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An Estimation of Dynamic Properties of Soils from Block Vibration Tests

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SYNOPSIS: The paper presents departures that have to be made in the conduct of block vibration tests from the standard method and in the analysis of test data under unusual conditions. Disturbed soil condition under an edge of the block leads to occurrence of double peaks in amplitude versus frequency curves from vertical vibration test. Two methods have been devised to analyse such double peaks. The first method assumes a correlation between dynamic coefficients. The dynamic properties can be predicted from non-dimensional curves of correction factor versus ratio of effective base area. The second method assumes linear variation of coefficient of elastic uniform compression and its maximum value is estimated from non-dimensional curves of correction factor versus ratio of frequencies at first and second peaks. Comparison of results of a repeat test under near-ideal conditions with corrected values of soil parameters confirms the adequacy of the presented methods.

INTRODUCTION

Several methods of test are available for in-situ determination of dynamic properties of soils required for analysis and design of machine foundations. They lead to a wide range of variation of values as the strain levels associated with these tests are widely different (Ishihara 1971). Since a properly designed machine foundation introduces a strain level of the order of 10^{-3} (Silver & Seed,1971), Prakash (1975) has strongly advocated the use of block vibration tests as the strain levels introduced and nature of loading are similar. Designers depend mainly on the values of dynamic properties of soils determined by these tests.

The Indian Standard Code (IS:5249-1977) prescribes size of block (1.5 m x 0.75 m x 0.70m high), size of pit (4.5 m x 2.75 m in plan, depth = depth of foundation), method of conducting and method of analysing results of block vibration tests. The author has had opportunity of carrying out block vibration tests for determination of dynamic soil properties required for design of foundations of a number of turbo-generators/gas turbines of some important power projects of the country and discusses in this paper some problems encountered in the conduct of such tests, such as very high water table submerging the block,disturbance of soil under one edge, failure of the equipment to cover the resonance, etc. Remedies of such situations have been suggested.

BLOCK VIBRATION TEST

The following vibration tests are conducted on the model block foundation:

1. Vertical vibration test
2. Horizontal vibration test

These tests are conducted by mounting a mechanical oscillator on top of the block. The oscillator is positioned to produce vertical or horizontal excitation. The oscillator is driven by a D.C. shunt motor, the speed of which is varied with a speed control unit. The vibrations of the block are picked up by a vibration pick-up (velometer or accelerometer), signal of which is processed and indicated at vibration meter. The line diagram in Fig.1 shows the test arrangement. The equipment shown in dotted blocks is in addition to the equipment required as per IS: Code and has been discussed later.

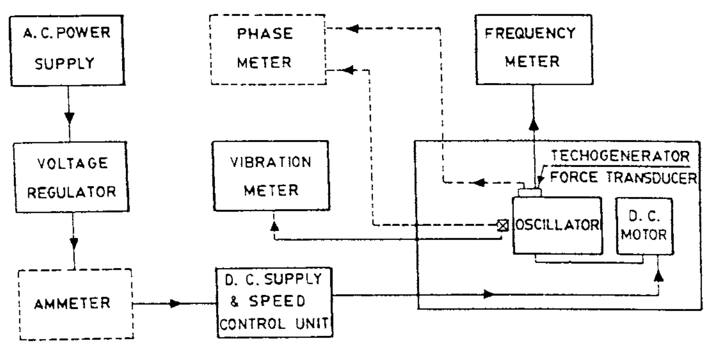

Fig.1 - Line Diagram of Test Equipment

VERTICAL VIBRATION TEST

The mechanical oscillator is mounted centrally on the block such that it generates vertical harmonic exciting force and the line of action of the excitation passes through the centre of gravity of the block. The vibration pick-up is fixed on top of the block with its sensing axis in the vertical direction. Amplitudes of vibration are observed on vibration meter and recorded for different frequencies and at different angles of eccentricity of the oscillator. Amplitude versus frequency curves at different eccentricities are plotted. A typical and normally obtained curve is shown in Fig.2.

