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Dynamic Response of Block Foundations

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SYNOPSIS This paper presents the results of comparison of the computed and observed response of two block foundations made of concrete. The test blocks measuring 3.0m x 1.5m x 0.7m and 1.5m x 0.75m x 0.70m were cast on level ground. The blocks were excited into vertical vibrations using a speed controlled mechanical oscillator. The amplitudes of vibration at different frequencies of excitation were measured in each case using acceleration transducers mounted on appropriate faces of the block. Dynamic shear modulus at this site was also determined by conducting in-situ tests namely the wave propagation test, the cyclic plate load test, and the standard penetration tests. From this data the dynamic shear modulus versus shear strain plot was obtained. The natural frequencies and the vibration amplitudes of the test blocks were then calculated by (i) the linear spring method, (ii) the elastic half space method. A comparison was then made of the observed and computed natural frequencies and the vibration amplitudes of the blocks. The results of this comparison showed that for the cases of vertical vibrations, the natural frequencies in this case could be reasonably predicted by either of the methods used. The calculated and observed amplitudes, however, showed a wide variation. The details of tests performed and the analysis are discussed in this paper.

INTRODUCTION

Rigid concrete blocks are commonly used as foundations for supporting reciprocating machines. In order to ensure long term satisfactory performance of a foundation supporting a machine, its design should meet the criteria for static and dynamic stability. The criteria for static design are the same as for an ordinary foundation namely, no shear failure in soil, and no excessive settlement of the footing. The criteria for dynamic stability requires that the natural frequency of the foundation soil system should be far away from the operating frequency of the machine, and the amplitude of vibration under normal operating conditions should not exceed the specified limits. The vibrations produced due to operation of the machine should not be harmful to the people working in the vicinity of the machine, and to the adjacent structures. The design of the machine foundations is generally made either by the linear spring method (Barkan, 1962) or by the elastic half space method (Richart, Hall and Woods, 1970; Prakash and Puri, 1988; Das, 1992). Very little data is however available on the calculated response of a machine foundation and its actual performance. In fact no attention is paid to the measurement of vibration amplitudes until some problem develops.

This paper presents the results of a comparison of the computed and observed response of two block foundations made of concrete. The test blocks were excited into vertical vibrations and their natural frequencies and amplitudes were measured. The pertinent soil properties were determined by conducting in-situ tests and oscillatory shear tests in the laboratory. The response of the two test blocks was then computed by the (i) linear weightless spring method, and (ii) elastic half space method. A comparison was made of the observed and predicted response of the test blocks. The details of the tests conducted, data obtained, and comparison of the observed and computed response are discussed here.

TESTS CONDUCTED

Block Vibration Tests:

The block vibration tests were conducted on rigid concrete blocks. The sizes of the test blocks were 1.5m x 0.75m x 0.70m and 3.0m x 1.5m x 0.7m. The blocks were cast on level ground. Vertical vibration tests were conducted on each of these two blocks. These tests were conducted by exciting the block in the vertical direction with the help of a mechanical oscillator. A speed controlled D.C. motor was used to operate the oscillator. The oscillator-motor assembly was mounted centrally on the top of the test block, and rigidly attached to it. The block was set into vertical vibrations by operating the mechanical oscillator. The vibrations of the block were measured with an acceleration transducer mounted on the top of the block and oriented so as to sense vertical vibrations. The output from the accelerometers was amplified and recorded. A schematic sketch of the test set up is shown in Figure 1. Records of vibration were obtained for different frequencies of excitation. The tests were repeated by changing 'θ' the angle of setting of the eccentric masses. From the recorded data, the frequency and the corresponding amplitudes were determined. The data was then plotted in the

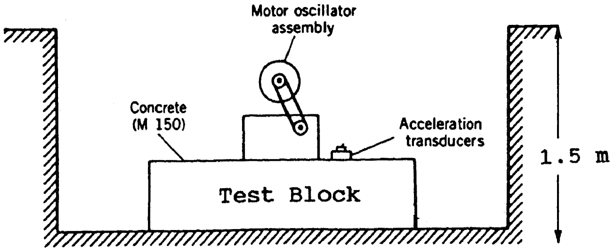

Fig.1 Test Setup For Block Vibration Tests.

