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# DYNAMIC SOIL-STRUCTURE INTERACTION

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A general summary is presented of main results from research into the importance of foundation compliance to response of tall buildings to earthquakes presented at an international conference on the planning and design of tall buildings. The criteria for importance are given in terms of the frequencies of a rigid building rocking, swaying, and twisting on the ground as compared to the fundamental frequency of a building on rigid ground. The criteria are illustrated by computations for a typical building of various heights and founded over various soils. A very still apartment building in Caracas, Venezuela is mentioned as an example of a building for which foundation interaction is quite important.

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# DYNAMIC SOIL-STRUCTURE INTERACTION

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Robert V. Whitman

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Technical Committee No. 16: Earthquake Loading

Invited Discussion

# DYNAMIC SOIL-STRUCTURE INTERACTION

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## 1. INTRODUCTION

As indicated by Prof. Seed in his state of art report, the effect of soil upon the response of buildings to earthquakes may be separated, conceptually, into two parts:

1. The stiffness and thickness of soil strata affect the motion at the surface of the soil. This effect is often referred to as soil amplification.
2. The deformability of the soil immediately beneath a building affects the response of the building to the surface motion. When most investigators use the phrase soil-structure interaction, they mean this effect.

Prof. Seed then suggests that the first effect is much more important than the second effect, and that the effect of interaction is not likely to exceed several tens of percent.

The discusser fully agrees with these generalizations. However, Prof. Seed has noted that interaction may cause larger effects upon response in some cases. Moreover, for some types of structures, especially nuclear power plants, much more attention is given (probably erroneously) to interaction than to amplification. Hence it is desirable to have some criteria by which the possible importance of interaction may be judged.

While studies using finite element representation for the soil have provided useful results, the clearest understanding of the nature and importance of the interaction effect has come from studies in which soil is represented by foundation springs (1, 3, 6). The discusser also recommends use of lumped spring representation for design studies, since this approach is most adaptable to the necessary variation of parameters studies.

## 2. GENERAL CRITERIA

Suppose for the moment that a building were completely rigid. Then several characteristic periods may be defined (see Fig.1)

$T_R$: rigid structure rocking period

$T_H$: rigid structure swaying period

$T_T$: rigid structure torsional period

There will be two values of $T_R$ or $T_H$ for a building, corresponding to the two axes of the building.

The effect of interaction upon dynamic response along any axis may be judged by how much interaction affects the fundamental period for that axis. The fundamental period $T_1$, considering the effect of interaction, may be estimated with considerable accuracy from Dunkerley's approximation

$$T_1^2 = T_S^2 + T_R^2 + T_H^2 + T_T^2$$

where $T_S$ is the fundamental period of the building upon a completely rigid foundation. Studies have shown that interaction has a noticeable effect upon response if the fundamental period is increased by more than 10%. The effect becomes important (exceeds several tens of percent) when the fundamental period is increased by more than 30%.

For a tall building, usually $T_H$ and $T_T$ are considerably less than $T_R$, and only rocking has significant influence upon the dynamic response. Rocking primarily effects the response of the fundamental mode; indeed, if the mode slope for the fundamental mode is a straight line, then it may be proven mathematically that rocking interaction has no influence upon higher modes. However, even if swaying and torsional interaction are important, so that interaction does more than just affect the fundamental mode, the foregoing inequalities may be used to judge the importance of the over-all effect of interaction.

Often the importance of interaction is expressed in terms of its contribution to the total motion at the top of a building. Motion at the top is mainly the result of response in the fundamental mode. For a shear building resting upon rocking and swaying springs, the total motion $\Delta$ at the top in the fundamental mode is, to a good approximation

$$\Delta = \Delta_S \left[ 1 + \left(\frac{T_R}{T_S}\right)^2 + \frac{1}{2}\left(\frac{T_H}{T_S}\right)^2 \right]$$

where $\Delta_S$ is the motion if the structure is on a rigid foundation. Thus, especially for tall buildings where $T_H < T_R$, the contribution of interaction to motion is much the same as the contribution to the fundamental period.

