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"The Use of Stone Column as a Countermeasure for Liquefiable Ground" (Paper ID 111)

Written by
Muhammad Hamzah Fansuri, Hsu-Jen Lin, Muhsiung Chang, Togani Cahyadi Upomo, Rini Kusumawardani, Rina Rebut Rayhansah

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The Use of Stone Column as a Countermeasure for Liquefiable Ground

Muhammad Hamzah Fansuri[1], Hsu-Jen Lin[2], Muhsiung Chang[3], Togani Cahyadi Upomo[4], Rini Kusumawardani[5], Rina Rebut Rayhansah[2]

[1]Lecturer, Dept. Civil Engineering, Universitas Pertahanan Republik Indonesia (Unhan RI), West Java, Indonesia
[2]Master Student, Dept. Civil & Construction Engineering, National Yunlin Univ. of Sci. & Tech. (YunTech), Yunlin, Taiwan, ROC
[3]Professor, Dept. Civil & Construction Engineering, National Yunlin Univ. of Sci. & Tech. (YunTech), Yunlin, Taiwan, ROC
[4]Ph.D. Student, Graduate School of Engrg. Sci. & Tech., National Yunlin Univ. of Sci. & Tech. (YunTech), Yunlin, Taiwan, ROC
[5]Assoc. Professor, Dept. Civil Engineering, Universitas Negeri Semarang (Unnes), Central Java, Indonesia

Abstract

Soil liquefaction and associated ground failures are one of the most destructive natural hazards that cause damages to engineering structures during the earthquake. This paper presents an alternative to mitigate the risk of liquefaction and associated ground deformation by stone column (SC). In this study, a three-dimensional finite-element (FE) simulation using OpenSeesPL is performed to address this issue. The development of model for mitigation in liquefiable ground follows physics (mechanics) of the problem closely possible and allows for more realistic representations of the involved static and dynamic responses. The software is capable of modeling the coupling responses between soil skeleton and pore fluid as well as redistributions of pore pressure during excitation either in two or three dimensions. The prevention of excess pore pressure generation and reduction of liquefaction-induced deformation would generally mitigate the consequence of liquefaction. The results show that the SC mitigation is found to be effective in reducing in sand stratum lateral deformation. In other words, the results indicate that there is an interaction among deformation and excess pore pressure related to soil type for mitigation. For this purpose, a systematic parametric study is conducted to investigate the effectiveness of the SC approach on the basis of couple SC permeability and ground inclination. Special emphasis is given to the computed results of soil response shaking, excess pore pressure, and lateral displacement of deposit. The numerical simulations provide a framework for the analysis of factors affecting liquefiable ground and insights for the improvement by the SC mitigation measure.

Keywords: soil liquefaction; stone column; numerical simulation; OpenSeesPL

Introduction

Civil engineering structures in earthquake-prone areas may be partially or completely damaged in strong earthquakes. Usually, in mildly sloping ground, the soil flows following the liquefaction are lateral spread, flow, bearing capacity failures, buoyancy effects, local subsidence, and ground oscillation (O'Rourke and McCaffery 1984). Particularly, one of the major earthquake-resistant design strategies is to avoid liquefaction-induced deformation of foundation soils.

Various ground improvement techniques have been performed in order to avoid the liquefaction-induced soil deformations and associated damage, including densification, solidification (e.g., cementation), prefabricated vertical drains, deep soil mixing, and gravel drains or stone columns (Seed and Booker 1977; Boulanger et al. 1988; Elgamal et al. 2009). Although, a limited number on the effectiveness of ground improvement techniques have been identified for liquefaction mitigation.

The stone column as a liquefaction mitigation technique was initially studied by Seed and Booker (1977). The stone column technique is adopted for mitigating liquefaction because of its effectiveness and simple construction involved. The stone columns were offered the possible benefits including dissipation of excess pore pressure, densification of surrounding, non-cohesive soil, and redistribution of earthquake-induced. (Adalier et al. 2003). The most of the routine designs mitigating liquefaction have been based on the conceptual understanding analysis. In addition, the comprehensive understanding on mitigating liquefaction is needed for reliable numerical simulations to evaluate the mitigating liquefaction-induced excess pore pressure and soil deformation to suitable levels for construction.

This paper simulates the effectiveness and verification of applicability of the mitigating liquefaction technique of stone column in liquefiable ground. Hence, through rigorous numerical simulations, this study was carried out to investigate the influences of various factors, including permeability and ground inclination. The results of examined parametric study are discussed, highlighting of the influence of mitigating extend and the characteristic of the deployed countermeasure. Finally, insigths and conclustions are addressed in the report results.

