns as Liquefaction Countermeasure in Non-Plastic Silty Soils”, Soil Dynamics and Earthquake Engineering, Vol. 23, No. 7, pp. 571-584

Chen, H.T., Chen W.H. (2005), “Effectiveness of Diaphragm Wall in Reducing The Potential of Soil Liquefaction Induced by Earthquake”, Second International Conference on Urban Earthquake Engineering, Tokyo Institute of Technology, Tokyo, Japan

Chen, H.T., Simatupang R.M. B.C. Ridla and Lee, C.J. (2011), “Numerical Simulation of Liquefaction of Sandy Stratum with Silt Intralayers,” Proceedings of 2011 Taiwan-Japan Symposium on Advancement of Urban Earthquake Hazard Mitigation Technology, National Central University, Jhongli, pp. 1-6

Jou, J.J. (2000), “Seismic Responses Analysis of Pile Foundations of Bridges”, PhD. Thesis, Department of Civil Engineering, National Central University, Chungli, Taiwan (in Chinese)

Kokusho, T. (1999), “Water Film in Liquefied Sand and Its Effect on Lateral Spread”, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 125, No.10, pp. 817-826

Simatupang, R.M. (2011), ”A Numerical Investigation on Stone Columns as a Countermeasure for Liquefaction of Sandy Soil Stratum with Interlayers of Silt,” Master Thesis, Department of Civil Engineering, National Central University, Jhongli, Taiwan

Zienkiewicz, O.C. and Shiomi, T. (1984), “Dynamic behaviour of saturated porous media; the generalized Biot formulation and its numerical solution,” International Journal for Numerical Methods in Engineering, 8, pp.71–96