MECHANISM OF PERFORMANCE STONE COLUMN SUBJECT TO STRUCTURE ON DEEP LOOSE SATURATED SAND DEPOSITS

Mohsen Bagheri
Graduate Student, Department of Civil Engineering, Babol University of Technology, Babol, Iran
bagheri.m@hotmail.com

Abdolah Fathi
Graduate Student, Department of Civil Engineering, Babol University of Technology, Babol, Iran
behnam.fathi64@gmail.com

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ABSTRACT

This paper presents the fully coupled nonlinear effective stress dynamic analyses carried out on structures on deep loose saturated sand deposits to better understand the failure mechanisms of stone column (SC) and structure founded on loose sediment ground. Seismically induced settlement and lateral displacement of buildings with shallow foundations on liquefiable soils has resulted in significant damage in earthquakes. Each model was subjected the ground motion event obtained by scaling the amplitude of the El Centro (1940) earthquakes. The models included layers of loose sand thickness, and different surcharge on shallow foundation. This paper uses simplified conversion method to obtain the equivalent plane-strain model which the column width is matched based on the equivalence of column area and investigates its applicability to multicolumn reinforced ground. In a series of four separate numerical models, these models are studied first without, then with stone columns, as a free-field situation, and with a surface foundation surcharge. The underlying mechanism and effectiveness of the stone columns are discussed based on the recorded dynamic responses. Effect of the stone column (SC) on excess pore pressures and deformations is analyzed and compared. The numerical simulation demonstrate that stone columns cannot be an effective technique in the remediation of liquefaction induced settlement and lateral displacement of loose sand deposits particularly under shallow foundations, or surcharge larger than approximate 60 kPa.

INTRODUCTION

The economic construction method often involves structure onto loose or liquefiable deposits with little or no ground improvement. Hence in a seismic environment, these structures are potentially vulnerable to failure due to pore pressure generation effects of the underlying deposits.

During many large earthquakes, soil liquefaction results in ground failures in the form of sand boils, differential settlements, flow slides, lateral spreading, and loss of bearing capacity beneath buildings. Such ground failures have inflicted much damage to the built environment and caused significant loss of life. The risk of liquefaction and associated ground deformation can be reduced by various ground-improvement methods including densification, solidification (e.g., cementation), and gravel drains or stone columns Adalier Korhan and Elgamal Ahmed (2004).

Geotechnical earthquake engineers conduct extensive research to understand and characterize various SC and pile-pinning applications and to assess their effectiveness as liquefaction countermeasures, through

field case histories (Mizuno H. (1987) and Matsui T. and Oda K. (1996) and Tokimatsu K., and Asaka Y. (1998)), field tests ((Ashford et al. (2000) and (2006), and experiments(Abdoun T. et al. (2003) and Brandenberg et al .(2005) and Wilson et al .(2000) and Juirnarongrit and Ashford (2006) and Lu et al. (2011))and numerical simulation(Elgamal et al .(2011) and Asgari et al. (2013)).
In a series of four separate numerical models, these models are studied first without, then with stone columns, as a free-field situation, and with a surface foundation surcharge. In this paper, for the precision in the assessment of the stone column (sc) at a site affecting the safety and cost of the design are evaluated.

MODEL GEOMETRY AND SOIL PROPERTIES

A series of numerical analyses are carried out to investigate various factors affecting the seismic performance of Stone Column (SC). The Mohr–Coulomb and Finn model was used to simulate the nonlinear soil behaviour. The model is based on the plane strain conditions and is formulated in terms of effective stresses. Table 1 presents the soil and stone column parameters used in the model.

Table 1.Soil and foundation data for deterministic analysis

Soil property	Gravel	Loose sand
moist unit weight, γ (kg/m3)	2100	1650
Bulk modulus, K (Mpa)	94	5.8
Shear modulus, G (Mpa)	56	2.7
Relative density, Dr (%)	-	30
Internal friction angle, ϕ (degree)	40	26
Dilation angle, ϕ (degree)	-	-
Drained cohesion, C (kPa)	1	0
Poisson’ ratio, (υ)	0.25	0.3
Permeability, k (m/s)	$1\text{x}10^{-6}$	$1\text{x}10^{-2}$
$N_{1(60)}$	-	8
Stone Column data		
Diameter D (kg/m)		80
Spacing, S (kg/m)		2.4
unit weight, γ (kg/m)		2400
Bulk modulus, K (Mpa)		25
Shear modulus, G (Mpa)		11.5
Permeability, k (m/s)		$2\text{x}10^{-2}$

