NUMERICAL STUDY OF EFFECTIVENESS OF JET-GROUT COLUMNS IN LIQUEAFACTION MITIGATION

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ABSTRACT

Liquefaction is one of the major problems in liquefiable soils during earthquakes. Following devastating effects of liquefaction, researches and efforts are focused on finding methods to mitigate liquefaction by soil improvement techniques. In this study, a series of numerical studies are carried out to investigate the effectiveness of jet grout columns in liquefaction mitigation. For this purpose, performance of a site in Turkey where the soils were improved with jet-grout columns were investigated through parametric analysis using an effective stress based model UBC3D-PLM introduced by Puebla et al. (1997), Beaty and Byrne (1998). In order to be able to show the effect of jet grout columns on the reduction of liquefaction risk, numerical analysis are performed for different ratios of stiffness for the jet grout columns and improved soil and different area ratios. The results of the numerical analysis are evaluated by going through the shear stress sharing mechanism that generate between jet-grout column and surrounding soil. The numerical analysis results showed that jet-grout columns play important role in reduction of shear stress generated during earthquake loading. The study also provided an insight into the parameters that influence the ratio of shear stress reduction factor and its practical values that is widely used for jet grout columns in design practice.

Introduction

As liquefaction is one of the major problems in liquefiable soils during earthquakes, researches and efforts are focused on finding methods to mitigate liquefaction by soil improvement techniques. Nowadays, stone columns, rammed aggregate piers and jet-grout columns are the improvement methods that are widely used to reduce liquefaction induced hazards in geotechnical engineering practice. The mechanisms that these improvement methods provide are basically densification of the surrounding soil during liquefaction, reducing the generation of excess pore water pressure and decrease the shear stress that the surrounding will be subjected during earthquake. The experiences gained from reported case histories and some limited centrifuge model tests showed that the high modulus columns resist higher seismic shear stresses than the existing soil and therefore reduce the adverse effects of liquefaction (Rayamajhi et al. (2012), Mitchell and Wentz (1991), Adalier et al.(2003), Martin et al. (2004)). Although, there is not sufficient experimental data from field and laboratory revealing that these mechanisms play role in the reduction of liquefaction potential, reliable numerical methods provide important and useful information in order to be able to understand the effectiveness of high modulus columns in liquefaction mitigation.

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In this study, a series of numerical studies are carried out to investigate the contribution of jet grout columns in liquefaction mitigation through a case history. For this purpose, liquefaction behaviour of a shopping center site where the soils were treated with jet-grout columns and subjected to the 1999 Kocaeli Earthquake were investigated through parametric analysis using an effective stress based model UBC3D-PLM (Puebla et al. (1997), Beaty and Byrne (1998)). In order to be able to show the effectiveness of jet grout columns on the reduction of liquefaction risk, numerical analysis are performed for different ratios of stiffness and area ratios. The results of the numerical analysis are evaluated by going through the shear stress sharing mechanism that generate between jet-grout column and surrounding soil. The effect of jet-grout columns on reduction of liquefaction potential is demonstrated by computing the ratio of shear stress reduction factor for different stiffness ratios and area ratios. The analysis results also provide an insight into the parameters that influence the ratio of shear stress reduction factor and its practical values that is widely used for jet grout columns in design practice.

Numerical Analysis of a Site Improved with Jet-Grout Columns

A shopping center site in Turkey where the soils were improved with jet-grout columns were subjected to the 1999 Kocaeli Earthquake (M_w=7.4). The soil profile where the shopping center was constructed on consists of soft, saturated alluvial sediments consisting of soft to medium clay, loose sands and silts. The ground water table at the site is located 2m below the ground surface. The site is located very close to the earthquake epicenter and the ruptured fault system. The site was subjected to peak ground accelerations of 0.24g during the earthquake. Due to the presence of soft and loose sediments, the site were improved using surcharge fills and wick drains, and jet-grout columns (Fig. 1). The main purpose of the soil improvement at the site was to increase the bearing capacity of the foundation systems and to reduce liquefaction potential of a silty sand layer that was 1–3 m thick across the site (Martin et al (2004)). Jet grouting was not completed when the earthquake struck. The observations carried out at the site following the earthquake showed that there was a considerable difference between the performance of improved and unimproved areas. The improved areas were observed to have undergone no damage, on the other hand, unimproved areas and the constructed buildings were observed to have suffered liquefaction-related settlements of up to 10 cm (Martin et al (2004)).