## 3. EVALUATION OF RIGID STRUCTURE PERIODS

Evaluation of $T_R$, $T_H$ and $T_T$ requires knowledge of (a) mass and moment of inertia and (b) the foundation spring constants.

The distribution of mass in a building may be determined readily, and estimates made during preliminary planning for a building will usually be of sufficient accuracy. Various expressions are available for estimating the equivalent mass and equivalent moment of inertia of the soil (2, 5). With tall buildings, such equivalent masses and moments of inertia usually are negligibly small compared to the corresponding mass and moments of inertia of the building.

Satisfactory estimates for the spring constants are more difficult. For buildings having rigid, square foundation mats, elastic theory provides the following expressions

$$\text{rocking spring constant } k_R = \frac{0.5GBL^2}{1 - \upsilon}$$

$$\text{swaying spring constant } k_H = 1.9(1 + \upsilon)G\sqrt{BL}$$

where G = shear modulus, $\upsilon$ = Poisson's ratio, L = width of foundation parallel to ground motion, and B = width of foundation normal to ground motion. Various references provide corresponding expressions for other geometries and for torsion, and suggest procedures applicable to other than mat foundations (4, 5).

An average value of Poisson's ratio of 0.4 may be used without introducing much error. The real problem is choosing a representative shear modulus G. Several techniques, using either plate bearing tests or in-situ wave velocity measurements as laboratory tests on undisturbed samples, are available for this purpose (4, 5). Considerable judgement and experience is necessary for selecting a representative value.

This approach generally gives nearly an upper limit estimate for the spring constant, since the expressions presume elastic behavior and since the modulus applies only at small strains. It is possible to correct for the effect of strain using the lower part of Fig. 6 in Seed's report. However, the discusser prefers simply to adopt a range of values for spring constant and to assume that any value within this range is possible. If $k_0$ is the spring constant determined by the approach given above using reliable data for shear modulus, then the following ranges are proposed:

| | |
|---|---|
| Rocking | $0.33k_0$ to $k_0$ |
| Swaying | $0.5k_0$ to $k_0$ |

The ranges are intended to cover a variety of uncertainties arising from the non-linear behavior of soil. If the data used for shear modulus are not reliable, even larger ranges should be used.

## 4. EXAMPLES

To illustrate the change in fundamental period, a series of buildings all 75 ft. by 75 ft. in plan but having different height were assumed to rest on a series of different soils. The rocking and swaying spring constants were taken as 1/2 the values from elastic theory. The period of the buildings was taken to be

$$T_S = \alpha N$$

where N is the number of stories. The following table gives the computed ratio of $T_1$ to $T_S$. $C_S$ is the shear wave velocity for the soil.

| $C_S$ - ft/sec | Flexible building $\alpha = 0.12$ | | | | Stiff building $\alpha = 0.06$ | | | |
|---|---|---|---|---|---|---|---|---|
| | N=10 | N=20 | N=30 | N=40 | N=10 | N=20 | N=30 | N=40 |
| 500 (soft clay) | 1.14 | - | - | - | 1.48 | - | - | - |
| 800 (medium clay) | 1.08 | 1.09 | - | - | 1.21 | 1.26 | - | - |
| 1100 (dense sand) | 1.03 | 1.05 | 1.06 | 1.08 | 1.13 | 1.16 | 1.22 | 1.30 |
| 1500 (cemented sand) | 1.01 | 1.02 | 1.03 | 1.04 | 1.08 | 1.08 | 1.11 | 1.16 |

With flexible buildings, the effect of interaction is hardly noticeable except for the shortest building. With stiff buildings, the effect of interaction is noticeable, and in some cases verges on being important. (The blanks in the table indicate that buildings cannot be founded directly upon softer soils without use of piling.)

The discusser has been involved with an unusual set of 45-story buildings in Caracas. The economy of Venezuela dictated the use of concrete, and apartment occupancy dictated use of shear wall construction. As a result, the buildings were very stiff, with an estimated period $T_S$ = 1.3 seconds in the transverse direction ($\alpha = 0.03$). For an assumed range of foundation stiffnesses, $T_R$ was estimated to be from 0.85 to 1.90 seconds. Thus, foundation interaction led to 20% to 80% increase in the fundamental period. Interaction was quite important for this building.