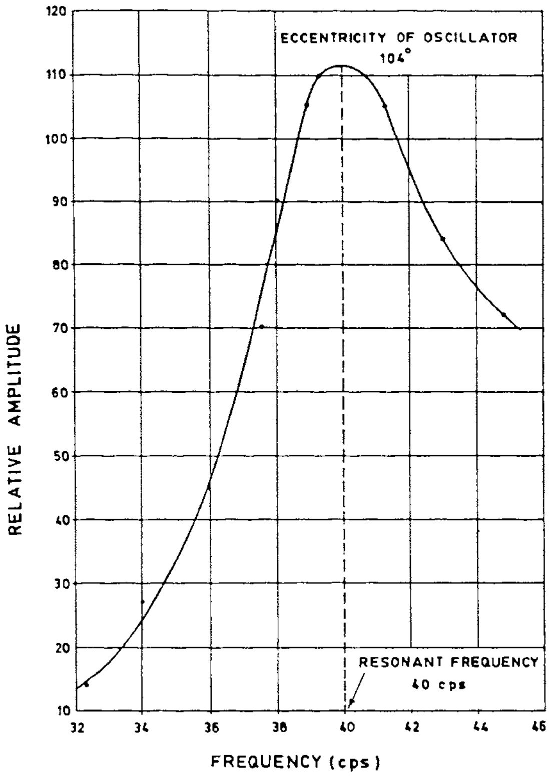

Fig. 2 - A Typical Amplitude v/s Frequency from Vertical Vibration Test

The co-efficient of elastic uniform compression (C_u) is obtained by using the following expression:

$$C_u = \frac{4\pi^2 . f_{nz}^2 . m}{A} \qquad ...(1)$$

where

m = Mass of the block plus that of the motor, oscillator and other mountings

A = Base area of the block = 150 x 75 Sq Cm

f_{nz} = Resonant frequency in the vertical mode of vibration.

A typical set of calculations for C_u are shown in Table-1. The values of C_u so calculated correspond to the base area of the model block. The values of C_u corresponding to actual foundation area are calculated from the relationship:

$$\frac{C_{u1}}{C_{u2}} = \sqrt{\frac{A_2}{A_1}} \qquad ...(2)$$

where C_{u1} and C_{u2} correspond to base areas A_1 & A_2 respectively. Such a relationship is valid for small areas upto about 10 sq m. For base area greater than 10 sq m, the value of C_u remains almost constant (Barkan 1962).

TABLE-1

Resonant Frequencies and Values of C_u from Vertical Vibration Test

ANGLE OF ECCENTRICITY OF OSCILLATOR	RESONANT FREQUENCY f_{nz} (cps)	DYNAMIC FORCE (kg)	C_u (kg/cm³) A = 1.125 m²	C_u (kg/cm³) A = 10 m²
1	2	3	4	5
68°	36.7	160	9.10	3.05
104°	35.8	215	8.66	2.90
140°	34.9	244	8.23	2.76

HORIZONTAL VIBRATION TEST

The oscillator is positioned and mounted on top of the block such that it produces horizontal harmonic excitation parallel to longitudinal axis of the block. The vibration pick-up is mounted with its axis horizontal and parallel to the excitation. Horizontal amplitudes of vibration are recorded for different frequencies and at different settings of eccentricity of oscillator. Amplitude versus frequency curves from horizontal vibration test for different eccentricities are plotted.

The horizontal excitation at top of the block causes the block to vibrate in coupled translation along the longitudinal axis and rocking motion about transverse axis of the block. The system has two degrees of freedom and hence two natural frequencies.

A method using three acceleration pick-ups to determine whether the resonant frequency obtained corresponds to first or second mode of vibration is given in the code (IS:5249-1977). Another way to do this using one pick-up is to observe amplitudes carefully for different frequencies of the oscillator varying from zero till first resonance is observed. This may be called method of 'frequency scanning'. It is experience of the author that only first mode peak without exception is obtained. After determining the mode of vibration, the co-efficient of elastic uniform shear (C_t) is calculated using the expression:

$$C_t = \frac{8\,\pi^2 \gamma f_{nx}^2}{(A_o + I_o) \pm \sqrt{(A_o + I_o)^2 - 4 A_o I_o \gamma}} \quad \ldots(3)$$

where

γ = M_m/M_{mo}

f_{nx} = Resonant frequency obtained from horizontal vibration test

A_o = A/m

I_o = 3.46 I/M_{mo}

M_m = Mass moment of inertia (m m i) of block with mountings about the horizontal axis passing through centre of gravity of the block and perpendicular to the direction of vibrations

