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INVESTIGATION OF THE PERFORMANCE OF ELASTIC AND YIELDING STRUCTURES IN IMPROVED SOIL-FOUNDATION-STRUCTURE SYSTEMS

Konstantinos TREVLOPOULOS[1]

ABSTRACT

This paper briefly discusses critical issues which arise during the assessment of the seismic performance of elastic or yielding structures on improved soil. As far as foundation ground improvement is concerned, it focuses on the case of typical stone columns and granular columns by mixtures of gravel and granulated rubber. The aim is to highlight that the seismic demand, in terms of the acceleration versus displacement response spectra, currently used by established assessment methods, as well as in terms of required ductility and required force-reduction factor, is affected by these types of ground improvement. Time-history finite element analyses of coupled soil-foundation-structure systems are employed, in which the structure is modeled with an elastic or yielding single degree-of-freedom oscillator. It is seen that the performance point of the elastic superstructure in the case of improved soil conditions may vary significantly from the spectra resulting from the corresponding system with the original, unimproved soil, but the trend of the results is not clear. Then the discussion is expanded by taking into account structural yield. The required ductility and force-reduction factor, the elastic and inelastic spectra at the base of the structure are calculated in the case of the original and the improved foundation ground. Most importantly, it is stressed that it is uncertain whether the effect on the demand is favourable or not.

INTRODUCTION

The assessment of the seismic performance of structures on improved ground is challenging, as there are uncertainties about the effect of major factors in this process: the effect of soil-foundation-structure interaction on the elastic response of structures; seismic demand on ground surface of soft or loose soils even in the absence of any type of ground improvement; their combined effect on the performance of yielding structures; and the effect of ground improvement in particular.

As far as ground motion is concerned, Pitilakis et al. (2012) using the strong-motion database of project SHARE and applying a logic-tree method highlighted the uncertainties concerning the site amplification factor of the elastic response spectra in Eurocode 8 in the case of soil Type D sites (soil profiles requiring improvement generally belong to this class) and suggested that site-specific ground response analyses should be employed to estimate seismic loads on ground surface. In the case of soil Type C sites (in which improved soil is generally classified) they suggested a significantly higher soil factor of 1.70 instead of the 1.35 currently in the code. Furthermore, the effect of ground improvement and soil-foundation-structure interaction on foundation input motion and structural response ranges from favourable to detrimental and depends heavily on the configuration of each soil-foundation-

[1] Ph.D. candidate, Aristotle University of Thessaloniki, Thessaloniki, Greece, ktrevlop@auth.gr

structure in particular and the characteristics of the excitation (Kirtas and Pitilakis, 2009, Pitilakis et al., 2010).

Jarernprasert et al. (2013) proposed an analytical method to estimate the displacement and ductility demands of hysteretic nonlinear structures taking into account soil-structure interaction. They showed that these demands are larger and the force-reduction factor of design spectra is lower when soil-structure interaction is considered in comparison to the corresponding fixed-foundation structures. That agrees with earlier results of Mylonakis and Gazetas (2000), who also stressed the importance of rigid-body motion in the calculation of ductility demands and most importantly showed that soil-structure interaction has an uncertain effect on structural response. Mylonakis and Voyagaki (2006) showed that yielding oscillators under near-fault record excitations with forward rupture directivity pulses may have a ductility demand significantly higher than the ductility demand calculated based on the equal-displacement or equal-energy rules, which are part of modern prevalent performance assessment methods. Such pulses are known to exist in the recordings from the earthquakes of Chi-Chi, Northridge and Kobe (Cox and Ashford, 2002).

This paper focuses on two cases of ground improvement; typical stone columns and columns consisting of a mixture of gravel and granulated rubber. This type of composite granular material has been proposed as foundation ground replacement material (Tsang, 2008). Both these ground improvement methods reinforce the foundation ground and increase drainage. Thorough documentation of the properties of soil-rubber mixtures is found in Anastasiadis et al (2012a, 2012b), Senetakis et al. (2012a, 2012b). I assess numerically the performance of a simplified structure within a coupled improved soil-foundation-structure system. Firstly the effect of ground improvement on the peak performance of the elastic structure is investigated. Next, the demand of the yielding structure is directly assessed and I elaborate on it using as reference the performance of the fixed-base structure based on the N2 method (Fajfar and Gašperšič, 1996, Fajfar, 2000, Aydinoğlu, 2012) and the spectra of Eurocode 8 (Comité Européen de Normalisation, 2004).

