EFFECT OF FOUNDATION FLEXIBILITY ON DYNAMIC BEHAVIOUR OF BUILDINGS

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SUMMARY

This study examines and compares the free vibration and seismic response of buildings supported by various types of flexible foundations. A single large mat foundation, smaller mats for individual rows of columns and piles are considered. Mat foundations are supported by a deep deposit or a stratum of limited thickness. Piles are considered in different configurations; pull-out stiffness and damping differ from push-in values and uplift of the cap is prevented or allowed. It is shown that seismic response and storey shear depend on the type of foundation and soil stiffness.

INTRODUCTION

Flexibility of the foundation affects the modal properties of structures in a few ways: it modifies vibration modes, lowers natural frequencies, generates damping through energy dissipation in the soil, and modifies the damping that the structure would have with a rigid foundation. Also, the structure may affect the seismic motion of the ground in the vicinity of the footing. The final effect of these factors on seismic loads and displacements of the structure depends on the degree of foundation flexibility, type and intensity of seismic excitation and the type of the foundation. Most authors have found that for shallow foundations, base shear is reduced due to soil-structure interaction but an increase may also occur (Refs. 1,2). Nevertheless, the predominant opinion is that for shallow foundations soil-structure interaction is a favourable factor which usually reduces base shear. This opinion was adopted even in the well known document ATC (Ref. 3), which allows a reduction of base shear of up to 30 percent on account of soil-structure interaction.

Much of the shear reduction derives from the anticipated increase in total damping. Damping of structure-foundation systems is also very important in the design of modern tall buildings against wind loading because the physiological criteria for acceleration are often more difficult to satisfy than the criteria for strength. Another question addressed in this paper is whether pile foundations can produce similar effects as shallow foundations. Bielak and Palencia (Ref. 4) identified some of these effects using a single storey building and harmonic excitation. In this study, multistorey buildings with different types of foundations are exposed to

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seismic excitation.

MODELLING THE BUILDING AND ITS FOUNDATION

The mathematical model chosen represents a multistorey shear building supported by shallow foundations or piles. The mass of the floors is assumed to be equal and five to twenty storeys are considered. Three rows of columns are assumed to facilitate the choice of various foundations.

The types of foundations considered are schematically depicted in Fig. 1. For shallow foundations, two types of mats are chosen: one large mat supporting all columns and three separate smaller mats supporting individual columns. The soil is either a deep deposit modelled by a homogeneous viscoelastic halfspace or a shallow layer modelled as a homogeneous viscoelastic stratum of limited thickness.

The pile foundations comprise groups of floating or endbearing piles whose number and the configurations vary. Each pile is treated as an endbearing pile as long as there is a downward end force produced by the pile tip. When this force vanishes or starts tending upward due to pull-out forces, the pile is treated as floating. This distinction implies overall nonlinearity but is necessary because friction piles provide less stiffness but more damping than endbearing piles (Ref. 5). Pile heads are either connected to the cap in a tension resistant way or are allowed to separate from the cap in which case uplift and nonlinearity occur as indicated in Fig. 2. A complete solution of the response of the pile supported buildings should allow for kinematic interaction and wave scattering between piles as considered, e.g. by Wolf and von Arx (Ref. 6). For ordinary buildings such complex analysis would rarely be justified and therefore the much simpler impedance function approach is used here and limited to consideration of inertial interaction. Then, both shallow and deep foundations can be treated in the same way once the impedance functions of the foundation have been established.

Impedance Functions of Foundations

Impedance functions of foundations are complex and frequency dependent but can be described in terms of true stiffness constants k and constants of equivalent viscous damping c. Then, the relationship between the applied force P and moment M and the horizontal translation of the base u_b and its rotation in the vertical plane ψ can be written in the standard form.