M_{mo} = m m i of block and mountings about the horizontal axis passing through centre of base area of the block and perpendicular to the direction of vibration

I = Second moment of area of base of the block about the horizontal axis passing through the centre of gravity of the area and perpendicular to the direction of vibration.

Use the +ve sign for second mode of vibration and -ve sign for the first mode.

For the size of the standard block used in the test and first resonant frequency equation (3) reduces to:

$$C_t = f_{nx}^2 / 125 \quad \ldots(4)$$

The values of C_t from equation (4) correspond to base area of the block. The values of C_t corresponding to actual foundation area upto 10 Sq m may be obtained using the relationship:

$$\frac{C_{t1}}{C_{t2}} = \sqrt{\frac{A_2}{A_1}} \quad \ldots(5)$$

where C_{t1} and C_{t2} correspond to areas A_1 and A_2 respectively. A typical amplitude versus frequency curve from horizontal vibration test and table of calculations of C_t being similar in nature to those of vertical mode of vibration have not been shown in this paper.

COFFICIENTS OF ELASTIC NON-UNIFORM COMPRESSION (C_ϕ) AND ELASTIC NON-UNIFORM SHEAR (C_ψ)

In the absence of direct field tests as at present, the IS:Code prescribes the following relationship for determination of these coefficients:

$$C_\phi = 3.46\ C_t \quad \ldots(6)$$

$$C_\psi = 0.75\ C_u \quad \ldots(7)$$

PROBLEMS OF BLOCK VIBRATION TESTS

In most cases, conduct of block vibration tests or analysis of test results does not pose any problem. However, on account of some unusual field conditions, conduct of the test as per the standard method may become difficult if not impossible. In some situations, the test observations especially of the vertical vibration test may show no clear resonant peak or may show two peaks. Both these situations being abnormal are discussed.

CLEAR RESONANT PEAK NOT AVAILABLE IN VERTICAL VIBRATION TEST-

Such a condition arises when the equipment for generation of harmonic excitation is unable to cope up with the power requirements of the test especially near resonance. D.C. supply and speed control unit is always equipped with tripping arrangement at limiting currents for safety reasons. High resonant frequencies of the soil-block system, low damping factor associated with the system, low voltage etc. individually or severally may cause limiting current tripping before crossing the resonant peak. A typical amplitude versus frequency curve from vertical vibration test under such a condition is shown in Fig.3.

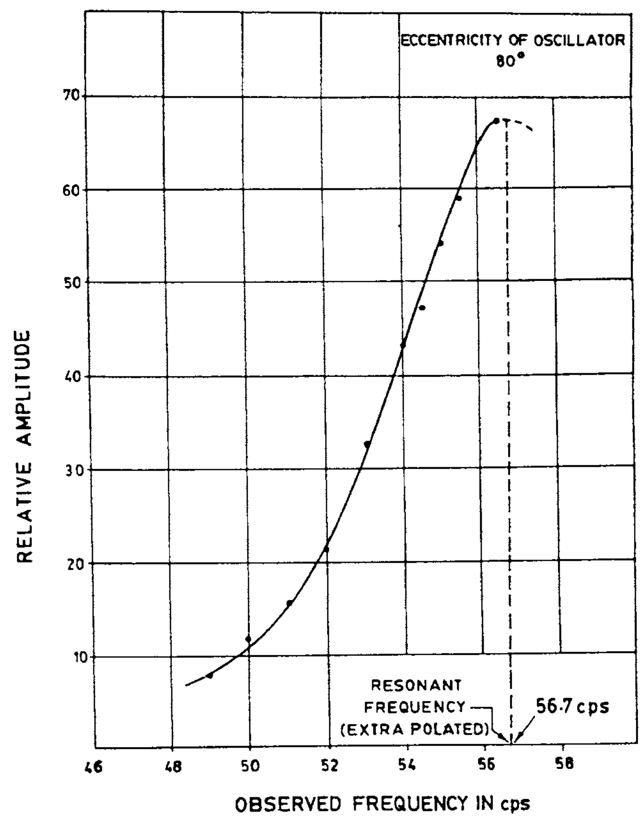

Fig. 3 - A Partial Peak Amplitude v/s Frequency Curve from Vertical Vibration Test (Ref.: Miglani 1987)

