Seismic Response of Structures Rested on Improved Soils

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Abstract: **The objective of the current study is to study the seismic response of structures on improved soil condition using stone columns as a liquefaction countermeasure. For this purpose, numerical simulations of a building modelled as single degree-of- freedom (SDOF) is performed using time history analysis considering two different cases of the beneath the model. The first case deal with the original unimproved soil, while the second one considers an improved base soil supporting the SDOF building model. An efficient discrete springs and dashpots to represent the sway and rocking movements of the soil mass. Moreover, the equivalent-linear approach is used to numerically simulate the seismic soil response. Three different records of different intensities are used to excite the SDOF model to perform the analysis. The examined cases indicate that the use of improvement technique may simultaneously have a beneficial or harmful effect on the global seismic response of the system during earthquake loads.**

Keywords: **Soil improvement; Vibro stone columns; Dynamic soil properties; SDOF; Liquefaction.**

I. INTRODUCTION

During interdisciplinary studies of past and recent earthquakes, soil-structure interaction (SSI) has been found to significantly affects the seismic response of superstructures and foundations [1, 2]. When a structure is subjected to strong ground shakings, foundation oscillates depending on the supporting soil type, the foundation, and inertia of the superstructure. Recent studies proved that seismic response of structures founded on soft soil may significantly differ from those that founded on improved soil [3]. This fact is principally due to the influence of soil properties modification on the seismic response of the structure. In the geotechnical engineering field, liquefaction has been a matter of great interest for more than four decades. Liquefaction of supporting soil is a phenomenon occurs in saturated cohesion less soils subjected to ground shakings of long duration. Most structures whose foundations stand directly on liquefiable soil will experience significant damage. In addition to this, foundations settled due to dominant liquefaction-induced building displacement [4, 5]. Discrete vibro-stone columns are an acceptable method of subsoil improvement. It is often used for liquefaction mitigation of loose sand potentially subjected to severe earthquakes. The stone column technique is an acceptable method that is used since late 1950s to improve the strength parameters of soil and mitigate seismically-induced liquefaction hazards to structures rested on liquefiable soils. The construction of stone columns involves adding crushed or cobbled stones vertically that can be arranged to form a group of columns of either triangle or square forms with specified gap distances, diameters and distances. These formed groups are put below the level of base foundation of depth no less than 4 m [6, 7]. Unlike other techniques of soil improvement, the use of vibro technique induces slight vibrations that guarantees an appropriate choice for mitigating hazards due to the induced liquefaction. Moreover, these traditional techniques for improvement of ground requires a relatively short period installation time. The present paper aims to investigate the performance of the coupled soil -structure system supported on unimproved soils under seismic actions. For simplicity, a SDOF structure and improved-soil-foundation structure system shown in figure 2 is also considered in the analysis to examine the influence of installation of stone columns on the global responses of foundations and structures. Different seismic records from different regions are used to excite the building model. The equation of motion is derived, and numerical attempts to evaluate the seismic responses of coupled soil -structure system are utilized using a developed discrete time state space equation in time domain. Moreover, this paper focuses on the effects of reinforced soil by stone columns on the induced responses and peak responses for both base and the superstructure of a SDOF model founded on original and improved soil and seismically excited by three different ground motions.

II. DYNAMIC SOIL PROPERTIES

One of the most important inherent property of soil under cyclic loading is the nonlinear stress-strain behaviour. Therefore, consideration of that is inevitable. Dynamic properties of soil such as Stiffness and damping properties are very significant parameters for any dynamic soil structure interaction analysis which change with the cyclic shear strain amplitude under seismic loading. (see Figure 1). It is noted that the maximum shear modulus, Gmax, is the peak value of secant shear modulus at very low strain amplitude. The value of the maximum shear modulus is often used in practice with combination of both modulus degradation (G/Gmax-γ) and damping (D-γ) curves to solve dynamic problems when the soil enters to the range of plastic behavior. On the other hand, the damping ratio decreases with increasing stiffness; consequently, the damping ratio varies inversely with the shear modulus. Owing to the complexity of the nonlinearity mechanism, the well-known equivalent linear method proposed by [8] is used for dynamic analysis of the soil medium. A series of linear analyses is performed to investigate the effect of soil nonlinearity where the values of dynamic soil parameters mentioned above are varied until their values become compatible with the induced strain level in the soil. Moreover, supposition of soil behavior being a linear elastic can be considered for low level of strain in the soil. In an equivalent linear model, It is essential to obtain the compatible values of dynamic soil parameters using modulus reduction curve according to shear strain level in soil.