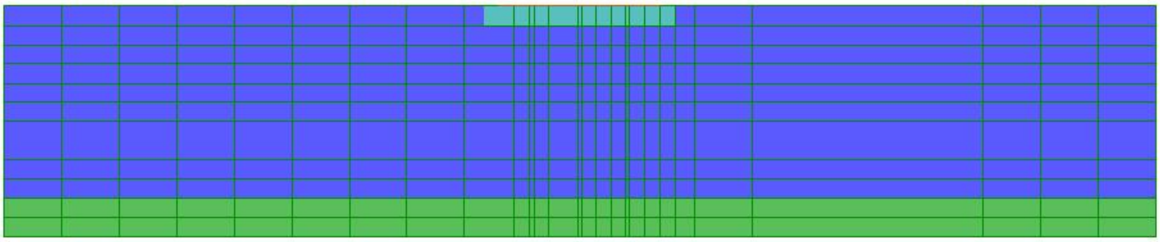
A method of converting the axisymmetric unit cell into the equivalent plane-strain model is used for two-dimensional numerical which the column width is matched based on the equivalence of column area This paper uses simplified conversion method to obtain the equivalent plane-strain model (Ashour et al. (2009)). An alternative geometrical transformation is based on the equivalence of the column drainage capacity in both axisymmetric and plane-strain conditions, whose concept has been proposed in a vertical drain study by Indraratna and Redana (1997) to convert vertical drain system into the equivalent plane-strain drain walls. This method hence preserves the cross sectional areas of the column and the surrounding soil for the same total area in both conditions. The plane-strain column width is given by the following relationship based on the equivalence of area replacement ratio:

$$b_c = B\frac{r_c^2}{R^2} \quad (1)$$

Which results in smaller plane-strain column widths and larger flow path lengths as compared to the previous method, as seen in (Figure 1.). The relationship between R and B may be given by the following equation based on the equivalence of total area for a square pattern of columns Barron (1948):

$$R = 1.13B \tag{2}$$

Correspondingly, the radius of drainage zone R can be taken equal to the equivalent plane-strain width B.



(a)

(b)

Figure 1. Cross section of shallow foundation on liquefiable soil without, then with stone columns, respectively.

These models are studied first without, then with stone columns, as a free-field situation, and with a surface foundation surcharge (Figure 1.). Each model was subjected the ground motion event obtained by scaling the amplitude of the El Centro (1940) earthquakes (Figure 2.)

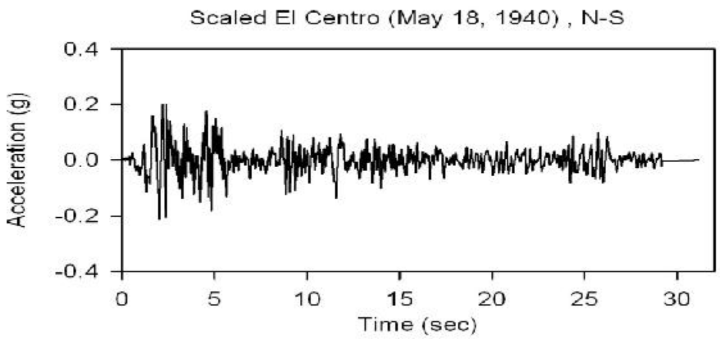


Figure 2. Horizontal acceleration history for the El Centro (1940) with scaled PGA of 0.2g.

The initial geostatic stress for steady state in a free field is one of the primary values related to grid zones which force the model to reach equilibrium by performing mechanical calculations. In the static analysis, the soil–structure system was under gravity loading only; the base boundary was fixed in all directions and the side boundaries were fixed in x direction. Structures represent a 4, 6 and 8-storey building with a contact pressure of 40 kPa, 60 kPa and 80 kPa, respectively. The numerical simulation includes a liquefiable soil layer ($D_r = 30\%$) with a prototype thickness $\left(H_L\right)$ of 10 m underlying a layer of gravel soil with thickness of 4 m.A series of realistic earthquake motions (Table 1.) were applied to the base of the model (Figure 1.). Each model include 60cm-diameter of Stone Column at 2.4 m spacing from each other(Figure 1.). During dynamic analyses, pore fluid simply responds to changes in pore volume caused by mechanical dynamic loading. The average pore pressure does not vary significantly during the analysis (Itasca,2008). It is known, however, that pore pressure may build up considerably during cyclic shear loading.

