CONTRIBUTION OF SOIL MATERIAL DAMP-ING TO THE DEMANDS OF SOIL-MDOF STR-UCTURE SYSTEMS

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ABSTRACT

In this paper, the role of soil material damping in the seismic response of soil-structure systems is investigated subjected to 59 ground motions. For this purpose, the superstructure is modeled as a nonlinear multi-degree-of-freedom shear building. The beneath soil is simulated based on the cone model concept. The 3-, 10-, 15- and 25-story models are considered as low- and high-rise buildings, respectively. Two values of 0 and 0.25 are assigned to soil material damping in order to show how soil material damping affects the responses. A comprehensive parametric study is carried out and effects of various parameters such as non-dimensional frequency, structural nonlinearity, and number of stories on the contribution of soil material damping to the structural responses are detected.

INTRODUCTION

Seismic assessment of multi-story buildings are typically based on the assumption that they are mounted on a rigid medium and Soil-Structure Interaction (SSI) effects are ignored. In contrast, SSI phenomenon can tremendously affect the response of structures. The fixed-base assumption is inappropriate for many structures, and structural systems that incorporate stiff vertical elements for lateral resistance (e.g. shear walls, braced frames) could be very sensitive to the small translational and rotational movements that are disregarded in the fixed-base assumption.

SSI effects influence structural responses through two main different mechanisms. First, kinematic SSI that results from the presence of relatively stiff elements of the foundation on soil and causes Foundation Input Motion (FIM) to completely deviate from Free Field Motion (FFM) (FEMA 440). Such phenomenon filters the ground motion experienced by the structure via base-slab averaging and embedment effects (Kim and Stewart, 2003). Second, after the ground motion is sensed by the superstructure and it starts vibrating, inertial SSI incorporates into the structure movements and influences its responses through foundation flexibility and damping of the soil. Foundation flexibility refers to springs usually used by structural engineers in order to model deformations occurred at the base of the structure (Liou and Huang, 1994). Foundation damping includes radiation and material damping related to the soil (Stewart et al. 1999). Various models have been used by researchers in order to include SSI mechanism into the seismic analysis of structures. In many investigations, Finite Element (FE) and Boundary Element (BE) approaches were employed (Yerli et al. 2003); however, such rigorous methods are very time-consuming and structural engineers are not in favour of conducting FE-BE-based analyzes. Instead, discrete models have been drawn the attention of structural engineers due to their simplicity and efficiency (Wolf and Deeks, 2004). It is confirmed that the discreet models such as cone model can meet the sufficient engineering accuracy. A deviation of the -20 % to +20 % of the results of the cone model from those of the rigorous methods such as finite element for one set of input parameters is generally sufficient since all the uncertainties can never be eliminated (Wolf and Deeks, 2004)

A discussed earlier, soil material damping is one of the main factors incorporating into the inertial SSI analysis. Many researchers have been focused on the soil material damping in seismic analysis of soil-structure system and there is no unanimity on the contribution of soil material damping to the analysis. Richart et al. (1970) ignored material damping versus radiation one assuming a perfectly elastic medium for the soil. In contrast, Sienkiewicz (1993) claimed that the effects of material and radiation dampings might be of the same magnitude. However, in their model, the superstructure was not explicitly modeled. Wolf (1985) demonstrated that in case of shallow foundation, the impacts of material damping could be more significant than the radiation one. Recently, Ambrosini (2006) made attempts to elucidate the effects of soil material damping on seismic analysis of soil-structure systems. It was noted that soil material damping is effective on bringing down the peak displacement of the superstructure. However, the model, used for superstructure, was based on Vlasov's theory of thin beams and the model was not capable of evaluating variations of seismic parameters over the structure height. The effects of the structure parameters such as structural ductility and number of stories, desirable for structural engineers, were not investigated and favourable seismic design variables like interstory drift ratios, story shears and their distributions along the height of the structure were not detected. Furthermore, only three earthquake records were employed to assess the responses which cannot be reliable.

