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(Reaffirmed 1995)

भारतीय मानक

मृदा के गत्यात्मक गुणधर्म ज्ञात करने की परीक्षण पद्धति

(दूसरा पुनरीक्षण)

Indian Standard

DETERMINATION OF DYNAMIC PROPERTIES OF SOIL — METHOD OF TEST

(Second Revision)

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FOREWORD

This Indian Standard (Second Revision) was adopted by the Bureau of Indian Standards, after the draft finalized by the Foundation Engineering Sectional Committee had been approved by the Civil Engineering Division Council.

Several Indian Standards have been published for the design and construction of foundation for machines of various types. These involves the use of dynamic properties of soil. The need for a standard procedure for the determination of such properties therefore arose. The standard is meant to fulfil this need.

The designer should choose the method appropriate to the codditions at a given site. *In-situ* dynamic test by the forced vibration method may be found useful in most of the cases even though it has the limitations of the plate load test. In layered soils, the wove propogation test has the advantage that the dynamic properties of the layer of interest can be determined by suitably adjusting the distance between the geophones. The results obtained by a free vibration test should be used with caution.

This standard was first published in 1969 and subsequently revised in 1977 which included the block vibration tests both under free and forced vibration conditions, shear modulus tests, wave propagation tests and cyclic plate load tests. Guidelines are provided for choosing the design parameters consistent with the conditions of confinement and strains which are likely to occur in an actual problem. This revision has been taken up to incorporate further improvements found necessary in light of determination of dynamic properties of soil, since its last publication.

In the formulation of this standard due weightage has been given to international co-ordination among the standards and practices prevailing in different in addition to relating it to the practices in the field in this country.

In reporting the result of a test made in accordance with this standard, if the final value, observed or calculated is to be rounded off, it shall be done in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'.

Indian Standard
DETERMINATION OF DYNAMIC PROPERTIES OF SOIL – METHOD OF TEST

(Second Revision)

1 SCOPE

This standard covers methods of conducting block vibration test, cyclic plate load test and wave propagation test for evaluation of *in situ* dynamic and damping properties of soils. Guidelines for choosing parameters for design and analysis are also provided.

2 REFERENCES

The Indian Standards listed in Annex A are necessary adjuncts to this standard.

3 TERMINOLOGY

3.0 For the purpose of this standard, the relevant definitions in IS 2810 : 1979 and the following shall apply. The notations given in Annex B shall also apply.

3.1 Natural Frequency

Number of cycles per unit time with which the system oscillates under the influence of forces inherent in the system.

3.2 Undamped Natural Frequency

Number of cycles per unit time with which the system oscillates under the influence of forces inherent in the system without considering damping effect.

3.3 Damped Natural Frequency

Natural frequency of the system considering its damping.

3.4 Coefficient of Elastic Uniform Compression (C_u)

It is the compressive stress causing unit elastic uniform compression for a given area under dynamic loading conditions.

3.5 Coefficient of Elastic Non-Uniform Compression ($C\phi$)

It is the ratio of compressive stress and elastic non-uniform compressive deformation for a given area under dynamic loading conditions (kg/cm).

3.6 Coefficient of Elastic Uniform Shear ($C\tau$)

It is the ratio of shear stress to elastic uniform shear displacement for a given area under dynamic loading condition.

3.7 Damping Coefficient (ξ)

The ratio of damping of system to the critical damping.

3.8 Coefficient of Attenuation

Coefficient which has dimensions of l/distnace used in the expression for determining the amplitude at any distance from the vibration source. The coefficient is a characteristic of soil (m^{-1}).

4 APPARATUS

4.0 One of the apparatus utilized in conducting these test are listed in **4.1** to **4.15**. Other suitable apparatus or mesuring devices may be utilized for conducting the test.

4.1 Mechanical Oscillator

The mechanical oscillator should be capable of producing a sinusoidally varying force and have a frequency range commensurate with the size of the block to be tested and type of the soil. It should have the provision for altering dynamic force level by simple adjustment of eccentric masses.

4.2 d.c. Motor

Motor of suitable power rating so as to run the above oscillator in the required frequency range at full load. This should be of type that its own vibrations are negligible.

4.3 Speed Control Unit

Capacity commensurate with d.c., motor being used, capable of operation at 220 V a.c. input supply and giving variable d.c. voltage output. The maximum drop in voltage at full load should not exceed 2 percent.

4.4 Acceleration Pick-up

Three in number, of same response characteristics, maximum range should be commensurate with equipment used in **3.1**, useful frequency range d.c. 100 Hz or more. Natural frequency should be 220 Hz undamped and 140 Hz damped. The response should be linear, deviation from linearity being 1 percent or less with amplitude changes.