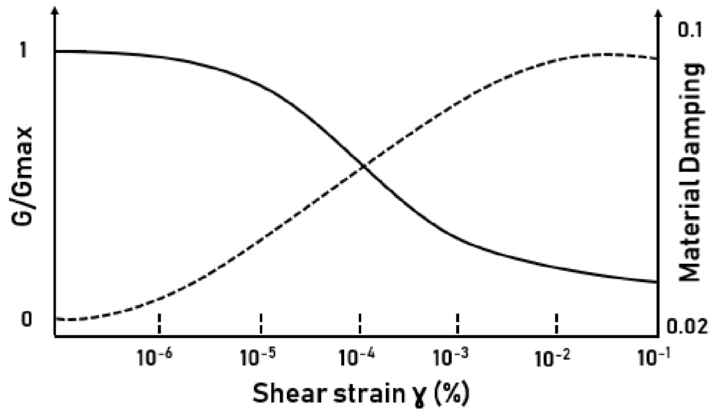

Fig. 1. the shear modulus and material damping curves used in equivalent linear model

Due to the simplicity and sufficient accuracy of lumped-mass parameter model, it is used to model supporting soil, improved and original soil condition, and describe the nonlinear behavior of soil beneath the base. In order to predict the dynamic through-the-soil interaction, an efficient discrete model is formulated for the rigid rectangular foundations. In this model the subsoil is modeled as isotropic and homogeneous half-space. The model involves a combination of horizontal and rocking soil movements by utilizing independent springs and dashpots.

The model parameters that effectively used to represent the stiffness coefficients of the soil-foundation system, as well as the damping coefficients can be found in Ref. [9].

To predict the maximum shear modulus Gmax,imp of an improved ground zone supporting a structure, an approach, called compatibility approach, based on small-strain shear-wave velocity measurements , can be described as[10]:

$$G_{max,imp} = G_{max,soil} [Gr. Ar + (1 - Ar)] \quad (1)$$

where $G_{\_max,soil}$ denotes the assigned peak value of shear modulus of the original unimproved soil, and Gr refers to the ratio between the small strain shear modulus of the stone column and the corresponding small strain shear modulus of stone column surrounding soil. In addition, Ar refers to the ratio between the column area and the loaded area [11]. Furthermore, the densities and shear modulus of the stone columns and intervening soil are assumed as constant throughout depth of soil layers.

III. MODELING AND IDEALIZATION

Seismic response behaviors of structure during earthquakes are affected by supporting soil conditions. In order to evaluate the influences of soil improvement on the seismic response of structures, a rigid foundation simple SDOF building model with the same damping ratio and period of vibration supported on weak soil, which later reinforced by stone columns, were conducted using three different time-history records. In order to compensate the lateral displacement and rocking of the unimproved and improved supporting soil, a lumped-parameter model consisting of springs, dashpots is used.

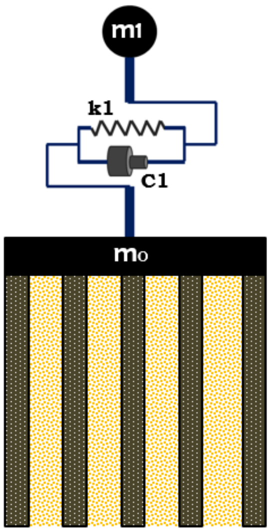

Fig. 2. Idealizes SDOF model

In Fig. 2, the idealized SDOF model of height h is represented by a mass m1 lumped at roof level and connected to a rigid foundation of mass mb through massless columns with stiffness k_1 and damping coefficient c_1. Also, the rotation and vertical deflection at the end of the columns are ignored. The suspension parameters (namely, stiffness and damping coefficient) shall be calculated as follows:

$$k_1 = \frac{4\pi^2 m_1}{T_1^2};\ \ c_1 = 2\xi_1 \tag{2}$$

Where T_1 and ξ_1 respectively represent the fundamental time period and damping ratio of the SDOF model. The stiffness and damping characteristic of the compliant soil-foundation system can be represented by k_h and c_h in the horizontal direction and by k_r and c_r in the rotational direction.