As it was discussed previously, a comprehensive study is required to detect the importance of soil material damping on the different design demands of the structure and clarify how the structure demands can alter due to the change in the soil material damping value in the seismic SSI analysis. Therefore, the main objective of this paper is to conduct an in depth sensitivity and parametric study in order to elucidate the importance of soil material damping in determination of seismic demands of structures. To this end, an extensive suit of 59 far-fault ground motions are used as input seismic motions. A nonlinear shear multi-story structure is employed as the superstructure and soil beneath the foundation is simulated based on cone model concept.

SOIL-MDOF STRUCTURE MODEL

The superstructure model is based on the structural modeling explained by FEMA 440. On the basis of FEMA 440 (chapter 2), in some cases (e.g. shear beam or strong beam-to-weak column frames), engineers can simplify complex structural models into equivalent MDOF models which are called stick models. Herein, the stick model of shear beam is used. Consider an n-story shear building as shown in Figure 1, supported by swaying and rocking springs and corresponding dashpots. m_i and I_i stand for the mass and the mass moment of inertia around its geometric center in the i^{th} story, respectively. The story height and the effective load (dead as well as live load) are taken 3.3 m and 10 kN/m^2 as for the conventional buildings. Also, lateral stiffness and yielding strength over the structure height are distributed nonuniformly to account for higher-mode effects. To this end, the vertical distribution factor is computed as suggested by ASCE/SEI 7-10 standard.

It should be noted that 3-, 10-, 15-, and 25-story buildings are assumed for superstructure with respective fundamental fixed-base periods of 0.3,, 1.1, 1.5, and 2.3 s. Viscous damping ratio of the system is determined based on *Rayleigh's* damping concept and the damping ratio corresponding to each mode is assumed to be 5 %. The analysis includes a sufficient number of modes to obtain a combined modal mass participation of at least 90 percent of the actual mass based on ASCE/SEI7-10 standard. Therefore, upper period, used in order to calculate Rayleigh damping coefficients, corresponds to the fundamental fixed-base period and lower period complies with the last mode providing cumulative modal mass participation factor of at least 0.9.

The story shear force-interstory drift relationship is to be modeled by a normal bilinear hysteretic rule and the post-elastic stiffness ratio of each story is considered 0.05. The nonlinearity in the superstructure is described based on structural ductility assuming 2 and 8. The most convenient parameter to quantify the global ductility of structural systems under different ground motions is the displacement or translational ductility, which is defined as the ultimate-to-yield roof displacement ratio. However, displacement ductility should be expressed as story drift ductility rather than roof lateral displacement, as employed herein. Story translational ductility is a measure of the ductility distribution along the height in multi-story structures and can be utilized to detect localized inelastic demands in irregular structures. Herein, for each soil-structure system under each ground motion record, story ductility is calculated as maximum story drift divided by yield story drift in each story. Therefore, structural ductility is taken as the peak of story ductility which can occur at any story.

