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SYNOPSIS This paper deals with the problem of nonlinear seismic analysis of building - foundation soil systems. The building considered is modeled as a shear - type building supported on the surface of homogeneous isotropic elastic half-space. The governing nonlinear equations of motion for the structure - soil system are solved in the time domain using the step-by-step linear acceleration method of analysis with Wilson-θ modification. Different nonlinear models to simulate the behaviour of reinforced concrete under cyclic loading are used. A parametric study has been performed on a single story shear-type building with differenet natural frequencies supported on the surface of different soils to show the effect of different parameters on the behaviour of such structures under seismic excitation. These parameters include the type of soil, the soil conditions, the structure flexibility, and the type of analysis (elastic or inelastic). The results show that the soil rigidity, the soil layer depth, and the structure period have great influence on the response of such structures.

INTRODUCTION

In the analysis of buildings under seismic forces, the amplification of seismic waves caused by the soil and the flexibility of the foundation media should be considered. This leads to more degrees of freedom of the system compared to the case of fixed-base structures, Balendra et al. (1986). Many investigators have studied linear structures supported on the surface of homogeneous, isotropic half-space, Parmelee and Kudder (1974) and Takemori et al. (1979).

In the present paper the analysis is made for single-story reinforced concrete shear-type building with nonlinear properties. The foundation medium is represented by a set of horizontal and rotational springs and dashpots representing a theoritical half-space surrounding the structure. The interaction forces at the soil-structure interface are then produced by both the horizontal translation and rocking of the elastic foundation medium. The effect of the site condition is taken by considering the soil layer depth in the expressions representing the interaction forces.

BASIC EQUATIONS

A typical single-story shear type building, as shown in Fig. 1, has a base width of 2b and rests on the surface of a homogeneous elastic half-space. This system has three degrees of freedom, one horizontal translation at the floor level and two interaction displacements at the building foundation interface. The equations of motion for this system are given by :

For the horizontal translation of the superstructure:

$$m\ddot{y} + c\dot{u} + K_i u = 0 \qquad (1)$$

For the horizontal translation of the whole system:

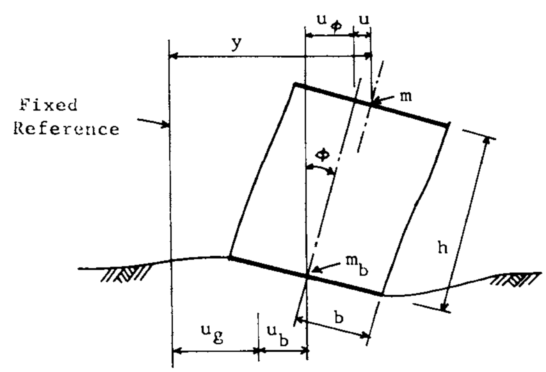


Fig. 1. Idealized Building Foundation System.

$$m_b(\ddot{u}_g + \ddot{u}_b) + m\ddot{y} + P(t) = 0 \qquad (2)$$

and for the rotation of the whole system :

$$I_t \ddot{\phi} + m\ddot{y}h + Q(t) = 0 \qquad (3)$$

Where m = the top mass of the structure
m_b = the base mass
c = the damping in the structure
K_i = the story stiffness at time t
u = the story drift
u_g = the free-field displacement
u_b = the interaction displacement
y = the total horizontal displacement of the top mass with respect to a fixed vertical axis
ϕ = the base rotation
h = the story height
I_t = the total mass moment of inertia of the top mass and the base mass about their axis of rotation.
$P(t)$ = the interaction force at time t
$Q(t)$ = the interaction moment at time t

Interaction Forces

A set of springs and dashpots in parallel at the base of the structure can be used to represent the theoretical half-space. The dynamic stiffness and the damping coefficients were determined by Parmelee and Kudder (1974), and they are given by:

$$K_T = \frac{1.68}{1.34 - \nu} \rho V_s^2 \quad (4)$$

$$C_T = \frac{7.66}{3.24 - \nu} \rho V_s b \quad (5)$$

$$K_\phi = \frac{1.58}{1.12 - \nu} \rho V_s^2 b^2 \quad (6)$$

and $$C_\phi = \frac{0.5}{1.12 - \nu} \rho V_s b^3 \quad (7)$$

where K_T and C_T are the translational dynamic stiffness and the associated damping coefficients, respectively. K_ϕ and C_ϕ are the same coefficients for the rotation mode. Also, b is the half width of the base, ρ , ν , and V_s are the mass density, Poisson's ratio, and shear wave velocity of the foundation medium, respectively. The shear wave velocity is a function of the shear modulus G of the foundation medium and the relation is given by:

$$V_s = \sqrt{\frac{G}{\rho}} \quad (8)$$

Empirical expressions have been developed for the shear modulus of sand for low amplitude of vibration. These expressions are given by Das (1983) as :
for round-grained sands :

$$G = \frac{6908\ (2.17 - e)^2}{1 + e} \bar{\sigma}_o^{0.5} \quad (9)$$

for angular - grained sands :

$$G = \frac{3230\ (2.17 - e)^2}{1 + e} \bar{\sigma}_o^{0.5} \quad (10)$$

Where e is the void ratio, and $\bar{\sigma}_o$ is the mean octahedral stress. For normally consolidated clays of modest sensitivity, Eq. (10) can be used to predict the shear modulus reasonably, Das (1983). The shear modulus of an overconsolidated clay of moderate sensitivity can be expressed by an empirical relation as, Das (1983), Seed et al. (1984):

$$G = \frac{3230\ (2.17 - e)^2}{1 + e} (OCR)^k \bar{\sigma}_o^{0.5} \quad (11)$$

where OCR is the overconsolidation ratio, and k is a factor dependant on the plasticity index PI of soils, and its value can be obtained from Table I.

It should be noted that for practical purposes the value of the shear modulus obtained by the above technique will represent the soil conditions at an average depth (at midpoint of the soil deposit). Das (1983), Idriss and Sadigh (1976).

TABLE I. Values of k

PI	K
0	0.00
20	0.18
40	0.30
60	0.41
80	0.48
100	0.50

The interaction forces P(t) and Q(t) presented in Eqs. (2) and (3) can then be expressed as:

$$P(t)=K_T u_b(t) + C_T \dot{u}_b(t) \quad (12)$$

and $$Q(t) = K_\phi \phi(t) + C_\phi \dot{\phi}(t) \quad (13)$$

SOLUTION OF BASIC EQUATIONS

The incremental form of the equations of motion (Eqs. (1) to (3)) can be derived by taking the difference between the dynamic equilibrium conditions defined at time t_{i+1} and at time t_i. These equations may be written after the substitution of Eqs. (12) and (13) as:

$$m(\hat{\Delta}\ddot{u}_i + \hat{\Delta}\ddot{u}b_i + \hat{\Delta}\ddot{u}_{\phi i}) + C\hat{\Delta}\dot{u}_i + k_i\hat{\Delta}u_i + m\hat{\Delta}\ddot{u}_g = 0 \quad (14)$$

$$m(\hat{\Delta}\ddot{u}_i + \alpha\hat{\Delta}\ddot{u}_{b_i} + \hat{\Delta}\ddot{u}_{\phi_i}) + C_T\hat{\Delta}\dot{u}_{b_i} + k_T\hat{\Delta}u_{b_i} + \alpha m\hat{\Delta}\ddot{u}_{g_i} = 0 \quad (15)$$

$$mh^2(\hat{\Delta}\ddot{u}_i + \hat{\Delta}\ddot{u}_{b_i} + \eta\hat{\Delta}\ddot{u}_{\phi_i}) + c_\phi\hat{\Delta}\dot{u}_{\phi_i} + k_\phi\hat{\Delta}u_{\phi_i} + mh^2\hat{\Delta}\ddot{u}_{g_i} = 0 \quad (16)$$

where :

$$\alpha = \frac{m + mb}{m} \quad (17)$$

$$\eta = 1 + \frac{I_t}{mh^2} \quad (18)$$

and $$u_\phi = h\ \phi \quad (19)$$

The solution of Eqs. (14) to (16) is carried out using the step-by-step linear acceleration method with Wilson-θ modification, known as Wilson-θ method.
A computer program called "NSABFS" has been developed for the solution of Eqs. (14) to (16). The output of this program is controlled to print time-history response when required and also prints the maximum response values.

NUMERICAL RESULTS

Five different buildings are considered in the analysis. The geometry of these buildings are chosen to represent typical buildings. The story height and the bay span are taken to be 4.0m for each and are the same for all buildings. The difference between these buildings is considered in their column cross sections and reinforcement. These cross sections are presented in Table II.