Table 2. Earthquake Data for the Parametric Analysis

Earthquake motion parameters	Elcentro (USA)/N-S
Date of occurrence	18/05/1940
Recording station	117 Elcentro
Magnitude of earthquake, M_w	7.1
Maximum horizontal acceleration, MHA (g)	0.314
Predominant period, T_p (sec)	0.5
Bracketed duration (sec)	28.78
Significant duration, D_{5-95} (sec)	23.84
Time of MHA (t_p (sec))	2
PGV/PGA (sec)	0.113
Arias intensity for scaled $PGA = 0.35g$ (m/sec)	2.175
Energy flux for scaled $PGA = 0.35g$ $(J.m^{-2}.sec^{-1})$	2469
Number of significant excitation cycles, N_c	14.5

RESULTS AND DISCUSSION

This section describes the profession's understanding of effects of structures, Stone Column (SC) on excess pore pressure ratio $(r_u)$and the vertical and horizontal displacement on liquefiable deposits.

Fig. 3 depict that Schematic illustration the deformation of structure constructed on shallow foundations (80 kPa) without, then with stone columns subjected to El Centro (PGA= 0.2g) during the earthquake. The combined effect of vertical and horizontal deformation under structure compels structures experienced excessive tilt that leads to severe damage to adjacent lighter/heavier structures.

Fig. 4 shows excess pore pressure ratio at the centerline of shallow foundation compared to the free-field in during the El Centro event (PGA = 0.2 g). Results of the parametric analyses show that smaller excess pore pressure can be expected to create under structure comparing to the free field.

In contrast of the observed behavior in the free field, the minimum excess pore pressure ratio under the foundation occurs at shallow depths and the maximum excess pore pressure ratio occur at intermediate depth however, this ratio under structures is always smaller than free field (see Fig. 4). However, the most vertical and lateral displacement of the soil stratum in shallow depth below foundation is mainly dependent on the earthquake-induced shear stresses and structure-induced static and dynamic shear stresses (Fig. 5).

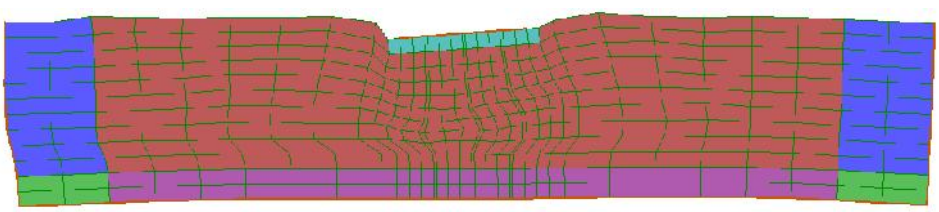
In addition, that most of incremental changes of excess pore pressure occur during the strong motion and then decreases.

It can be seen that the presence of Stone Column (SC) causes dissipation process takes place faster than in the without SC during the earthquake which means their strength and stiffness has been dramatically returned .

It is noteworthy to mention that Stone Column (SC) has better performance in drainage process in shallow depth and it is observed that by increasing the depth, the efficiency of Stone Column significantly decrease.

It can be deduced that the Stone Column has not enough strength and stiffness safety against lateral displacement.

As presented in Table 3, structure underwent notable non-uniform vertical deformation and deform horizontally underneath the structure foundation during the ground motion event, especially when no ground improvement is conduct.



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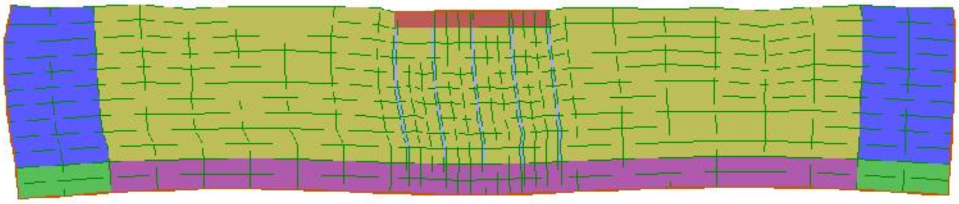