The curve can be extrapolated to obtain the resonant peak by using curve fitting technique. However, the result may suffer from errors to an extent of 10-20%. Two better methods have been tried and are suggested below.

(i) By Measuring Phase Difference between Force and Displacement Components: This can be done by fixing a force transducer to the mechanical oscillator. The transducer can work as techogenerator as well and using a phase meter to read angle of phase between force and displacement vectors (See Fig. 1). The output from the force transducer may have to be attenuated to match with that of the vibration pick-up. It is well known that at resonance, phase angle (Ø) between force and displacement of a single degree of freedom system is 90°. Plot of phase angle (Ø) versus frequency ratio 'r' (ratio of oscillator frequency to natural frequency of the system) can be seen in any standard test book on theory of vibrations, e.g., by Thomson(1958).

Damping factor 'ζ' associated with block-soil system has been observed to lie between 0.08 and 0.16. For these values of ζ it may be observed that when frequency ratio 'r' varies from zero to 0.9, phase angle 'Ø' varies zero to 37°(ζ=0.08), 43°(ζ=0.10), 49°(ζ=0.12) and 57°(ζ=0.16). Experience of using phase meter has shown that the electrical system very rarely trips for phase angles below 80°. An enlarged picture of plots of phase angle 'Ø' versus frequency ratio 'r' greater than 0.96 & upto 1.00 for ζ=0.08, 0.10, 0,12, 0.14 & 0.16 are shown in Fig.4.

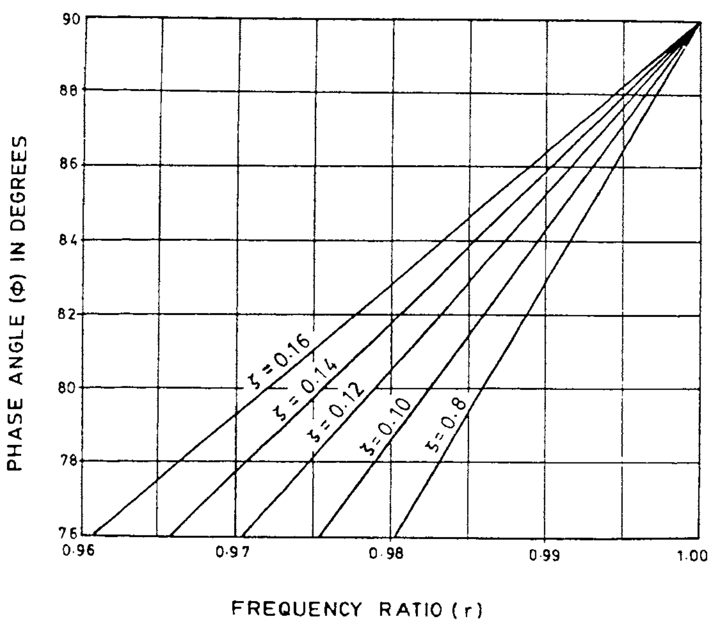

Fig.4 - Phase Angle versus Frequency ratio 'r' Plots near Resonance.

A fairly good estimate of resonant frequency can be made by assuming ζ=0.12 and reading 'r' against phase angle 'Ø' when the system trips. For example, take an extreme case of systemtripping at oscillator frequency = 46 cps when angle of phase = 76°. Using the Ø-r curve for ζ = 0.12, at Ø = 76°, r = 0.97. Therefore resonant frequency = 46/0.97 = 47.4cps. Similarly resonant frequency may be obtained assuming other possible values of ζ (between 0.08 & 0.16). Thus resonant frequency works out to be between 47.9 and 46.9 cps. It can be clearly inferred that using Ø-r curve for ζ = 0.12 gives a fairly accurate (error being less than 1%) value of resonant frequency. The illustration is an extreme case and in other cases, the errors associated in extrapolating resonance are much smaller.

