DOI: http://dx.doi.org/10.12989/sem.2006.24.5.641
Structural Engineering and Mechanics, Vol. 24, No. 5 (2006) 641-645

Technical Note

The effect of soil-structure interaction on hysteretic energy demand of buildings

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(Received October 15, 2005, Accepted July 11, 2006)

1. Introduction

In seismic design, the soil beneath the structure is usually assumed to be rigid, i.e., the soil-structure interaction (SSI) effect is usually disregarded. However, this is known for many years that the soil flexibility affects the structural response (Veletsos and Meek 1974). The SSI not only changes the elastic response of structures, but also affects their inelastic behavior (Bielak 1978, Dutta *et al*. 2004, Ghannad and Ahmadnia 2006). Therefore, the dissipated energy in the structure, which is an index for structural damage, is also affected by SSI. In this paper, the effect of SSI on hysteretic energy demand of buildings will be studied parametrically using an ensemble of alluvium site records.

2. 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 model. The structure is modeled as a bilinear SDOF system with the same period and damping ratio as the fixed-base structure in the first mode of vibration. The soil beneath the structure is replaced by a discrete model, with sway and rocking degrees of freedom, based on the concept of Cone Models (Wolf 1994). The model also considers for the frequency dependency of the soil dynamic stiffness. The soil-structure model is then solved by direct step-by-step integration method in the time domain. As the base excitation, 24 alluvium site records are examined. Hysteretic energy demands for structures with a wide range of natural periods are computed by averaging the results for individual records. An optimization procedure, similar to

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the method of Riddell and Garcia (2001), is used for averaging the spectral ordinates. The approach is based on minimization of the average of coefficient of variation of energy spectra in each spectral region.

3. Key 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. Two indices with the most effect on the response are selected as the key parameters of the problem (Ghannad *et al.* 1998):

1) A non-dimensional frequency as a representative of structure to soil stiffness ratio

$$a_0 = \frac{\omega h}{V_s} \tag{1}$$

where ω, h, and V_s are respectively the circular frequency of the fixed-base building, its height, and the shear wave velocity.

2) Aspect ratio of the building *h/r*.

4. Energy demand in soil-structure systems

Generally, the hysteretic energy dissipated in a structure under an earthquake can be highly affected when the stiffness of the soil beneath the structure is altered. The effect 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. Fig. 1 displays the results for a typical structure on two different soils with a_0 of 1 and 2. The yield force was assumed to be the same for both cases. The differences are the result of the variations occurring in both the displacement and the force under SSI effect. It is worth mentioning that although the loops corresponding to the a_0 value of 2 seem intuitively to have larger area than those with a_0 of 1, the computations do not imply so. Evaluating the area under each graph gives $E_H(a_0 = 1) = 5.44j$ and $E_H(a_0 = 2) = 3.27j$. The total

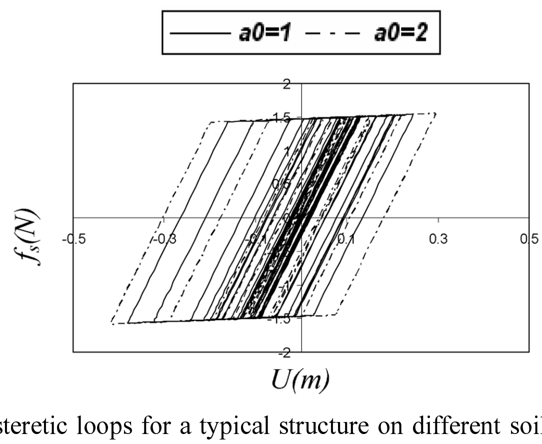

Fig. 1 Hysteretic loops for a typical structure on different soil conditions

area is in fact dependent on the number of oscillations and the dimensions of the loop corresponding to each oscillation. Thus, hysteretic loops surrounded by seemingly larger ones may not necessarily have smaller area.

5. Numerical results

In this study, the yield strength considered for a flexible-base building is the yield strength that the corresponding fixed-base building must have to reach the target ductility of 3. For attaining an inclusive understanding of the effect of soil stiffness, a_0 is increased up to 3 while it hardly happens in reality for a building on alluvium. The energy spectra are assessed in three regions, separately.

Fig. 2 displays the energy spectra in the acceleration region for different sets of a_0 and h/r. The graphs show that in squatty buildings, moving towards looser soils causes less energy to be dissipated in the structure. Although the ordinates corresponding to a_0 of 1 are nearly the same as the fixed-base case, for larger values of 2 and 3, severe drop is observed.

The trend observed in squatty buildings is not exactly repeated in slender ones; for periods less than around 0.3 sec, increasing a_0 amplifies the dissipated energy. Regarding the significant increase in the ductility demand of such structures under SSI effect (Ghannad and Ahmadnia 2006), the amplification of energy demand is justified. Yet, it should not be forgotten that a building with h/r of 3 cannot be stiff enough to vibrate with such small periods, e.g., 0.3. The graphs thus do not have any practical significance in this range. After 0.3 sec, a trend of decrease, but considerably smaller than that for squatty buildings, is usually seen. The differences are small even for a_0 of 2. However, for systems with significant SSI effect, i.e., a_0 equal to 3, the discrepancies are great.

Figs. 3 and 4 demonstrate the spectra in the velocity and displacement regions, respectively. In these regions, softer soils demand less energy dissipation. The differences become usually smaller towards longer periods. It is also observed that in very tall buildings, the SSI effect on hysteretic energy demand of buildings is nearly negligible. In fact, for such very long period buildings, if any, little difference exists between their energy dissipation when designed on rigid base and implemented on flexible soil.