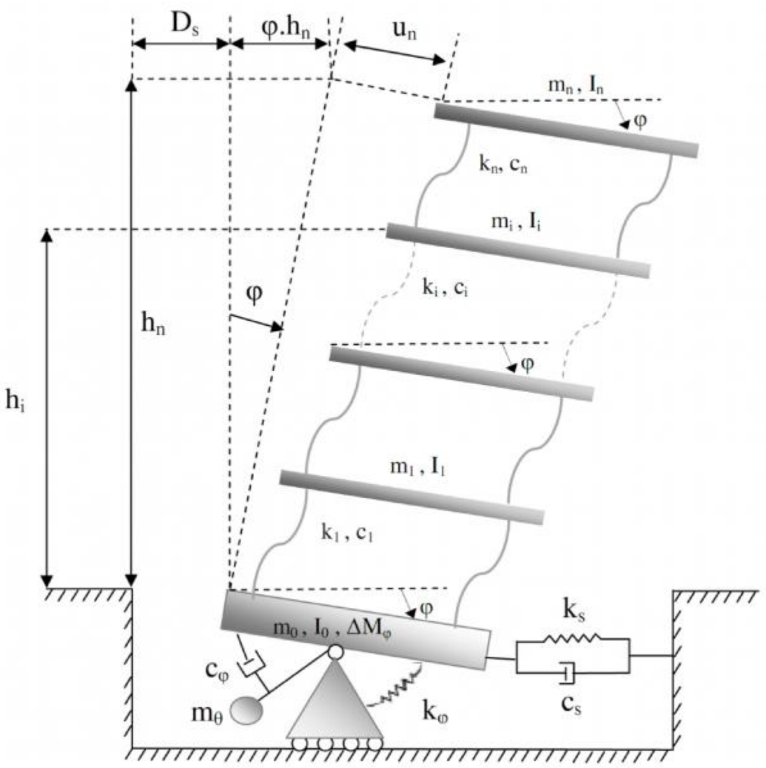

Figure 1. Soil-MDOF structure model

The foundation is treated as a circular rigid disk and the flexibility of the foundation is not taken into account. The mass and mass moment of inertia of the foundation is denoted by m_0 and I_0, respectively. The foundation mass is considered so that foundation uplift does not occur due to design earthquake load according to ASCE7-10 as well as considering the practical relationship between the ratio of m_0 and total mass of structure, M, for typical buildings. In this case, $0.2 \leq m_0/M \leq 0.5$ is selected for the studied structures. Note that only the inertial part of the SSI is considered in this paper. In other words, the kinematic part of the SSI is not included assuming the rigid foundation to lie on the surface of the soil with no embedment and subject to vertically incident plane shear waves with particle motion in the horizontal direction. No scattered analysis exists as well. A lumped-mass parameter model is adopted to take into account soil and interaction mechanism. The soil underlying the foundation is regarded as a homogenous half-space and substituted with a simplified 3-DOF system on the basis of cone model concept. Cone model was proposed by Meek and Wolf (1993) and Wolf (1994) in order to avoid carrying out time-consuming and laborious analysis. In comparison with the more rigorous numerical methods, cone model requires only simple numerical manipulation within reasonable accuracy in engineering practice. The cone model is based on the assumption that the interaction mechanism can be estimated approximately by a truncated semi-infinite cone.

The horizontal (sway), s, and the rocking, φ, degrees-of-freedom are considered as representatives of the translational and rotational motions of the foundation, respectively. D_s and φh_n indicate the horizontal displacement components caused by the sway and rocking motions at the roof story. u_n represents the deformation that is associated with the strain in the superstructure. To consider the frequency-dependent rotational spring and dashpot coefficients, the additional internal rotational degree of freedom, θ, is assigned to a polar mass moment of inertia, m_θ, and connected to the foundation node using a rotational dashpot. In the case of nearly incompressible and incompressible soil ($0.33 < \upsilon < 0.50$ where υ is Poisson's ratio of soil), two features are enforced into the soil model: (a) the axial-wave velocity, V_a, is limited to $2V_s$; (b) a trapped mass moment of inertia, ΔM_φ, associated with soil, which moves as a rigid body in the same phase with the foundation for the rocking motion, is ascribed to the foundation node. ΔM_φ is added to I_0 for the soil with Poisson's ratio greater than 0.3. The coefficients of springs and dashpots for the sway and rocking motions are computed using the following formulas:

$$k_s=8\rho V_s^2 r/(2-\upsilon),\quad C_s=\pi\rho V_s r^2 \tag{1}$$

$$k_\varphi=8\rho V_s^2 r^3/(3(1-\upsilon)),\quad C_\varphi=\pi\rho V_a r^4/4 \tag{2}$$

$$m_\theta=(9\pi^2/128)\rho r^5(1-\upsilon)(V_a/V_s)^2,\quad \Delta M_\varphi=0.3\pi(\upsilon-0.33)\rho r^5 \tag{3}$$