(ii) By Measuring Input Power: This can be done by using an A.C. ammeter or watt-meter as shown in Fig.1. This method is not as good as the first method but can be used with advantage in the absence of a force transducer. The concept can be understood from the following derivation:

Work done by exciting force per cycle $= \pi P_o X_o \sin Ø$ (Grover 1972)

where P_o = Exciting force amplitude
X_o = Amplitude of vibration
= Phase angle between P_o & X_o

Therefore,

work done per second $(W) = \pi f P_o X_o \sin Ø$

where f = Oscillator frequency in cps.

The expression can be reduced to:

$$W = \frac{\zeta r^6 \times \text{constant}}{(1-r^2)^2 + (2\zeta r)^2} \qquad \ldots(8)$$

where r = frequency ratio
$= f/f_{nz}$

Plots of 'W' versus 'r' for different values of ζ are shown in Fig.5, which explains that power requirement for running the test near resonance is relatively much higher. In view of the earlier statement in respect of phase angle at the time of tripping and discussion, resonant frequency can be estimated to be within 7 percent higher than the frequency at which the electrical system trips. The purpose of using ammeter is to ensure that there has been general steep rise in power requirement and that the system has not tripped on account of some other reason.

The values of C_u thus determined could be verified from values of C_t as mentioned later.

