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Effect of Soil-Structure Interaction on Energy Dissipation of Buildings

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Abstract
The effect of Soil-Structure Interaction (SSI) on hysteresis energy dissipation of buildings under the SCT (Mexico, 1985) earthquake ground motion (EQGM) is investigated. A parametric study is done using the aspect ratio of the structure and a non-dimensional frequency as a representative of structure to soil stiffness ratio. The soil beneath the structure is considered as a homogeneous elastic half space and is modeled via the concept of cone models (CMs). Using direct step-by-step integration, the system is analyzed in time domain. The results are presented in the form of energy spectra. The energy spectra imply on non-conservativeness of the conventional fixed-base design practice for short-to-medium-period and medium-size buildings and on their safety for long-period ones. Before a threshold period which is dependent on the characteristics of soil profile, both making the structure more slender and softening the soil beneath the structure make the energy dissipation increase, but the behavior is reversed after this period.

Keywords: Soil-Structure Interaction, Hysteresis Energy Dissipation, Cone Models, Energy Spectra

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Introduction

During the recent decade, the classical methods of design in most of the building codes have been gradually substituted by the new concept of performance-based seismic design engineering (PBSDE). Also, the necessity of estimating the vulnerability of existing structures and looking for reliable methods of their retrofication have greatly attracted the attention of civil engineers in most of seismic zones throughout the world in the last twenty years.

As known, one of the factors that greatly affect the performance of a structure under strong ground motions is its capacity to dissipate hysteresis energy. More the capacity of a structure to dissipate energy, better its performance. Thus, to have a better insight into the new approach of PBSDE, the hysteresis energy dissipation of structures under earthquakes should be comprehensively assessed.

In spite of many studies on energy dissipation in structures, there exist few researches on the effect of soil-structure interaction on energy dissipation of structures. Rodriguez and Montes (2000) suggested a method for the approximate evaluation of the hysteresis energy dissipated by a multistory building resting on flexible soil.

As known, in conventional design practice, the soil beneath the structure is assumed to be rigid while it is not so in reality. Both the period and damping of the structure change when the soil is considered to be flexible instead of the unreal assumption of being rigid. The variations occurring in the dynamic characteristics of the system may thus influence the response to a great extent. Both the ductility and strength demanded by squatty structures located on soft soils decrease under the effect of SSI (Ahmadnia, 2001). For structures of medium and large slenderness ratio with the soft soil beneath, for periods less than a threshold value, SSI effect amplifies the ductility and strength demands while a reversed trend is encountered in large periods. Regarding the considerable variations of nonlinear structural responses under SSI effect, the significance of considering the effect of soil on energy is sensed well.

Soil-Structure Model and Method of Analysis

Using the sub-structure method, the structure and the soil are modeled separately and then combined to constitute the soil-structure system (see Figure 1) .The structure is modeled as a bilinear-single degree of freedom (SDOF) system with the same period T_{fix} and viscous damping coefficient ζ_s as those of the fundamental mode of the fixed-base structure. The effective mass and height corresponding to the first mode of vibration of the fixed-base structure are also shown as m and h, respectively. Also considered in the model are the structural mass moment of inertia I, the mass moment of inertia of the foundation I_f, and the foundation mass m_f.The soil is modeled as a truncated cone based on the one dimensional wave propagation theory. Cone Models (CMs) (Wolf, 1994) can be used with sufficient accuracy in engineering practice (Meek and Wolf, 1993). The horizontal (sway) degree of freedom (DOF) and the rocking DOF are introduced as representatives of translational and rotational motions of the foundation, respectively, ignoring the slight effects of vertical and torsional motions. To consider frequency dependency of the rotational spring and dashpot coefficients, an internal degree of freedom φ_1, assigned to a mass moment of inertia M_φ situating with the rotational damper in series, is introduced. This new 3DOF model, called monkey-tail model, fulfills the same interaction moment-rotation relationship as the 2DOF one with the frequency-dependent springs and dashpots. Also, to avoid more complications in time-domain analysis, the material damping of soil is assumed to be viscous, while being hysteresis intrinsically. The total system has thus been finally modeled as a 4DOF system. The coefficients of springs and dashpots for the sway and rocking motions are evaluated using the following formula, respectively