NUMERICAL ANALYSIS

For this study plane-strain finite element analyses of coupled soil-foundation-structure systems were performed with OpenSEES (Mazzoni et al. 2009). The structure is a single-degree-of-freedom oscillator on a rigid foundation. Sliding or uplift of the foundation was not considered and constraints of equal degrees of freedom were assigned to the nodes of the beam elements of the foundation and the corresponding nodes of the quad elements of the foundation ground. General schematics of the models and their configurations are shown in Fig.1. I assumed they are representative of a single-column pier with a surface foundation of a two-lane overhead bridge crossing. Kirtas et al. (2009) have thoroughly validated this modelling scheme; theoretically and experimentally. The structure has been adopted from Mylonakis et al. (2006) with the exception of the foundation width (2B), which was increased to 8.0 m although our study concerns foundation grounds of higher strength.

The series of excitations (Table 1) was scaled to peak acceleration of 2.94 m/s^2 (0.30 g) and applied to the lower boundary of the models which was modelled as an elastic bedrock. The shear modulus of the original soil elements in the two dimensional analyses was uniformly assigned a single value across the model. Its value was selected as the average value resulting from a series of one-dimensional equivalent linear analyses with EERA (Bardet et al., 2000) where the same excitations were used. The assumption was made that the developed shear strains in the one-dimensional analyses represent those in the two-dimensional models as well. Such a procedure is described by Pitilakis et al. (2011). The improved ground zone has a width and depth of 16.0 m, which is double the length of the foundation (4B).

The first set of analyses concern a linearly elastic superstructure and at next step the yielding behaviour of the superstructure was taken into account. This was achieved through a rotational spring at the base of the beam element of the superstructure assuming concentrated plasticity at that point.

