EFFECT OF FOUNDATION FLEXIBILITY ON THE SEISMIC RESPONSE OF PANEL BUILDINGS

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SUMMARY

The effect of foundation flexibility on the seismic response of panel buildings is investigated by considering typical crosswall buildings with different number of stories and various soil conditions. The natural frequencies and effective damping of the structures on a rigid base and on flexible foundations are compared, as well as displacements and forces under an artificial earthquake of the Newmark-Blume-Kapur type. In addition the effects of a mat foundation versus individual strip footings is investigated, accounting in the last case for the coupling of the footings through the soil and including the inplane flexibility of the slabs.

INTRODUCTION

The effect of the flexibility of the foundation on the dynamic response of structures has been a subject of considerable interest and research in recent years. This effect, known as soil structure interaction, has been shown to be important when dealing with heavy and very stiff structures, such as nuclear power plants, under seismic excitation. As a result most of the recent research has been focused towards this type of application. For regular, framed, buildings founded on competent soils it is commonly believed that soil structure interaction effects are small and can be neglected. This is not the case, however, when dealing with short shear wall or panel buildings, which become again very massive and stiff. The work described in this paper was conducted as part of an extensive study on the seismic behavior of prefabricated panel buildings which included studies on the effect of the inplane flexibility of the slabs and the overall three dimensional behavior (1), the nonlinear behavior of the joints (2) and the foundation flexibility (6).

DESCRIPTION OF MODEL

The buildings considered for the study had the configuration of typical crosswall construction in the United States but they were simplified for analysis purposes. The mathematical model consisted of five parallel walls with 24 ft. width and 8 inch thickness at 30 ft. spacings. The interstory height was 9 ft. and the modulus of elasticity of the concrete in the walls was taken as 614000 kips per square foot with a unit weight of 150 pounds per cubic foot. The slabs were modelled as beams connecting the center lines of the walls, with a modulus of elasticity equal to one-fourth of that of the concrete in the walls to account for the fact that they are made of hollow planks with a concrete topping. The total mass of the top floor was 16.5 kips x $\sec^2$/ft. and that of the other floors 22 kips x $\sec^2$/ft. The structures studied had 5, 10 and 15 stories to cover a range of typical heights.

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The seismic excitation used for the analyses was an artificial earthquake generated so as to match the Newmark-Blume-Kapur response spectrum for 5 percent damping and a peak ground acceleration of 0.25g. The motion had a total duration of 15 seconds consisting of 3 seconds rise time, 9 seconds of strong motion duration and 3 seconds decay time. Since the analyses are elastic the maximum ground acceleration was not a significant parameter (all results could be scaled for any other level of acceleration) although the actual soil properties would in fact be affected by the intensity of shaking.

In order to reproduce in the parametric studies realistic situations, a number of actual buildings for which information was available on the soil characteristics were examined. From the design vertical loads, the number of stories and the dimensions of the foundations of these buildings the ultimate bearing capacity of the soils was estimated. Three soil profiles were considered:

Soil type 1 consisted of dry sand with an angle of internal friction of 30 degrees, a relative density of 40%, a Poisson's ratio of 0.33, a unit weight of 110 lbs. per cubic foot and an allowable bearing capacity estimated at 6 kips per square foot. The shear wave velocity was estimated from the above data at 670 ft./ second and the shear modulus at 1530 kips/sq. ft.

Soil type 2 was a silty clay with sand sublayers. It had a Poisson's ratio of 0.45, an allowable bearing capacity of 3.5 kips/sq. ft., a unit weight of 115 lbs./cu. ft., an estimated shear wave velocity of 1070 ft./sec. and a shear modulus of 4085 kips/sq. ft.

Soil type 3 was a homogeneous brown clay with an allowable bearing capacity of 8 kips/sq. ft., Poisson's ratio of 0.45, unit weight of 115 lbs./cu. ft., shear wave velocity of 1600 ft./sec. and a shear modulus of 9300 kips/sq. ft.

For all three soils an internal, material, damping of 5 percent was assumed. On the basis of these properties foundation dimensions were selected for the buildings studied as a function of the number of stories, assuming individual strip footings for the walls. The five story building had rectabular footings of 4 x 24 ft. on soil type 1, 6.7 x 24 on soil type 2 and 3 x 24 on soil type 3. The corresponding sizes for the 10 story building were 8 x 24, 13.4 x 24 and 6 x 24 respectively, and for the fifteen story structure 12 x 24, 16 x 24 and 9 x 24.

In a first series of studies it was assumed that all slabs acted as rigid diaphragms, the common assumption in the seismic analysis of buildings but one which is open to question when dealing with stiff shear wall or panel construction, particularly with a small number of stories (1). In this case the coupling between the various footings through the soil was neglected. The mathematical model was then reduced to the consideration of a single wall with one fifth of the mass of each floor lumped at the story levels and its individual footing. Results were obtained for the 5, 10 and 15 story buildings. For the five story building, where the effect of the slab flexibility has been shown to be more significant in relation to the distribution of shear forces among the walls (1), analyses were performed next considering the complete building and determining the foundation stiffnesses for the set of five footings (including the coupling terms between footings). In addition a solution with a continuous rigid mat foundation under the complete building was also studied for the purposes of comparison.