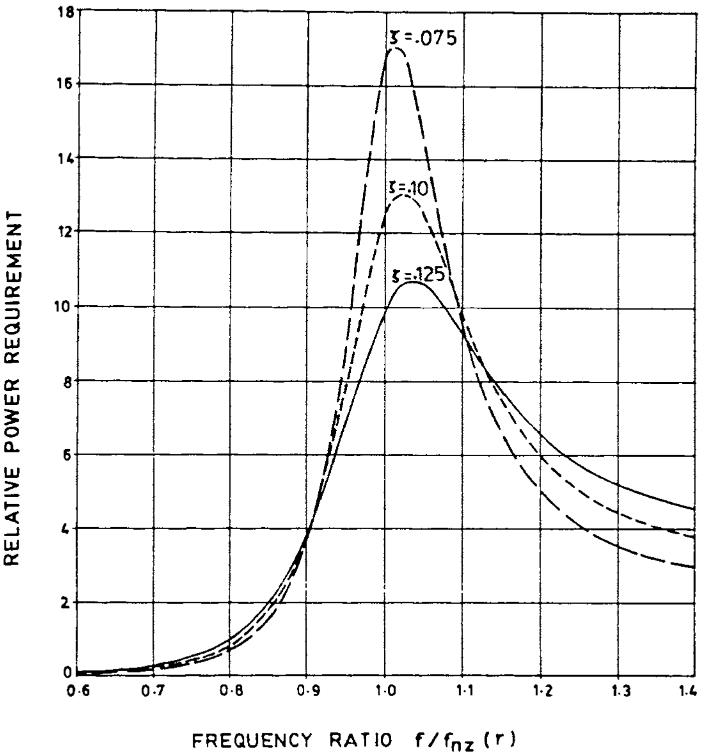

Fig.5 - Power Requirement versus Frequency Ratio Curves

TWO RESONANT PEAKS OBSERVED IN VERTICAL VIBRATION TEST -

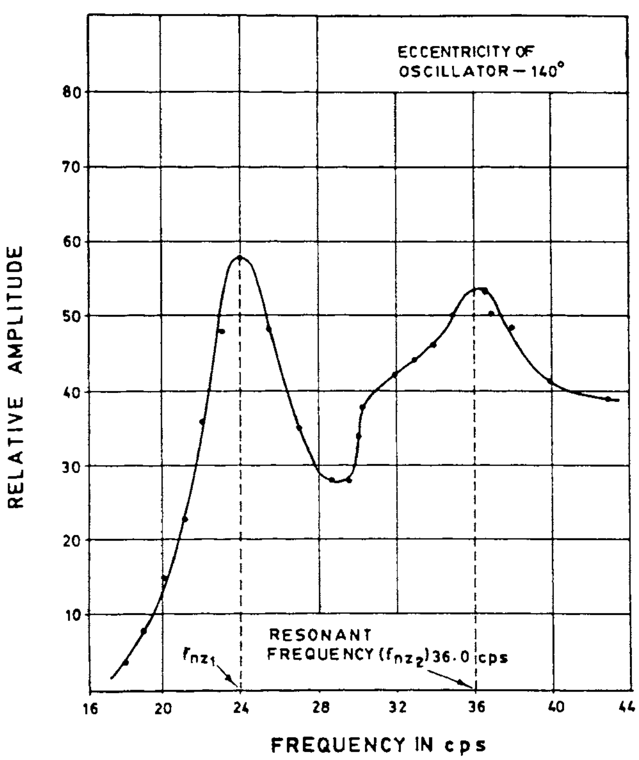

Fig.6 - A Double Peak Amplitude v/s Frequency Curve from Horizontal Vibration Test

Though rare, two peaks (in place of normally one peak) have been seen sometimes in amplitude versus frequency plots from vertical vibration tests. Such dual peaks have been observed at three sites for turbogenerators of different stages of a prestigeous power project of the country and also at a site for heavy machinery on desert soil. A typical plot is shown in Fig.6.

On account of high water table submerging even the block, loose soil etc., a departure from standard pit had to be made. For example, at the three sites mentioned above, the vibration tests were conducted on standard blocks in wells of internal diameter 3.5 m and at depths of the order of 4.5 m for retaining the soil. To keep the water table low, two additional wells of 2 m internal dia adjacent to the main well were provided and water from them pumped out. The arrangement is shown in Fig.7.

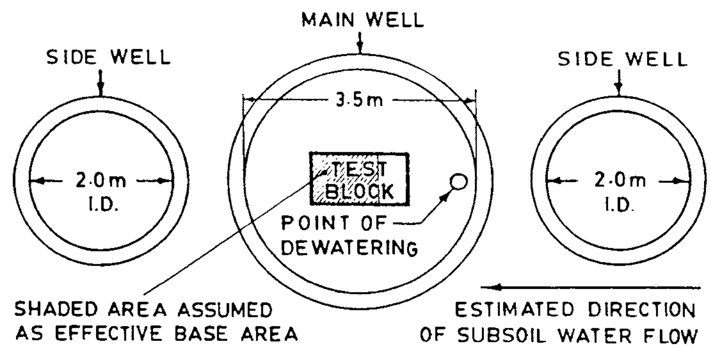

Fig.7 - Plan of Test Arrangement

One such case history has been reported by the author (Miglani 1988a) wherein pumping out of water from side wells was not enough and pumping from within the main well also had to be resorted to to lower the water level to at least below the top surface of the block. The point chosen for this purpose was on the longer axis of the block near the well boundary and as far as possible near the surface of water. This was done with a view to cause least distrubance of soil. Later at a different site for a turbo-generator, pumping from within the main well was not resorted - however, subsurface flow of water was capable enough to cause distrubance of soil near one edge (Miglani 1988b). Deviation from non-uniform reaction causes the block, subjected to central vertical excitation, to vibrate in two modes (& hence two resonant peaks);

(i) rocking about a horizontal axis passing through the centre of the base area, &

(ii) vertical

It can be easily worked out that the first resonant peak corresponds to the rocking mode and the second corresponds to the vertical mode of vibration. Therefore, to estimate the correct value of C_u, only the second resonant frequency is considered. The values of C_u obtained by using equation (1) need corrections.

It has been observed and may be noted that the effect of disturbance of soil near one short edge of block on resonant frequency in horizontal vibration test is highly pronounced. The values of C_t by using equation (3) or (4) drop more steeply as compared to the values of C_u.

Two methods have been devised by the author to estimate correction factors applied to the values of soil parameters obtained in the tests.