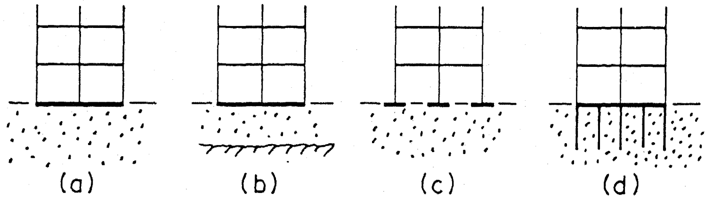


Fig. 1 Types of foundations

The constants k and c were taken from Ref. 7 for the halfspace and from Ref. 8 for the strata. The constants were determined for the first natural frequency of the system and then considered as frequency independent.

For pile foundations, impedance functions are also becoming available (e.g. Refs. 9 to 11) but further research is needed. The greatest obstacle to the description of impedance functions for pile groups stems from pile-soil-pile interaction (group effect) which is much more complicated for dynamic loads than for static loads. Because of the comparative character of this study and the desirability of an unambiguous description of impedance functions, pile-soil-pile interaction effects are neglected and the group impedance functions are evaluated using the single pile data given for a homogeneous soil profile in Ref. 12 and the formulae for groups available in Ref. 13.

Material damping of soil was assumed to be hysteretic, i.e. frequency independent, and characterized by damping ratio β. Finally, nonlinearity of soil behaviour is always of concern particularly with piles. Here, it is assumed to be accounted for approximately by adjusting soil shear modulus and material damping to the expected level of strain.

Governing Equations

With the impedance functions determined, the governing equations of the building motion can be written in the usual form as

$$[m]\{\ddot{u}\} + [c]\{\dot{u}\} + [k]\{u\} = \{P\} \tag{1}$$

in which $\{u\}$ is the displacement vector and $[m]$ the mass matrix; the damping matrix $[c]$ and the stiffness matrix $[k]$ contain the foundation stiffness and damping matrices as submatrices. For a shear building, floor rotations $\psi_i = \psi$, the mass matrix has large off-diagonal terms and with ground acceleration $\ddot{u}_g$ the loading vector $\{P\}$ becomes

$$\{P\} = -[\{m\} \,\vdots\, m_b + \Sigma m_i,\ \Sigma m_i h_i]^T \ddot{u}_g \tag{2}$$

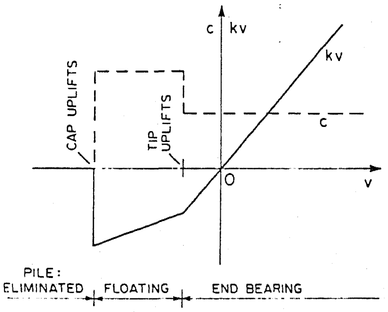


Fig. 2 Pile restoring force kv and damping coefficient c vs. vertical displacement v

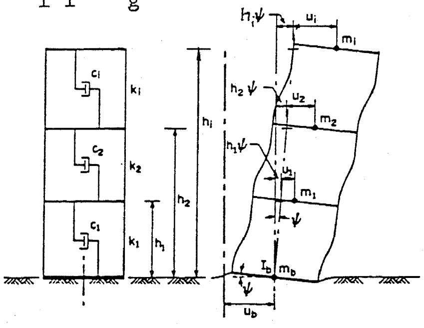


Fig. 3 Shear building

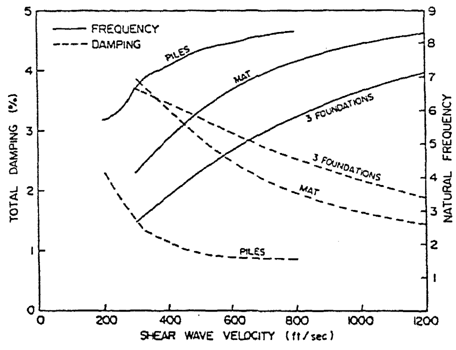


Fig. 4 First natural frequency and damping ratio for ten storey building (1 ft=0.305 m)

