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EARTHQUAKE RESPONSE OF SIMPLE DEGRADING STRUCTURES SUPPORTED ON FLEXIBLE SOILS

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SUMMARY

The earthquake response of simple elastoplastic and stiffness degrading structures with embedded mat foundations or pile foundations is examined. Two different idealized sites are considered, a soft soil stratum in Mexico City, and a stiffer halfspace in California. Numerical results indicate that, under the assumption of linear soil behavior, soil-structure interaction effects are less significant for structures responding inelastically, than for the corresponding elastic structures. The effects of stiffness degradation and P-Δ effects in elastoplastic structures are more important. Interestingly, stiffness degradation tends to offset the P-Δ effects. In addition, energy calculations for a prescribed ductility ratio show that the hysteretic energy dissipated in structures during the 1985 Mexico earthquake is almost ten times greater than that due to the 1940 El Centro earthquake. This helps explain the widespread damage observed in Mexico City.

INTRODUCTION

The main objective of this study is to gain a better understanding of the inelastic behavior of building-foundation systems under earthquake excitation, by means of simple models. The present study is motivated primarily by the extensive damage experienced by buildings located in the lakebed region of Mexico City during the 19 September 1985 earthquake. Since the lakebed consists primarily of very deformable silty clay deposits, it is of interest to examine the effects that soil-structure interaction may have had on structural response, and to compare it to the response of structures supported on more competent soils. Also, consideration of inelastic effects becomes crucial due to the long duration and long dominant period of the excitation, and to the amplification of the incoming seismic motion by the soft soil deposits. Thus, answers to several questions are sought: (a) How is the ductility demand of buildings affected by the flexibility of the surrounding soils for different ground excitations? (b) How significant are the P-Δ effects on the inelastic response of soil-structure interaction systems? (c) How is the response influenced by structural degradation? and (d) How is the energy dissipated distributed between the structure and the surrounding soil?

In order to obtain answers to these questions we conduct a parametric analysis of an idealized single-story plane model, meant to represent the "fundamental mode" response of actual buildings, using two prototype soil conditions and appropriate building foundations; one is for simulating conditions in Mexico City, and the other for a California site. In the first case, a single soft soil layer supported on a rigid base is subjected to a free-field surface excitation given by the EW component of the surface motion recorded at

SCT during the 1985 earthquake. Here, low-rise structures are supported on embedded mat foundations, while structures four-stories and taller rest on friction piles. For the California site the soil is taken to be an infinite viscoelastic halfspace, all the buildings are supported on embedded mat foundations, and the excitation corresponds to the NS component of the 18 May 1940 El Centro earthquake.

DESCRIPTION OF THE MODEL

The model considered for the first set of calculations is shown on Fig. 1. Hereinafter we will refer to it as the Mexico City model. For the California site, denoted in the following as the El Centro model, the layer is replaced by a halfspace and the piles are removed. In order to represent the "fundamental mode" response of multistory buildings under linear oscillations, the properties of the superstructure are selected as follows. It is assumed, for simplicity, that the fixed base natural period of the superstructure, $T_1 = 0.1N$ (in s), where N = number of stories. Considering an interstory height of 3m, and a modal height, H, equal to 0.7 the total building height, then $H = 21T_1$. Only square buildings in plan, with side length a, have been considered here. We define an effective radius $R = a/(\pi)^{1/2}$, and the slenderness ratio H/R. A unit weight of 9.8kN/m^2 is considered for each floor, and the modal mass, m_1, is taken as 0.75 of the total building mass (this gives $m_1 = 1.12HR^2$). Viscous damping for all structures is 5 percent of the critical value for the fixed-base system, i.e., $c_1 = 0.1(k_1m_1)^{1/2}$. Two constitutive models are considered for analyzing the structural response in the inelastic range: the elastoplastic and the Takeda's stiffness degrading models.

Embedded mat foundations are represented by lateral and rocking springs and dashpots. Their properties, including embedment and layering effects, are evaluated from the material compiled in Ref. 1. Constant values of stiffness and damping are used, corresponding to the fundamental frequency of the soil-structure interaction system. For the El Centro site, ρ=1.96kN-s^2/m, V_s=200m/s, ν=0.35. For Mexico City, ρ=2kN-s^2/m, V_s=70 m/sec, and ν=0.4. Linear hysteretic damping is included at both sites, with D=0.02. In order to estimate the number of piles per building for the Mexico City calculations a vertical load capacity of 588kN per pile was assumed, which corresponds approximately to piles of 0.5m diameter. Arrangements of pile groups in plan which are typical of Mexican construction practice were considered. Lateral and vertical stiffness and damping properties of the equivalent elements were derived from the material in Refs. 2 and 3, including the recommendation in Ref. 3 for estimating pile group action.