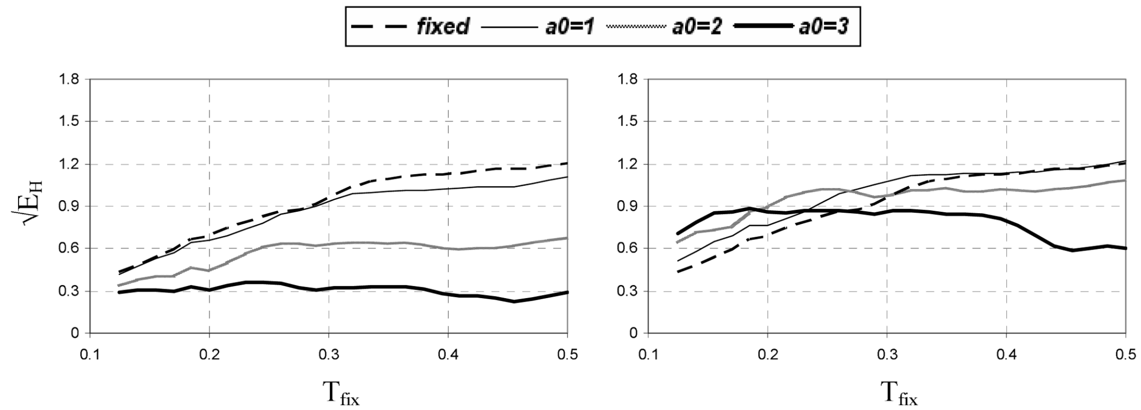

Fig. 2 Effect of SSI on hysteretic energy dissipation in the acceleration spectral region for $h/r = 1$ (left) and $h/r = 3$ (right)

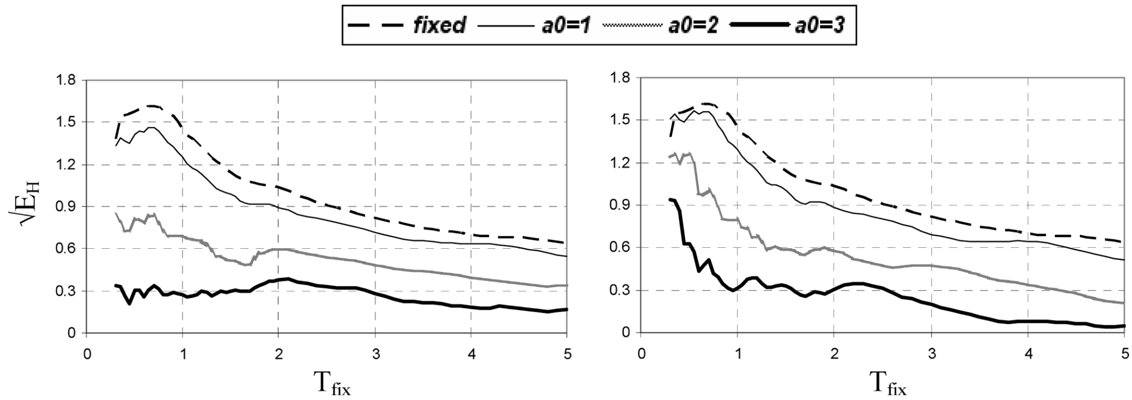

Fig. 3 Effect of SSI on hysteretic energy dissipation in the velocity spectral region for $h/r = 1$ (left) and $h/r = 3$ (right)

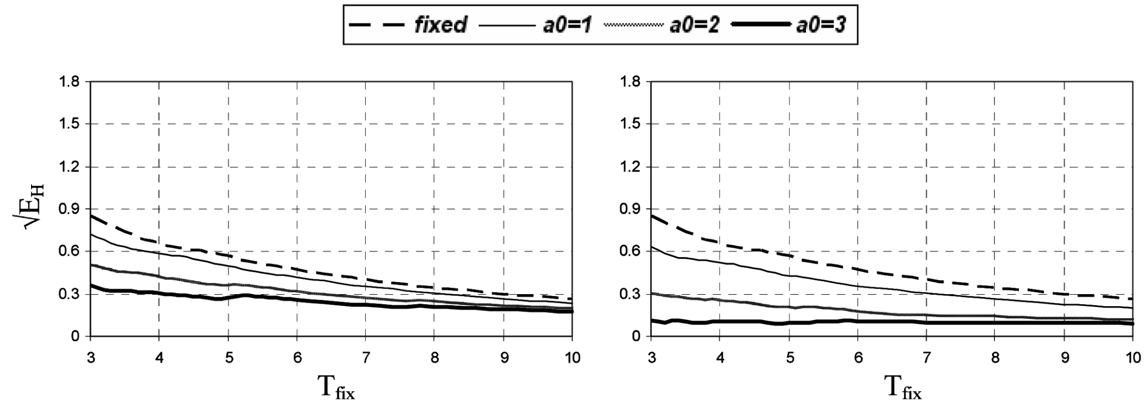

Fig. 4 Effect of SSI on hysteretic energy dissipation in the displacement spectral region for $h/r = 1$ (left) and $h/r = 3$ (right)

6. Conclusions

It can be stated that for conventional buildings, neglecting the flexibility of soil results in an overestimation of the energy demand. Therefore, buildings designed to be rigid in base would have lower hysteretic energy demand when locating on flexible soil. This extra capacity of energy dissipation, however, does not guarantee the better performance of the building. Inquiry on the effect of SSI on damage, which is in fact a function of both dissipated energy and ductility demand, is required in this case.

Acknowledgments

This technical note reflects part of the outcomes of the first author's Master's Thesis in Sharif

University of Technology. Their support is appreciated. The authors also express their special gratitude to Prof. R. Riddell for kind responding to queries on optimization procedure.

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