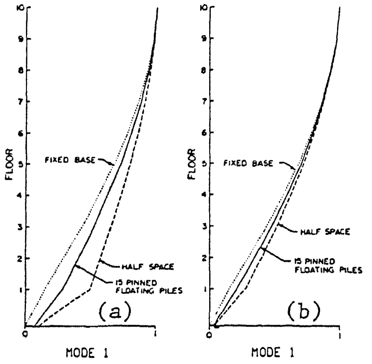


Fig. 5 First vibration mode of building on different foundations (a) - V_s=300ft/s, (b) - V_s=600ft/s

in which the symbols have the meaning apparent from Fig. 3.

FREE VIBRATION

In the absence of external excitation, $\{P\} = \{0\}$ and Eq. 2 describes free vibration, the analysis of which is of interest because it elucidates the effect of foundation flexibility on modal properties of the building-foundation system. These properties can be evaluated in terms of undamped modes, a common approach, or damped modes, a more rigorous approach. For fundamental modes and small damping, both approaches usually give almost the same results (Ref. 14).

Fig. 4 shows the first circular natural frequencies and total damping ratios of a ten storey shear building calculated for three types of foundation, depicted as cases (a), (c) and (d) in Fig. 1. The data are plotted for different values of soil shear wave velocity assuming a structural damping ratio of 1 percent for the basic case of a rigid foundation. The pile foundation consists of fifteen floating reinforced concrete piles per bay. In this and future examples the building density is 10 lb/ft^3 (158 kg/m^3), the pile diameter is 0.75 ft (0.23 m) and the pile length to diameter ratio is 40. Fig. 4 indicates that the pile foundation provides the highest natural frequency but lowest damping. The three separate mats yield lower frequencies and, for stiffer soils, higher damping than one large mat. The differences in the damping ratios and natural frequencies are associated with the differences in the shape of vibration modes (Fig. 5). For higher vibration modes the variation of damping with soil stiffness is not, in general, monotonic and the evaluation of soil generated damping on the basis of an energy consideration and undamped modes may result in considerable errors (Ref. 14). The damping ratio of a higher mode, D_j, can be evaluated more accurately using the complex eigenvalue μ_j as

$$D_j = -\mathrm{Re}\ \mu_j/|\mu_j| \tag{3}$$

SEISMIC RESPONSE OF BUILDINGS WITH DIFFERENT FOUNDATIONS

The different types of flexible foundations depicted in Fig. 1 may have a profound effect on the response of buildings to seismic excitation,