First Method

This method assumes a correlation between the dynamic coefficients C_u and C_t. Values of C_t of a particular soil may be found to lie between half to two third values of C_u, more commonly being close to half of C_u. The method also assumes that C_u and C_t are constant over a certain base area away from the distrubed edge . Ratio of effective base area to actual base area (p) may be obtained by drawing curves between 'p' and ratio f_{nz2}/f_{nx} observed from vertical vibration test and horizontal vibration test as follows:

Equations (1) & (3) give ratio of f_{nz2} & f_{nx} which can be expressed as

$$\frac{f_{nz2}}{f_{nx}} = \sqrt{\frac{C_u}{C_t} \cdot \frac{2A_o\gamma}{(D-E)}} \quad ...(9)$$

where $D = A_o + I_o$

$E = \sqrt{D^2 - 4A_o\, I_o\, \gamma}$

For the standard block, equation (9) reduces to

$$\frac{f_{nz2}}{f_{nx}} = \sqrt{\frac{C_u}{C_t} \cdot \frac{150}{d - e}} \quad ...(10)$$

where $d = 121.1 + 223.9\, p^2$

$e = \sqrt{d^2 - 70581\, p^2}$

Using equation (10), ratio f_{nz2}/f_{nx} versus 'p' curve has been drawn in Fig.8, using $C_u/C_t = 2$.

Correction factor versus effective base area parameter 'p' curve in Fig.8 has been derived using equation (2). Thus, the procedure to predict the correct values of C_u and C_t for base area of the block can be summerised as follows:

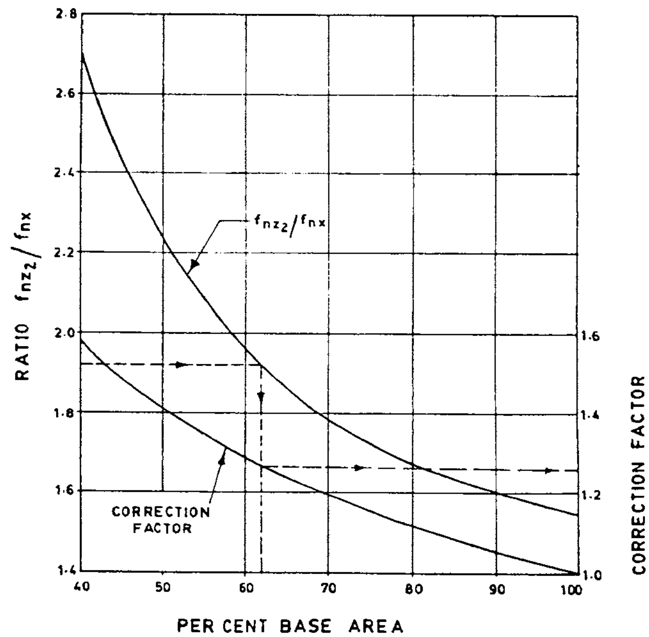

Fig.8 - Ratio of Frequencies (f_{nz2}/f_{nx}) and Correction Factor v/s Effective Base Area Curves

(a) From amplitude versus frequency curves of vertical and horizontal vibration tests, determine the ratio: f_{nz2}/f_{nx}.

(b) Use curve f_{nz2}/f_{nx} versus 'p' and determine the value 'p' against f_{nz2}/f_{nx} value obtained in step (a).

(c) Use correction factor versus 'p' and determine the correction factor against 'p' obtained in step (b).

(d) Determine C_u from equation (1) using f_{nz2}. Multiply this with the correction factor obtained in step (c). This is the corrected value of C_u.

(e) C_t is determined by multiplying C_u with 0.5.