## 5. CONSEQUENCES OF INTERACTION

During any one earthquake, interaction may shift the fundamental period either from a peak to a valley, or from a valley to a peak, of the response spectrum. Thus, interaction may be either harmful or beneficial for any one earthquake. However, from the standpoint of design based on a smooth response spectrum or the average of many earthquake inputs, interaction always acts to reduce the stresses in a tall building. (In short buildings swaying interaction would act to increase stresses were it not for the large damping associated with swaying interaction.) The buildings in Caracas could not economically have met design specifications had not advantage been taken of this reduction.

From the standpoint of stresses within the structure, it is conservative to use stiff foundation springs or to neglect interaction. Interaction of course increases the motion at the top of a building, and this increased motion may be important when there is only a small separation between buildings. From the standpoint of motions, it is conservative to underestimate foundation stiffness.

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## LIST OF SYMBOLS

$B$ width of foundation in direction perpendicular to motion

$C_S$ shear wave velocity

$G$ shear modulus

$k_H$ swaying spring constant

$k_R$ rocking spring constant

$k_0$ spring constant for elastic conditions

$L$ width of foundation in direction of motion

$N$ number of stories

$T_H$ swaying period of rigid structure on flexible foundation

$T_R$ rocking period of rigid structure on flexible foundation

$T_S$ fundamental period of structure on rigid foundation

$T_T$ torsional period of rigid structure on flexible foundation

$T_1$ fundamental period considering flexibility of structure and foundation

$\alpha$ coefficient relating period to number of stories

$\Delta$ motion at top of structure

$\Delta_S$ motion at top of structure on rigid foundation

$\upsilon$ Poisson's ratio

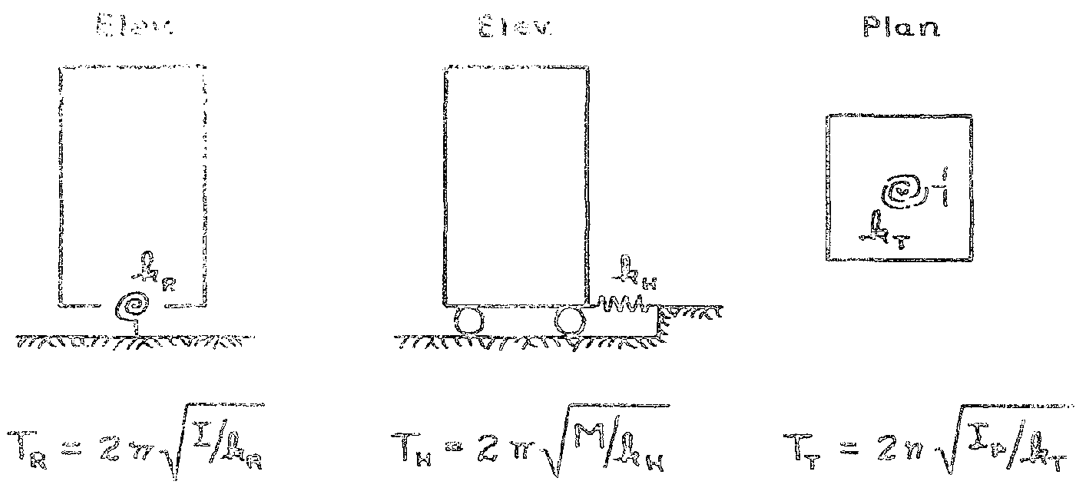


FIGURE 1: Characteristic Periods of Rigid Structure upon Soil.

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KEY WORDS: apartment buildings, dynamics, earthquakes, foundations, natural frequencies, soil-structure interaction, tall buildings

General summary of main results from research into importance of foundation compliance to response of tall buildings to earthquakes. Criteria for importance are given in terms of the frequencies of a rigid building rocking, swaying and twisting on the ground as compared to the fundamental frequency of a building on rigid ground. The criteria are illustrated by computations for a typical building of various heights and founded over various soils. A very stiff apartment building in Caracas is mentioned as an example of a building for which foundation interaction was quite important.

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