The parameters used in the above equations are defined as the followings:
ρ : Mass density of soil which also depends on shear-wave velocity and assumes to be 2.35 and 1.95 t/m^3 for shear-wave velocity greater than 750 m/s and shear-wave velocity less than 750 m/s, respectively.
r : Radius of circular rigid foundation
V_a : Axial-wave velocity
V_s: Shear-wave velocity

As suggested in the FEMA 440, the strain-degraded shear modulus should be used for computing soil stiffness. In this regard, in order to approximately address the effect of soil nonlinearity, the degraded soil shear-wave velocity, which is consistent with strain level in the soil, is used in the model. It is well known that effects of structure size and the soil attributes can be best considered by two parameters of non-dimensional frequency and aspect ratio (Veletsos, 1997). In order to include soil flexibility in the studied systems, non-dimensional frequency, a_0, is defined as an indicator for the structure-to-soil stiffness ratio, $\omega_{fix}h_n/V_s$, where ω_{fix} and h_n, denote circular frequency of the fixed-base structure and total height of the superstructure, respectively. Stewart et al. (1999) suggested that the single most important parameter controlling the significance of inertial SSI is $h_n/(T_{fix}V_s)$, and that inertial SSI effects are not generally important for small values of $h_n/(T_{fix}V_s)$. If this parameter multiplies by 2π, a_0 factor will be attained. This factor can have values of up to 3 for conventional buildings located on very soft soil and values very close to zero are representatives of the fixed-base structures. In this study, this parameter is assumed to be 1 and 3. The aspect ratio which shows slenderness of the superstructure is defined as the ratio of total height of the superstructure to the foundation radius, i.e., h_n/r. In this paper, values of 1 and 4 are assigned to this parameter to include a wide range of aspect ratios.

Prior to investigate soil material damping effects on structural responses, it is necessary to select an appropriate model for soil material damping. For modeling material damping of soil, three models are addressed in previous references. The first option is viscous material damping model (Wolf, 1984, 1994). In this model, the correspondence principle is applied directly to cone model, enabling viscous material damping to be introduced. Each original spring is augmented by a dashpot and each original dashpot is augmented by a mass. Although experiments verify that the material damping ratio does not depend on the excitation frequency, in the viscous material damping, the material damping ratio is presumed to be linearly proportional to frequency. Going a step farther from viscous type model, the second option, more realistic linear-hysteretic damping is represented by replacing the augmenting dashpots and masses by frictional elements (Wolf and Deeks, 2004). Material damping affects the spring and damping coefficients of the dynamic-stiffness factor. Straightforward application of the correspondence principle to the analytical expression of the elastic dynamic-stiffness coefficient for harmonic loading yields the more complicated coefficient including material damping. This type of damping was employed by Amborosini (2006) to present material damping of soil. The decrease of the spring coefficient and the increase of the damping coefficient are qualitatively correct tendencies but do not agree quantitatively with experiments. The third and best alternative for soil material damping is nonlinear hysteretic damping model (Wolf, 1994). The formal procedure of augmenting each elastic spring and dashpot in the cone model of the foundation by an additional element is very attractive, both conceptually and computationally. To capture realistic frequency-independent hysteretic material damping, it would be desirable to keep the analogy and simply replace the augmenting dashpot and pulley-mass associated with viscous model by suitable causal nonlinear elements. For frictional (non-linear hysteretic) material damping which preserves causality, non-linear frictional elements replace the augmenting dashpot and pulley-mass. Herein, the values 0 (radiation damping only) and 0.25 are assumed for soil material damping.

EARTHQUAKE GROUND MOTION ENSEMBLE

In order to investigate the effects of soil material damping on various seismic demands of the soil-MDOF structure systems, an extensive assembly of records is required. A suit of 59 far-fault records with their corresponding characteristics provided by peer strong database motion is presented in Saylabi et al. (2012). This ground motion ensemble includes earthquakes with moment magnitude (M_s) ranged from 5.8 to 7.5.