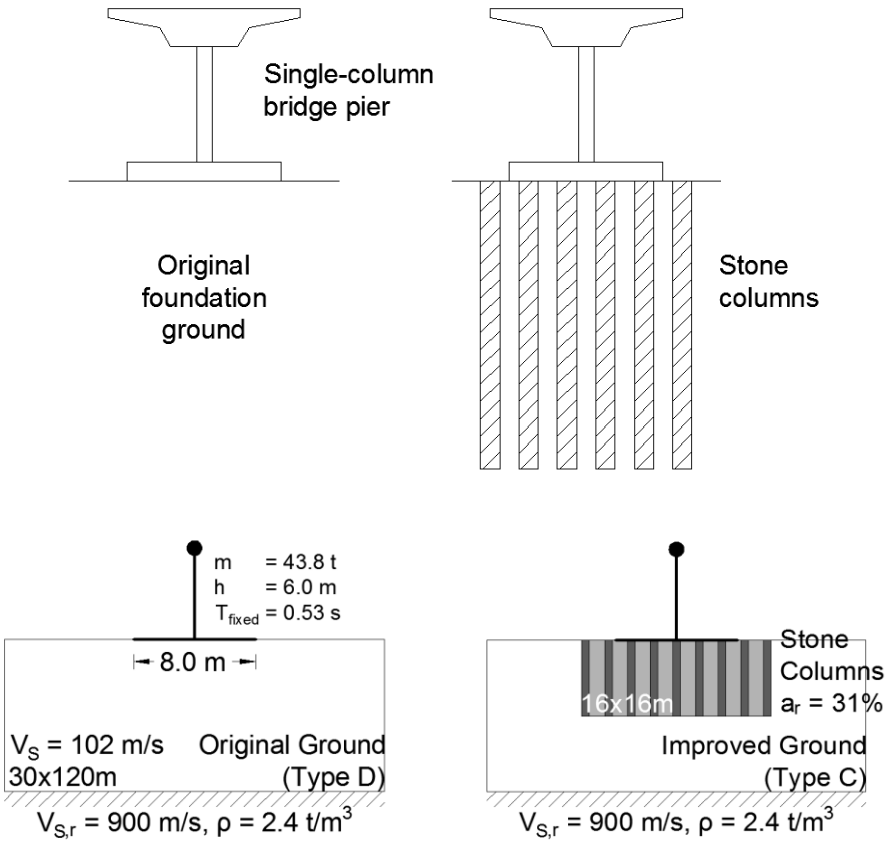


Figure 1. General schematics of the finite element models of the soil-foundation-structure systems

Table 1. Records used as bedrock excitation after being scaled to peak acceleration of 0.30 g.

Event	M_w	Station	Component	PGA (g)
[1] Kozani (Greece) 1995	6.5	1320 (Prefecture)	X	0.21
[2] Chi-Chi (Taiwan) 1999	7.6	Chiayi	90°	0.81
[2] Kobe (Japan) 1995	6.9	KJMA	00°	0.82
[2] Kobe (Japan) 1995	6.9	Takatori	00°	0.79
[2] Northridge (USA) 1994	6.7	Pacoima Dam, Downstream, CSMIP Station No. 24207	265°	0.43

1: Margaris (2001), 2: Archuleta et al. (1999)

PERFORMANCE OF THE ELASTIC SUPERSTRUCTURE

Fig.2 shows the performance points of the superstructure on the original and on the improved ground with stone columns for each excitation. The performance of the superstructure is assessed with a direct method. The performance point of the superstructure for each analysis is defined by the pair of values of the maximum absolute values of the acceleration of the superstructure and its relative displacement to the node at the middle of the foundation. Fig.2 features also the elastic spectra of Eurocode 8 for soil Types C and D, to which the improved and the original foundation ground are respectively classified. The performance of the superstructure in the case of the improved foundation ground in comparison to the case of the original ground results either lower or higher depending on the excitation.

If the effective period of the structure (i.e. taking into account the effect of soil-foundation-structure interaction) was given and we were to assess the performance of the superstructure in two cases; on the original ground and on the improved ground, and we were to use the spectra of Eurocode 8 (Fig.3), we would conclude with certainty that the superstructure on the improved ground has a better performance. For the problem at hand, that would be 15 % lower acceleration in the case of the improved ground. Based on the results of the analyses however, which have no discernible trend, we cannot be certain that superstructure acceleration in the case of the iproved ground is lower than in the case of the original ground and consider that a rule of thumb.

PERFORMANCE OF THE YIELDING SUPERSTRUCTURE

The inelastic structure has a yield superstructure acceleration of 4.23 m/s^2, which corresponds to a force-reduction factor of 2.0 in relation to the elastic spectrum for Type C soil for design acceleration (a_g) of 2.94 m/s^2 (0.30 g). The displacement demand of the yielding structure, based on the demand of the linear elastic structure, is 0.064 m and 0.091 m for Type C and Type D soil according to Eq.(1) (Fajfar, 2000).

$$S_d = \frac{S_{de}}{R_\mu}\left(1 + \left(R_\mu - 1\right)\frac{T_C}{T^*}\right) \tag{1}$$