NUMERICAL RESULTS

Results of the parametric study are presented in this section. First, normalized pseudoacceleration elastic spectra for the El Centro and Mexico City models, and for the corresponding limiting rigid soil cases are shown in Fig. 2. Despite the coincidental agreement in the peak values, the distribution over period of the two sets of spectra is completely different, reflecting the difference in the local soil conditions at the two sites. As expected, soil-structure interaction has little effect on the response for the El Centro model, except at very low periods, despite the somewhat low shear wave velocity considered for that site. In Mexico City, the effect is more pronounced, even resulting in an increase in the response at moderate periods. Results for inelastic structures are shown in Figs. 3 to 5. The required seismic coefficient, defined as the yield force/weight required to produce a prescribed ductility ratio μ, is shown on Fig. 3 for μ=4, for several combinations of system parameters. A summary comparison of the effects of stiffness degradation and P-Δ on response is provided by Fig. 4, which depicts the ductility demand that would be exhibited by a structure designed for a ductility ratio μ= 4 under purely elastoplastic behavior, and ignoring P-Δ effects. Figs. 5 and 6 present detailed time histories of the total displacement of the top mass, corresponding to the same yield forces used in Fig. 4. The bar graphs, full steps and half steps, respectively, identify the times during which the superstructure is either yielding along the horizontal branch or vibrating with a reduced stiffness.

From Figs. 3 to 6 we observe the following: (i) In Mexico City all structures vibrate with a predominant period of 2s, independently of natural period. This is a consequence of the long duration and nearly monochromatic nature of the excitation in the lakebed region. In El Centro, structures respond primarily with their own fundamental natural period; (ii) Soil-structure interaction is less significant under inelastic action than for the corresponding elastic structures; (iii) The response of the degrading model exceeds that of the elastoplastic systems for several periods, provided the P-Δ effects are disregarded. Including gravity effects in the elastoplastic systems leads to a drastically increased maximum response and residual drift in Mexico City, due to the intrinsically unstable dynamic behavior of these systems and large structural displacements. This effect is apparent only for tall structures in El Centro, and at a reduced level. Surprisingly, however, the degrading systems is unaffected by gravity, perhaps because the structure spends very little time on the horizontal branch; also, as the structure vibrates with the reduced stiffness it tends to swing back and forth about the original equilibrium position, without accumulating a significant permanent deformation. Separate calculations show that a small amount of strength hardening would be sufficient to offset the destabilizing effect of the structure's weight.

In recent years, it has become clear that the extent of damage in structures due to earthquakes is related not only to the maximum deformations, but to the amount of energy dissipated due to inelastic action. Fig. 7 shows the three types of energy dissipated in the systems per unit weight, i.e., viscous damping and inelastic hysteretic damping in the structure, and radiation and material damping in the soil, for elastoplastic structures and a ductility ratio $\mu=4$, neglecting P-Δ effects. It is seen that the contribution from the soil is small for all periods. More importantly, the structural hysteretic energy dissipated during the 1985 earthquake is generally one order of magnitude greater than that due to the El Centro earthquake. This helps explain the widespread damage observed during the Mexico earthquake.

CONCLUSIONS

The preceding results have shown, for two very different seismic environments, that soil-structure interaction effects involving inelastic structural behavior with linear soils are not very significant. On the other hand, varying assumptions about the structure's nonlinear behavior can lead to considerable change in the response. This points to the need of gaining a better understanding of the actual inelastic properties of structures and to the importance of incorporating this behavior correctly in dynamic analysis and design.

ACKNOWLEDGMENT

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REFERENCES

1. Gazetas, G., "Analysis of Machine Foundation Vibrations : State of the Art," *Soil Dynamics and Earthquake Engineering,* Vol. 2, No. 1, pp. 2-42, 1983.
2. Poulos, H.G., "Behavior of Laterally Loaded Piles: I-Single Piles," *Journal of the Soil Mechanics and Foundations Division,* ASCE, Vol. 97, No. SM5, pp. 711-731, May 1971.
3. Poulos, H.G., "Load-Settlement Prediction for Piles and Piers," *Journal of the Soil Mechanics and Foundations Division,* ASCE, Vol. 98, No. SM9, pp. 879-897, September 1972.