Geotechnical field investigations including SPT, CPT and V_s measurements were undertaken at the site for geotechnical design and site soil improvement applications. The overall evaluation of the field test results as given in Fig. 2a indicated the presence of potentially liquefiable soil layer (SM) at an average depth of 6 m. Therefore, jet-grout columns were installed beneath the structures as given in Fig.1 in order to reduce liquefaction susceptibility of the silty sand layer (SM). As shown in Fig. 2b, primary and secondary grids of columns were installed across the site in rectangular patterns. The jet grout columns in the primary grid were 0.6 m in diameter with a center-to-center spacing of 4 m and extending from the ground surface to a depth of 9.0 m. The secondary grid consisted of short jet-grout columns extending from a depth of 6.5m to 9.0 m. The secondary columns were mainly installed to increase the liquefaction resistance of the 2.5m thick silty sand layer (Martin et al. (2004)).

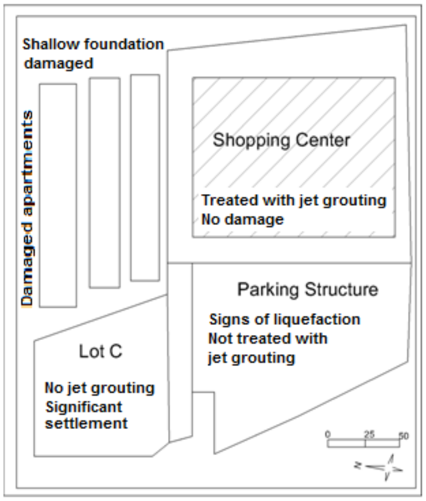
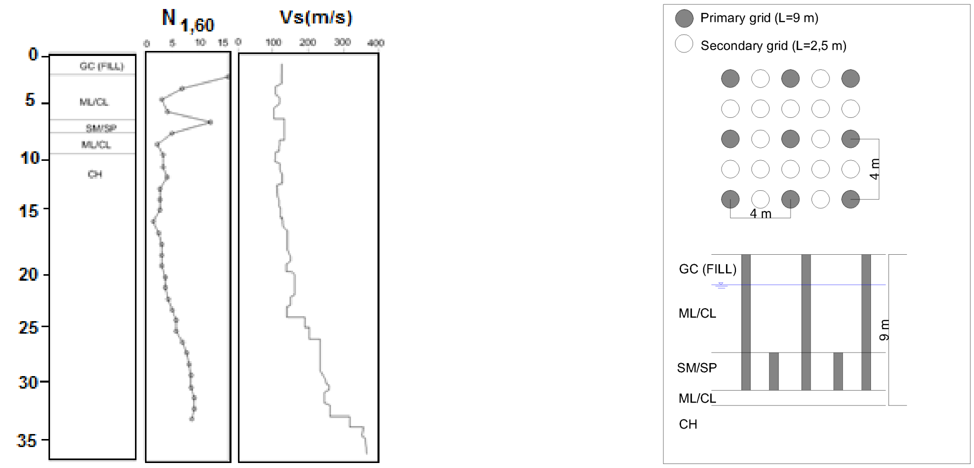


Figure 1. Site plan of shopping center area showing improved area and unimproved areas (Martin et al. (2004))



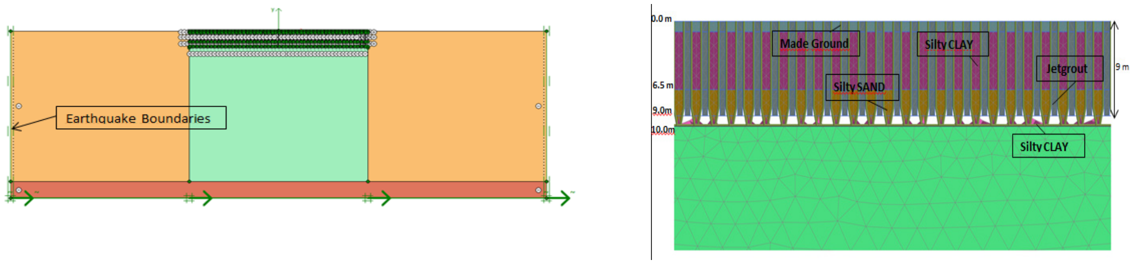
(a)

(b)

Figure 2. (a) Field test results obtained from the shopping center area (b) Layout of jet-grout columns (Martin et al. (2004))

2D Finite Element Modelling of the Improved Site with Jet-Grout Columns

The finite element analysis of the improved site with jetgrout columns were carried out by using an effective stress based model UBC3D-PLM on PLAXIS software program. The UBCSAND is a nonlinear elastic-plastic model that is capable of capturing seismic liquefaction behaviour of sands and silty sands (Beaty and Byrne (2011)). The UBCSAND model, with some modifications, has been implemented as a user defined soil model in the finite element program PLAXIS (Petalas and Galavi (2013)). The simplified finite element model of the improved site is shown in Fig. 3.