Literature review

Most researchers in geotechnical engineering investigate the various stone column application and assess the effectiveness as liquefaction mitigation, through filed case histories (Tokimatsu and Asaka 1998), field test (Ashford et al. 2000), experiments (Adalier et al. 2003), and numerical simulation (Elgamal et al. 2009). Using the stone column as a liquefaction mitigation technique was first studied by Seed and Booker (1977). The full-scale test conducted by Ashford et al. (2000) analyzed the behavior of improved ground before and after mitigation using stone column. They reported that the excess pore pressure build-up was reduced and the rate of pore pressure dissipation was increased by stone column installation.

Elgamal et al. (2009) conducted the simulations by using OpenSeesPL to evaluate remediation of soil liquefaction by stone column (SC) and pile-pinning approaches on the basic of a systematic parametric study. They found SC mitigating was effective in reducting sand stratum lateral deformation. However, in similar stratum with permability in silt layer, the SC mitigating was resulted to be ineffective, regardless of the higher permeability of SC conducted. Recently the remediation of SC is considered to identified and examined important factors for mitigation of liquefaction-induced lateral deformation and thus generating the excess pore pressure including area replacement ratio, R_r, ground slope angle, soil and SC permeability, ground motion characteristics. Hence in this paper reviews the evidence which show their interactions on the seismic response through 3D simulation using OpenSeesPL.

Numerical simulations

Computation framework

The simulations are carried out by using a computation platform. A mixed-method of simulation approach was employed using OpenSees (Mazzoni et al. 2006; McKenna et al. 2010) and DEEPSOIL (Hashash 2018). The OpenSeesPL approach is adopted to create a finite-element model for numerical simulations. It has capabilities for carrying out a large variety of 3D finite-element simulations based on the OpenSees computational platform (Elgamal and Lu 2009).

Second, DEEPSOIL is one-dimensional site response analysis program that can perform, including 1-D nonlinear time domain analyzes with and without pore water pressure generation, 1-D equivalent linear frequency domain analyzes (convolution and deconvolution), and 1-D linear time and frequency domain analyzes (Hashash 2018).

Prior to analyze the numerical simulation, a deconvolution is performed to determine the acceleration time history that can be applied to the base of the foundation to reproduce the specific free-field acceleration time history at the base of a case study, as shown in Fig. 1. The calibrated base acceleration time history is then adopted to the base of foundation to analyze the seismic analysis. These procedures is importance, but understudied, when the researchers do not has a comprehensive information.

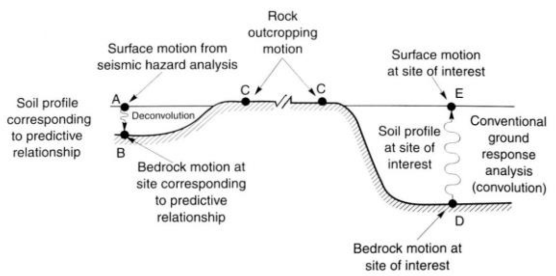

Fig. 1. Illustration of convolution and deconvolution procedures (base sketch from Kramer 1996)

Analysis procedures and outputs

All simulations were developed and executed using OpenSeesPL based on u-p formulation. The 3D finite element soil is domain is represented by 8-4 node, fully coupled (soil-fluid) brickUP elements. In this scenario, numerical analyzes composed of clays and silts layers beneath a deposit of very loose sand to medium sand with low permeability. The model of numerical simulations was performed with a groundwater level of 3.84-m below ground surface. The selected input motion is adopted from the deconvolution procedure. The initial record motion is adopted from CHY002 during 1999 of Chi-Chi earthquake. The process that evaluate the seismic motion at depth of a soil profile, which can then be used as input motion in analyzes. We described the results obtained from 3D seismic response with considering the behavior of soil in center and edge of soil. The results were discussed with respect to the depths, permeability, and ground inclination. In total, 10 simulations were performed to explore different combinations of permeability and ground inclination including the original cases (without any improvement).

In the following, the plane are of simulation was 2.8 × 2.8 m (square area). The SC permeability and slope angle are preasumed to vary from k_{sc} = 0.0001 to 1 m/s and α = 0°, 3°, 6°, respectively, for purpose of assessing its influence on the seismic response on SC. The SC geometric configuration (i.e., 1 × 1) was adopted a 0.8-m- diameter of SC and R_r = 6.41%. In addition, simulation results were examined for the behavior of soils in the center and edge of model.