IV. EARTHQUAKE MODELING

For performing the dynamic time-history analysis and for comparative purpose, the SDOF building model considered herein in the study is subjected to three earthquake motion records from different locations namely; El-Centro, Loma-Prieta and Nahanni as shown in Fig.3. The absolute peak ground acceleration values of each of the selected records are 0.34g for the El-Centro, 0.63g for Loma-Prieta and 0.93g for Nahanni with time durations range from 10s to 15 s. The selected three earthquake records are scaled so as to match the specified intensity level before being used as input motions for carrying out the inelastic dynamic time-history analyses.

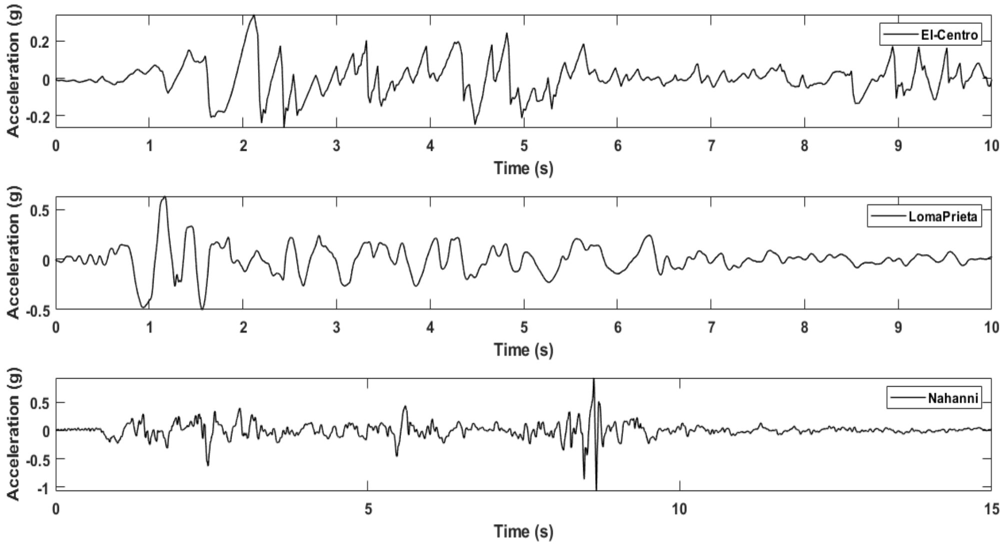

Fig. 3. Acceleration time history for the records used to perform the analysis

V. GOVERNING EQUATION OF MOTION

To examine the dynamic response of structure idealized as SDOF with a rigid foundation located at soil susceptible to liquefaction while considering the effect of soil improvement, dynamic analysis of improved-soil-foundation structure system has been carried out considering a suit of three earthquake records. The equation of motion describing the building model under earthquake loading is given by:

$$M\ddot{U} + C\dot{U} + KU = -M^{*}\ddot{U}_g \qquad (3)$$

where M is the mass matrix; C is the damping matrix and K is stiffness matrix; the vector $\ddot{U}$ is the relative acceleration and the vectors $\dot{U}$ and U are the relative velocities and the relative displacements, respectively. $\ddot{U}_g$ is the ground acceleration vector. M^{*} indicates the right-hand side mass vector.

The matrices and vectors of Eq. (3) which represent SDOF mathematical model are introduced in the following expressions:

$$M = \begin{pmatrix} m_1 & m_1 & m_1 h \\ m_1 & m_1 + m_b & m_1 h \\ m_1 h & m_1 h & m_1 h^2 \end{pmatrix}, C = \begin{pmatrix} c_1 & 0 & 0 \\ 0 & c_h & 0 \\ 0 & 0 & c_r \end{pmatrix}, K = \begin{pmatrix} k_1 & 0 & 0 \\ 0 & k_h & 0 \\ 0 & 0 & k_r \end{pmatrix} \qquad (4a)$$

$$\ddot{U} = \begin{pmatrix} \ddot{u}_1 \\ \ddot{u}_o \\ \ddot{\phi} \end{pmatrix}, \dot{U} = \begin{pmatrix} \dot{u}_1 \\ \dot{u}_o \\ \dot{\phi} \end{pmatrix}, U = \begin{pmatrix} u_1 \\ u_o \\ \phi \end{pmatrix} \qquad (4b)$$

Let u_1 be the horizontal movement of mass m_1 with respect to to the ground. $\dot{u}_1$ and $\ddot{u}_1$ denote to the velocity and acceleration of the mass m_1, respectively. The symbols u_o refers to the relative horizontal deformation between the foundation and rigid body motion of the ground. Also, φ refers to the rotation of the foundation due to base moment of the structure.