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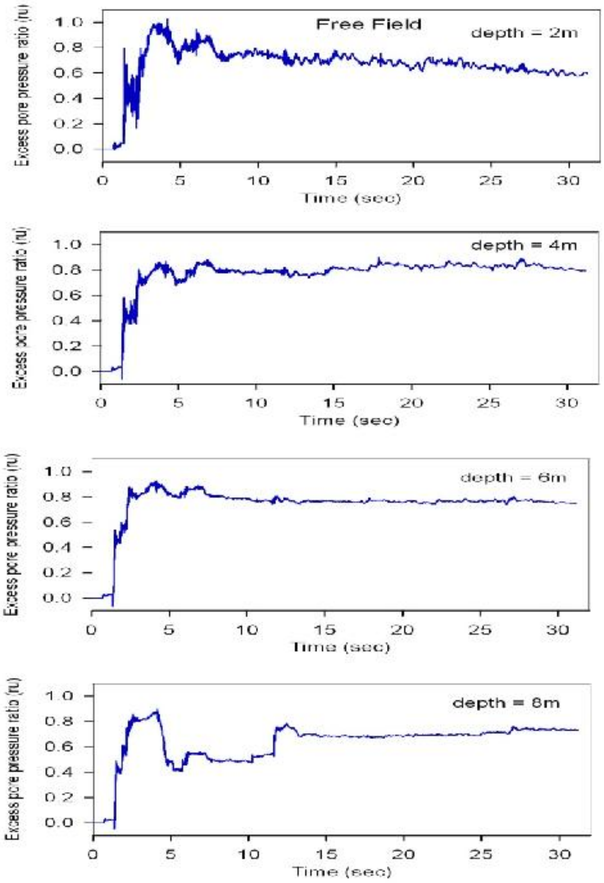
Figure 3. Schematic illustration the deformation of structure constructed on shallow foundations (80 kPa) without, then with stone columns subjected to El Centro (PGA= 0.2g) during the earthquake.



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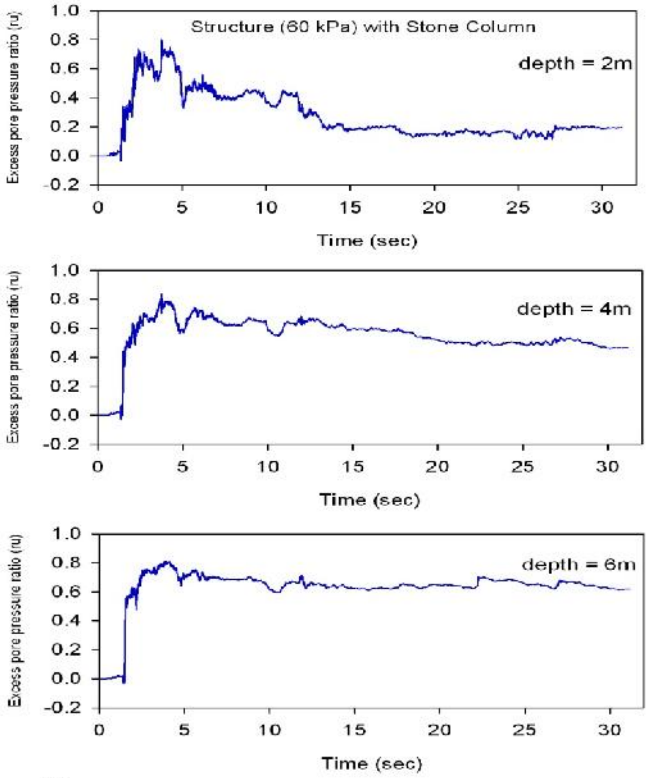

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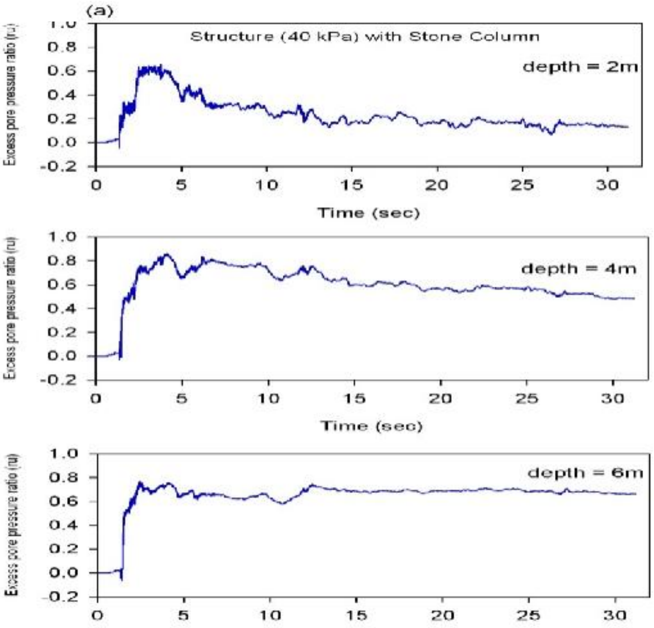