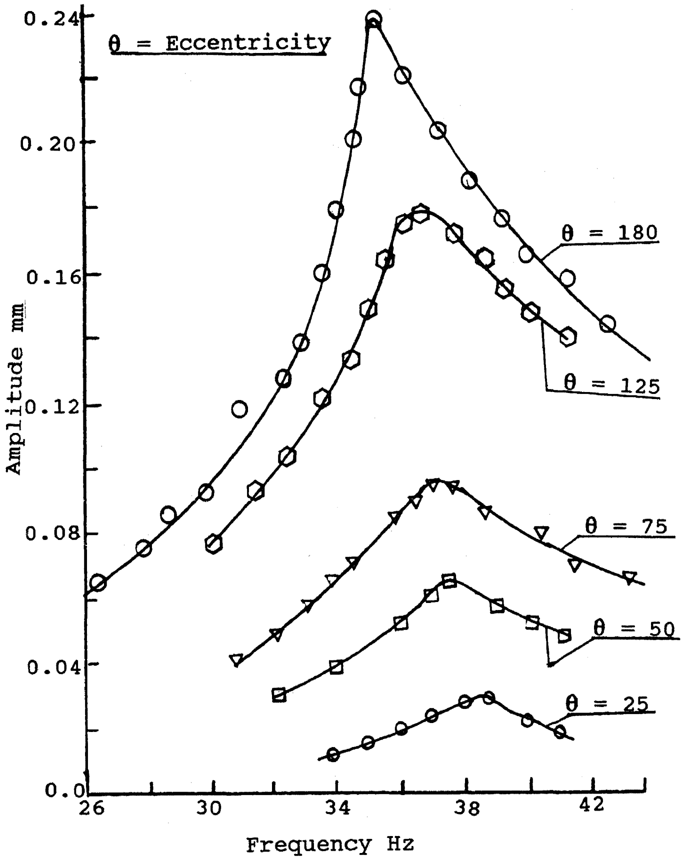

Fig.2 Amplitude versus Frequency Plots for Vertical Vibration Test on 1.5 m x 0.75m x0.7 m High Block.

form of amplitude-frequency plots. Typical amplitude versus frequency plots are shown in Figures 2 and 3.

Tests for Determination of Dynamic Soil Properties

The dynamic properties of the soil used in the analysis of machine foundation may be determined by a number of laboratory or in-situ tests. These properties are affected by a number of factors which should be accounted for when selecting the design values. The most important parameters which affect these properties are (1) the mean effective confining pressure, (2) the shear strain amplitude, and (3 density in the soil. A good discussion on these corrections has been presented by Prakash and Puri (1977), Nandakumaran et al (1977), Prakash and Puri (1981) and Indian Standard Code (IS 5249 - 1977).

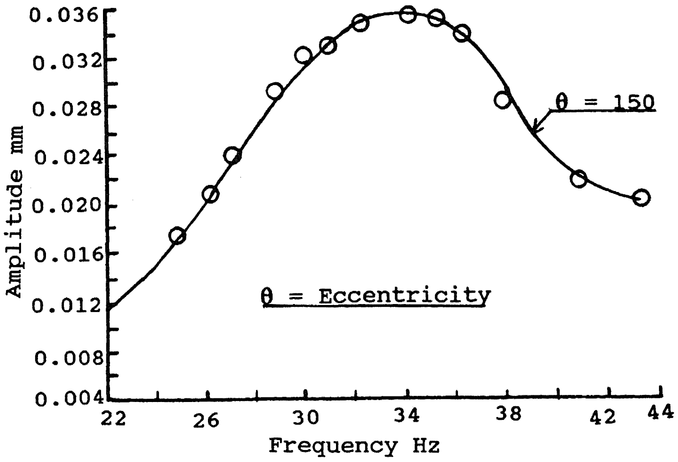

Fig. 3 Amplitude versus Frequency Plots for Vertical Vibration Test on 3.0 m x 1.5m x0.7 m High Block.

In-situ Soil investigations consisted of (1) wave propagation tests, (2) cyclic plate load tests and (3) standard penetration tests. From the cyclic plate load test data, values of dynamic shear modulus "G" were computed. From the uncorrected standard penetration (N) values shear wave velocity V_s at a particular depth was determined from equation (1) Imai (1977) and dynamic shear modulus "G" was computed from equation (2)

$$V_s = 91.0\, N^{0.337} \quad \ldots\ldots\ldots \quad (1)$$

$$G = V_s^2 \times \rho \quad \ldots\ldots\ldots \quad (2)$$

in which $\rho = \gamma/g$ = mass density of soil. Values of "G" from different tests were corrected for (1) effective confinement in each case and computed for an effective overburden pressure of 100kN/m² using equation (3).

