MEASURED EFFECT OF FOUNDATION EMBEDMENT ON RESPONSE

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SUMMARY

The fundamental resonant frequency, damping ratio, and mode shape of a single story model structure were measured at foundation embedment ratios of 0, 0.45 and 0.90. Analysis of the experimental results led to the determination of the stifness and damping coefficients of the system; the soil-foundation coefficients were found to increase with embedment. The calculated embedment factors were generally greater than those resulting from current theoretical formulations.

INTRODUCTION

The dynamic behavior of structures under earthquake loading can be determined by lumped parameter analysis. This analysis requires the modelling of the structure by lumped masses, elastic springs, and viscous dashpots. The effects of foundation-soil interaction are introduced by modelling the supporting soils by impedance functions which describe the in-phase and out-of-phase reactions of the supporting soil. These impedance functions are dependent upon the excitation frequency, size of the foundation, soil stiffness, and wave speed.

Embedment factors, which modify the non-embedded foundation impedance functions, are used to account for the effect of foundation embedment. With a few exceptions, the theoretical embedment factors are frequency independent.

This report presents the results of an experimental program in which the response of a one-story model structure was measured at three foundation embedment depths, corresponding to embedment ratios ($\delta = d/r_0$) of 0, 0.45, and 0.90 [Ref. 1,2,3]. The system impedances, and embedment factors for rocking and translation of the foundation, were calculated from the measured response.

DESCRIPTION OF THE EXPERIMENT

The model structure consisted of a 3.05 m square-topped concrete box foundation with a steel framed concrete superstructure. The overall height of the structure was 3.5 m and the foundation depth was 1.5 m. The mass of the structure, divided in a ratio of two-to-one between foundation and superstructure was 1.1×10^5kg, which was also the mass of the soil displaced by the foundation. The model had dimensionless similitude to several prototype structures that have been examined extensively [Ref. 4,5]. The fixed base fundamental frequency in the east-west (principal) direction was estimated to be 17.5 Hertz.

Because of the size of the structure, it was not possible to cast the foundation directly against the soil; instead, the foundation walls were formed and cast-in-place. After completion of the tests at full foundation embedment, the foundation was partially excavated to half-embedment, then finally completely exposed. The structure is shown in Fig. 1.

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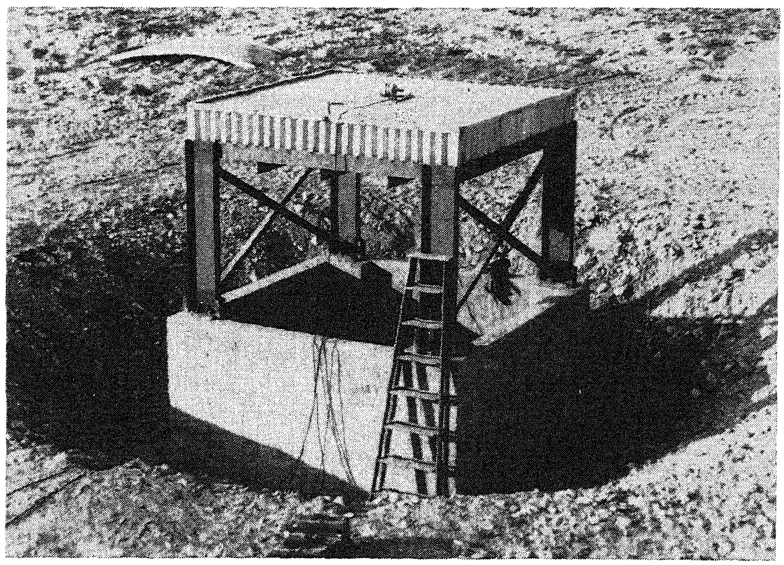

Fig. 1 Model structure with non-embedded foundation. Principal test direction is along the major axis of the columns. Note the seismometer at top of superstructure.