For the purpose of evaluating the dynamic responses of buildings, the dynamic equilibrium equation, Eq. (3), is solved numerically using a built MATLAB code following the state-space approach which formulate a mathematical model of a physical system. For the state-space analysis, the dynamic state responses in terms of mass deformations, velocities and accelerations are evaluated numerically to define and capture the responses of the system at a specified time.

VI. RESPONSE ANALYSIS AND DISCUSSIONS

An investigation of SDOF building model with supporting soil medium represented in the form of elastic continuum with and without stone columns was conducted to determine the dynamic response of both base foundation and superstructure using the time history record. MATLAB is also used for developing code to implement the analysis for the aforementioned scenarios under the considered excitation records.

Figure 3 illustrates time variation of story responses, displacement, velocity and acceleration, time-histories of the SDOF building considering and ignoring the effect of soil improvement for the Elcentro, Loma Prieta and Nahanni earthquakes. In addition, the obtained peak responses of the superstructure considering and ignoring the effect of the soil-stone column-structure interaction are presented in Table I for the considered earthquake records with different characteristics. As it can be seen from figure 3, highly significant differences between the two plots are exist. Furthermore, the results indicate that the maximum response values obtained for the improved base soil are much more evident especially for the displacement of the superstructure responses. It is worth noting that ground improvement with stone columns significantly reduce the shear wave velocity, accordingly the induced story displacements decreases.

TABLE I: PEAK RESPONSES FOR THE BUILDING MODEL CONSIDERING AND IGNORING SOIL IMPROVEMENT UNDER DIFFERENT EARTHQUAKE RECORDS

Earthquake	Soil condition	Response quantities		
	Responses	u	$\dot{u}$	$\ddot{u}$
Elcentro	Unimproved Soil	0.1659	0.4685	3.7550
	Improved Soil	0.1060	0.4964	4.5452
	% change in response due to improvement	36 ↓	6 ↑	21 ↑
LomaPrieta	Unimproved Soil	0.1084	0.6499	6.8178
	Improved Soil	0.1008	0.7641	7.7234
	% change in response due to improvement	7 ↓	18 ↑	13 ↑
Nahanni	Unimproved Soil	0.1432	0.4098	9.9363
	Improved Soil	0.0842	0.5207	11.2158
	% change in response due to improvement	41 ↓	27 ↑	13 ↑

On the other hand, the peak velocity and acceleration responses are increased with improving soil conditions. The obtained results indicate that the computed peak deformation responses of the building model founded on improved ground are reduced by around 36, 7, and 41% for the Elcentro, Loma Prieta and Nahanni earthquakes, respectively compared to those of the building model founded on unimproved ground. On the other hand, there was a significant increase in the percentage of both peak values of story velocity ranging 6, 18 and 27% and peak values of story acceleration ranging 21, 13 and 13% for improved supporting soil with stone columns, for the Elcentro, Loma Prieta and Nahanni earthquakes, respectively compared to those of the building model founded on unimproved ground.

The simulation results indicate that inclusion of stone column reinforcing elements in subsoil effectively increases soil stiffness in comparison to unimproved soil. Additionally, the soil begins to regain its strength. Subsequently, the soil is able to retrieve sufficient resistance, thus providing strength to the structure with a considerable reduction in displacement response. As demonstrated in Fig. 4, untreated soil can significantly elongate the fundamental period of structure, hence the structure becomes laterally flexible. The results prove that the displacement response of the building model founded on soft soil increase vibration amplitudes, which may result in further cracking that weakens the structure and decrease the stiffness and thereby decrease its eigenfrequencies, increase the damping due to local plasticity, and potentially lower velocity response of superstructure.