FORMULATION

The first step for all analyses was the determination of the dynamic stiffnesses of the strip footings, either isolated or as a complete set. Solutions are now available and tabulated for the stiffnesses of circular mats on the surface of an elastic or viscoelastic half space (7). These stiffnesses are complex functions of frequency: the real part can be interpreted as the constant of an equivalent spring whereas the imaginary part represents the loss of energy by radiation of waves away from the foundation and can be interpreted as the constant of an equivalent dashpot. It is common practice when dealing with rectangular foundations whose aspect ratio (ratio of the lengths of the sides) is less than four to use the solutions for circular mats defining an equivalent radius for each particular effect. In this case, however, aspect ratios varied from 1.5 to 8, a range much larger than the one encountered in other applications. Furthermore no published solution was available for the set of five footing.

The solution of this problem was carried out by determining numerically at each frequency the appropriate Green's function using a program developed by Gonzalez (4). Each foundation is discretized into a number of small nearly square areas. For a harmonic load (horizontal or vertical) distributed over each one of these areas desplacements are computed at the centroids of all areas establishing with the results an influence, or flexibility, matrix F. If U is the vector of displacements (3 components for each node) and T is the vector of applied tractions, with the same number of components one can then write

$$U = FT \tag{1}$$

Considering each foundation to be rigid the displacements of the various nodes can be related to those of the centroid of the foundation by a rigid body transformation of the form $U = LU_o$ where U_o is a vector with six displacement components (three displacements and three rotations) for each foundation. In the same way, when dealing with rigid foundations one is only interested in the resultants of the elementary tractions over the foundation areas. One can write as a result a corresponding transformation on forces $P_o = L^T T$ where P_o has six components (3 forces and 3 moments) for each foundation. From equation 1 one can then derive

$$T = F^{-1}U \tag{2}$$

$$P_o = L^T T = L^T F^{-1} L U_o \tag{3}$$

and the stiffness matrix of the foundation is

$$K = L^T F^{-1} L \tag{4}$$

The numerical determination of the influence coefficients (terms of the matrix F) was performed using a formulation in cylindrical coordinates in which forces are applied at the top of a column of finite elements surrounded by the free field. The free field is reproduced by a consistent boundary matrix developed by Kausel (5) and displacements are obtained at any point in the free field through the expansion of the solution in terms of Mankel functions. Advantage is taken of symmetric characteristics of *the results, applying a shifting technique to minimize the number* of points for which the problem has to be solved. The computation of the stiffness matrix of coefficients and with as many right hand side vectors as there are columns in L. This gives directly the product $F^{-1}L$, which is then multiplied by L^T. The operations have to be repeated for each frequency of interest.

A number of parametric studies were conducted determining the static stiffnesses and the frequency variation of the real and the imaginary part of the dynamic stiffnesses for isolated rectangular foundations of various aspect ratios. The results were compared with those obtained by Dominguez (3) using a boundary integral formulation with excellent agreement. It was also found that the common assumption described above seems to be justified when the aspect ratio is not too large.

Once the stiffness matrix of the foundation was obtained the seismic analysis of the buildings including soil structure interaction offects was carried out in the frequency domain obtaining the transfer functions for all desired effects, multiplying them by the Fourier transform of the input earthquake and obtaining time histories of the results by computing the inverse transform of these products. From these transfer functions it was also possible to determine the natural frequencies and the mode shapes, as well as estimates of the effective modal damping. Natural modes and frequencies were determined independently through a normal eigenvalue analysis using in this case the static stiffnesses. In addition estimates of the natural frequencies and effective modal dampings including interaction *effects were obtained using approximate formulae corresponding to a single* degree of freedom system. Excellent agreement was found between all these results.

RESULTS

The main effect of soil structure interaction are a change in the natural period of the system which will elongate, an increase in the effective damping due to the additional loss of evergy by radiation and a change in the behavior due to the appearance of base rotations. Tables I, II and III show the results for the 5, 10 and 15 story buildings respectively, assuming that the slabs act as rigid diaphragms (considering therefore a single wall), without interaction effects and for the three soil conditions studied. From these results it can be observed that the increase in the fundamental period of the building is very large for the five story building on soft soil (soil 1), by a factor of almost 3. This effect decreases with increasing height, thus flexibility, of the structure and with increasing stiffness of the soil. It should be noticed, however, that the effect is still noticeable for the 15 story building on soil type 3. The increase in damping due to radiation is very small in all cases due to the dimensions of the footing and decreases as the period of interest increases. The variations in the forces (base shears and overturning moments) seem to be somewhat erratic, without a clear trend. While the artificial earthquake was generated to match a Newmark-Blume-Kapur spectrum no iterations