4.5 Velocity Pick-up

Two in number, of suitable type, sensitive enough to record even feeble ground vibrations. Natural frequency<10 Hz and dampling less than 1 percent of the critical damping.

4.6 Displacement Pick-up

Amplitudes may be directly measured using displacement pick-ups. These should be of appropriate capacity and should have flat frequency response in the range 0 to 100 Hz or more and should be of high sensitivity; accuracy should be not less than 2 percent.

4.7 Geophones

Similar characteristics as of velocity pick-up (*see* **4.5**).

4.8 Universal Amplifier

4.9 Ink Writing Oscillograph

Frequency response above 100 Hz; number of elements 3 (preferable); natural frequency above 140 Hz; maximum amplitude ± 20 mm: paper speed 5, 25, 125 mm/s: capable of operation of 220 V a.c. 50 Hz supply, optimum damping with external resistance.

4.10 High Gain d.c. Amplifier

To match velocity pick-up or geophone as the case may be.

4.11 Steel Plate for Fixing Oscillator and d.c. Motor

Thickness 20 mm, length and width depending upon size of oscillator unit.

4.12 Measuring Tape

Steel or metallic tape of 30 m length.

4.13 Hammer

A sledge hammer or a drop hammer weighing 10 kg or any other device to impart blow to the block for exciting under conditions of free vibrations or for generating waves in the ground.

4.14 Plate Load Testing Equipment

Conforming to IS 1888 : 1982. Arrangement for loading may be of mechanical or hydraulic type with facility to apply of remove the loads quickly for conducting cyclic plate load tests.

4.15 Apparatus for Measuring Field Density of Soil at Site

In accordance with IS 2720 (Part 28) : 1973 or IS 2720 (Part 29) : 1975.

NOTES

1 Equipment given in **4.1** to **4.14** are found suitable. Alternative equipment may be used where available.

2 In addition to above equipment, optical or mechanical equipment for analysing records of wave propagation tests shall be required.

5 BLOCK VIBRATION TEST

5.1 Test Pit

A test pit of suitable size depending upon size of block should be made. For block size as in **5.2**, the size of the pit may be 3 m × 6 m at the bottom and a depth preferably equal to proposed depth of foundations. The test should be conducted above the ground water table. In case of rock, the test may be performed on the surface of rock bed itself. The bottom of the pit should be level and horizontal and the size of the pit should be at stable slope and may be kept vertical where possible.

5.2 Test Block

A plain cement concrete block of M-15 concrete should be constructed in the test pit as shown in Fig. 1. The size of the block should be selected depending upon the sub-soil conditions. In ordinary soils it may be 1 m × 1 m × 1.5 m and in dense soils it may be 0.75 m × 0.75 m × 1 m. In boulder deposits the height may be increased suitably. The block size should be so adjusted that the mass ratio

$$Bz = \left[\left(\frac{1-\varepsilon}{4} \times \frac{m}{\rho_{ro}^{3}} \right) \right]$$ is always more than unity

the concrete block should be cured for at least 15 days before testing. Foundation bolts should be embedded into the concrete block at the time of testing for fixing the oscillator assembly. Details of the test block are shown in Fig.1.

5.3 Test Set-up

Vibration exciter should be fixed on the concrete block and suitable connection between power supply, speed control unit, should be made as shown in Fig. 2. Any suitable electronic instrumentation may be used to measure the frequency and amplitude of vibrations.

5.4 Forced Vibration Test

5.4.1 *Vertical Vibration Test*

The vibration pick-ups should be fixed at the top of the block as shown in Fig.1, such that it senses vertical motion of the block. The vibration exciter should be mounted on the block such that it generates purely vertical sinusoidal vibrations and line of action of vibrating force passes through the centre of gravity of the block. The exciter is operated at a constant frequency. The signal of the vibration pick-ups are fed into suitable electronic circulatory to measure frequency and amplitude of vibration. The frequency of the exciter is increased in steps of small values, (1-4 cycles/sec) up to maximum frequency of the exciter and the signals measured. The same procedure should be repeated if necessary for different excitation levels. The dynamic force should never exceed 20 percent of the total mass of the block and exciter assembly.

Amplitude versus frequency curve shall be plotted for each excitation level to obtain the natural frequency of the soil and the foundation block tested. A typical plot is shown in Fig. 3.