(a) (b)

Figure 3. Simplified finite Element Model of the Improved Site with Jet Grout Columns
(a) Earthquake boundaries (b) Finite element mesh

Standard earthquake boundaries were assigned and ground motion record from the IZT recording station approximately 8 km away from the site was used as an input motion at the base of the model. The UBCSAND model parameters for the liquefiable soil layer, hardening soil model parameters for the unliqueafible silty-clay layer and elastic parameters for the jet-grout columns for different stiffness ratios (G_r) used in the numerical analysis are summarized in Table 1 and Table 2, respectively. The constant volume friction angle, the peak friction angle were evaluated from SPT and CPT field test results. The elastic shear modulus number (k_{Ge}), plastic shear modulus number (k_{GP}), elastic bulk modulus number (k_B^e) and the failure ratio were obtained with the following equations as recommended by (Beaty ve Byrne (2011)).

$$k_G^e=21.7A\,(N_1)_{60}^{0.333} \tag{1}$$

$$k_B^e= k_{Ge}\,\alpha \tag{2}$$

$$k_G^P= k_{Ge}((N_1)_{60})^2 0.003 +100 \tag{3}$$

$$R_f= 1.1\,(N_1)_{60}^{\;-0,15} \tag{4}$$

where, $(N_1)_{60}$ is the SPT-N number corrected with respect to overburden stress and energy ratio, A and α are the constants within the range of 15-20 and 0.7-1.3, respectively. m_e, n_e are constants equal to 0.5 and n_p is another constant equal to 0.4.

Results and Evaluation of Parametric Studies

In order to show the effectiveness of jet grout columns on the reduction of liquefaction potential of the site, numerical analysis were carried out for different ratios of stiffness and area ratios. For this purpose, numerical models were carried out with area ratios of 3%, 5% , %7 , %10% , 15 % and with stiffness ratios of Gr =5, 10, 15, 20. For the case analyzed in this paper, the stiffness ratio and area ratio applied at the site were in the order of 10 and 7%, respectively. The analysis results were evaluated based on the effect of jet-grout columns on the distribution of shear stress, shear strain and excess pore water pressure in the liquefiable soil layer and shown as a function of depth within the liquefiable soil layer.

Table 1. Numerical model parameters for the liquefiable and unliquefiable soil layers

Model	UBCSAND	
Parameter	Definition	Silty Sand
$(N_1)_{60}$	SPT value	9
ϕ_{cv} $^{(o)}$	Constant volume friction angle	33
ϕ_{pi} $^{(o)}$	Peak friction angle	33.9
G_0 (kPa)	Maximum shear modulus	23440
k_{Ge}	Elastic Shear Modulus	902
k_{Be}	Elastic Bulk Modulus	632
k_{GP}	Plastic Shear Modulus	319
R_f	Failure Ratio	0.79
m_e	Elastic Bulk Modulus Index	0.5
n_e	Elastic shear Modulus Index	0.5
n_p	Plastic shear Modulus Index	0.4
fac_{hard}	Densification factor	0.45
fac_{post}	Post liquefaction factor	0.02

Model	Hardening Soil	
Parameter	Definition	Silty Clay
$(N_1)_{60}$	SPT value	8
γ_{unsat} (kN/m^3)	Unsaturated unit weight	17
γ_{sat} (kN/m^3)	Saturated unit weight	19
c (kPa)	Cohesion	5
$\phi^{(o)}$	Friction angle	24
E_{50}^{ref} (kPa)	Secant stiffness modulus	8000
E_{oed}^{ref} (kPa)	Oedometric tangent modulus	8000
E_{ur}^{ref} (kPa)	unloading/reloading modulus	24000
m	Exponent for power law	1
ν_{ur}	Unloading/reloading Poisson's ratio	0.2
K_0^{nc}	Coefficient of earth pressure in situ	0.5933
R_{inter}	Interface Ratio	1
Rf	Failure Ratio	0.9