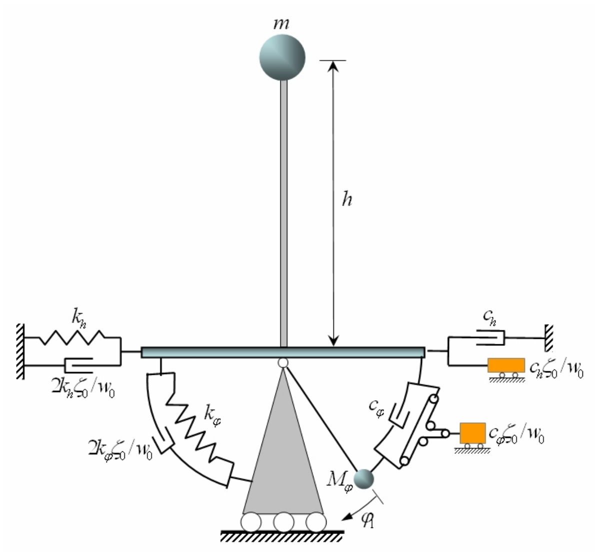


Figure 1: Soil-Structure Model

$$k_h = \frac{8\rho V_s^2 r}{2-\upsilon} \quad , c_h = \pi\rho V_s r^2 \tag{1}$$

$$k_\varphi = \frac{8\rho V_s^2 r^3}{3(1-\upsilon)} \quad , c_\varphi = \frac{\pi}{2}\rho V_s r^4 \quad , M_\varphi = \frac{9\rho\pi^2 r^5(1-\upsilon)}{32} \tag{2}$$

where ρ, υ , V_P, and V_s are respectively the specific mass, poisson's ratio, and the compressive and shear wave velocities of soil and r is the radius of the equivalent circular foundation. Also, to modify the effect of incompressibility of the soft soil of Mexico, a trapped mass moment of inertia ΔM_φ equal to $0.3\pi(\upsilon - \frac{1}{3})\rho r^5$ is added to I_f for υ equal to 0.5 in this case.

Problem Parameters

Generally, the response of soil-structure system depends on the size of the structure, its dynamic properties, and the soil profile as well as the applied excitation (Ghannad et al, 1998; Veletsos, 1977). Among the six below items, the first two are more affective on the response than the other four coming after and are selected as the key parameters of the system. The latter group is usually assigned constant values extracted for common buildings.

1) The non-dimensional frequency as the representative of the structure to soil stiffness ratio

$$a_0 = \frac{\omega h}{Vs} \tag{3}$$

where ω is the circular frequency of the fixed-base structure.

2) Aspect ratio of the building *h/r*, an index for its slenderness ratio

3) Structure to soil mass ratio index, set equal to 0.5.

$$\overline{m} = \frac{m}{\rho r^2 h} \tag{4}$$

4) Foundation to structure mass ratio m_f/m, assigned 0.1.

5) Poisson's ratio of soil υ , equal to 0.5 for the soft soil of Mexico.

6) Material damping ratios of the soil ζ_0 and the structure ζ_s set to 5% of the critical damping at the effective period of the soil-structure system.
The response of the 4DOF system is then computed through simultaneous solving of the four differential equations of dynamic equilibrium of the system.

Hysteresis Model

Modeling the hysteresis behavior of structural elements is one of the core aspects in the nonlinear structural analysis programs. The amount of hysteresis energy dissipated during inelastic deformation reversals (equal to the total area of all the loops) is highly dependent on the type of the hysteresis loop considered (Minami and Osawa, 1988). Some models of hysteresis loops have a large capacity for plastic strain energy absorption, while others have very poor energy absorption capacity and can hardly consume hysteresis energy. In some others, instantaneous stiffness deteriorates as plastic deformation develops and the hysteresis loops become thin, but moderate absorption capacity still remains. The hysteresis loop should thus be selected so as to match the behavior of the element in reality. The bilinear model used here (Figure 2) is vastly applied for various structural elements such as columns, beams, shear walls, and rotational springs. The strain hardening ratio was taken as 2% in this research.

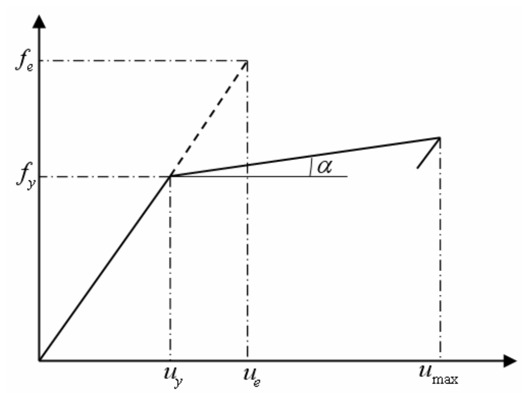
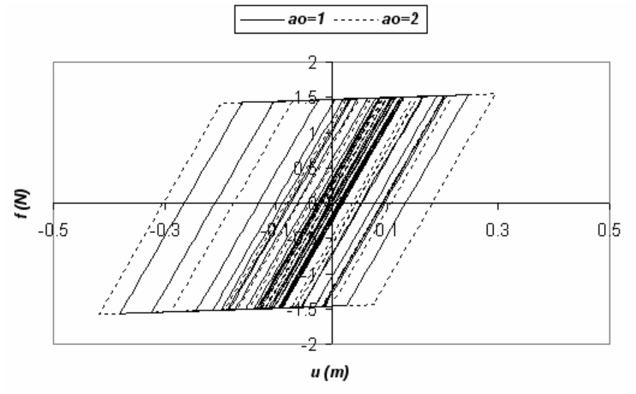