Numerical simulation

A series numerical analysis was carried out to investigate the influences of various factors, including permeability and ground inclination. The numerical analyzes are dominated by deposit sand. In a mitigating area of large extent, the periodic boundary technique offers an effective approach for employing 3D analyses (Law and Lam 2001). A multi-yield-surface plasticity model was adopted for the analysis conducted for this study based on the constitutive laws applicable to all types of soils (Prevost 1985). The physical properties of stone column are presented in Table 1. The seismic data was based on the earthquake of Chi-Chi (1999) which has adopted through deconvolution process, as shown in Fig. 2. The model adopted in numerical analyzes is shown in Fig. 3.

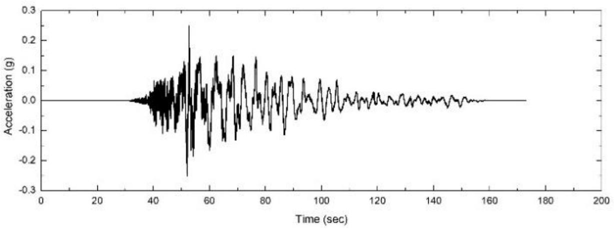

Fig. 2. Based input motion of model

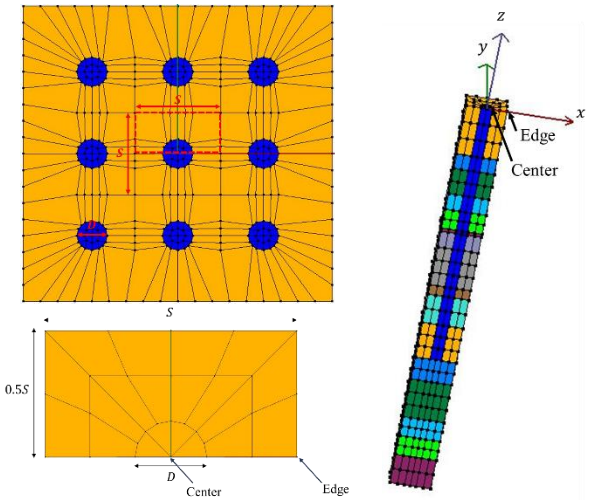

Fig. 3. Schematic plan view and 3D views of numerical simulation

Table 1. Stone column parameters

Parameters	Unit	Medium Gravel
Mass density γ_m	Mg/m^3	1.9
Friction angle ϕ	deg	33
Cohesion	kPa	0.3
PT angle ϕ_{PT}	deg	27
Contr. parameters c_1		0.07
Dilation param. d_1		0.4
Dilation param. d_2		2
Liq. parameter l_1	kPa	10
Liq. parameter l_2		0.01
Liq. parameter l_3		1

Simulation Results

Soil response of shaking

Fig. 4 shows the acceleration amplitude increases as the ground inclination become higher, with the largest acceleration amplitude observed when the slope is 6°. However, the highest slope has no longer time to reach peak acceleration. Indeed, as the SC permeability increases, the acceleration would generally increase in SC. The acceleration response does not differ much, however, in the center and edge of model.

The soil near the SC tends to response as a drained condition when the SC soil type becomes permeable. In accordance, the acceleration slightly reduce as the SC permeability increases. The evidence that when the soil in level ground with the highest permeability would reduce the acceleration in soil, and hence the soil becomes pervious.

Fig. 5 shows the peak amplitudes of spectral acceleration appear to reduce with ground inclination in SC. The natural period would be decreasing, when the SC becomes permeable and tends to reduce in spectral acceleration. The results is consistent with that of acceleration time history.

Behavior of soil

Fig. 6 shows the excess pore pressure occurred at various ground inclination (i.e., a = 0° to 6°) and SC permeability (i.e., k_{sc} = 0.001 to 1 m/s). Generally, the highest SC permeability cause radial drainage resulting in faster dissipation of excess pore pressure. The level ground would be decreasing the excess pore pressure, however, this reduction is more significant with increasing SC permeabiliy. There has been realible evidence that the decreasing in excess pore pressure arises to be an important factor in restricting deformation to a potentially tolerable level.