TABLE II. Dimensions and Reinforcement of Columns.

Building	1	2	3	4	5
Section b.h cm	25x25	30x30	35x35	40x40	50x50
Cover cm	3	3	4	4	4
Tens. rft. cm^2	2.65	3.98	5.34	6.03	8.51
Comp. rft. cm^2	2.65	3.98	5.34	6.03	8.51
Web rft. cm^2/m	-	12.00	9.83	12.56	13.17

The modulus of elasticity for concrete and steel are 230 t/cm^2 and 2100 t/cm^2, respectively. The yield strength of steel is 2300 kg/cm^2; the cylinder strenth of concrete is 240 kg/cm^2, and modulus of rupture of concrete is 22 kg/cm^2. The damping ratio of the superstructure is taken to be 5% of the critical value. These buildings

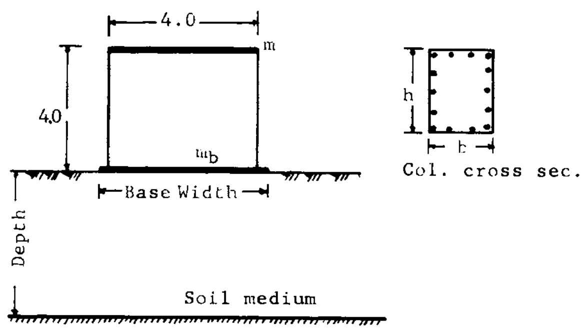


Fig. 2. Cases Considered

are considered to be supported on different soil media, the properties of these soil types are given in Table III. The soil depth is taken to be 10, 15, 20, and 30 meters. The response of these structure-soil systems to El-Centro 1940 N-S component is obtained.

TABLE III. Properties of Different Soils.

Soil Type	Soft Clay	Stiff Clay	Loose Sand	Dense Sand
Bulk Density	1.25	1.9	1.5	2.0 KN/m^3
Submerged Density	0.3	0.95	0.55	1.1 KN/m^3
Void Ratio	2.0	0.40	1.2	0.2
Poisson's Ratio { bulk	0.4	0.1	0.3	0.2
Poisson's Ratio { sub.	0.5	0.4	0.3	0.2
Friction Angle	-	-	20	20

The numerical results show that the base shear decreases as the superstructure period increases for different soils. Also, the base shear is smaller for weak soils than for hard ones as presented in Fig. 3. As the soil layer depth gets heigher the base shear is also increased. This phenomenon is recognized for all soil types and is shown in Fig. 4. Also, the elastic analysis gives heigher values for the base shear than the nonlinear analysis. As shown from Fig. 5 the maximum drift increases with the increas of the period for all types of soils and elastic and inelastic analyses. The same relations are also recognized between the drift and the soil layer depth as shown in Fig. 6.

CONCLUSIONS

The analysis of results show that the soil type has a great influence on the response of structures. Weak soils (soft clay and loose sand) give the same response for elastic and inelastic analyses. This is due to the fact that the structure is being rigid with respect to the soil and does not reach its nonlinear stage.

The structure response is also affected by the soil layer depth, which necessitates to take the effect of the soil layer depth in the design of buildings.

REFERENCES

Balendra, T., and Heidebrecht, A.C. (1986), "Influence of Site Condition on Seismic Response of Buildings", Proc., 8th ECEE, Lisbon, Portugal, 6.6/89-96.

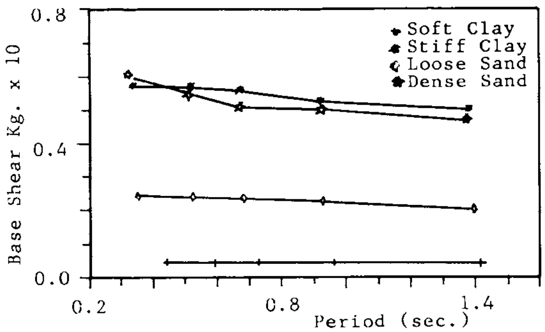
Das, B. M., Fundamentals of Soil Dynamics, Elsevier Science Publishing Co., Inc., New York, 1983.

Idriss, I.M., and Sadigh, K. (1976), "Seismic SSI of Nuclear Power Plant Structures", Journal of the Geotechnical Engineering Division, ASCE, Vol. 102, No. GT7.