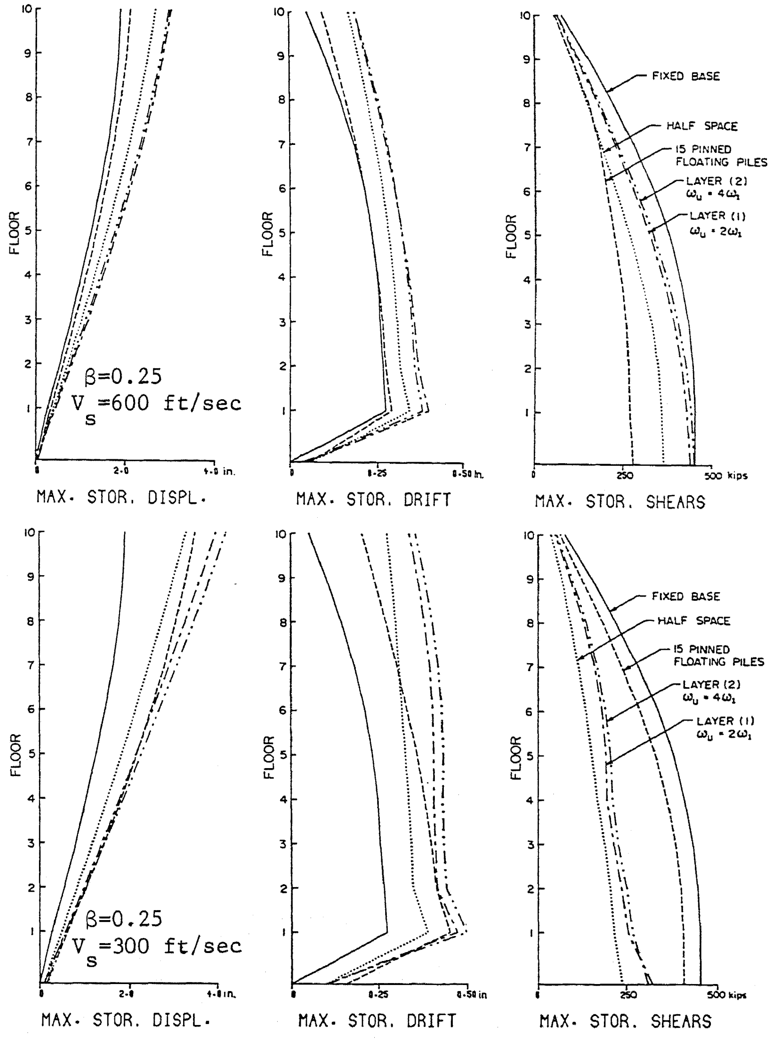


Fig. 6 Maximum storey displacements, drifts and shears for ten storey buildings on different foundations and for two soil shear wave velocities (1 in = 2.54 cm, 1 kip = 4.45 kN)

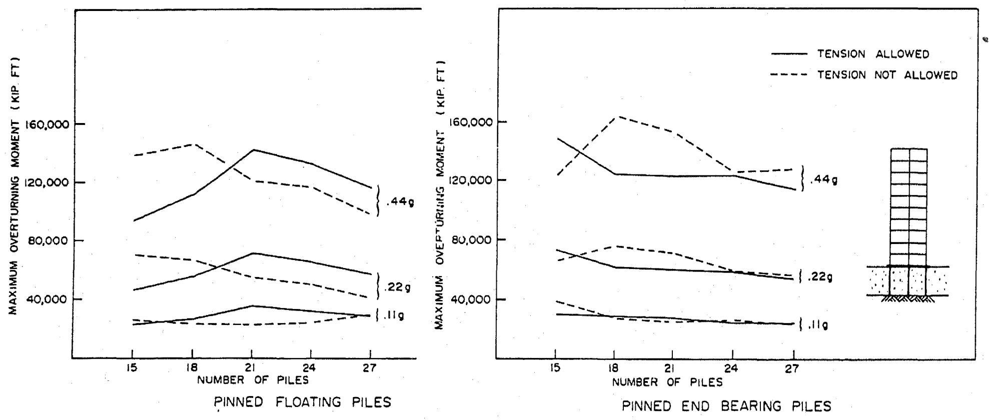
the resultant storey shears and the base shear. Examples of these effects are presented for a ten storey building in Fig. 6. The response was calculated for the San Fernando Valley earthquake 1971, component S90W with peak acceleration of 0.11 g. The Wilson θ-method was used. The soil layer indicated as case (b) in Fig. 1 is of two different depths, yielding the first natural frequency of the layer equal to either $2\omega_1$ or $4\omega_1$ where ω_1 is the fundamental natural frequency of the building on the elastic halfspace.

With a layer, a significant loss of geometric damping occurs. Despite the compensating effect of soil material damping, characterized here by a damping ratio $\beta = 0.025$, the limited depth of the layer results in larger displacements and storey shears than those obtained with the halfspace (Fig. 6). The effect of piles depends on the number and type of piles, as is shown in more detail in the next paragraph, and, as with the other foundations, soil stiffness and the kind of seismic excitation. For all foundations, the maximum storey shear is reduced by foundation flexibility.