EVALUATION OF SOIL MATERIAL DAMPING EFFECTS ON SEISMIC RESPONSES

In this section, it is intended to elucidate the contribution of soil material damping to seismic analysis of soil-structure systems. To this end, variations of some engineering demand parameters (EDPs) are examined in order to reflect the role of material damping in these seismic responses. In this study, the assessed EDPs are divided into two groups of displacement and force demands and are completely explained in the following. To quantify the material damping effects on a desired EDP, corresponding relative reduction percentages (E) are computed as:

$$E^{i}_{EDP}\ (\%)=100[EDP(\mu_s=0)-EDP(\mu_s=0.25)]/\ EDP(\mu_s=0) \qquad (4)$$

Where EDP(μ_s=0) denotes the value of desired EDP for radiation damping only. EDP ($\mu_s= \mu_i$) stands for the response quantity considering material damping too (radiation as well as material damping). In fact, $E_{EDP}{}^{i}$ indicates the relative decrease in a particular seismic response at soil material damping level of μ_i subjected to a specific ground motion. Finally, the mean of $E_{EDP}{}^{i}$ obtained from all 59 ground motions are computed to evaluate the soil material damping effects.

Two different types of displacement demands considered in this section are roof drift angle (θ_r) and story drift angle (θ_i). Roof drift angle is defined as the roof displacement divided by the structure height. Story drift angle is expressed as the relative displacement between two consecutive stories normalized by story height. Consequently, maximum story drift angle (θ_m) is the peak value of θ_i among all stories. Figure 3 illustrates $E_{\theta r}$ versus story numbers for soil-structure systems with various values of a_0. As it was noted previously, a_0 is the single most important parameter which controls the significance of inertial SSI effects. It can be seen that as a_0 parameter increases, the effects of material damping increase. Generally, increasing a_0 leads to increase in both material and radiation damping values. However, in squat structures, herein $h_n/r=1$, the radiation damping value is very higher than its material counterpart. Therefore, the role of material damping in responses reduces and there is not considerable change in the system's damping due to the material damping. According to Figure 3-b, the maximum reduction due to material damping is around 10 % for squat structures. As the structure slenderizes, the damping quantity due to radiation in the soil significantly decreases and the material damping of the soil governs the responses so that the decrease of responses reaches around 40 % in extreme cases. Let assume buildings which have the same height but different aspect ratio. So, in this case, as the aspect ratio increases, the foundation radius decreases assuming the same height for buildings. Decreasing the foundation radius leads to decrease of radiation damping since foundation ability to scatter structure energy toward semi finite soil reduces. Thus, soil material damping effects is more pronounced in slender structures and should be included in SSI analysis in order to achieve more reasonable demands.

For the case of slender structures which is the influence of soil material damping is considerable, as the Figure 2-a confirms, increasing number of stories (e.g. elongation of structure period) results in higher decrease of responses. It implies that for structures whose aspect ratios are the same, the response of the taller structure is more sensitive to the soil material damping. As it is seen in Figure 2-a, in the case of a_0=3 and μ_s=0.25, considering soil material damping decreases responses by around 23% and 40 %, respectively for 3- and 25-story buildings. The reason might lie in the fact that rocking movements of the foundation are more efficiently contributed to dissipate energy at higher h_n/r. Consequently, as the story number or structure height increases, rocking motion effects at the roof level, i.e. φh_n, is more effectual and leads to higher contribution of material damping.