$$\frac{G_1}{G_2} = \left(\frac{\bar{\sigma}_{v1}}{\bar{\sigma}_{v2}}\right)^{0.5} \quad \ldots\ldots\ldots \quad (3$$

in which G_1 = shear modulus at an effective overburden pressure of $\bar{\sigma}_{v1}$

and G_2 = shear modulus at an effective overburden pressure of $\bar{\sigma}_{v2}$

The laboratory investigation consisted of oscillatory shear tests conducted on undisturbed representative samples. The tests were conducted using several different combinations of normal and shear loads. The values of dynamic shear modulus 'G' from the laboratory oscillatory shear tests were also computed for an effective overburden pressure of 100kN/m². Based on the results of in-situ and laboratory tests, a plot of dynamic shear

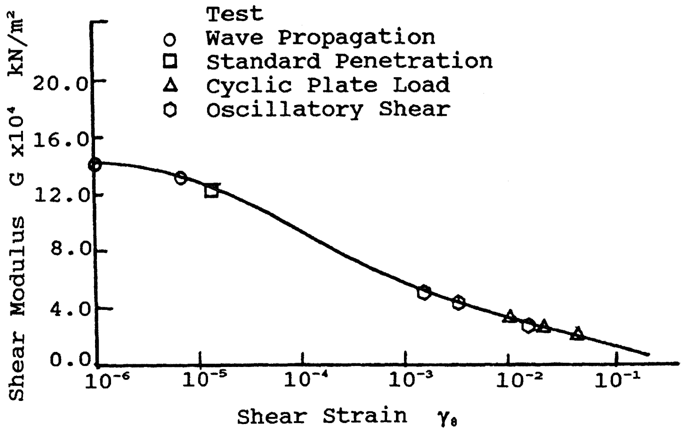

Fig.4 Dynamic Shear Modulus versus Shear Strain

modulus 'G' versus shear strain 'γ_θ' was obtained as shown in Figure 4.

PREDICTED RESPONSE OF THE TEST BLOCKS

The methods commonly used for the analysis and design of foundations for machines are (1) Barkan's approach and (2) elastic half space approach. In the Barkan's approach or the linear spring method (Barkan, 1962) the foundation soil system is represented as a spring-mass system. The spring stiffness due to the soil and mass of the foundation and supported equipment only are considered and inertia of the soil and damping are neglected. In the elastic half space approach the vibrating footing is treated as resting on the surface of an elastic, semi-infinite, homogenous, isotropic half space (Richart, 1962). The elasticity of the soil and the energy carried into the half space by waves travelling away from the vibrating footing (geometric damping) are thus accounted for and the response of such a system may be predicted using a mass-spring-dashpot model (Richart and Whitman (1967) and Richart, Hall and Woods (1970)).

The dynamic response of the foundation was computed using both the above methods of analysis. The values of dynamic shear modulus were selected depending on the effective overburden pressure and the shear strain induced in the soil by the vibrating block.

Effective overburden pressure at a depth equal to one half of the width of test block was used and was obtained from equation (4).

$$\bar{\sigma}_v = \bar{\sigma}_{v1} + \bar{\sigma}_{v2} \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

in which $\bar{\sigma}_{v1}$ = Overburden due to weight of soil

and $\bar{\sigma}_{v2}$ = Vertical stress intensity at a depth equal to ½ width due to superimposed load of machine and foundation and may be computed using Boussinesq theory.

(a) <u>Barkan's Method</u>

Natural frequency of vertical vibrations ω_{nz} is given by

$$\omega_{nz} = \sqrt{\frac{C_u . A}{m}} = \sqrt{\frac{K_z}{m}} \quad \ldots\ldots\ldots\ldots \quad (5)$$

and amplitude of vertical vibration A_z is given by

$$A_z = \frac{P_z}{m(\omega_{nz}^2 - \omega^2)} \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

in which,

m = mass of the foundation and machine
k_z = stiffness of vertical soil spring
ω = operating frequency, and
C_u = the coefficient of elastic uniform compression and is given by equation (7).

$$C_u = \frac{1.13 \times 2G(1+\nu)}{(1-\nu^2)} \cdot \frac{1}{\sqrt{A}} \quad \ldots\ldots\ldots \quad (7)$$

in which ν = Poissons ratio (assumed 0.337).

The computed values of undamped natural frequencies and undamped amplitudes of vibration as obtained from the linear spring method, for the two test blocks, are given in Tables 1 and 2.