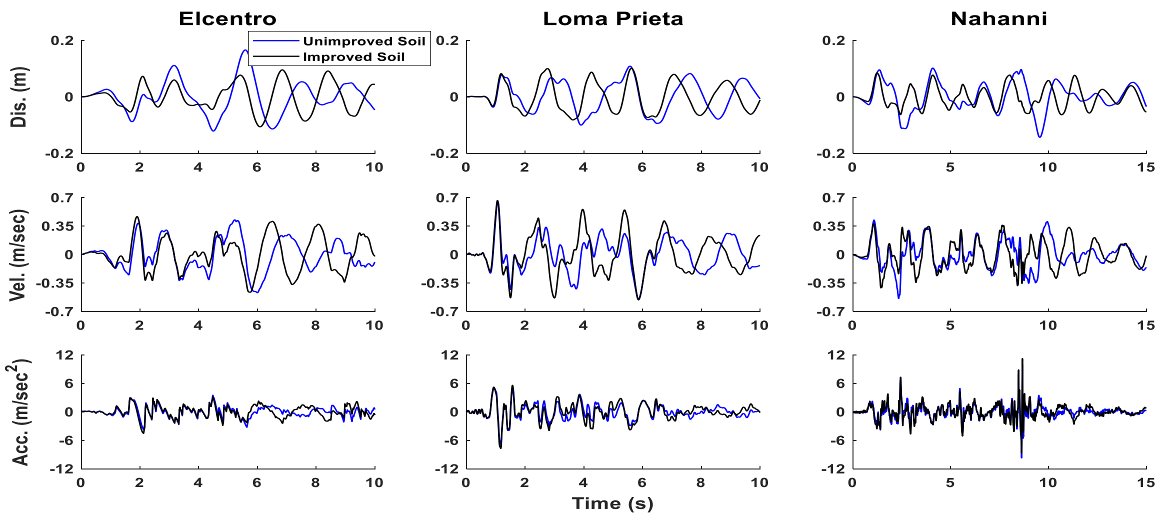

Fig. 4. Responses of the building model rested on unimproved and improved soil under the Elcentro, Loma Prieta and Nahanni earthquake records.

As shown in the figures 5, 6, and 7 improving subsoil with stone columns resulted in significant decrease in the obtained maximum response values in terms of base linear and angular responses. The captured peak linear displacements at the base of the building model founded on unimproved ground are 0.0526 m, 0.0547 m, and 0.0515 m under Elcentro, Lomaprieta and Nahanni earthquakes, respectively. Nevertheless, the corresponding maximum values when the foundation subsoil was improved are 0.0017 m, 0.0035 m, and 0.0040 m, respectively. The numerical values of the above imply that the stabilization of soil through stone columns has great ramifications and play important roles by altering the base responses of the building model. The peak values of the remaining linear and angular base responses for the considered herein ground motions are summarized in Table II. From Table II, it is evident that the effect of soil improvement is more evident for the induced base angular responses and less important for the corresponding base linear responses. Moreover, the maximum base displacements increase with negligence of soil improvement. The increase in base displacements are observed to be more in case of base angular responses when compared to base linear responses. The presented values in the table have been clearly demonstrated that there are a reduction in induced linear and angular base responses of buildings on improved ground where the soil become stiffer compared to unimproved ground thereby the interaction with the foundation becomes insignificant.

TABLE II: MAXIMUM RESPONSES FOR THE BASE OF THE BUILDING MODEL FOR TWO TYPES OF THE SOIL

Earthquake	Maximum base responses (unimproved soil condition) soil				Maximum base responses (improved soil condition)			
	u_0	$\ddot{u}_0$	φ_0	$\ddot{\varphi}_0$	u_0	$\ddot{u}_0$	φ_0	$\ddot{\varphi}_0$
Elcentro	0.0526	3.6803	0.0104	0.1443	0.0017	1.9153	9.78×10^{-5}	0.0049
Loma Prieta	0.0547	6.7883	0.0082	0.1482	0.0035	1.7947	9.52×10^{-5}	0.0098
Nahanni	0.0515	10.9109	0.0078	0.1352	0.0040	8.4311	7.9×10^{-5}	0.0161

u_0 = maximum displacement at base (m), $\ddot{u}_0$ = maximum acceleration at base (m/s^2), φ_0 = maximum base angular displacement (rad), and $\ddot{\varphi}_0$ = maximum base angular acceleration (rad/s^2)