5.4.2 *Determination of Coefficient of Elastic Uniform Compression of Soil*

The coefficient of elastic uniform compression (C_u) of soil is given by the following equation:

$$C_u = \frac{4\pi^2 f_{nz}^2 M}{A}$$

where

f_{nz} = Natural frequency;
M = Mass of the block, exciter and motor; and
A = Contact area of the block with the soil.

From the value of C_u obtained for the test block of contact area A the value of C_{u1} for the foundation having contact area A_1 may be obtained from the equation:

$$C_{u1} = C_u \sqrt{A/A_1}$$

NOTE – This relation is valid for small variations in base area of the foundations and may be used for area up to $10 m^2$. For actual foundation areas larger than $10 m^2$, the value of C_u obtained for $10 m^2$ may be used.

5.4.3 *Determination of Damping Coefficient of Soil*

In case of vertical vibration test, the value of damping coefficient ε of soil is given by the following equation:

$$\varepsilon = \frac{f_2 - f_1}{2 f_{nz}}$$

where

f_2, f_1 = Two frequencies at which the amplitude is equal to $\frac{X_m}{\sqrt{2}}$

X_m = Maximum amplitude; and

f_{nz} = Frequency at which amplitude is maximum (resonant frequency). This is shown in Fig. 4.

5.5 Free Vibration Tests

The block shall be excited into free vertical vibrations by the impact of sledge hammer or any suitable device, as near to the centre of the top face of the block as possible. The vibrations shall be recorded on a pen recorder or suitable device to measure the frequency and amplitude of vibration. The test may be repeated three or four times.

In case of free vertical vibrations tests, the value of C_u shall be obtained from the natural frequency of free vertical vibration using equation given at **5.4.2**.

The damping coefficient may be obtained from free vibration tests using the following equation:

$$\varepsilon = \frac{1}{2\pi} \log_e \frac{X_m}{X_{m+1}}$$

For X_m and X_{m+1} are as explained in Fig. 5.

5.6 Evaluation of Coefficient of Attenuation

The test set up is same as that for the block resonance test. The pick-up fitted on the block is removed and installed at a certain distance d_1 (approximately 30 cm) from the block. The second pick-up is fixed in line with this pick-up and the centre of the block at a distance of d_2 The amplitude of vibration at these two locations are measured for different frequencies. The coefficient of attenuation is calculated from the following expression:

$$A_2 = A_1 \sqrt{\frac{d_1}{d_2}} \cdot e^{-\alpha(d_2 - d_1)}$$

where

A_2 = Amplitude at distance d_2,
A_1 = Amplitude at distance d_1, and
α = Coefficient of attenuation

Table for typical values of α

Soil type	α, m^{-1}
Saturated sand or sandy silt	0.1
Saturated silty sand	0.04
Saturated sandy silty clay	0.04-0.12

6 CYCLIC PLATE LOAD TEST

6.1 Equipment

Suitable arrangement for providing reaction of adequate magnitude depending upon size of plate employed should be used. The load mechanism should have facility to apply and remove the loads quickly. A hydraulic jack or any other suitable equipment may be used.

6.2 Test Procedure

6.2.1 The equipment for the test shall be assembled according to the details given in IS 1888 : 1982. The plate shall be located at a depth equal to the depth of the proposed foundation in a pit excavated as given in IS 1888 : 1982.

6.2.2 After the set-up has been arranged the initial readings of the dial gauges should be noted and the first increment of static load should be applied to the plate. This load shall be maintained constant throughout for a period till no further settlement occurs or the rate of settlement becomes negligible. The final readings of the dial gauges should then be recorded. The entire load is then removed quickly but gradually and the plate allowed to rebound. When no further rebound occurs or the rate of rebound becomes negligible, the readings of the dial gauges should be again noted. The load shall then be increased gradually till its magnitude acquires a value equal to the proposed next higher stage of loading, which shall be maintained constant and the final dial gauge readings should be noted as mentioned earlier. The entire, load should then be reduced to zero and final dial gauge readings recorded when the rate of rebound becomes negligible.

6.2.3 The cycles of loading, unloading and reloading are continued till the estimated ultimate load has been reached, the final values of dial gauge readings, being noted each time.