Table 2. Elastic parameters for the jet-grout columns for different stiffness ratios

Lineer -Elastic	Jet-grout (Gr=5)	Jet-grout (Gr=10)	Jet-grout (Gr=15)	Jet-grout (Gr=20)
γ_{unsat}(kN/m^3)	25	25	25	25
E' (kN/m^2)	292900	586000	878800	1171750
ν'	0.25	0.25	0.25	0.25
G (kN/m^2)	117200	234400	351525	468700
E_{eod} (kN/m^2)	351500	703100	1055000	1407000

Shear Stress and Shear Strain Distribution

The results of numerical analyses were evaluated to quantify the distribution of seismically induced shear stresses and shear strains under varying stiffness ratios and area ratios. These results are produced by considering the liquefiable soil layer extending from a depth of 6.5m to 9.0 m. Variation of shear stresses and shear strains with time are shown in Figure 4 at various depths of 6.6 m, 7.7m and 8.9m for G_r=10 and A_r=10%. It is seen that jet-grout columns attracted the great portion of the shear stresses compared to the surrounding soil as they are stiffer than the liquefiable soil layer. On the other hand, as can be seen in the plots of shear strain vs time , the stiff columns were not strained too much compared to the surrounding soil. It is seen that jet-grout columns were subjected to negligible shear strains of 0.2%-%0.3, while peak strains in the soil reached 1%.-4%. This result basically shows that the jet-grout columns do not fulfill the expected shear strain compatibility. By adopting the scheme presented in Figure 4, analysis results obtained for cases with different stiffness ratios and area ratios were evaluated and the variation of maximum values of these shear stresses are expressed in terms of shear reduction factor, S_R. The shear stress reduction factor proposed by Baez (1995) is based on the assumption of shear strain compatible deformation of high modulus column and results in a reduction in the seismic shear stress in the surrounding liquefiable soil. This ratio is used as an multiplier for the value of cyclic stress ratio (CSR) in liquefaction analyses of level ground sites. In its simplest form, shear reduction factor (S_R) is expressed as below;

$$S_R = \frac{\tau_S}{\tau} = \frac{1}{G_R} x \frac{1}{\left[A_R + \frac{1}{G_R}(1 - A_R) \right]} \tag{5}$$

Here, A_r is area replacement ratio, G_r shear-modulus ratio ($G_{jet-grout)}/G_{soil}$), τ_s is the shear stress developed in the soil between the jet-grout columns; τ is the average total shear stress that acts on soil and jet-grout column composite system; $G_{jet-grout}$ is shear modulus of jet-grout column; and G_s is shear modulus of soil. In this study, S_R values are determined by computing the ratio of (τ_S/τ) in which τ_s and τ_{JG} values were taken from the numerical analysis and τ is computed as follows:

$$\tau = \tau_S A_S + \tau_{JG} A_{JG} \quad \tau_s A_S + \tau_{JG} A_{JG}$$

(6)

Based on the analysis results, the shear stress reduction factor (S_R) are plotted against depth for different area ratios for Gr=10 and shown in Fig. 5a, while the shear reduction factor for different stiffness ratios and for A_r=10% are shown in Fig. 5b.

From the plots presented in Fig. 5, the increasing A_r values cause the S_r value to increase while increasing Gr cause to decrease. For the considered case study, with the values of A_r=7% and G_r= 10 as applied in the project, by assuming a shear strain compatibility, the average shear stress reduction is computed to be on the order of 70-80%. However, this reduction concluded from equation (5) is in contradiction with the computed seismic shear strains developed in the liquefied soil mass. The shear stresses in the jet-grout columns were computed to be higher than those in the liquefied soil as the jet grout columns are stiffer and subjected to more shear stress; however, based on the analysis results performed for this case, it is believed that they were not subjected to enough shear stress to reduce the shear strains considerably in the liquefiable soil layer. The same conclusion is also reached by Olgun and Martin (2008) in which the role of Jetgrout columns were numerically analyzed by DIANAFLOW with total stress analyses where pore pressure generation was not considered.