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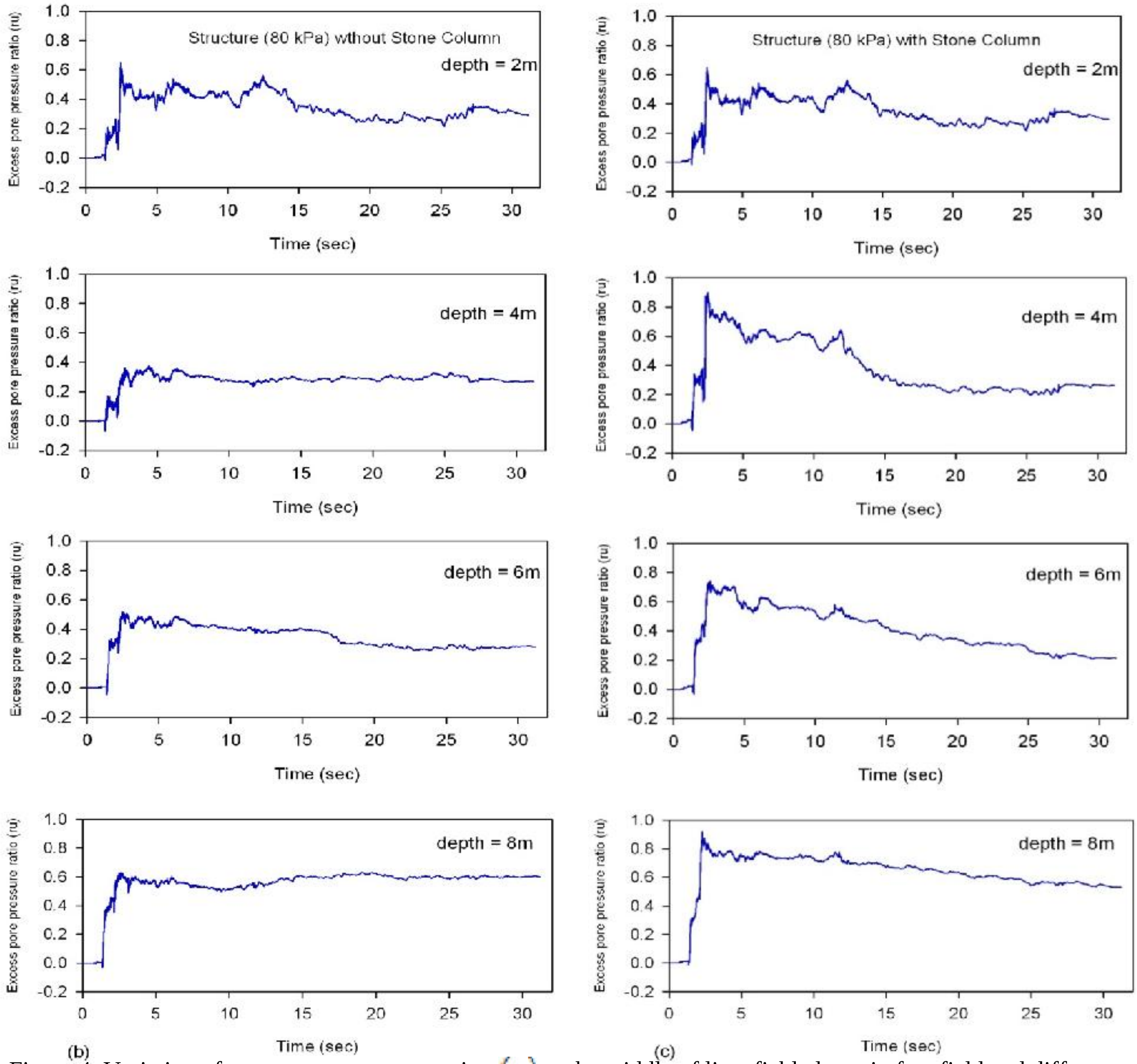

Figure 4. Variation of excess pore pressure ration (r_u) at the middle of liquefiable layer in free field and different structure (40kPa, 60kPa, 80 kPa) during the El Centro event PGA=0.2g.