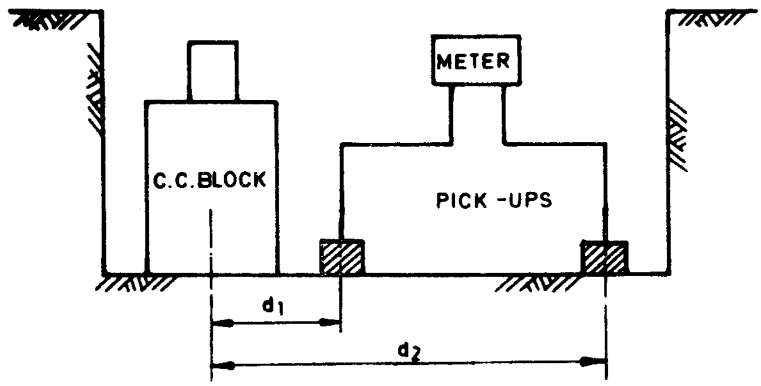


FIG. 1 SET-UP FOR BLOCK VIBRATION TEST

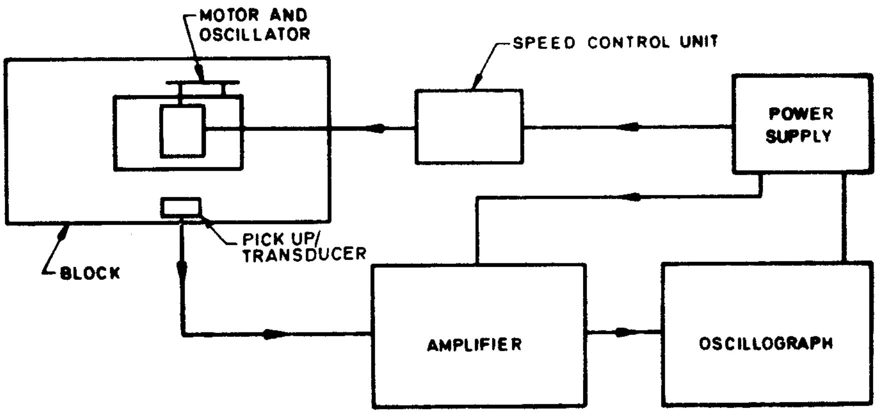


FIG. 2 BLOCK DIAGRAM OF TESTING EQUIPMENT FOR BLOCK VIBRATION TEST

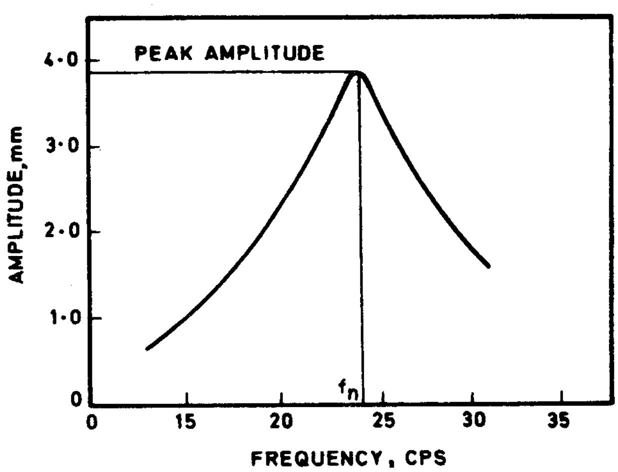


FIG. 3 TYPICAL AMPLITUDE VERSUS FREQUENCY CURVE (VERTICAL VIBRATION TEST)

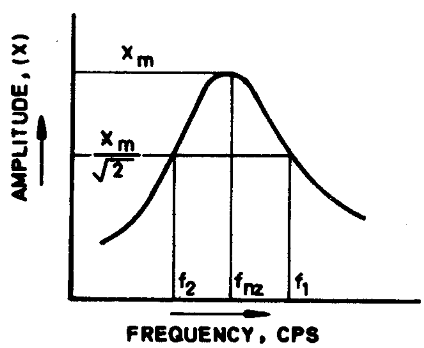


FIG. 4 DETERMINATION OF DAMPING FROM FORCED VIBRATION TEST

6.2.4 The magnitude of the load increment should be such that the ultimate load is reached in five to six increments. The initial loading and unloading cycles up to the safe bearing capacity of the soil should be with smaller increments in load. The duration of each loading and unloading cycle upon the type of soil under investigation.

6.2.5 *Coefficient of Elastic Uniform Compression from Cyclic Plate Load Test*

From the data obtained during cyclic plate load test, the elastic rebound of the plate corresponding to each intensity of loading shall be obtained as shown in Fig. 6. The load intensity versus elastic rebound shall be plotted as shown in Fig. 7.

The value of C_u shall be calculated from the equation given below:

$$C_u = \frac{P}{S_e} \text{ kgf/cm}^3$$

where

P = Corresponding load intensity kg/cm², and

S_e = Elastic rebound corresponding to P in cm.