Illustration and adequacy of the method have already been reported (Miglani 1988a)

Second Method

This method assumes linear variation of C_u and uses the first and second resonant peaks of the amplitude versus frequency curves of the vertical vibration test. However, full base area is assumed to participate. From the two resonant frequencies, with these assumptions, the values of C_u across the length of the base can be computed:

$$C_u = \frac{4\pi^2 f_{nz2}^2\, m}{A} \pm \frac{4\pi^2 f_{nz1}^2\, M_{mo}}{I} \quad ...(11)$$

The negative sign is of no consequence for maximum value of C_u. The correction factor is to be with respect to the first part of the expression for C_u in this equation. Therefore,

$$\text{Correction factor} = \frac{f_{nz1}^2}{f_{nz2}^2} \times \frac{M_{mo}\ A}{m\ I} + 1 \quad \ldots(12)$$

For the standard block, correction factor versus ratio of frequencies f_{nz2}/f_{nz1} curve is shown in Fig.9.

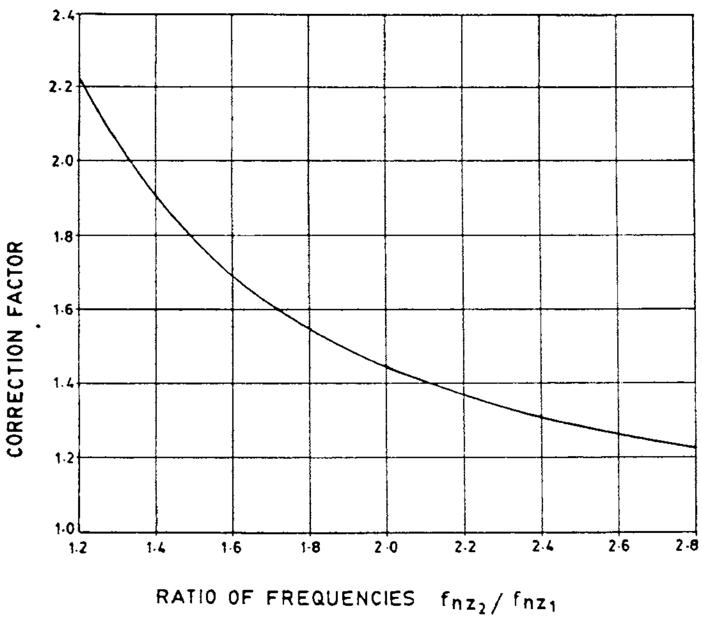

Fig.9 - Correction Factor v/s Ratio of Frequencies f_{nz2}/f_{nz1} Curve

To use this method:

(a) From vertical vibration test amplitude versus frequency curves obtain f_{nz1}, f_{nz2} and their ratio f_{nz2}/f_{nz1}.

(b) Calculate C_u from equation (1) using f_{nz2}.

(c) Read correction factor from curve in Fig.9 against ratio f_{nz2}/f_{nz1} obtained in step(a) and apply it to value of C_u obtained in step(b).

As already mentioned, adequacy of the first method has been tested through a repeat test under near-ideal conditions. A comparison of values of C_u determined by the two methods and by the repeat test is shown in Table-2.

TABLE-2

Comparison of Uncorrected, Corrected values of Dynamic Coefficients and Values from Repeat Test

DYNAMIC COEFFICIENT	UNCORRECTED VALUES	PREDICTED VALUES kg/cm³		VALUES FROM REPEAT TEST kg/cm³
		METHOD 1	METHOD 2	
C_u	5.96—6.49	8.95—9.83	11.32—12.32	8.18—8.75
C_t	1.15—1.31	4.47—4.92	5.66—6.16	4.95—6.50

It can be seen that the second method gives upper bound values of C_u on account of extreme assumption and the first method gives fairly good values of the coefficient. The actual values of C_t lie between those determined by the two methods. Importance of the two methods can be easily gauged from the comparison of the corrected and un-corrected values of dynamic coefficients, especially C_t.

CONCLUSIONS

1. Certain field conditions such as high water table, loose soil etc. necessitate departure from the standard method.

2. Introduction of phase meter between force and vibration transducers or A.C. ammeter can greatly facilitate extrapolating resonant peaks, should the electric system be unable to cope up with power requirement near resonance in vertical vibration test.

3. The two methods devised to analyse the double peaks in amplitude-frequency curves from vertical vibration test have been found quite effective. It is suggested that, should such double peaks occur in the amplitude - frequency curves, values of C_u and C_t be determined by both the methods and judicious values be adopted.

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