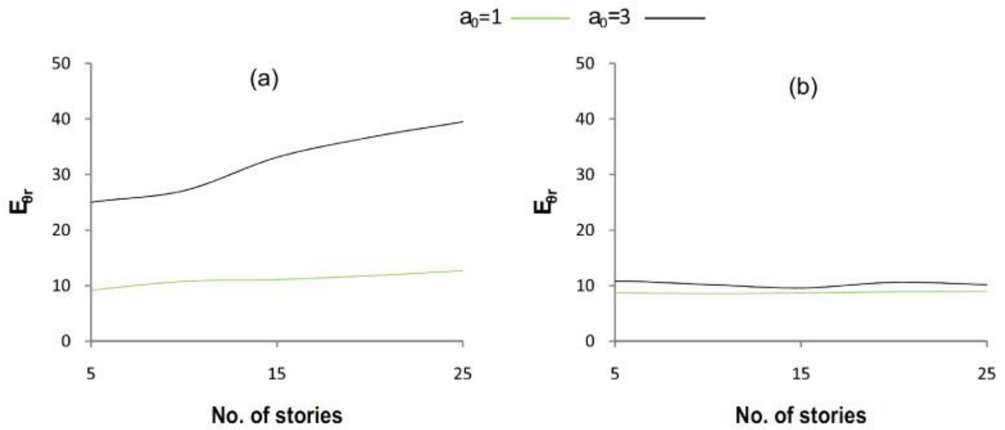

Figure 2. $E_{\theta r}$-values versus number of stories for soil-structure systems with μ=8 for (a) $h_n/r=4$ (b) $h_n/r=1$

In order to show how ductility can affect the contribution of soil material damping to structural responses, $E_{\theta r}$-values are illustrated for ductility of 2 and aspect ratio of 4 in Figure 3. Comparing Figure 3 to Figure 2-a reveals that as the structure undergoes higher level of nonlinear deformations, it results in higher importance of soil material damping in the SSI analysis. The flexibility of nonlinear soil-structure system partially comes from the foundation flexibility and partially the structural nonlinearity. As the system undergoes inelastic behaviour, the effect of base flexibility and consequently the gain of damping from radiation of waves in soil decreases. Therefore, soil material damping plays an important role in determination of structural responses. As it can be seen, change of the ductility from 2 to 8 causes a significant decrease in roof drift angle demand. It can be concluded that as the structure yields and nonlinearity increases, the part of soil material damping in dissipation of structure energy cannot be ignored.

Figure 4 illustrates $E_{\theta m}$-values versus number of stories for soil-structure systems with μ=8 and $h_n/r=4$. Comparison of Figure 4 with Figure 2-a indicates that influence of soil material damping on the decrease of roof drift angle is more pronounced than maximum story drift angle. It might be justified by the fact that at high h_n/r ratios, which effects of soil material damping are significant, rocking motion of the foundation dominates comparing to sway movement. Therefore, the roof story might undergo the most decrease in displacement since the rocking effects, φh_n, is the most significant at roof story. However, maximum story drift occurs at lower stories which are closer to the foundation and affected less by rocking motion of the foundation. The force demands considered herein includes base shear (BS). This demand is used extensively in force-based design procedures suggested in seismic standards and codes. Figure 5 illustrates E_{BS} versus story numbers for soil-structure systems with various values of a_0.

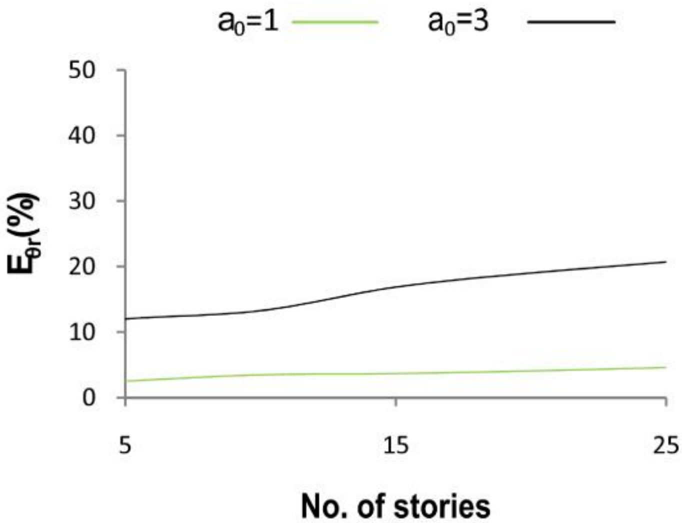

Figure 3. $E_{\theta r}$-values versus number of stories for soil-structure systems with μ=2 and $h_n/r=4$