The soil at the Azusa, California, site consisted of geologically recent alluvial deposits of silts, sands, gravels, and cobbles. The material was non-cemented, and fairly homogeneous to a depth of almost 300 m. The soil was dry during the test program. The water table was located 75 m below the surface. A shear wave velocity of 300 m/sec and soil unit weight of 14.5 kN/m^3 were measured.

Structural excitation was provided by three types of input vibrations. Ambient vibration was used to obtain estimates of the first few modes of response of the structure. The fundamental modal damping was estimated from the results of the free vibration tests. Steady state sinusoidal excitation was used for the majority of the tests to obtain detailed frequency-response curves, resonant mode shapes, and near field ground motion at the fundamental resonant frequency.

In a departure from other forced vibration tests, the variable frequency eccentric mass vibration generator was mounted on an open topped concrete box foundation 14.5 m from the specimen, providing input motion to the structure in the form of horizontally incident, anti-plane shear waves. This type of force input is believed to better represent earthquake ground motions, and the effect of simultaneous translation and torsional response may also be determined. Furthermore, the installation of the vibration generator on the structure would have added a sizeable seismic mass to the structure.

The experimental setup permitted excitation of the structure in only one (the principal) direction. The excitation frequencies ranged from 7 to 70 Hertz, corresponding to dimensionless frequencies ($a_0 = \omega r/C_s$) of 0.25 to 2.5. The plan of the experimental site is shown in Fig. 2.

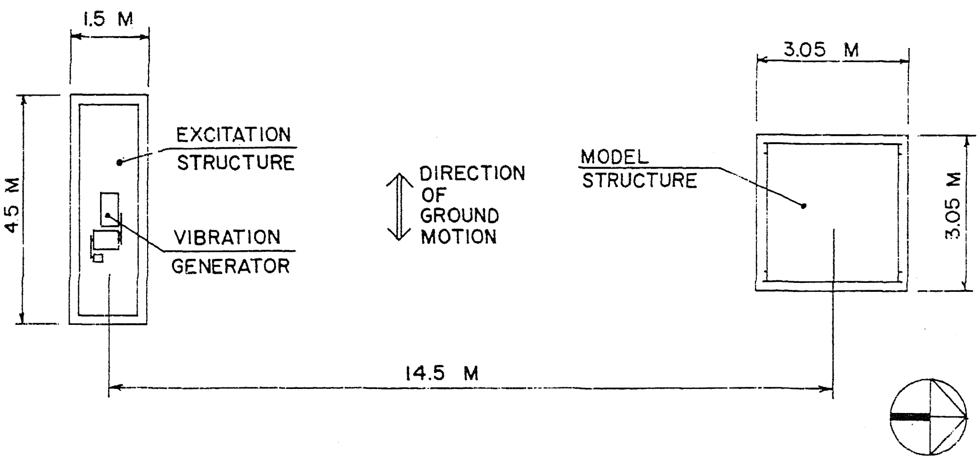

Fig. 2 Site plan showing relation of excitation and model structures.

Prior to construction of the model, vertical and horizontal ground motions induced by the vibration generator were measured at stations along the longitudinal and transverse centerlines of the model. The frequency response of the soil and the amplitude of ground motion as a function of distance from the excitation source were obtained during these tests.

The principal motion transducer used during the tests were Kinemetrics SS-1 seismometers. The SS-1 is a critically damped, velocity sensitive transducer with a nominal 1 Hertz natural frequency. Filtering and 2x to 100,000x amplification were provided by a battery-powered Kinemetrics SC-1 four-channel signal conditioner. The data was recorded on magnetic tape for laboratory analysis.

ANALYSIS

Free and Ambient Vibration Test

The analysis of the free vibration test data consisted of the graphical determination of the resonant frequency and damping ratio from the time histories. The ambient vibration time histories were analyzed by the computation of Fast Fourier Transforms on a Spectral Dynamics SD360 Digital Signal Processor.

Resonant Frequency and Damping Ratio from Forced Vibration

Because of the importance of the forced vibration data, a method was devised to compute the resonant frequency and modal damping from the frequency response curves. In this case, a least squares minimization, based on systems identification theory [Ref. 6], was developed.