7 WAVE PROPAGATION TESTS FOR DETERMINATION OF SHEAR MODULUS

7.1 The wave propagation tests for determination of shear modulus may be conducted by making seismic waves to pass through the ground by impact of a hammer and determining the time of travel of these waves between two points at a known distance apart or by measuring the phase difference between vibration at two pointer under steady vibrations.

7.1.1 *Steady State Vibration Test*

In case of uniform soil extending up to infinite depth, the wavelength of propagating vibrations is given by:

$$\lambda/4 = \frac{\pi S}{\pi + 2\ (\lambda_1 - \lambda_2)}$$

where the geophones have the same characteristics, that is $\lambda_1 = \lambda_2$

$$\lambda/4 = S$$

where

λ = Wavelength in cm,

S = Measured distance between geophones in cm,

λ_1 = Phase shift of geophones with respect to wave nearer to concrete block at the frequency of the propagating vibrations in radians, and

λ_2 = Phase shift of the other geophone at the frequency of the propagating vibrations in radians.

Velocity of shear waves V_s is given by:

$$V_s = \lambda f$$

where

f = Frequency of vibration at which the wave length has been measured.

When the test is conducted using a phase meter, the phase angle corresponding to different distances between the geophones should be recorded and a curve plotted between the phase angle and the distance. From the curve, the distance S between the geophones for a phase difference of 90 should be determined. The remaining computations should be done as in **7.1.1**

7.2 Hammer Tests

7.2.1 *Equipment*

A hammer to imart impact to the ground, a geophone or velocity pick-up or time marking device to record the time of impact, an acceleration pick-up (or a geophone) to monitor the time of arrival of waves, universal amplifier, ink-writting oscilloscope or a timer capable of measuring time interval up to a precision of 10 seconds, and a steel measuring tape.

7.2.2 *Procedure*

A suitable location in the area where this test is to be conducted is selected and radial lines are ranged out from this point for a distance of 30 m to 40 m. Points are marked on these lines at 2 m intervals. A velocity pick-up or a geophone is fixed at the origin of the radial lines and waves are generated near this point by impact of a 10 kg hammer falling through a height of 2 m on a steel plate of 150 mm × 150 mm resting on a the surface of ground. An acceleration pick-up is placed at a known distance along one of the radial lines, the pick-ups is amplified through universal amplifier and fed to two channels of the same pen recorder. The time taken by the waves to travel the distance between the two pick-ups can be obtained from these records. The test is repeated for different known distance between the pick-ups along all the marked lines one by one.

7.2.2.1 The test may be repeated at different locations to obtain a representative value of wave velocities in the area under investigation.

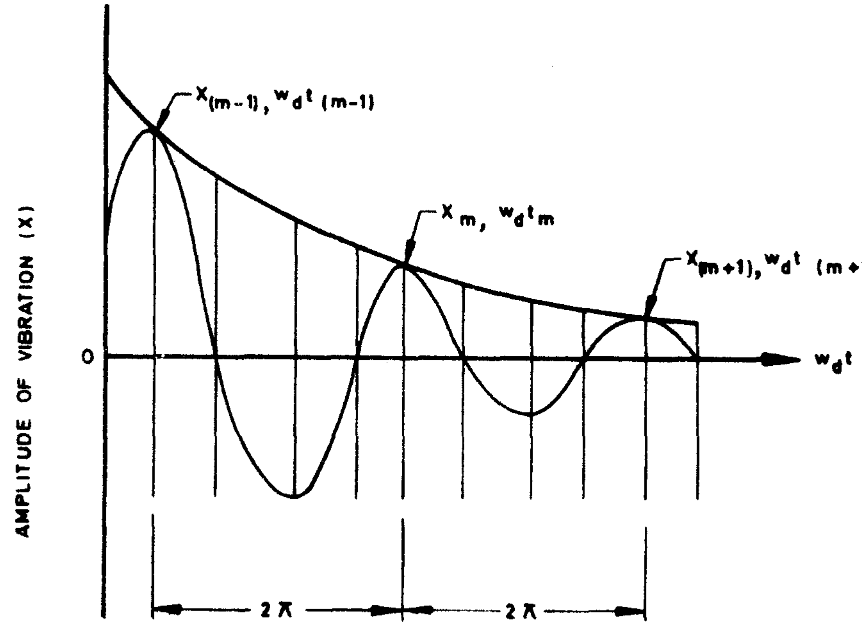
7.2.2.2 Alternatively, the time taken by the waves to travel a known distance may be obtained directly by feeding the output of the pick-ups to a timer.