To mitigate severe liquefaction, the SC permeability was replaced by highest permeability, and would significant to reduce the excess pore pressure at any sloping ground. As expected, the dissipation process in the original cases, with similar no any improvement, was highly dependent on soil permeability. On the other hand, the interaction between SC cause an increase excess pore pressure in the edge of model. Due to interaction effect as mentioned previously, the responses of excess pore pressure are apparently more "rigorous" than that in center model. It is apparent from the Fig. 6 that the dips in the excess pore pressure response occurred in low permeability (i.e., k_{sc} = 0.0001 m/s) which associated with the dilative response of saturated soil and reveal low permeability of the soil medium limits the drainage efficiency of SC.

Behavior of stone column

A summary of lateral displacement occurring during and after the Chi-Chi earthquake (1999) are shown in Fig. 7. The lateral displacements are observed to stop as soon as the seismic ended. The lateral displacement of SC increases gradually during excitation as the slope angle increase for original cases. The presence of permeability in SC would affect the lateral displacement.

We notice that the increase in permeability would tend to reduce the lateral displacement in soil. In other word, the increase in permebility would be similar to dissipate excess pore pressure, the lateral displacement of SC would therefore be reduced severe liquefaction due to increasing permeability. The effects of peak ground acceleration for various sloping grounds show that the trend of lateral displacement increases as the peak input acceleration increases. Addition, high SC permeabilty would be decreasing lateral displacement more effectively than level ground, which can also more efficienly a positive factor from the standpoint of lower cost.

Fig. 8 shows the maximum lateral displacement of SC during seismic shaking is examined for the cases with various permeability at different depths of concern. The lateral displacement of SC would be decreasing with depth, suggesting the lateral displacement of SC due to shaking would be amplified or maximized at the head of SC. In all cases, the magnitude of ultimate lateral resitance depends on the SC permeability, resulting in a decrease in the lateral displacement at center of model as the permeability increase. The increase permeability would generally reduce lateral displacement of soil by about 16%. The higher of slope angle would trigger severe movement of soil, however, the replacement of SC permeability would significantly resist lateral displacement due to seismic shaking.

The maximum lateral displacements slightly reduce as permeability increase from 0.0001 to 1 m/s in level ground, but, it tends to significantly reduce of its value when slope angle increase from 0° to 6°. The remediation of SC permeability is far more effective when it is conducted in sloping ground against liquefaction-induced lateral displacement. It is related to coincidental effects of dilative event and driving static shear stress component on the permanent accumulation lateral displacement. This result is those observed for excess pore pressure.

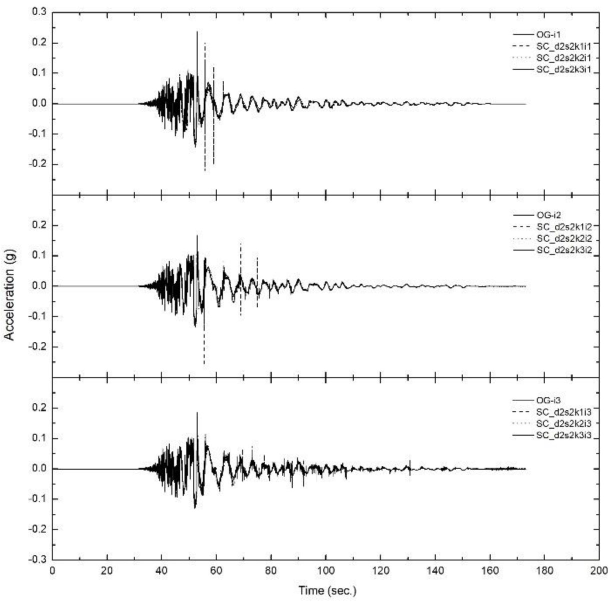

Fig. 4. Acceleration time histories with various permeabilities (0.0001m/s (k1), 0.01m/s (k2), 1.0m/s (k3)) of SC at 7-m deep for soils at the center of model.