The response of a damped single degree of freedom system is described by

$$x = \frac{A(f_i/f_n)^2 \sin 2\pi f_i}{\left[(1-(f_i/f_n)^2)^2 + (2\zeta f_i/f_n)^2\right]^{\frac{1}{2}}} \tag{1}$$

where ζ is the damping ratio, f_n is the resonant frequency, and x is the displacement of the mass with respect to the base. A measure of fit, J, is defined as the sum of the squares of the difference of $y(f_n,\zeta,f_i)$, as defined in Eq. (1), and the measured response $y(f_i)$, that is;

$$J = \sum_{i=1}^{N} (y(f_i) - y(f_n,\zeta,f_i))^2 \tag{2}$$

In this case, if the values of f_n and ζ are varied so that J is minimized over a band width around the response peak, it may then be assumed that the values that result in this best fit are the best approximations of the resonant frequency and modal damping of the measured system. This calculation was used to determine the resonant frequency and modal damping of all of the modes of response found during the forced vibration tests.

Calculation of System Impedances

The impedance of the structure and the foundation-soil system were found by modelling the fundamental mode response by a three degree-of-freedom system, consisting of rocking and translation of the foundation, and the relative displacement of the foundation and superstructure. In a lightly damped system at resonance, inertia forces may be assumed to be resisted by elastic forces, and the input forces are resisted by viscous damping. The equations of motion of the undamped system can be written in terms of the relative participation of the three degrees of freedom in the overall response. Rearrangement of these equations of motion leads to expressions for the stiffnesses of the system in terms of the relative displacement. Similarly, the damping coefficients of the system may be expressed in terms of the ratio of the resonant amplitude to the free-field amplitude.

Determination of Embedment Factors

After the impedance of the soil-foundation system for rocking and translation have been determined for each embedment case, the embedment factors are found by normalizing the values obtained for the two embedded cases by the corresponding values obtained for the nonembedded case.

RESULTS

Four modes of response were determined from the results of the ambient vibration tests. The results are shown in Table 1.

TABLE 1. RESONANT FREQUENCIES FROM AMBIENT VIBRATION TESTS

Embedment Ratio	Translation		Torsion	
	North-South	East-West	1	2
0.0	9.6 Hz	12.0 Hz	19.4 Hz	24.5 Hz
0.45	10.1 Hz	13.1 Hz	19.7 Hz	24.7 Hz
0.90	10.5 Hz	13.7 Hz	19.8 Hz	24.8 Hz

One of the principal results of the steady state vibration tests was the fundamental mode response (E-W), including the resonant frequency, model damping ratio, and modal displacement ratios. These results are listed in Table 2. Additional measurements indicated that the foundation responded as a rigid body, and possessed rocking and translatory motions.

TABLE 2. FUNDAMENTAL MODE RESPONSE (E-W)

Embed-ment Ratio	Resonant Freq.	Damp-ing Ratio	Contribution to Total Superstructure Displacement		
			Foundation Translation	Foundation Rocking	Interfloor Translation
0.0	11.33 Hz	0.80%	6.1%	21%	73%
0.45	13.28 Hz	0.83%	2.1%	14%	84%
0.90	13.75 Hz	0.81%	1.3%	5.4%	93%

Based on the measured mode shape, the total displacement of the superstructure was normalized to the free field input motion. The resulting values were 39, 47, and 44 for embedment ratios of 0, 0.45 and 0.90, respectively. The near field vertical and horizontal ground motions at resonance were also measured. The horizontal ground motions along the longitudinal centerline for the non-embedded case, which are shown in Fig. 3, were similar to the results obtained at the other embedment cases. Table 3 shows the values of the system stiffness and damping coefficients, which were calculated from the modal displacement ratios.