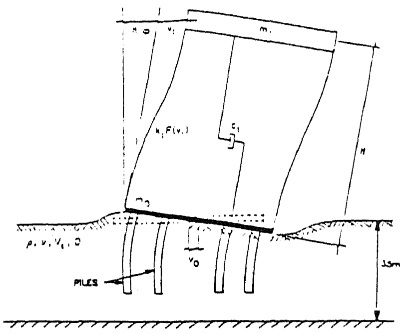
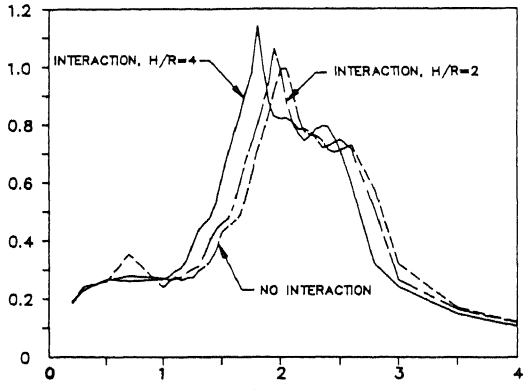
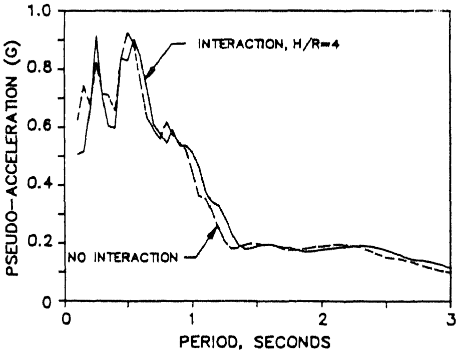


