

Code of Practice for

Foundations for machinery —

Part 1: Foundations for reciprocating machines

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Foreword

This Code of Practice has been prepared to give guidance to designers and other interested parties in the provision of foundations for machinery which may produce periodic disturbing forces.

The treatment in this Code is comprehensive and the extent to which it is applied will depend upon the particular circumstances of the installation.

This Part of the Code deals with the provision of foundations for reciprocating machinery. The preparation of further Parts, for example, for rotating machinery, is under consideration.

During the preparation of the Code the Drafting Committee has paid due attention to the current practices and the difficulties encountered and it is considered that, because of the growing demand for ever-increasing ratings, foundation blocks for such machines should be regarded as important civil engineering works.

For this reason, and also on account of the value and importance of the machinery, the best civil engineering practices should be employed. Proper responsibility should be vested in competent people through all phases of the work and the requirements specified in the British Standards to which reference is made should be followed throughout.

This Part of the Code does not deal with foundations for reciprocating machines required for marine and vehicle applications nor with frame foundations.

As part of BSI's programme of metrication, this Code is expressed in metric terms.

The metric values are given in SI Units: for further information, reference should be made to BS 3763, *"International System of units (SI)"* and PD 5686, *"The use of SI units"*.

The Code Drafting Committee wishes to acknowledge the work of the authors of the publications listed in the bibliography, see Appendix D, to which reference has been made in the preparation of this Part of the Code. References to these publications are given thus "frequency curves"¹.

Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 36, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

1 General

1.1 Scope

This Part of the Code deals with the design and construction of foundations for reciprocating machinery which normally rotates in the low (up to 5 Hz) and medium (5 Hz to 25 Hz) frequency ranges, and is of a size for which a rigid block type foundation is normally used.

Guidance is given on the information and data to be assembled and the steps to be taken in order to realize both a satisfactory design and an adequate control of the construction work on site.

The recommendations are generally applicable only to the design of foundations as an undamped single-mass spring system. It should be realized that there are conditions when damping needs to be considered.

References are included on the characteristics and use of resilient mountings but in cases where these devices are to be employed the designer should judge whether the conditions will permit an assumption that the soil is rigid or whether the design should be based on a multiple-mass spring system.

Recommendations are included for the responsibilities of the purchaser, the machine manufacturer, the main contractor, the consulting engineer, the civil or structural engineer and the supervising engineer, who are jointly responsible for the design and construction of the foundation.

NOTE The titles of the British Standard and Codes of Practice referred to in this Code of Practice are listed on the inside back cover.

1.2 Definitions

For the purposes of this Part of the Code, the following definitions apply.

NOTE Axes. Figure 1 shows the six degrees of freedom and Figure 2 shows the system of axes selected for use in the definitions and elsewhere in the Code.

supporting ground

that part of the ground carrying load arising from the machine and foundation

foundation

that part of the structure in direct contact with, and transmitting loads to, the supporting ground

external forces

the unbalanced part of the periodic inertia forces caused by the acceleration and deceleration of reciprocating parts. The primary inertia force has one complete cycle and the secondary inertia force two complete cycles per revolution of the crankshaft

for foundation design it is usually unnecessary to consider higher orders of inertia forces. These various forces are:

vertical force

an unbalanced force at machine speed or twice machine speed, or both, acting in the direction of the axis Z

horizontal force

an unbalanced force at machine speed or twice machine speed, or both, acting in the direction of the axis X

external couple

a moment which occurs when one inertia force is balanced by another but in a separate line of action for foundation design it is usually necessary to consider only the primary and secondary couples. These various couples are:

vertical couple

an unbalanced couple at machine speed or twice machine speed, or both, acting in the plane of axes YZ

horizontal couple

an unbalanced couple at machine speed or twice machine speed, or both, acting in the plane of axes XY

harmonic torque reaction

turning moment in plane of axes XZ, the frequencies of which depend on the number of cylinders and configuration of the machine

short circuit torque

a turning moment of restraint in the plane of axes XZ exerted on the coupling to the engine when a short circuit occurs on the alternator

synchronizing torque

a turning moment of restraint in the plane of axes XZ exerted on the coupling to the machine when faulty synchronizing occurs

mass moment of inertia

the resistance of a mass to rotation and equal to its mass times the radius of gyration squared