7.2.2.3 *Density of soil*

The *in situ* density of the soil should be determined by the method specified in IS 2720 (Part 28) : 1973 or IS 2720 (Part 29) : 1975.

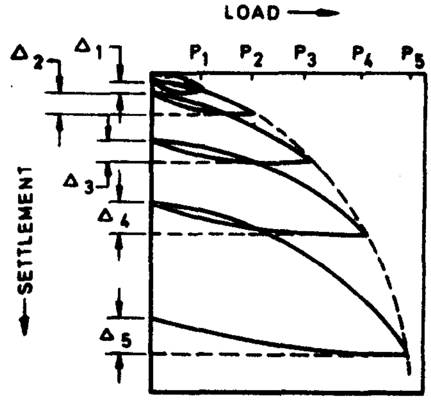
7.2.3 *Hammer Test*

The values of travel time of compression waves and the corresponding distance along each selected line



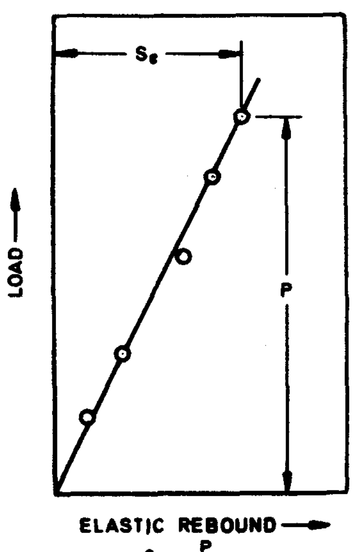
Wd = DAMPED NATURAL FREQUENCY OF SYSTEM

FIG. 5 DETERMINATION OF DAMPING FROM FREE VIBRATION TEST



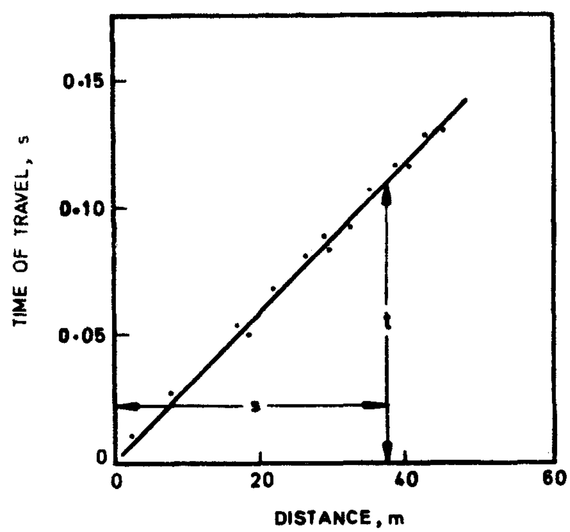
Δ1,Δ2....Δ5 ARE ELASTIC REBOUND AT LOAD P1, P2.....P5 RESPECTIVELY

FIG. 6 LOAD SETTLEMENT CURVE FOR CYCLIC PLATE LOAD TEST



$C_u = \frac{P}{S_e}$

FIG. 7 METHOD FOR OBTAINING VALUE OF C_u FROM CYCLIC PLATE LOAD TEST DATA



AVERAGE VELOCITY $V_c = \frac{s}{t}$ m/s

FIG. 8 DETERMINATION OF AVERAGE WAVE VELOCITY OF STRESS WAVE PROPAGATION IN SOIL MEDIUM (HAMMER TEST) at a location are plotted as shown in Fig. 8. A straight line is fitted through these points. The value of average velocity is obtained as:

$$V_c = s/t$$

where

V_c = velocity of compression waves, in m/s;

s = distance in m; and

t = corresponding time of travel of waves in sec.

7.3 Determination of Elastic Modulus and Shear Modulus of Soil

7.3.1 Elastic modulus E is determined by equation:

$$E = V_c^2 \rho \frac{(1 + \varepsilon) \ (1 - 2\varepsilon)}{(1 - \varepsilon)}$$

where

ρ = Mass density of soil

ε = Poision's ratio of soil

NOTE — The following values for Poission's ratio may be used:

Type of soil	ε
Clay	0.5
Sand	0.30 to 0.35
Rock	0.15 to 0.25

7.3.2 Depending upon the nature of medium involved, and if the distance between pick-ups is sufficiently large, both the arrival of compression and shear waves may be distinguishable from the records. In such a case both E and G can be determined independently.

$$E = 2\,G\,(1 + \varepsilon)$$

$$G = V_s^2 \rho$$

where

ρ = Mass density of soil in kg sec $^2/m^4$,

V_s = Velocity of shear waves, in m/s, and

ε = Poission's ratio of soil.