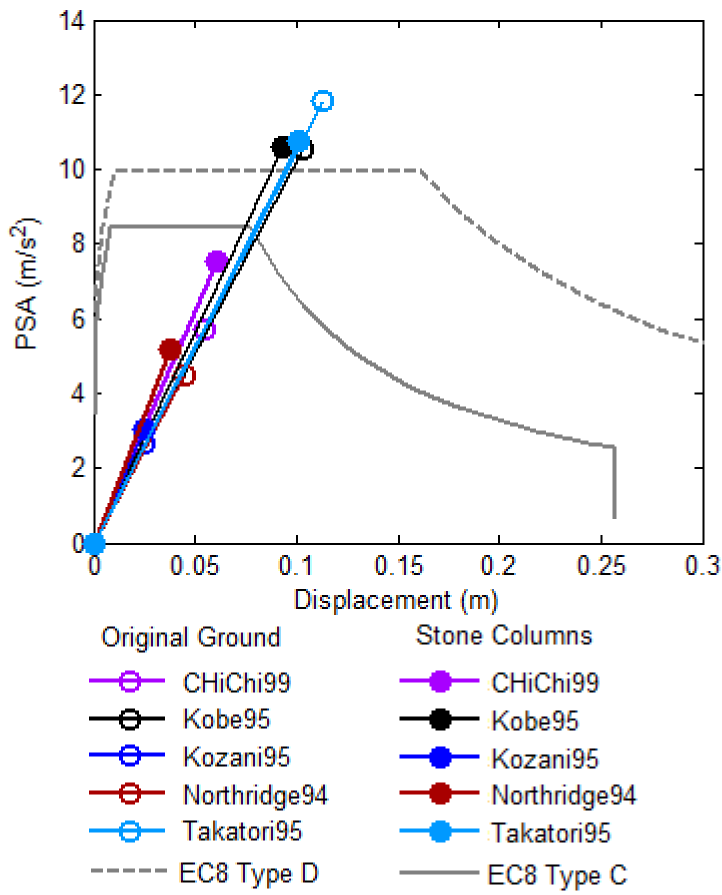


Figure 2. Performance points of the superstructure in the soil-foundation-superstructure models in the case of the original foundation ground and the improved with stone columns.

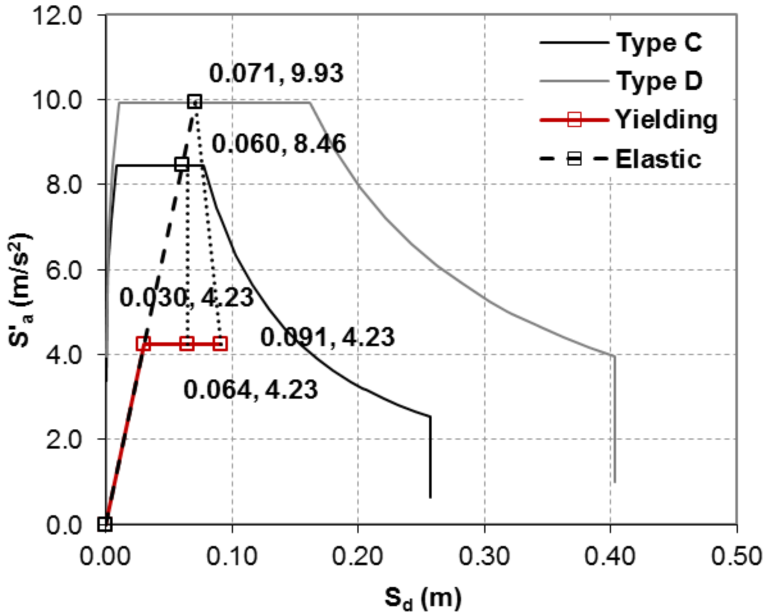


Figure 3. Performance assessment of the fixed-base structure based on Eurocode's spectra for the original (Type D) and the iproved foundation ground (Type C).