Figure 2: Bilinear Force-Deformation Relationship

As stated earlier, the hysteresis energy dissipated under a certain EQGM can be highly affected when the stiffness of the soil beneath is altered. The change may be an increase or decrease depending on the dynamic properties of the structure, the soil profile characteristics, and the record to which the structure is subjected. Figure 3 displays a change in the hysteresis energy dissipated in a structure with a period of 1.7 sec and an aspect ratio equal to 3.0 as a result of the variations occurring in the response (both displacement and force) under SSI effect. The yielding force is assumed to be constant regardless of the stiffness of the soil beneath. This is the force that makes the fixed-base structure reach a certain predetermined ductility, 3.0 in this case. As clear in the figure, the amount of energy dissipated is different for different structure to soil stiffness ratios. It is also worth mentioning that although the hysteresis loops corresponding to the a_0 value of 2.0 seem intuitively to have larger area than those of a_0 equal to 1.0, the computations do not imply so. Evaluating the area under the graphs using the integral $E_{hys} = \int f.du$ yields $E_{hys}(a_0 = 1) = 5.44\,j$ and $E_{hys}(a_0 = 1) = 3.27\,j$. The total area is in fact dependent on the number of oscillations and the dimensions of the loop occurring in each oscillation. A graph surrounded by another thus does not certainly have smaller area than the seemingly larger one. Hence, immediate comparison of the dissipated energy of two systems based on the appearance of their corresponding hysteresis loops should be avoided.



$$E_{hys}(a_0 = 1) > E_{hys}(a_0 = 2)$$

Figure 3: Hysteresis Loops for a Typical Structure with $T_{fix} = 1.7\,\mathrm{sec}$ **and** $h/r = 3$

Numerical Results

The figures presented in this section are the results of the analysis performed on the soil-structure model explained earlier under SCT (Mexico, 1985) EQGM. In Figure 4, the parameter a_0 was assumed as 2.0 to be a suitable representative of the soft soil of Mexico and three values of 1, 3, and 5 were selected as the slenderness ratios of the respectively squatty, medium size and slender buildings. Another approach was considered in Figure 5 for assessing the effect of softening the soil beneath the structure while assigning a constant slenderness ratio of 3.0 to the structure. Also, the target ductility of the fixed-base structure was assigned two values of 3 and 6. The yield force considered for a building locating on soil was selected so as to generate the primarily assumed target ductility in its corresponding fixed-base structure.

As is observed in the graphs of Figure 4, moving towards more slender structures increases the energy for periods less than a threshold period of about 1.5 sec, but the trend is reversed after this period. Note that a squatty structure with a period larger than about 3.0 s can hardly exist and this is nearly the same for slender structures of short periods, say 1.0 and less. This prevents us to compare directly too squatty and too slender structures in relatively short or long periods. However, regarding intermediate values of *h/r*, it can be strongly stated that increasing the slenderness ratio increases the hysteresis energy in buildings with periods shorter than a threshold period while more moderate energy dissipation is demanded when long period structures get more slender. For squatty structures, the decrease of energy in the short-period region can be justified by regarding the high damping ratios for such structures due to the radiation damping in the soil.

The investigations performed by the researchers show that the dissipated energy as one of the two main factors affecting the total damage in a structure during an earthquake has its maximum effect in medium range of periods. This clarifies the significance of dissipated hysteresis energy for conventional buildings.

In addition, the discrepancies between the periods at which the peak values of dissipated hysteresis energy of the SSI-considered and the fixed-base systems take place, increase and the periods of peak energy shift towards the left as the structure becomes more slender.