TABLE I

5 Story Building - Rigid Diaphragms

	Rigid Base	Soil Type 1	Soil Type 2	Soil Type 3
Natural period (sec)	0.16	0.45	0.26	0.23
Effective Damping	0.050	0.053	0.054	0.054
Top Displacement (ft)	0.017	0.139	0.056	0.037
Base Displacement	0	0.008	0.003	0.001
Base Shear (kips)	352	373	471	409
Base Moment (kp x ft)	11226	12336	14733	12385

TABLE II

10 Story Building - Rigid Diaphragms

	Rigid Base	Soil Type 1	Soil Type 2	Soil Type 3
Natural Period	0.55	1.02	0.68	0.63
Damping	0.05	0.051	0.051	0.051
Top Displacement	0.173	0.35	0.24	0.22
Base Displacement	0	0.07	0.002	0.001
Base Shear	565	375	507	555
Base Moment	34000	20000	30000	31000

TABLE III

15 Story Building - Rigid Diaphragms

	Rigid Base	Soil Type 1	Soil Type 2	Soil Type 3
Natural Period	1.17	2.05	1.37	1.37
Damping	0.05	0.05	0.05	0.05
Top Displacement	0.577	0.607	0.797	0.574
Base Displacement	0	0.003	0.003	0.001
Base Shear		485	699	588
Base Moment		26000	55000	44000

were performed to smooth it and the actual spectrum for 5 percent damping exhibited still several peaks and valleys. As a result changes in period can cause both increases and decreases in levels of response acceleration. It should also be noticed that while the 15 story building has approximately the same fundamental period on soils 2 and 3 the response is somewhat different. Differences existed in the period of the second mode which was also affected by the foundation flexibility.

In the second series of parametric studies the complete 5 story building was considered, accounting for the inplane flexibility of the slabs. As a result the displacements and the forces in the different walls were no longer the same. In addition the case of a unique, rigid mat foundation under the complete building was also considered. The natural period of the building on a rigid base was 0.17 seconds, very close to the 0.16 seconds obtained by considering only one wall. The structural damping was 5 percent (0.05). For the mat foundation the natural periods with interaction effects were 0.29, 0.21 and 0.18 seconds for the three soil types respectively; the values of effective damping were 15, 10 and 7.5 percent. For the set of five strip footings the corresponding values were 0.43, 0.26 and 0.23 seconds for the natural periods and 7, 6.5 and 6 percent for the damping. These results clearly indicate that because of the size of the mat foundation and its increased stiffness the period elongation is much smaller in this case, while the radiation damping becomes very significant. This could indicate that a complete mat might be advantageous from the dynamic point of view. On the other hand it must be realized that for a mat of this size (24 x 150 ft) the assumption of a rigid foundation may no longer be justified. This question should be investigated further before reaching a conclusion. For the set of five strip footings the natural periods are very close to those obtained before using only one wall: this indicates that the real part of the stiffness for the set of footings is very close to the sum of the stiffnesses of the individual foundations (coupling effects are not significant). There is, however, an increase in radiation damping which is significant (from 0.5 to 2 percent) although the total damping is still close to the structural damping.

Tables IV, V and VI show the displacements, base shears and overturning moments for the different walls. It is interesting to notice that as the soil becomes softer the distribution of loads among the different walls tends to be more uniform. Other studies ( ) have shown that the effect of the inplane flexibility of the slabs, resulting in nonuniform distribution of forces among the walls, is typically concentrated in the lower stories and is only significant for low rise buildings. A soft foundation soil would then tend to act as an additional story.

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TABLE IV

5 Story Building - Top Displacements (ft)

	Outside Walls	Inside Walls	Center Wall
Rigid Foundation	0.012 (0.70)	0.020 (1.17)	0.024 (1.40)
Soil Type 1	0.089 (0.89)	0.104 (1.04)	0.110 (1.10)
Soil Type 2	0.035 (0.79)	0.049 (1.10)	0.054 (1.22)
Soil Type 3	0.023 (0.76)	0.033 (1.11)	0.039 (1.30)

Numbers in parenthesis indicate fraction of average floor displacements.

TABLE V

5 Story Building - Base Shears (kips)

	Outside Walls	Inside Walls	Center Wall
Rigid Foundation	241 (0.68)	415 (1.16)	472 (1.32)
Soil Type 1	307 (0.90)	356 (1.04)	376 (1.10)
Soil Type 2	335 (0.77)	483 (1.11)	533 (1.22)
Soil Type 3	389 (0.76)	418 (1.10)	471 (1.30)

Numbers in parenthesis indicate fraction of average base shear.

TABLE VI

5 Story Building - Overturning Moments (kips x ft)

	Outside Walls	Inside Walls	Center Wall
Rigid Foundation	7550 (0.66)	13250 (1.16)	15340 (1.34)
Soil Type 1	9980 (0.91)	11500 (1.04)	12170 (1.10)
Soil Type 2	10880 (0.79)	15200 (1.10)	15750 (1.14)
Soil Type 3	8800 (0.76)	12670 (1.10)	14450 (1.25)

Numbers is parenthesis indicate fraction of average base moment.

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