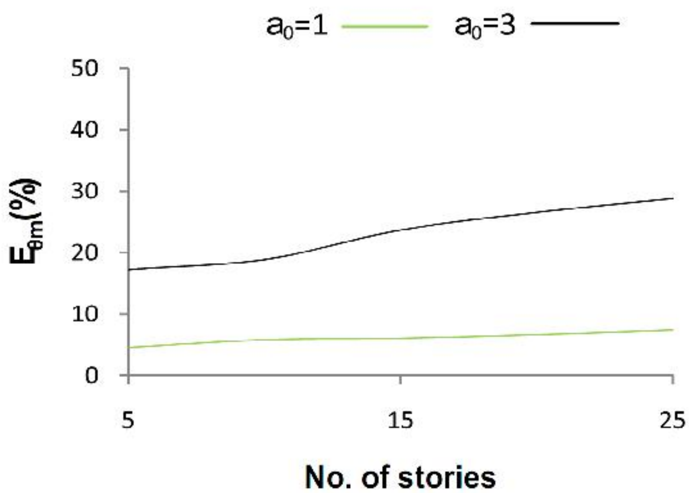

Figure 4. $E_{\theta m}$-values versus number of stories for soil-structure systems with μ=8 and h_n/r=4

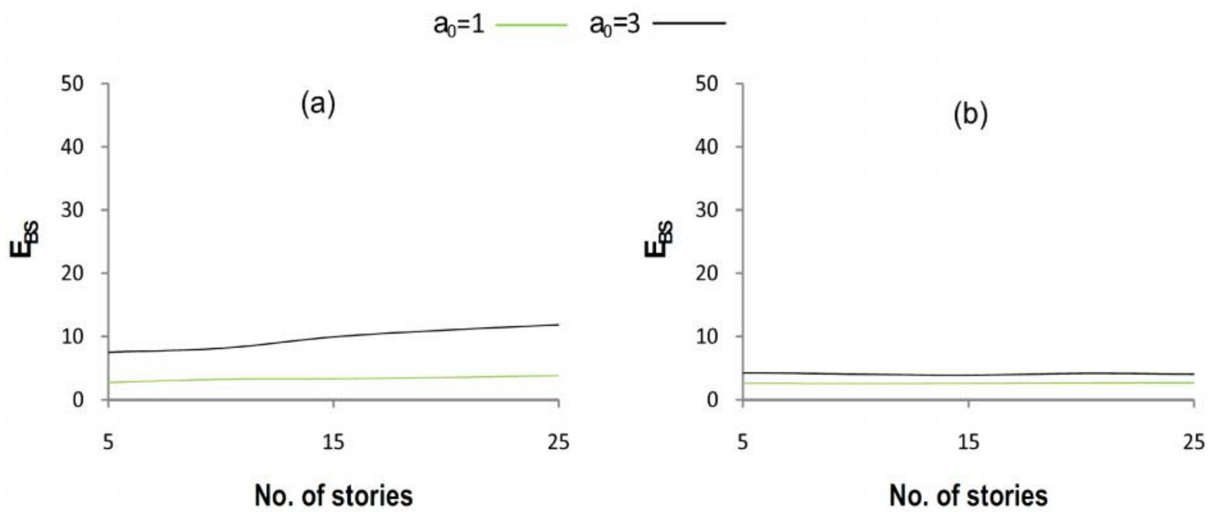

Figure 5. E_{BS}-values versus number of stories for soil-structure systems with μ=8 for (a) h_n/r=4 (b) h_n/r=1

Comparing Figure 5 with Figure 2 indicates that effects of soil material damping on force demands are comparatively lower than displacement demands. The decrease of base shear in its extreme case is about 12 % while the roof displacement is reduced about 40% by soil material damping effects. This discussion reveals that effects of soil material damping on displacement responses are more pronounced than base shear and material damping cannot be ignored while determining displacement responses. Although story number, aspect ratio, and ductility have the same effects on force demands as on the displace demands, the consequences of soil material damping on force demands mitigate in comparison with displacement demands.