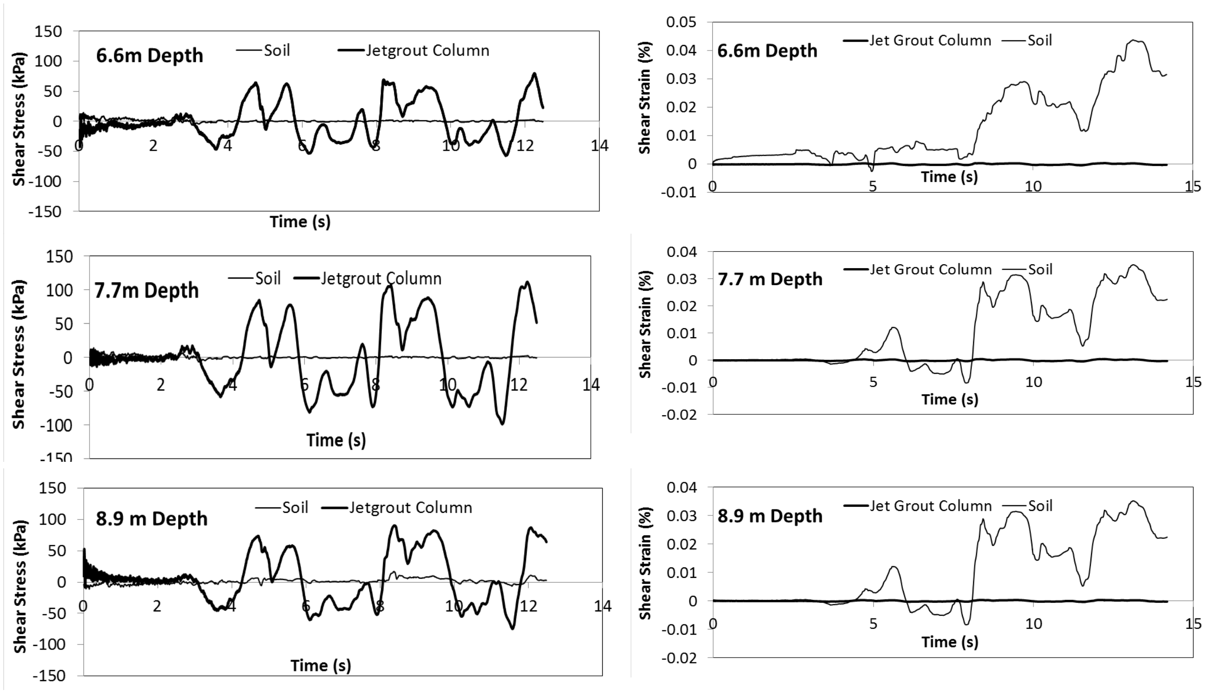
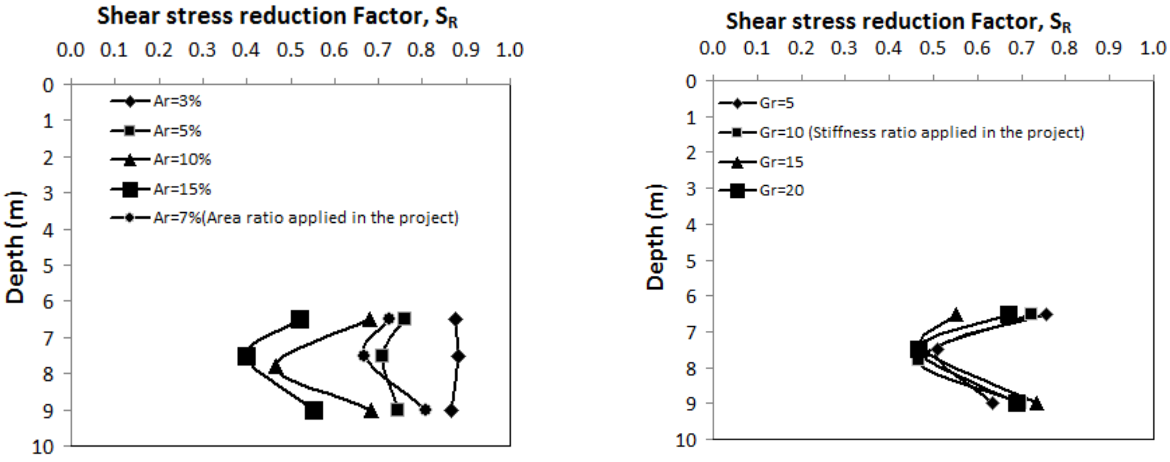