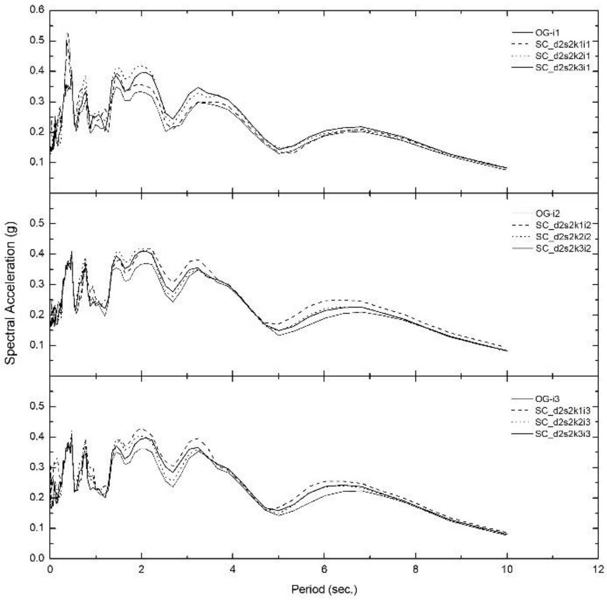

Fig. 5. Acceleration response spectra (5% damping) with various permeabilities (0.0001m/s (k1), 0.01m/s (k2), 1.0m/s (k3)) of SC at 7-m deep for soils at the center of model.

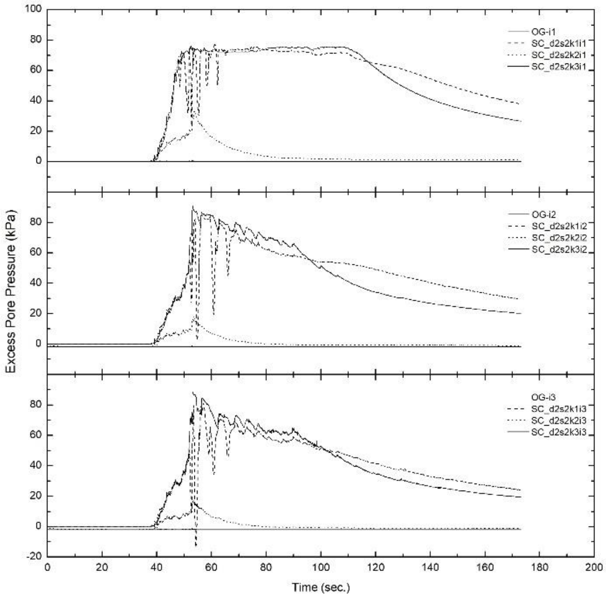

Fig. 6. Excess pore pressure time histories with various permeabilities (0.0001m/s (k1), 0.01m/s (k2), 1.0m/s (k3)) of SC at 7-m deep for soils at the center of model.

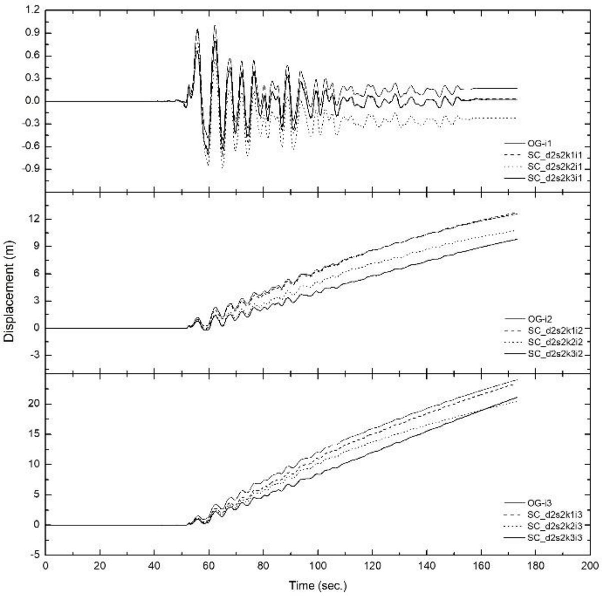

Fig. 7. Displacement time histories with various permeabilities (0.0001m/s (k1), 0.01m/s (k2), 1.0m/s (k3)) of SC at 7-m deep for soils at the center of model.

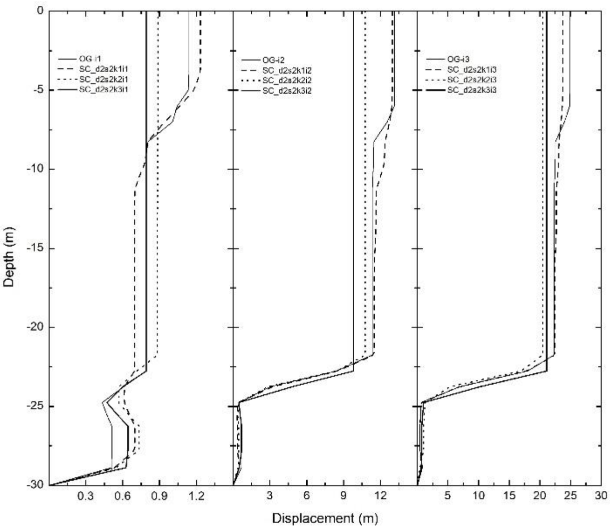

Fig. 8. Maximum lateral displacement profiles during shaking with various permeabilities (0.0001m/s (k1), 0.01m/s (k2), 1.0m/s (k3)) of SC at the center of model.