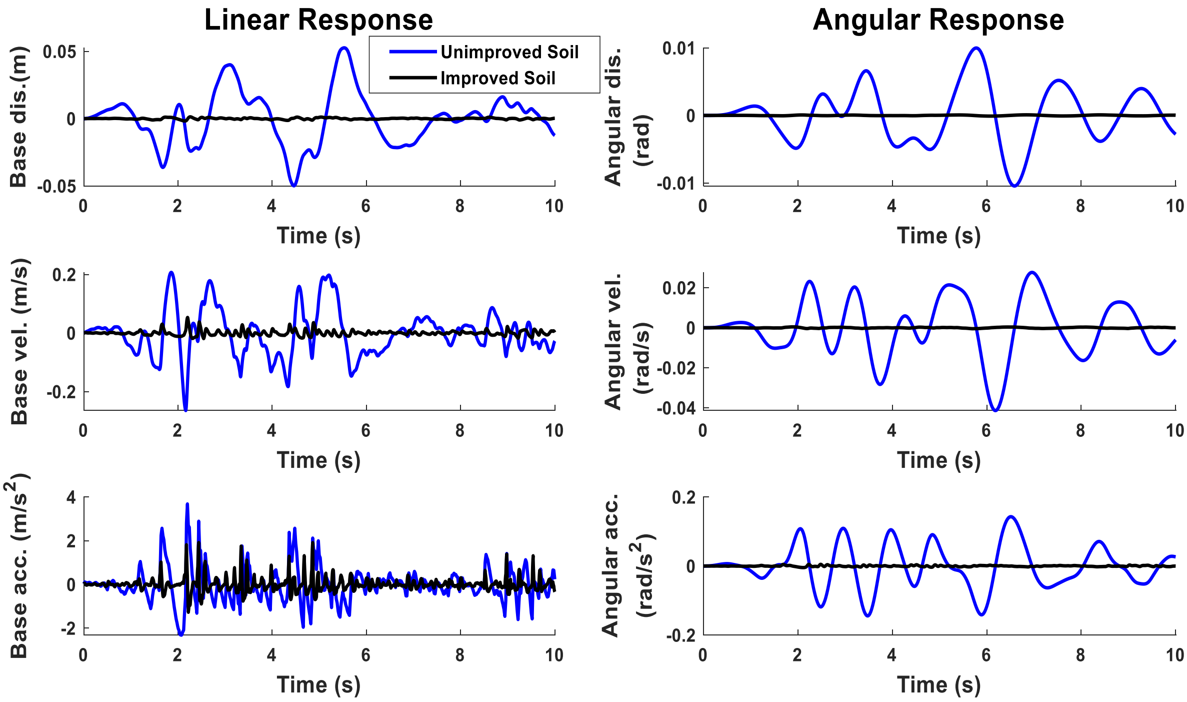

Fig. 5. Responses of building's base during the Elcentro records.