Figure 4. Variation of shear stresses and shear strains with time for G_r=10 and A_r=10% at various depths



(a) (b)

Figure 5. Shear stress reduction factor against depth (a) for G_r=10 (b) for A_r=10%

Effect of Jet-Grout Columns on Generation of Excess Pore Water Pressure

In this study, the effect of jet grout columns in mitigating the adverse of liquefaction in soils were also investigated by evaluating their effect on generation of excess pore water pressures with the aid of the effective stress based UBCSAND model. The development of excess pore water pressure was expressed in terms of excess pore water pressure ratio (r_u) and the variation of r_u with time is plotted in Figure 6 for the middle of the liquefiable soil layer (at 7.7 m) for different stiffness ratio (G_r) and area ratio (A_r) values. As it is seen in Figure 6, the change in area ratio and stiffness ratio do not influence the excess pore water pressure generation significantly and therefore jet grout columns result in almost no reduction in excess pore water pressures. The same conclusion can be also drawn from the computed shear strains of 1%-4% that are capable of producing high excess pore water pressures.

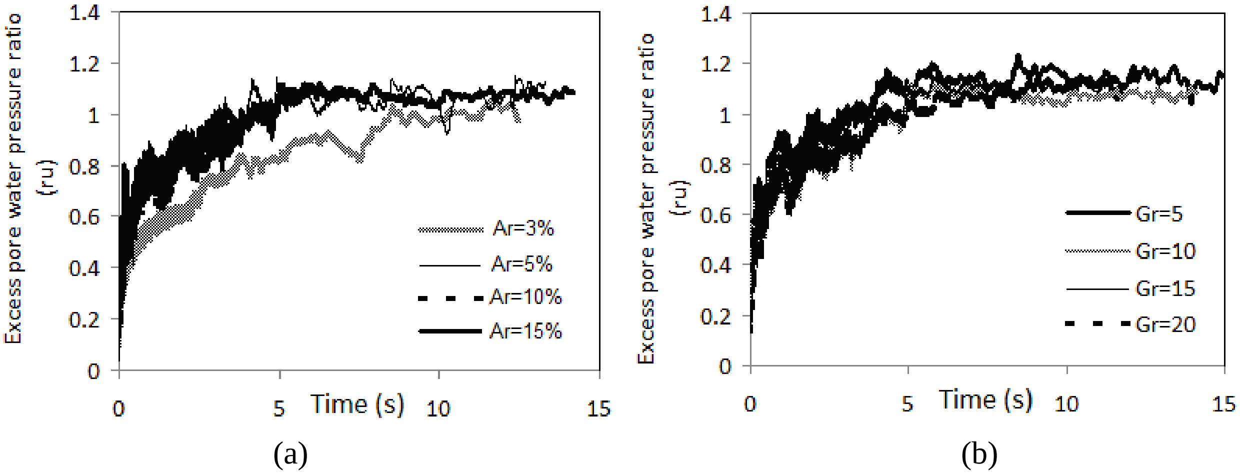


Figure 6. Variation of r_u with time at a depth of 7.7 m a) for different area ratios and G_r=10 b) for different stiffness ratios and A_r=10%

Conclusions

In this study, a series of numerical studies are carried out to investigate the effectiveness of jet grout columns in liquefaction mitigation through a case history. The results of the numerical analysis were evaluated in terms of shear stresses, shear strains and excess pore water pressure ratios by considering different stiffness ratios and area ratios. The computed shear stresses showed that jet-grout columns attracted the great portion of the shear stresses compared to the surrounding soil as they are stiffer than the liquefiable soil layer. The role of jet-grout columns in reducing the adverse effects of liquefaction was also analyzed by assuming shear strain compatible deformation and expressed in terms of shear reduction factor (S_R). The results indicated that for the considered case study, with the values of A_r=7% and G_r= 10 as applied in the project, the average shear stress reduction (S_R) is computed to be on the order of 70-80%. However, the shear stresses, shear strains and excess pore water pressure ratios showed that although jet-grout columns are stiffer and subjected to more shear stress, they did not contribute enough to reduce the shear strains and excess pore water pressures considerably in the liquefiable soil layer.

As a result of the performed numerical analysis, it is believed that although numerical analysis efforts provide important tool for understanding the mechanisms that take place in the response of sites improved with Jet-Grout Columns, real data from instrumented sites and experimental data from model tests can give better understanding of response of jet grout columns during liquefaction.

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