(b) <u>Elastic Half Space Method</u>

The natural frequency of the foundation in vertical vibrations is computed by equation (5). The soil spring is computed as follows (Prakash and Puri, 1988) and Richart, Hall and Woods, 1970):

$$K_z = \frac{4Gr_0}{1-\nu} \quad \ldots\ldots\ldots\ldots \quad (8)$$

in which, r_0 = Equivalent radius of the foundation and is obtained as follows:

For vertical vibrations or sliding

$$r_0 = \sqrt{\frac{A}{\pi}} \quad \ldots\ldots\ldots\ldots \quad (9)$$

The damped amplitude of vertical vibrations is given by

$$A_z = \frac{P_z}{k_z\{[1-(\omega/\omega_{nz})^2]^2 + (2\xi_z\omega/\omega_{nz})^2\}^{1/2}} \quad \ldots \quad (10)$$

Where,

$$\xi_z = \text{Damping ratio} = \frac{0.425}{\sqrt{B_z}} \quad \ldots\ldots\ldots \quad (11)$$

and

$$B_z = \text{Modified mass ratio} = \frac{(1-\nu)m}{4\rho r_0^3} \quad \ldots \quad (12)$$

The computed values of undamped natural frequencies and damped amplitudes of vibration obtained from the elastic half space method for the two test blocks are given in Tables 1 and 2.

Table 1 Comparison of Observed and Computed Response of 1.5m x 0.75m x 0.70m Block in Vertical Vibrations

Angle of Eccentricity θ°	Observed Data		Shear Strain γ_θ	Shear Modulus G kN/m^2	Coefficient of Elastic Uniform Compression C_u kN/m^3	Computed Data			
	Natural Frequency Hz	Amplitude Az mm				Linear Spring Method		Elastic Half Space Analog Method	
						Natural Frequency Hz	Undamped Amplitude Az mm	Natural Frequency Hz	Damped Amplitude Az mm
25	38.5	0.031	4.13×10^{-5}	35,500	266,600	44.8	0.36	41.4	0.127
50	37.5	0.069	9.2×10^{-5}	29,000	288,800	40.5	1.067	37.1	0.27
75	37.0	0.0975	1.3×10^{-4}	26,000	196,000	38.5	4.94	35.2	0.406
125	36.7	0.182	2.43×10^{-4}	22,100	166,500	35.3	3.23	33.1	0.531
180	35.0	0.240	3.3×10^{-4}	18,100	136,400	31.0	1.38	29.3	0.720

Table 2 Comparison of Observed and Computed Response of 3.0m x 1.5m x 0.70m Block in Vertical Vibrations

Angle of Eccentricity θ°	Observed Data		Shear Strain γ_θ	Shear Modulus G kN/m^2	Coefficient of Elastic Uniform Compression C_u kN/m^3	Computed Data			
	Natural Frequency Hz	Amplitude Az mm				Linear Spring Method		Elastic Half Space Analog Method	
						Natural Frequency Hz	Undamped Amplitude Az mm	Natural Frequency Hz	Damped Amplitude Az mm
25	36.0	0.006	4×10^{-6}	70,000	222,615	42.0	0.0954	42.0	0.0261
50	34.5	0.012	8×10^{-6}	67,500	214,660	41.2	0.157	41.3	0.0478
75	37.0	0.018	1.2×10^{-5}	66,000	209,900	40.8	0.449	40.7	0.0852
100	37.0	0.024	1.6×10^{-5}	65,000	206,700	40.5	0.616	40.4	0.109
125	35.0	0.030	2.0×10^{-5}	61,000	193,900	39.1	0.566	39.2	0.119
150	34.5	0.036	2.4×10^{-5}	60,000	190,800	38.8	0.578	38.8	0.127
180	33.5	0.053	3.5×10^{-7}	56,000	178,100	37.5	0.63	37.5	0.133

CONCLUSIONS AND DISCUSSION

1. It is observed from Tables 1 and 2, that the natural frequencies of the two test blocks calculated by using the linear spring method and the elastic half space method are generally of the same order. Also these calculated natural frequencies are in reasonable agreement with the observed natural frequencies. The calculated undamped natural frequencies are generally within 20% of the experimentally observed natural frequencies.

2. The undamped amplitudes of vertical vibration calculated by using the linear spring method are much higher than the observed amplitudes. This is to be expected since damping has been omitted in this method.

3. The damped vibration amplitudes as obtained from the elastic half space method are smaller than those calculated by the linear spring method. However, the amplitudes calculated by the elastic half space method also do not show any reasonable agreement with the observed amplitudes and are larger than the observed amplitudes.

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