FIGURE 1. MODEL OF BUILDING–FOUNDATION SYSTEM

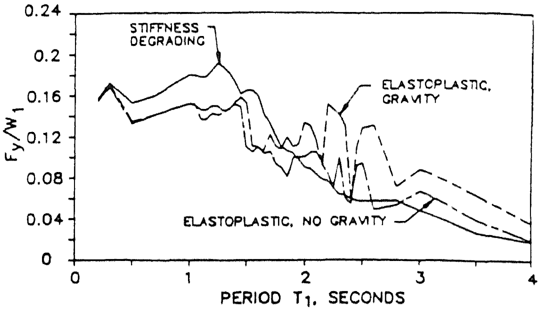


2a) MEXICO 1985

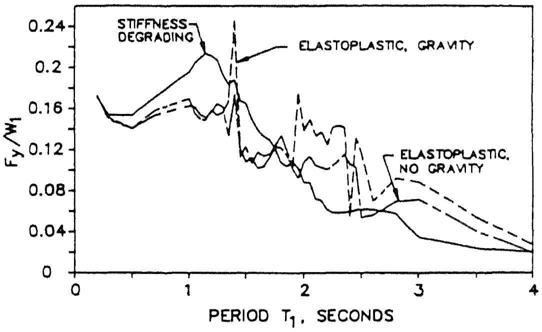


2b) EL CENTRO 1940

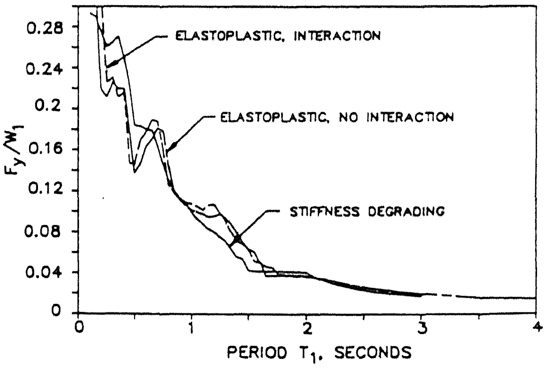
FIGURE 2. ELASTIC SPECTRA



3a) MEXICO 85, NO INTERACTION

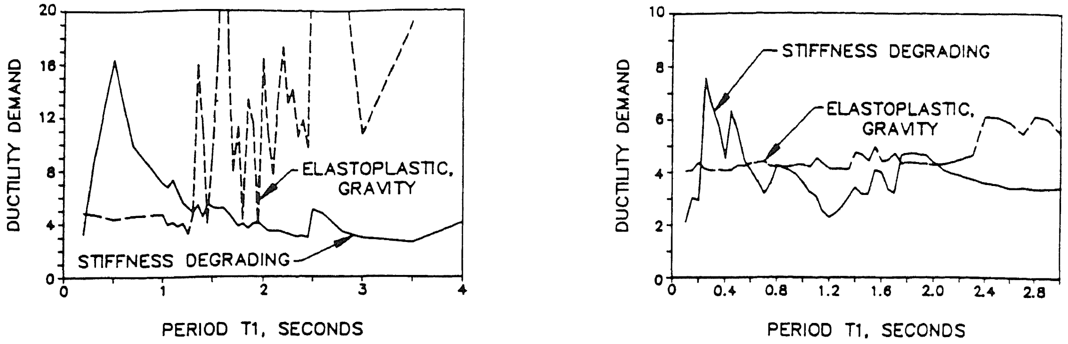


3b) MEXICO 85, WITH INTERACTION



3c) EL CENTRO 1940, H/R=4, NO GRAVITY

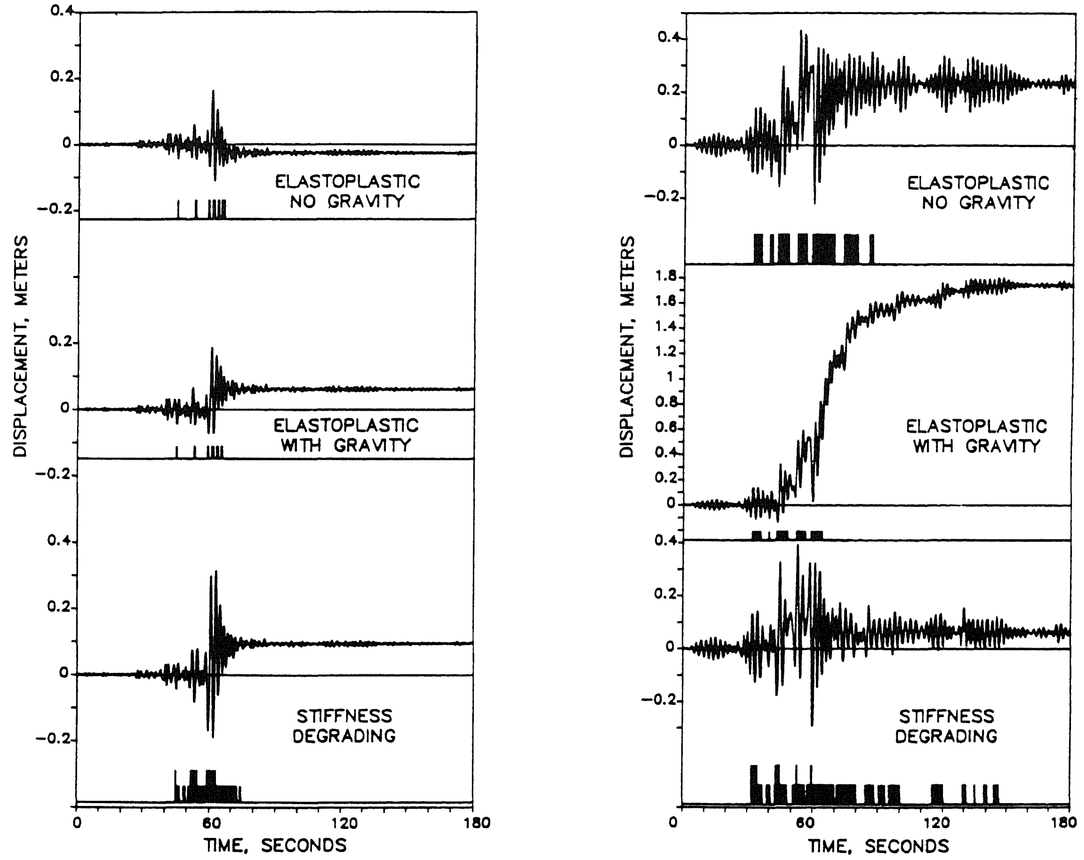
FIGURE 3. REQUIRED YIELD STRENGTH



a) MEXICO 1985