For strong earthquakes, the relations shown in Fig. 6 would change due to nonlinear behaviour of the structure but this nonlinearity may not be accounted for adequately unless foundation nonlinearity is considered as well.

Pile Cap Uplift

It is common design practice to attach the piles to the cap in a tension resisting way and if it appears necessary, to design the piles for tension. The aim of these often costly measures is to prevent cap uplift and, supposedly, to secure a greater measure of safety. It is, therefore, of interest to examine how the response and seismic loading change if rigid connection of the pile with the cap is not provided. Examples of this are shown in Fig. 7 in which the maximum overturning moment is given for a ten storey building. Variations with the number of piles, their



PINNED FLOATING PILES

PINNED END BEARING PILES

Fig. 7 Overturning moment of ten storey building vs. number and type of piles and intensity of ground shaking (1 kip.ft = 1.356 kNm) type and ground motion intensity are shown. The performance of the end-bearing piles follows the nonlinear pattern indicated in Fig. 2; the floating piles behave linearly up to the point of cap uplift. For low intensity of ground shaking there is no significant difference between the two arrangements as far as overturning moments and base shears are concerned. The difference increases with increasing intensity of ground shaking but the rigid connection of the piles to the cap may reduce or increase the seismic loading depending on the number and type of piles, type of building and other conditions.

However, with the cap uplift allowed, the vertical pile loading may significantly increase. This is depicted in Fig. 8 which shows pile forces and storey drift for a ten storey building supported by 27 piles installed in three rows or five rows, respectively, and differing in the tip conditions. Tension, denoted by a minus sign, is more likely to occur in floating piles. The magnitude of the pile forces can be seen to depend on pile configuration. The dramatic changes in pile forces caused by the elimination of even a small tension force are caused by the substantial decrease of group stiffness in rocking. In smaller buildings, pile tension is likely to occur only at high ground acceleration.

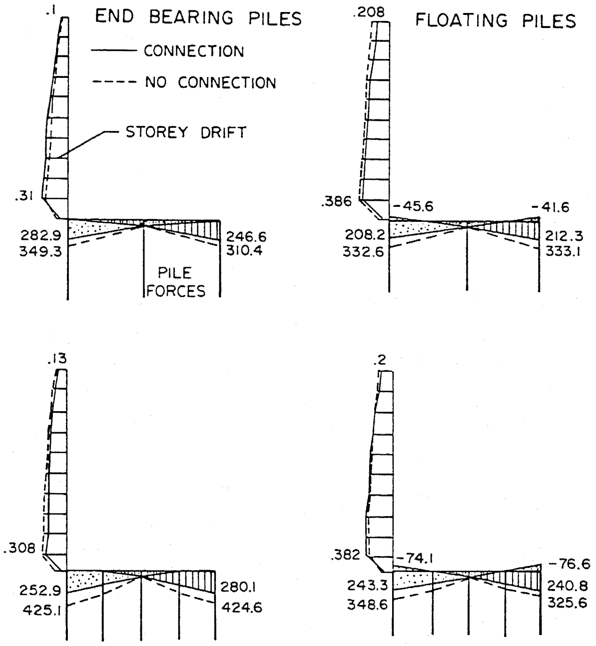


Fig. 8 Pile forces (kips) and storey drift (in) for ten storey building supported by 27 piles arranged in three or five rows (0.11 g)

CONCLUSIONS

The examination of dynamic behavior of buildings supported by different foundations suggests the following conclusions:

Natural periods and modal damping of buildings are affected by the type and stiffness of the foundation. Piles usually yield higher natural frequencies but lower damping than other types of foundations.

Seismic response and loading of buildings depend on the flexibility of the foundation and its type. Both the absolute and relative effect of different foundations vary with soil stiffness.

Rigid connection of piles with the cap may not always be necessary particularly not for small buildings and/or low intensity earthquakes.

ACKNOWLEDGEMENTS

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