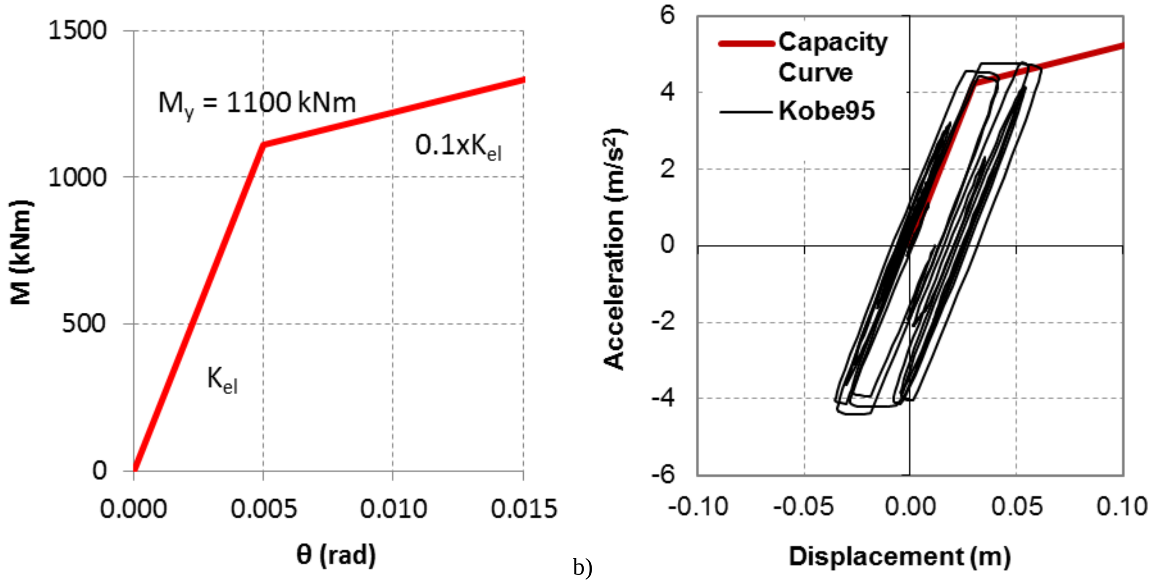
The required ductility factor (μ_{req}) in these cases is 2.1 and 3.0, corresponding to the improved and to the original ground. Therefore, based on the spectra of Eurocode 8 and neglecting soil-foundation-structure interaction effects, we would say with certainty that ground improvement has a favourable effect on ductility demand.

The spring used at the base of the beam finite element of the structure uses a bilinear hysteretic law (Ibarra et al. 2005, Lignos and Krawinkler 2009, 2010) as demonstrated by Eads et al. (2013). Any form of cyclic deterioration was ignored in its definition. Fig.4a shows the defined moment-chord rotation relationship and Fig.4b shows the acceleration versus displacement loops of the yielding fixed-base structure under an excitation causing post-yield rotation and the idealized capacity curve of the superstructure. The selected spring properties are considered to reflect efficiently the inelastic behaviour of the structure through the time-history analyses.4

The numerical results of acceleration versus the relative displacement of the superstructure to the foundation are shown in Fig.5a and Fıg.5b for the case of stone columns and GRM columns respectively. Based on the inelastic superstructure displacements the required ductility factors for each were calculated and their numerical values for these example are shown in Table 2. Next, usisg these factors the inelastic demand spectra were derived from the foundation time-history. Fig.6a and 6b show the elastic and inelastic response spectra in the case of the original and the improved ground. Dividing the corresponding elastic and inelastic acceleration spectra (Eq.2) results the required force-reduction factor (R_μ) as a function of the period (Fig.7a, 7b).

$$R_{\mu(T)} = \frac{S_{a,el(T)}}{S_{a,\mu(T)}} \tag{2}$$

Where $R_{\mu(T)}$ the force-reduction factor, $S_{a,el(T)}$ and $S_{a,\mu(T)}$ the elastic and inelastic spectrum values respectively. The plots of R_μ (Fig.7a, Fig.7b) have a distinctive peak at the neighborhood of the fundamental period of the soil profile. Increased demand at those periods is anticipated as response spectra of soil profiles of NEHRP category D may have distinguished strong peaks (Ziotopoulou and Gazetas, 2010). At that period range is the effect of soil improvement the strongest. Once again we see that the demand depends of the frequency content of the excitation. In the case of Fig.7a soil improvement results in increased demand, while in the case of Fig.7b results in lower demand.



a) b)

Figure 4. a) Backbone of of the non-liear rotation spring at the superstructure. b) Loops of superstructure acceleration of the fixed-base yielding structure versus its relative displacement to its base.