Table 3. Maximum Vertical and Lateral Displacement (cm) at the right and left of the shallow foundation with and without SC for different structures.

	Surcharge (kPa)	Vertical displacement (cm)		Horizontal displacement (cm)	
		At the left of the foundation	At the right of the foundation	At the left of the foundation	At the right of the foundation
Without Stone Colum	40	8	29.8	49.7	67.8
	60	8.5	30	44	73.2
	80	75	96.5	31.4	74.3
With Stone Column	40	7.05	7.1	62.8	62.8
	60	7.3	7	63.5	63.5
	80	32.6	38.2	96.2	96.2

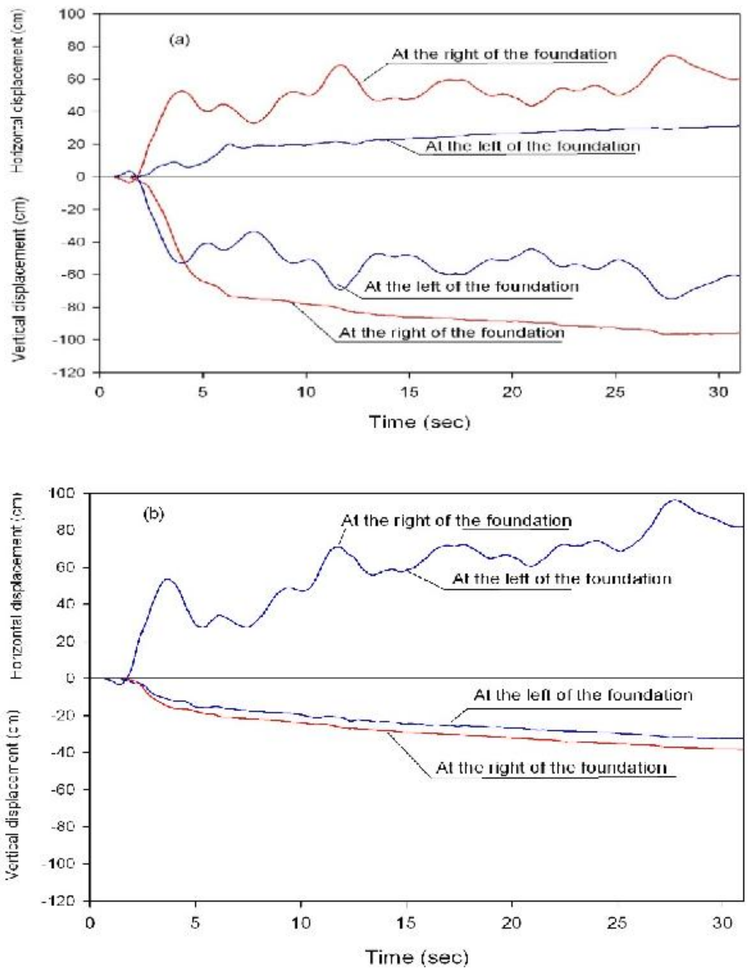

Figure 5. Time history vertical and horizontal displacement at the right and left of the shallow foundation during the El Centro event PGA=0.2g.

CONCLUSIONS

The numerical results are used to shed light on the failure mechanisms of stone column (SC) and structure founded on loose sediment ground. The conclusions are as following:

1. In all cases, excess pore pressure ratio (r_u) around of Stone Column significantly decrease compared to free field, especially diameter and permeability coefficient increased.
2. Although increasing of weight structure cause lower excess pore pressure ratio (r_u) , the combined effects of vertical and horizontal deformations under structure compel structures to experience excessive tilt which leads to severe damage even to adjacent structures.
3. Stone Column has significant influence on prevention of the asymmetrical vertical displacement for El Centro event. However, it has lightly significant influence lateral displacement and it somewhat decrease. Therefore, It is noteworthy that beneficial effect of the Stone Column decrease for heavier structure.
4. In contrast of the observed behavior stone column (SC) which has a significant effect in minimum excess pore pressure ratio in the soil below the foundation occurs at shallow depths, the maximum excess pore pressure ratio occur at intermediate depth where its effect decreases with depth.
5. Generally, The numerical simulation demonstrate that stone columns cannot be an effective technique in the remediation of liquefaction induced settlement and lateral displacement of loose sand deposits particularly under shallow foundations, or surcharge larger than approximate 60 kPa. This suggests that the pile-column combined method is used in order to ground improvement.

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