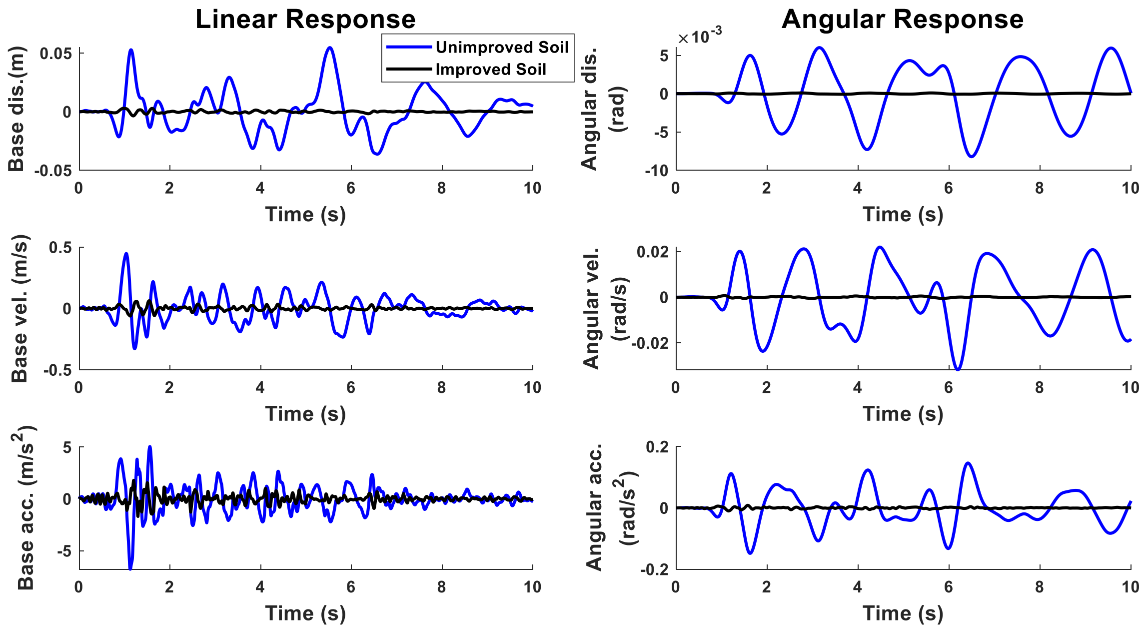

Fig. 6. Responses of building's base during the Loma Prieta records.

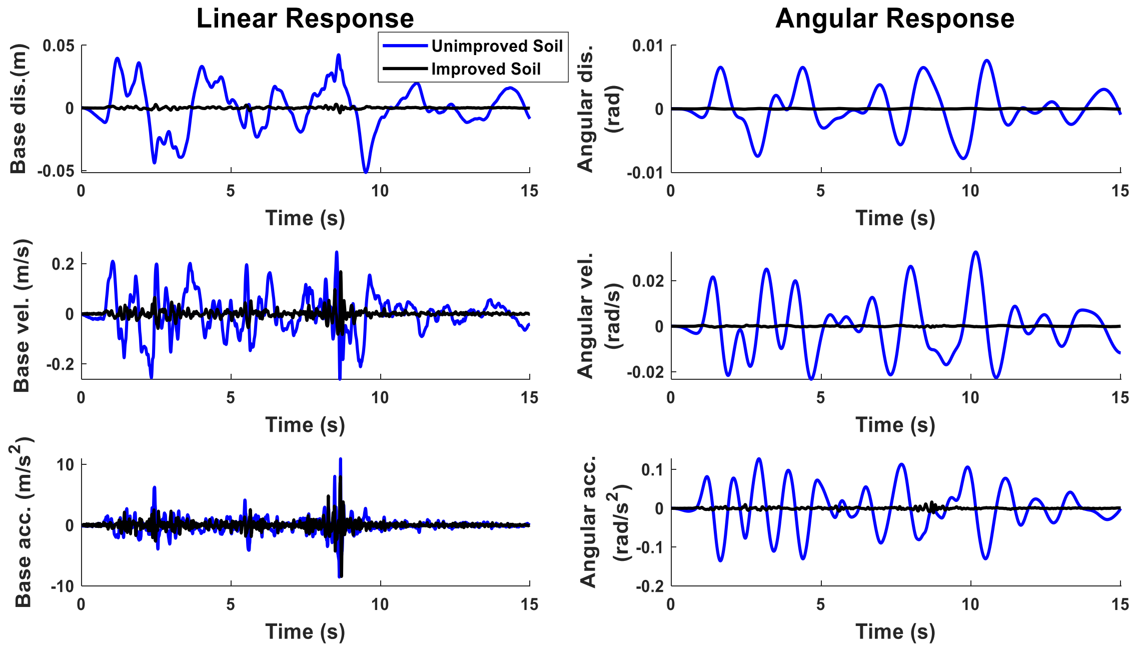

Fig. 7. Responses of building's base during the Nahanni records.

It is commonly accepted among earthquake engineers that the building important parameter known as natural period,T_n, is a robust parameter which influence on the seismic response of the buildings. To illustrate the effect of the installation of stone columns on the response of the SDOF building model seismically excited, different building models with a range of periods were used. Further, an investigation was conducted by varying the time period from 0.2 s to 2 sec.