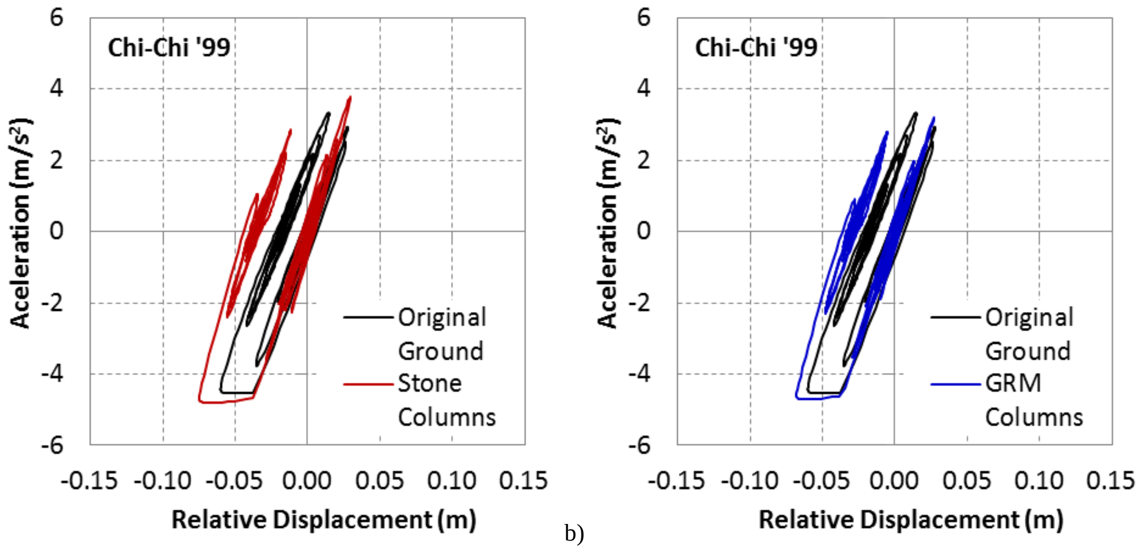


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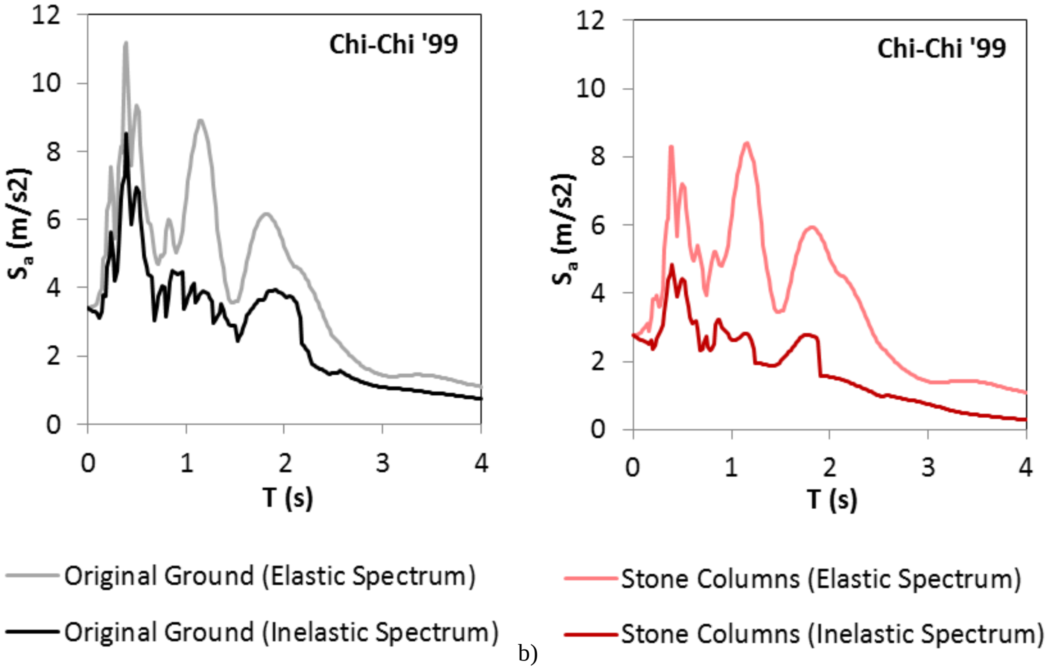
Figure 5. Loops of superstructure acceleration versus relative displacement to its foundation.