b) EL CENTRO 1940

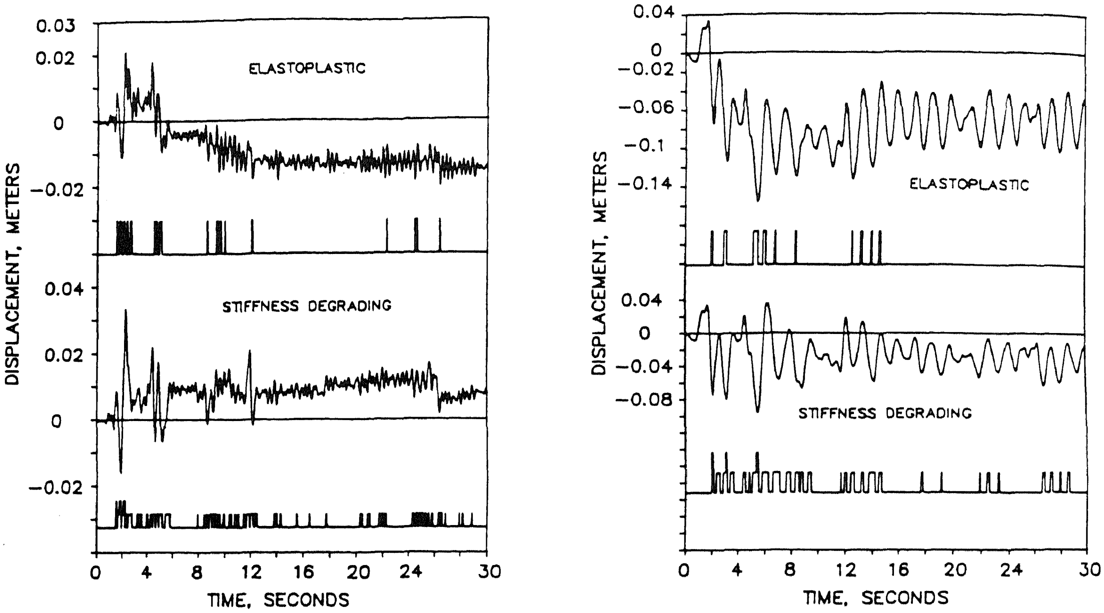
FIGURE 4. DUCTILITY DEMAND FOR F_y/W_1 CORRESPONDING TO AN ELASTOPLASTIC SYSTEM WITH $\mu = 4$, AND H/R=4



a) T1 = 1 SEC.

b) T1 = 2 SEC.

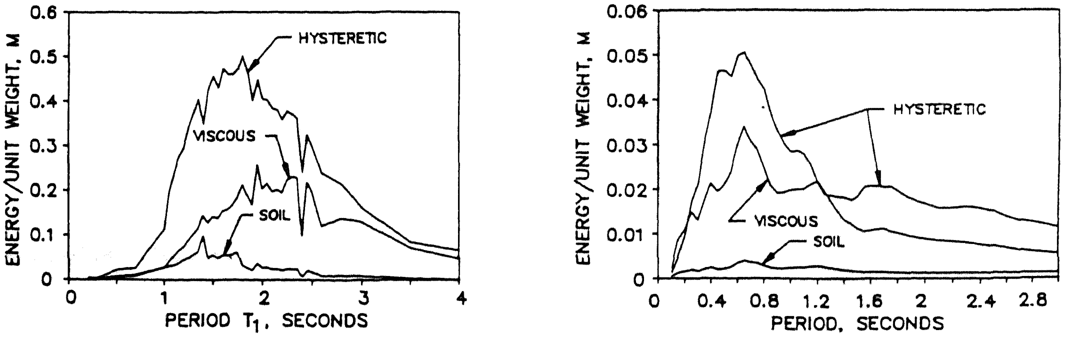
FIGURE 5. RESPONSE TIME HISTORIES, MEXICO 1985



a) T_1=0.3 SECONDS

a) T_1=1.25 SECONDS

FIGURE 6. RESPONSE TIME HISTORIES, EL CENTRO 1940, INTERACTION AND GRAVITY EFFECTS INCLUDED.



6a) MEXICO 1985

6b) EL CENTRO 1940

FIGURE 7. ENERGY DISSIPATED