amplitude of vibration

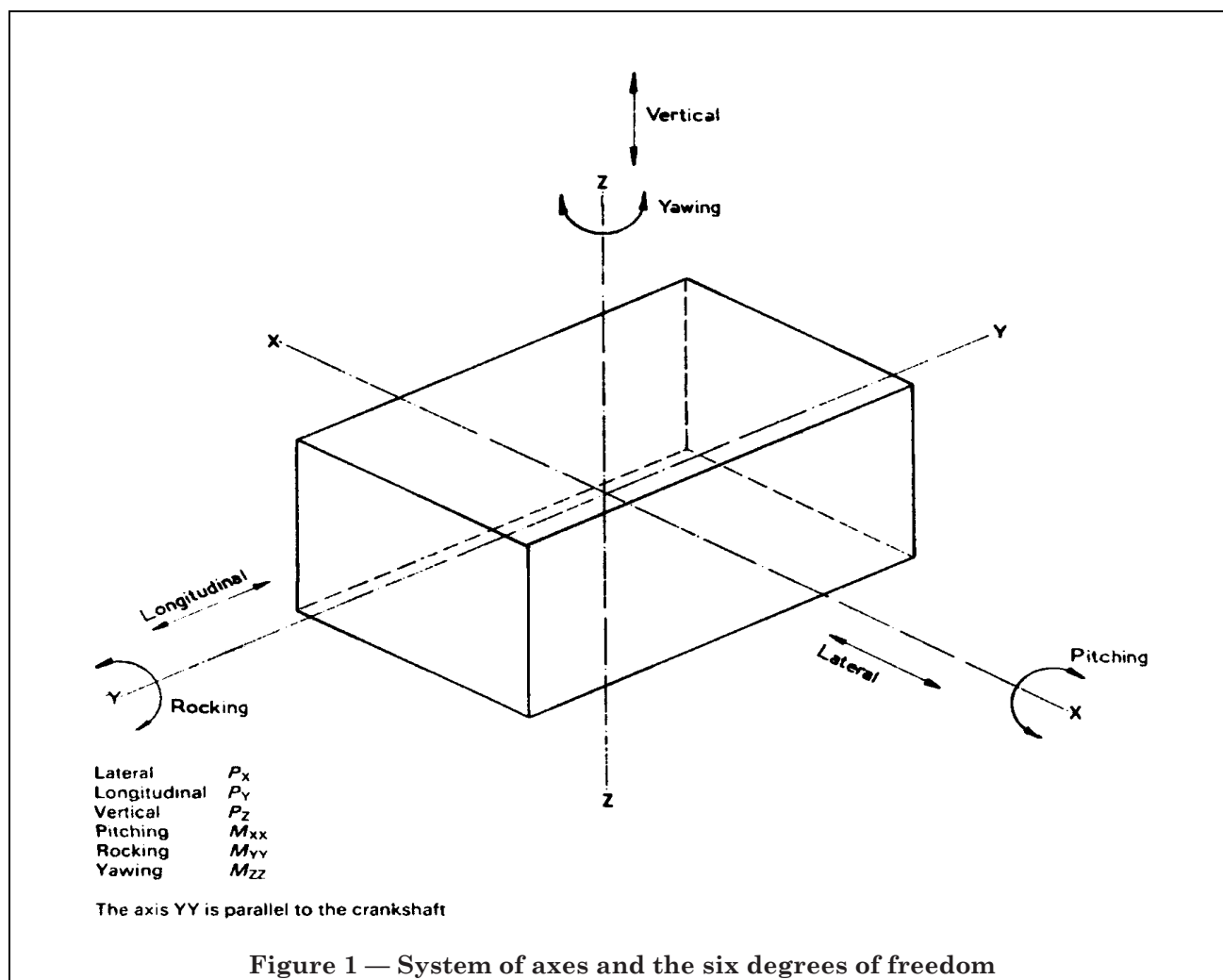
the maximum displacement from its position at rest of a vibrating particle

compression modulus of elasticity, E, for soils

soils have no unique modulus of elasticity in that the stress-strain relationship is almost never a straight line. Furthermore the modulus of elasticity varies when the soil is subjected to repetitional loading and it also varies with the confining pressure. Three moduli of elasticity are recognized; the *initial tangent modulus*, the *secant modulus* and the *hysteresis modulus*

initial tangent modulus

this is derived from a straight line drawn tangentially to the stress-strain curve at a point near the origin