7.3.3 The values of E and G can also be obtained from the values of C_u obtained as indicated in Annex D. Alternatively the values of C_u can be obtained from E and G values obtained in wave propagation tests.

8 THE COEFFICIENT OF ELASTIC UNIFORM SHEAR AND ELASTIC NON-UNIFORM SHEAR

8.1 Compression C_u, the coefficient of elastic uniform shear, $C\tau$, the coefficient of elastic non-uniform compression $C\phi$ and the coefficient of elastic non-uniform shear $C\psi$ are related to each other by the relations given below:

$$C_u = 1.5 \text{ to } 2\ C\tau$$

$$C\phi = 3.46\ C\tau$$

$$C\psi = 1.5\ C\tau$$

NOTE – The relation between C_u, $C\tau$, $C\phi$ and $C\psi$ depends upon elastic properties of medium, the soil, the size and shape of contact area and flexibility of rigidity of the foundation.

8.2 In case of very stiff soils the value of C_u may be so high that the natural frequency of the foundation soil system may not be reached because of limitations of the vibration exciting equipment. The frequency response curves in such cases may be extrapolated to obtain the resonant frequency of foundation soil system following the procedure suggested in Annex C.

9 GUIDANCE FOR CHOOSING DESIGN PARAMETERES FROM *IN-SITU* TESTS

9.1 The value of the dynamic shear modulus G is affected by a number of parameters out of which confining pressure, shear strain amplitude and relative density are most important. It is observed that changes in density from medium to dense state have relatively insignificant effect compared to effect of confining pressure and shear strain amplitude. Since the order of strain level and confining pressure associated with different *in-situ* tests are different, tests may be expected to show a large variation, as the strain associated with, say hammer test is very small and that with cyclic plate load test is very large. A rational apprroach is therefore, needed to arrive at a suitable design value.

9.2 In the range of strains associated with properly design machine foundations, the effect of variation in strain on shear modulus is small and the values of G for design purposes may be determined from the *in-situ* test values using the relation given below:

$$\frac{G_1}{G} = \left(\frac{\sigma_{01}}{\sigma_0}\right)^m$$

where

G_1 and G = Dynamic shear modulus for the prototype and from field test respectively;

σ_{01}, σ_0 = Mean effective confining pressure, associated with prototype foundation and the *in-situ* test respectively and

m = Constant depending upon the type of soil, shape of grains, etc. Its value has been found to vary from 0.3 to 0.7 and may on the average be taken as 0.5.

9.3 In situations where high strain levels are associated as in the case of analysis for earthquake conditions, the effect of strain level shall be considered along with that of confining pressure.

In such a case, the values of G from different field tests may first be reduced to same confining pressure (expected below the footing) and their variation with strain levels may be studied to arrive at an appropriate values corresponding to the expected strain level.

9.4 The value of damping in soils is also a function of strain level to which the soil is subjected. Damping is less at low strain levels and becomes significantly large at high strain levels.

9.5 The value of C may similarly be expected to vary as C_u and G are related to each other (*see* Annex D).

ANNEX A

(*Clause* 2)

LIST OF REFERRED INDIAN STANDARDS

IS No.	*Title*
1888 : 1982	Method of load test on soils (*second revision*)
2720 (Part 12) : 1981	Methods of test for soil : Part 12 Determination of the shear strength parameters of soil from consolidated undrained triaxial compression test with measurement of pore water pressure (*first revision*)
2720 (Part 28) : 1974	Methods of test for soil : Part 28 Determination for dry density of soils in-place, by the sand replace-ment method (*first revision*)
2720 (Part 29) : 1975	Method of test for soil : Part 29 Determination of dry density of soils in-place, by the core cutter method (*first revision*)
2810 : 1979	Glossary of terms relating to soil dynamics (*first revision*)

ANNEX B

(*Clause* 3.0)