CONCLUSION

In this study, the effects of soil material damping on seismic analysis of soil-MDOF structure systems are assessed. To achieve this aim, the superstructure is simulated as a nonlinear multi-story shear building and the underlying soil is considered based on cone model concept. In order to include effects of soil-material damping, frictional elements are adopted which are more realistic than other approaches. As the external excitation, an ensemble of 59 records is employed. The relative decrease between the state with no material damping (radiation damping only) and the state with material damping is adopted in order to evaluate the importance of soil material damping.

The results confirm that soil material damping should be taken into seismic analysis of soil-structure systems when the superstructure becomes slender. Moreover, as the nonlinearity in the superstructure increases, importance of soil material damping effect on the responses increases. Case of increasing story number or fixed-base period of the building also requires more attention to the incorporation of the soil material damping to the analysis. Generally, effects of soil material damping on displacement demands are more pronounced than force demands. Furthermore, roof displacement is impressed by soil material damping more than maximum story drift angle.

REFERENCES

Ambrosini, RD., 2006. Material damping vs. radiation damping in soil-structure interaction analysis. Computers and Geotechnics, 33:86-92.

ASCE/SEI 7-10. 2010. Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, ASCE, USA.

FEMA 356. 2000. Prestandard and Commentary for the Seismic Rehabilitation of Buildings. American Society of Civil Engineers, Reston, Virginia, United States of America.

FEMA 440. 2005. Improvement of Nonlinear Static Seismic Analysis Procedures. Applied Technology Council (ATC-55 project), Redwood City, California, United States of America.

Kim, S., Stewart, J.P., 2003. Kinematic soil-structure interaction from strong motion recordings. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 129(4): 323-335.

Liou, G.S., Huang P.H., 1994. Effects of foundation flexibility on impedance functions for circular foundations. Journal of Engineering Mechanics, ASCE, 120(7): 1429-1446.

Meek, W. and Wolf, J.P. 1993. Why cone models can represent the elastic half-space. Earthquake Engineering and Structural Dynamics, 22:759–771.

Richart, F., Hall, J., Woods, R., 1970. Vibration of soils and foundations. Englewood Cliffs (NJ): Prentice-Hall.

Seylabi E., Jhankhah H. and Ghannad MA, (2012). "Equivalent linearization of non-linear soil-structure interaction", Earthquake Engineering and Structural Dynamics, DOI: 10.1002/eqe.2156.

Sienkiewicz, Z., 1993. Dynamic impedances of a weakly anelastic medium. Earthquake Engineering and structural Dynamics; 22:1009:14.

Stewart, J.P., Seed, R.P., Fenves, G.L., 1999. Seismic soil-structure interaction in buildings. II: empirical findings. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 125(1): 38-48.

Veletsos. AS. 1997. Dynamic of structure-foundation systems, Structural and Geotechnical Mechanics, Englewood Cliffs (NJ), Prentice-Hall; p. 333–61. A Volume Honoring N.M. Newmark.

Wolf J.P. (1994), Foundation vibration analysis using simple physical models, Englewood Cliffs (NJ), Prentice-Hall.

Wolf, J.P and Deeks A. 2004. Foundation Vibration Analysis: A Strength-of-Materials Approach. Elsevier’s Science & Technology

Yerli, H.R., Kacin, S., Kocak S., 2003. A parallel finite-element model for two-dimensional soil-structure interaction problems. Soil Dynamics and Earthquake Engineering, 23: 249-53.