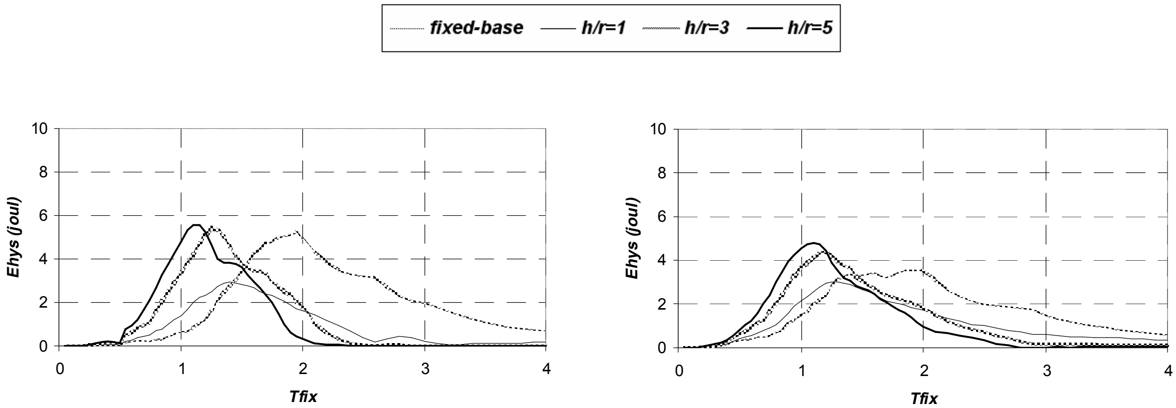


Figure 4: Effect of SSI on Hysteresis Energy Dissipation for $a_0 = 2$, $\mu_{fix} = 3$ (left), and $\mu_{fix} = 6$ (right)

The effect of softening the soil is seen in Figure 5. Evidently, more drastic interaction between the structure and the soil is expected for sites with looser soils. However, it should be emphasized that the important factor is the structure to soil stiffness ratio and not just that of the soil (Ghannad, 1998). Thus, larger a_0 implies on more severe interaction effect.

Softer soils seem to force the buildings dissipate more energy in short-to-medium period regions, but for long period buildings a reversed trend is observed. Also, while softening the soil beneath, the enlargement of the discrepancies between the periods at which the peak values of dissipated hysteresis energy of the SSI-considered and the fixed-base systems take place is clearly observed. The movement of the periods of peak energy towards the left may request some more capacity of energy dissipating in buildings of short-to-medium period.

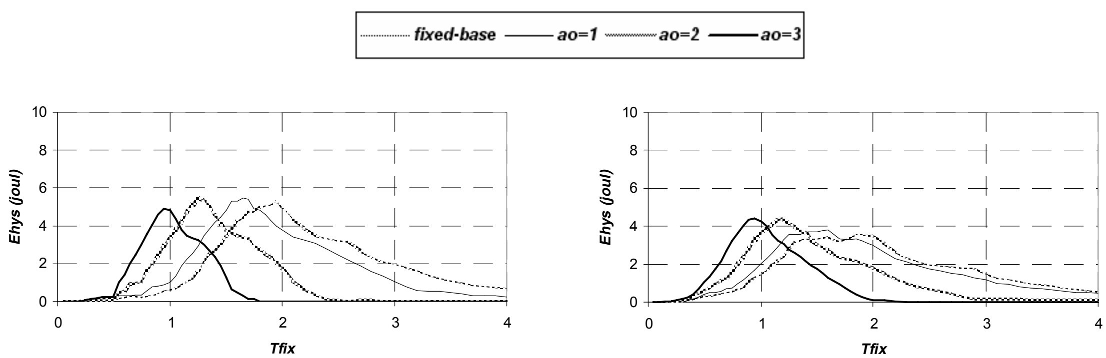


Figure 5: Effect of SSI on Hysteresis Energy Dissipation for $\frac{h}{r} = 3$, $\mu_{fix} = 3$ (left), and $\mu_{fix} = 6$ (right)

Conclusion

A soil-structure model was developed and analyzed for assessing the effect of SSI on hysteresis energy dissipation of buildings. The famous bilinear hysteresis model with a strain hardening ratio of 2% was selected for considering the SSI effect. The results show completely sensible variations of hysteresis energy dissipation under SSI effect. The variations are large enough to exceed the capacity of the building for dissipating energy. It was observed that more slender structures are forced to dissipate more energy in periods less than a threshold period, but they display a reversed trend after this period. The threshold period is highly dependent on the characteristics of soil profile. Also, buildings resting on softer soils have to dissipate more energy in short-to-medium period regions, but less in long period regions. In addition, both slenderizing the building and softening the soil shift the periods of peak energy towards the left.

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