NOTATIONS

SYMBOL	DESCRIPTION	UNIT
A	Contact area of block with soil	Cm^2
A_1	Contact area of actual foundation with soil	Cm^2
A_z	Vertical amplitude of vibration	mm
a_z	Vertical acceleration vibration	mm/s^2
C_u & C_{u1}	Coefficient of elastic uniform compression of soil for area A and A_1 respectively	kgf/cm^3
$C\phi$ & $C\phi_1$	Coefficient of elastic non-uniform compression of soil for area A and A_1 respectively	kgf/cm^3
C_τ & $C_{\tau 1}$	Coefficient of elastic uniform shear of soil for area A and A_1 respectively	
$C\psi$	Coefficient of elastic non-uniform shear of soil	kgf/cm^3
E	Young's modulus	kgf/cm^2
F_o	Peak dynamic force	kg
f	Frequency of propagating waves	Hz
f_1 & f_2	Frequencies at which amplitude is $X_m / \sqrt{2}$	Hz
f_{nx}	Horizontal resonant frequency of block and soil system	Hz
G	Dynamic shear modulus of soil	kgf/cm^2
g	Acceleration due to gravity	mm/s^2
I	Moment of inertia of foundation contact area about a horizontal axis passing through centre of gravity of the area and perpendicular to direction of vibration	cm^4
M	Mass of block	kg s^2/cm
M_m	Mass moment of inertia of the block about a horizontal axis passing through the centre of gravity of the block and perpendicular to direction of vibration	kgf/cm/s^2
M_{mo}	Mass moment of intertia of the block about the horizontal axis passing through the centre of gravity of contact area of block and soil and perpendicular to the direction of vibration	kgf/cm/s^2
S	Distance between geophones or pick-ups	cm
S_e	Elastic rebound	cm
V_c	Compression wave velocity	cm/s

SYMBOL	DESCRIPTION	UNIT
V_s	Shear wave velocity	cm/s
X_m	Maximum amplitude of vibration in forced vibration tests	mm
X_{m-1}, X_m, X_{m+1}	Successive amplitudes of vibration in free vibrations at 2 from each other respectively	mm
t	Time of travel of waves	s
ρ	Mass density of soil	kg s^2/cm^4
ε	Poision's ratio of soil	—
ξ	Damping coefficient of soil	—
λ	Wavelength of propagating waves	cm
λ_1	Phase shift of geophone near to radian centre of gravity of block at frequency (f) of propagating vibrations	radian
λ_2	Phase shift of geophone far away from centre of gravity of block at frequency (f) propagating vibration	radian
γ	Ratio M_m/M_{mo}	—

ANNEX C

(*Clause* 3.2)

EXTRAPOLATION OF FREQUENCY RESPONSE CURVE FOR OBTAINING NATURAL FREQUENCY OF THE SYSTEM

C-1 In case of stiff soils where the resonant frequency is higher than the limit to which the block can be excited by the vibration equipment, extrapolation of the response curve may be resorted to as indicated below to evaluate the resonant frequency of the system. This holds for a single degree of freedom system as in case of vertical vibrations. However, workable values of f_n may also be obtained for horizontal vibrations.

From the theory of mechanical vibrations the relation between the amplitude of vibrations (A_z) and the frequency (ω) for the forced vibrations is given by:

$$A_z = \frac{F_o}{\sqrt{(k - m\omega^2)^2 + c^2\omega^2}}$$

$$= \frac{m_o e\omega^2}{\sqrt{(k - \omega^2 M)^2 + c^2\omega^2}}$$

where

F_o = $m_o e\omega^2$ = Dynamic force,

m_o = Eccentric mass,

e = Eccentricity,

ω = Frequency of excitation

k = Spring constant, and

c = Coefficient of damping.

By substituting in above equation

$\omega = 2\pi f$

$A_1 = M/(m_o.e)^2$

$A_2 = (c^2 - 2kM)/\{(m_o.e)^2 (2\pi)^2\}$

and $A_3 = k^2/\{(m_o.e)^2 (2\pi)^4\}$,

$$A_1 f^4 + A_2 f^2 + A_3 = (f^4/A_z^2)$$

C-2 The above equation can be solved if a minimum of three points are known on the rising portion of the curve. Average values of A_1, A_2, A_3 may be obtained if more than three points are available by solving the equation for set of three points taken at a time. Knowing the value of A_1, A_2 and A_3 the amplitudes at different frequencies can be worked out and the frequency corresponding to maximum amplitude, that is, the resonant frequency determined.

ANNEX D

(*Clause* 7.3.3 *and* 9.5)

RELATIONSHIP BETWEEN SHEAR MODULUS, YOUNG'S MODULUS, COEFFICIENT OF ELASTIC UNIFORM COMPRESSION, ETC

Values of shear modulus G and Young's modulus E are related to each other by the relation given below:

$$G_1 = \frac{E}{2(1 + \varepsilon)}$$

where

ε = Poision's ratio,

C_u can be obtained from E by the equation

$$C_u = \frac{1.13\ E}{(1 - \varepsilon^2)\ \sqrt{A}}$$

where

A = area of contact

NOTE — This relation between C_u and E is based upon the assumption that E remains constant with depth.

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