Figure 8 shows the variation of peak storey responses against the variations of the periods of the SDOF model considering both the natural (unimproved) and ground-improved soils under various earthquake records. Referring to Fig. 8 some quantitative conclusions have been obtained, for instance the peak value of the displacement demand increases as the fundamental period increase of the SDOF model for both types of sub-base soil under all levels of earthquake excitations considered in the study. Moreover, significant differences between the plots for the peak responses obtained for the original subgrade soil and the corresponding values associated with the improved soil are observed. The results also revealed that the peak displacement values are found to be more in case of untreated soil as a supporting stratum than the other type of soil treated by stone columns leading to a significant reduction in the maximum displacement responses under all the ground excitations considered. As can be seen from the figure, when the SDOF model is of low fundamental natural periods, the difference between the plotted curves is much more pronounced. Moreover, it is worth noting that as the structural natural period increases, the difference between the obtained maximum displacement responses decreases, and thus the use of stone column as a mitigation technique seems to be insensitive. Hence, stabilization of soft soils with stone columns found to be an effective and valuable in decreasing displacement response values especially for buildings with short-periods subjected to seismic loads. In contrast, soil improvement with stone columns exhibiting high values of peak acceleration responses comparing with corresponding values obtained for the unimproved soil especially when the building is modelled to be of low natural periods for all the considered ground motions.

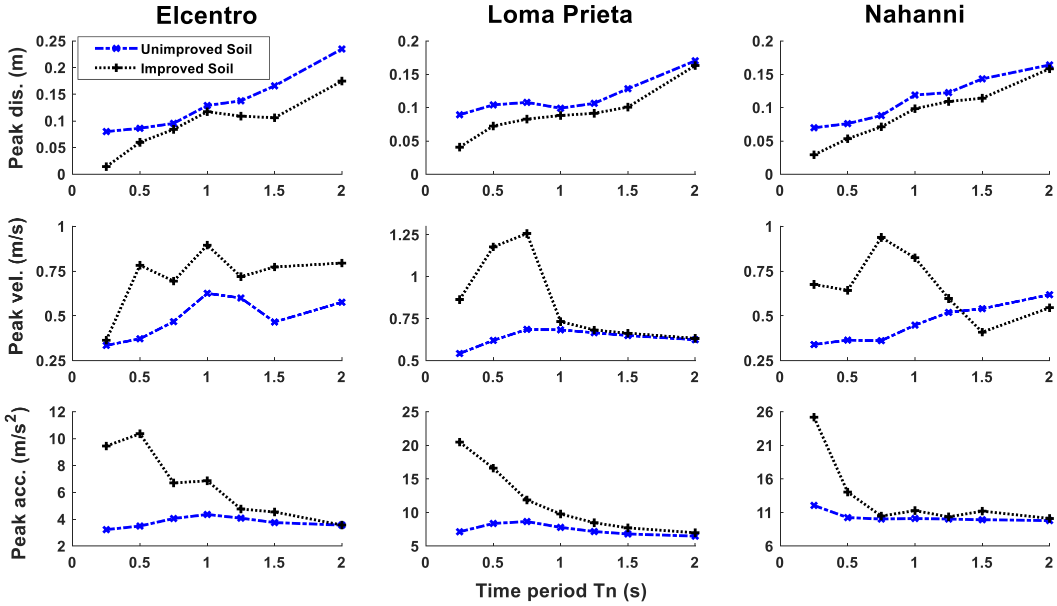

Fig. 8. induced peak superstructure responses for the building model founded on the original soil and the improved soil against fundamental periods during different earthquakes.

VII. CONCLUSION

In this study, an attempt is made to examine the influence of using stone columns technique in improving liquefiable soils. The performance of an SDOF building model under three different earthquake records is investigated. According to the obtained results from the analysis, it has been found that fixing stone columns into weak soil increases the stiffness of the soil and the resistance of the soil to ground deformation increases as well consequently. The enhancement in soil properties provides strength to the building model with substantial reduction in the obtained displacement responses. On the other hand, the induced acceleration of the building's storey increases as a result of adding stone columns to the weak soil beneath the SDOF building model. Regarding the base responses of SDOF building model, it has been found from the analysis that the use of mitigation techniques to strengthen the supporting soil has considerably reduced linear and angular displacement and acceleration responses. Changing the fundamental period of the model indicated that at lower values of building's periods, the efficiency of the used mitigation technique in reducing the displacement response is considerable. On the other hand, changing the fundamental period of the model has insignificant effect in reducing response of the base.

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