By fitting quadratic curves to the data points, embedment factors for the stiffness and damping coefficient of foundation translation and rocking were found to be;

Translatory stiffness:

$$\Delta K_x = 1 + 6.244\delta - 0.508\delta^2 \tag{3}$$

Rocking stiffness:

$$\Delta K\phi = 1 - 0.591\delta + 6.32\delta^2 \tag{4}$$

Translatory damping coefficient:

$$\Delta C_x = 1 + 3.782\delta + 2.719\delta^2 \tag{5}$$

Rocking damping coefficient:

$$\Delta C_{\phi} = 1 - 2.066\delta = 1 - 2.066\delta + 7.906\delta^2 \qquad (6)$$

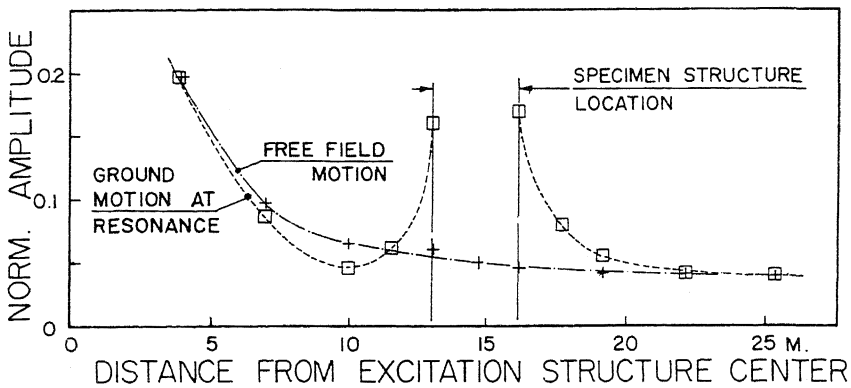

Fig. 3 Free field and resonant horizontal ground motions along longitudinal centerline of site. Results shown for half-embedment case.

TABLE 3. SYSTEM IMPEDANCES

Embed-ment Ratio	Superstructure Translation		Foundation Rocking		Foundation Translation	
	Stiffness (N/m)	Damping Coef. (N-s/m)	Stiffness (N-m)	Damping Coef. (N-s-m)	Stiffness (N/m)	Damping Coef. (N-s/m)
0.0	5.50×10^7	1.75×10^4	2.34×10^9	9.04×10^5	7.81×10^8	6.23×10^5
0.45	6.61×10^7	1.68×10^4	4.63×10^9	1.48×10^6	2.84×10^9	2.00×10^6
0.90	6.41×10^7	1.88×10^4	1.28×10^{10}	4.85×10^6	4.79×10^9	4.04×10^6

DISCUSSION

The modal frequencies increase with foundation embedment, although the effect is not very strong for the torsional response. The two torsional responses correspond to in-phase and out-of-phase rotations of the foundation and the superstructure. Since the foundation is square, the difference in the fundamental mode behavior in the N-S and E-W directions is due to the superstructure.

The effect of increased foundation embedment is clearly evident in the fundamental mode response (E-W). The contribution of foundation motions (rocking and translation) to the total response of the superstructure decreased with embedment, indicating stiffening of the foundation-soil system. In the limiting case, a deeply embedded foundation would approach the fixed base condition. The modal damping ratio did not change measurably with embedment. Similar results were obtained from the free vibration tests. The displacement ratios measured at the half-embedment case were similar to the results obtained at Millikan Library [Ref. 4].

Foundation-soil impedances calculated from the measured responses were in good agreement with results from evaluation of analytical expressions for the non-embedded foundation [Ref. 7]. The exception is the damping coefficient for translation, which was about five times higher than expected from the theory. In general, such differences do not have a significant effect on the overall response of the system.

The embedment factors given in Eq. (3) to (6) were, in general, higher than expected from present analytical formulations [Ref. 8,9,10,11], particularly in higher embedment ratios.

The resonance of the structure induced lateral and vertical ground surface motions at distances of up to three building radii. Vertical motions were detected along the transverse centerline of the model, indicating a significant rocking motion. The total ground motion, measured at the resonant frequency of the model, was significantly less than the free field motion at the same frequency at a distance of three to five building radii, in the direction toward the excitation source. This behavior may be indicative of the formation of standing waves.

ACKNOWLEDGEMENTS

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