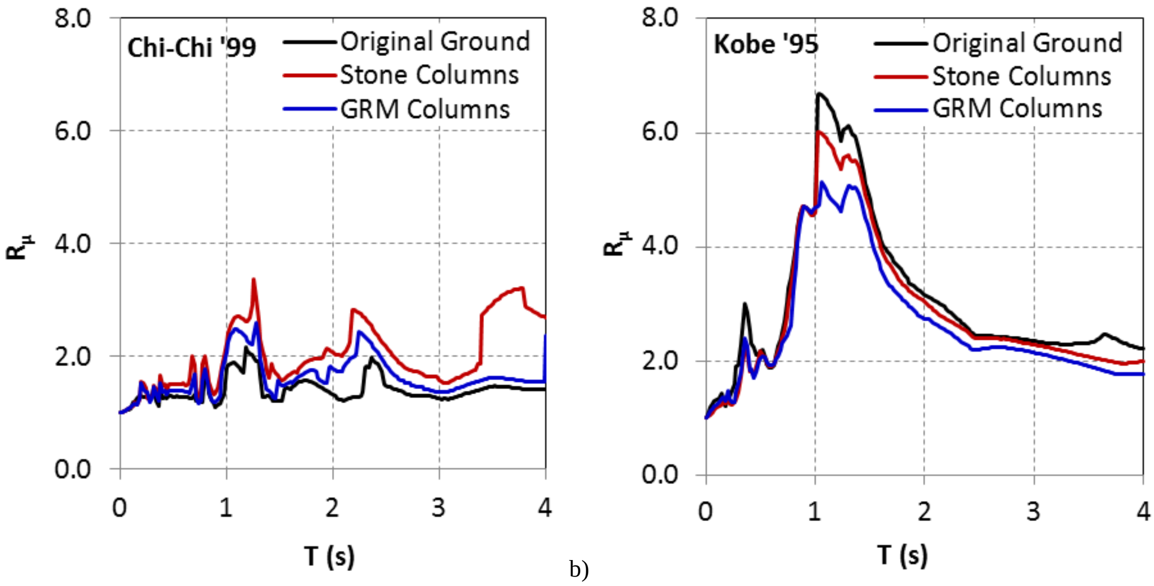
Table 2. Yield superstructure displacement and required displacement and demand for the Chi-Chi ’99 excitation.

	δ_y (m)	δ_{req} (m)	μ_{req}
Original	0.044	0.067	1.5
Stone Columns	0.037	0.074	2.0
GRM Columns	0.040	0.071	1.8



a) b)

Figure 6 Elastic and inelastic response spectra (for the requrired ductility) based on the time-history at the middle of the foundation of the soil-foundation-structrure models in the case of the original (a) and the improved (b) foundation ground.



a) b)

Figure 7 Force-reduction factor of the superstructure in the original and improved soil-foundation-structure system.

CONCLUSIONS

Elastic and inelastic time-history analyses were performed using a finite element modeling scheme to assess directly the seismic performance of a simplified structure on improved ground by taking into account soil-foundation-structure interaction. The performance points of the elastic structure were calculated for a series of excitations and it was observed that ground improvement with stone columns and GRM columns affects them significantly. However, it is not certain that this effect is in favor of the performance of the structure or not. Subsequently, the ductility demand and the required force-reduction factor ware calculated based on the models featuring a yielding structure. We saw that soil improvement resulted in increased demand for some excitations, while Eurocode 8 suggests that soil improvement reduces demand by switching from the spectrum of Type D sites to the spectrum of Type C sites.

The spectral values of the elastic spectrum of Eurocode 8 for soil Type C sites, which correspond to the improved ground, are significantly lower than the values of its spectrum for Type D sites. Such differences do not appear in the numerical results. The spectra for Type D2 and C2 according to the classification proposed by Pitilakis et al. (2013) may reflect better the difference between seismic demand on the original and improved ground in this study.

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