Conclusions

This paper was conducted to mitigate the risk of liquefaction and associated ground deformation by stone column with various factors including permeability and ground inclination. Major findings are summarized as follows:

(1) Deconvolution procedure revealed Equivalent-Linear would generate approximately the same motion on the within layers.

(2) The acceleration amplitude increases as the both ground inclination and SC permeability become higher. Thus, when the soil in level ground with the highest permeability would reduce the acceleration in soil, and hence the soil becomes pervious.

(3) The peak amplitudes of spectral acceleration and natural period would be decreasing, when the SC becomes permeable and tends to reduce in spectral acceleration.

(4) An increase in ground inclination would generally increase the excess pore pressure. In other word, in the level ground would dissipate excess pore pressure, however, the presence of SC permeability to excess quickly dissipation of excess pore pressure.

(5) An increase in SC permeability would generally reduce the lateral displacement. For any sloping grounds and lateral displacement increase as the peak ground acceleration increases. The high SC permeability would decrease lateral displacement efficiently than that the level ground.

References

1) Adalier, K., Elgamal, A., Meneses, J., Baez, J.I. (2003) Stone column as liquefaction countermeasure in non-plastic silty soils. Soil Dynamics Earthquake Engineering, 23 (7), 571-584
2) Ashford, S.A., Rollins, K.M., Bradford, S.C., Weaver, V.T.J., Baez, J.I. (2000) Liquefaction mitigation using stone columns around deep foundations: Full-scale test results. Transportation Research Record. J. Trans. Research Board, 1736, 110-118
3) Boulanger, R.W., Idriss, I., Stewart, D., Hashash, Y., Schmidt, B. (1998) Drainage capacity of stone columns or gravel drains for mitigating liquefaction. GSP, 1 (75), 678-690
4) Elgamal, A. and Lu, J. (2009) A framework for 3D finite element analysis of lateral pile system response. Proc., Int. Foundation Congress and Equipment Expo 2009, ASCE, Reston, 616-623
5) Elgamal, A., Lu, J., Forcellini, D. (2009) Mitigation of liquefaction-induced lateral deformation in a sloping stratum: Three-dimensional numerical simulation. J. Geotechnical Geoenvironmental Engineering, 135 (11), 1672-1682
6) Hashash, Y.M.A. (2018) Nonlinear and equivalent linear seismic site response of one-dimensional soil columns v.7. Dept. of Civil & Environmental Engineering, Univ. of Illinois, Urbana-Campaign, U.S.A.
7) Kramer, S.L. (1996) Geotechnical Earthquake Engineering. Prentice-Hall, Inc., Englewood Cliffs, N.J., U.S.A.
8) Law H.K. and Lam I.P. (2001) Application of periodic boundary for large pile group. Journal of Geotechnical and Geoenvironmental Engineering, 127, 889-892
9) Mazzoni, S., McKenna, F., Fenves, G.L. (2006) Open System for Earthquake Engineering Simulation (OpenSees) user manual. Berkeley, Pacific Earthquake Engineering Research Center, Univ. of California, Berkeley, C.A., U.S.A.
10) McKenna, F., Scott, M., Fenves, G. (2010) Nonlinear finite-element analysis software architecture using object composition. J. Comput. Civil Engineering, 24 (1), 95-107
11) O'Rourke, T.D. and McCaffrey, M.A. (1984) Buried pipeline response to permanent earthquake ground movements. World Conference on Earthquake Engineering. Proc., Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 7, 215-222
12) Prevost J.H. (1985) A simple plasticity theory for frictional cohesionless soils. International Journal of Soil Dynamics and Earthquake Engineering, 4, 9-17
13) Seed, H.B. and Booker, J.R. (1977) Stabilization of potentially liquefiable sand deposits using gravel drain systems. Journal Geotechnical Engineering Division, 103 (7), 757-768
14) Tokimatsu, K. and Asaka, Y. (1998) Effects of liquefaction-induced ground displacements on pile performance in the 1995 Hyogoken-Nambu earthquake. Soils Foundations, 38, 163-178

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