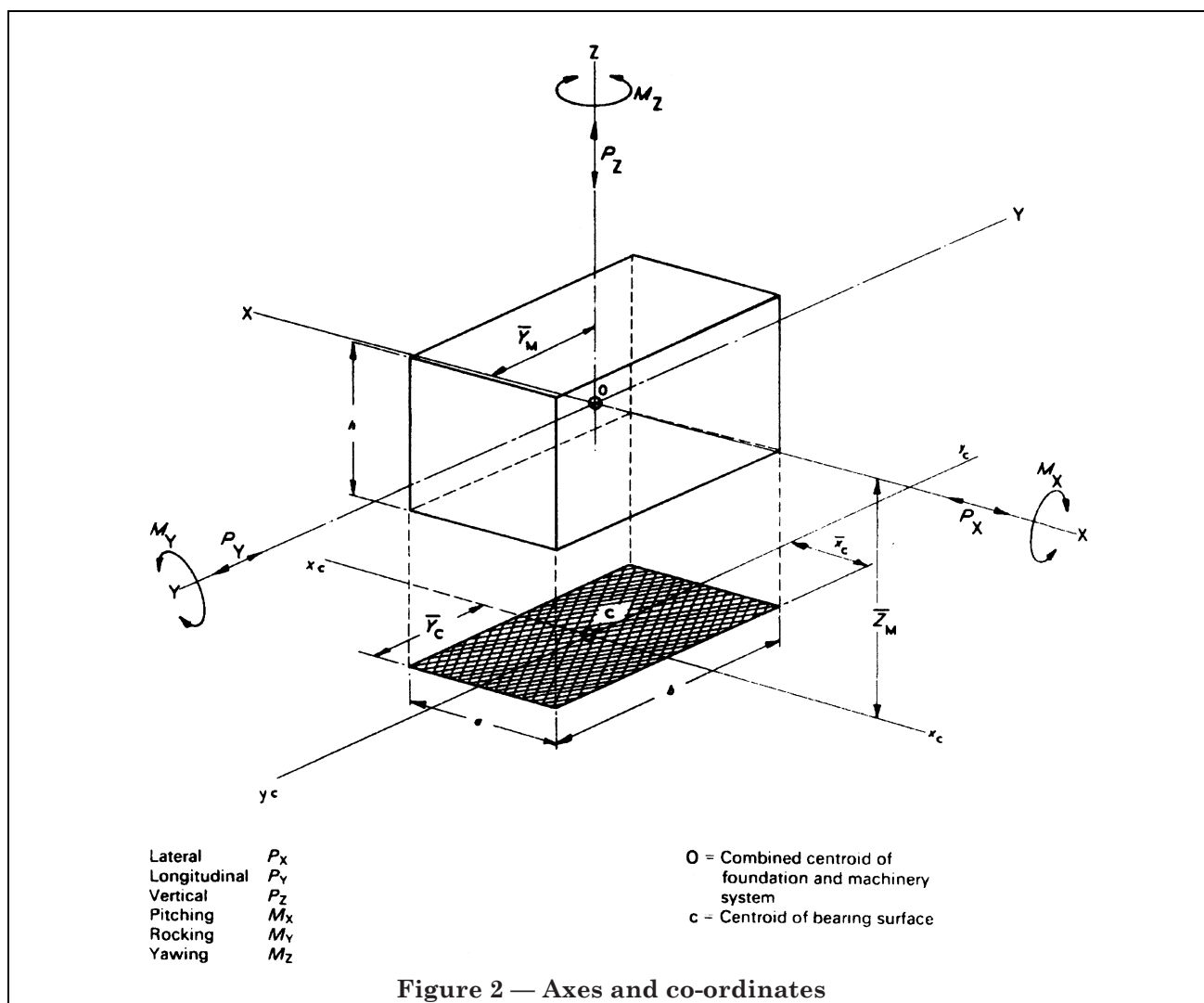


Figure 2 — Axes and co-ordinates

secant modulus

this is derived from a straight line drawn through the origin and through a point on the stress-strain curve corresponding to some arbitrary value of stress, generally the static pressure under the foundation

hysteresis modulus

soils become compacted when subjected to repetitions of load, when the stress-strain curve tends to become steeper and the tangent and secant modulus tend to become closer together. When full compaction has been achieved, the secant modulus of the ultimate and steepest curve is known as the hysteresis modulus

shear modulus of elasticity, G , for soils

the shear modulus, G , is the ratio between shearing stress and angular distortion suffered by the soil measured in radians. As in the case of the compression modulus there is no unique value of the shear modulus of a soil

poisson's ratio, μ , for soils

for an elastic material strained by a force in one direction, there will be a corresponding strain perpendicular to this equal to $\mu \times$ the strain in the direction of the force. The relationship between E , G and μ is $E = 2G(1 + \mu)$ and, as there are no unique values for E and G with soils, it follows that there is likewise no unique value of Poisson's ratio either