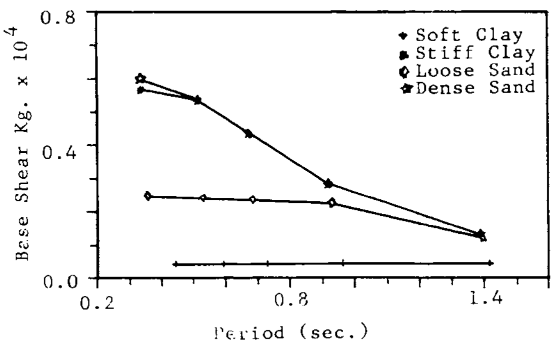
Parmelee, R.A., and Kudder, R.J. (1974), "Seismic Soil-Structure Interaction of Embedded Building", Proc., 5th WCEE, Vol. 2, 1941-1950.

Seed, H.B., Wong, R.T., Idriss, I.M., and Tokimatsu, K. (1984), "Moduli and Damping Factors for Dynamic Analysis of Cohesionless Soils", Report No. EERC/UCB-84/14, University of California, Berkeley, California.

Takemori, T., Kuwabara, Y., Ogiwara, Y., Suwabe, A., and Tanaka, K. (1979), "Comparison of Soil- Structure Interaction by Different Ground Models", Proc., 5th SMIRT, Berlin, Paper K 5/5.

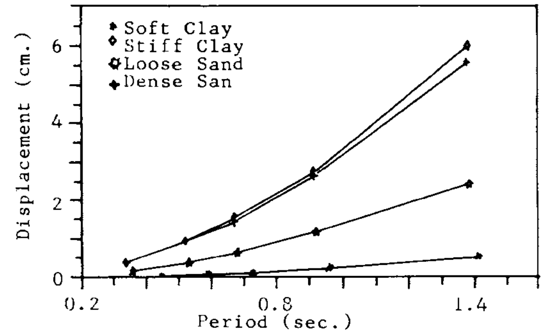


a. Elastic structure analysis

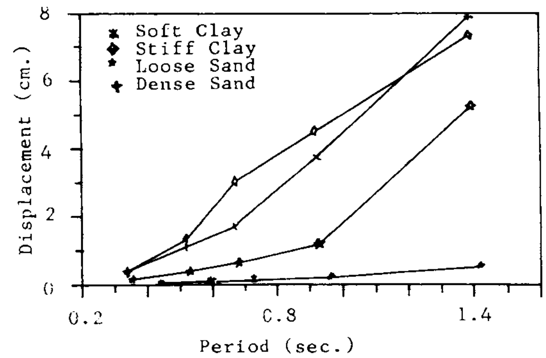


b. Bilinear structure analysis

Fig. 3 Effect of Period on Base Shear for Different Soils.



a. Elastic structure analysis



b. Bilinear structure analysis

Fig. 5. Effect of Period on Drift for Different Soils.

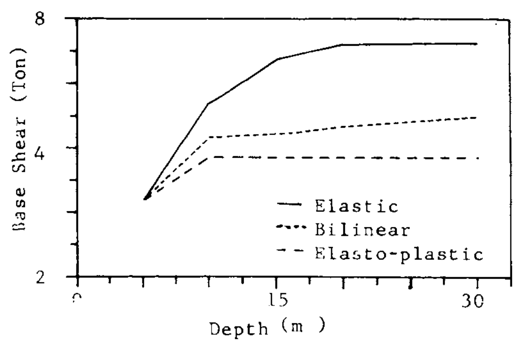


Fig. 4. Effect of Soil Depth on Base Shear (Stiff Clay).

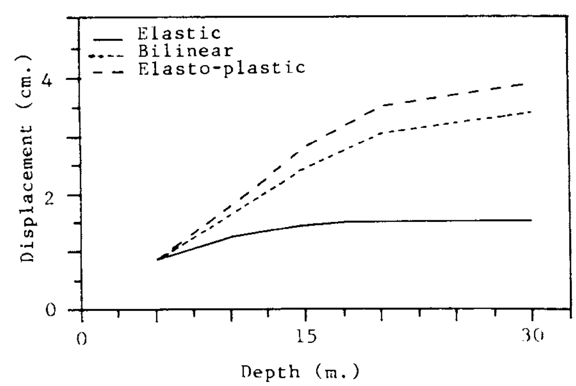


Fig. 6. Effect of Soil Depth on Drift (Stiff Clay).