NOTE The terms *initial tangent*, *secant* and *hysteresis modulus* relate to moduli derived from static tests. Where dynamic tests are concerned, only one value of the modulus is obtained and it is not quite certain which one it is. A modulus determined by dynamic means is usually thought to be preferable for the design of machinery foundations. Where only static tests have been carried out the *hysteresis modulus* should be used and it may be necessary to apply empirical factors to moduli obtained by these means in order to convert them into dynamic moduli.

bulk density

the mass per unit volume of any material including voids and the water contained in it

natural frequency

the frequency of free vibrations of a body

disturbing frequency

the frequency of a periodic force

resonance frequency

a condition which occurs when a periodic force is exerted on a body at a frequency equal to that of its natural frequency

1.3 Exchange of information

1.3.1 Data to be provided by the purchaser. The purchaser should provide at the outset a qualifying description of any limitations set by the environment in which the machinery is to operate together with any special conditions relating to sensitive equipment, machinery, buildings or persons.

1.3.2 Co-ordination of design. The machine manufacturer and the civil or structural engineer, who may be a consulting engineer or an engineer employed by a public authority or a commercial undertaking, should co-operate in the design of foundation blocks of this kind, taking into consideration the information provided by the purchaser. The machine manufacturer should indicate the basic form of the foundation block and provide all necessary information to the civil or structural engineer (see 3.2).

2 Materials and methods

2.1 Codes of Practice

All materials and methods used in the construction of foundations for machinery should comply with the recommendations contained in the latest editions of the following Codes of Practice: CP 114, CP 115, CP 116, CP 2001, and CP 2004.

2.2 British Standard specification

Methods of testing soils should comply with the requirements of the latest edition of BS 1377.

3 Design considerations

3.1 General considerations

The basic requirements for any machine foundation are that:

- 1) the machine can operate efficiently and reliably without excessive wear;
- 2) the foundation itself suffers no damage or settlement sufficient to cause the machine to function inefficiently or to require realignment;
- 3) the waves propagated through the soil by vibration of the foundation should not be harmful to persons or to adjacent structures, sensitive machinery and industrial processes;
- 4) the foundation adopted is the most economical which will meet all of the above requirements.

The machine manufacturer should prepare a preliminary arrangement drawing showing minimum foundation requirements to suit the details of the machine and any ancillary equipment to be supported on the machine foundation but without regard to particular conditions pertaining to the site in question. He should also provide all necessary data on the dynamic loads associated with the machine. The final design of the foundation should be in the hands of a civil or structural engineer specialized in this class of work and whose duty it will be to ensure that his design suits the manufacturer's minimum requirements and also the four criteria set out above.

The civil or structural engineer should also consider the possibility of the function of the machine being adversely affected by the transmission, through the soil and foundations, of vibrations from an external source. He should accordingly investigate carefully any neighbouring building which contains plant or apparatus likely to set up vibrations and, if necessary, he should carry out physical tests to determine their magnitude and frequency. Where a serious risk is found to exist, the civil or structural engineer should, if possible, design the machine foundation in such a way that it transmits only an acceptable proportion of the outside vibrations to the machine. Where this is not possible he should, jointly with the machine manufacturer, draw the client's attention to the danger and make recommendations, if appropriate, for reducing to acceptable limits the magnitude of the vibrations transmitted to the soil by the offending plant or apparatus.

A site investigation should be made, the scope of which should be commensurate with the size and characteristics of the machine and the expected difficulties of the site. This should include all tests necessary to assess the allowable bearing pressure of the soil and the immediate and long term settlement of the foundation for static loads and also the determination of the relevant dynamic soil constants needed for the particular method of vibration analysis to be used. It should also include the collection of full details of any existing or proposed adjoining structures, industrial processes etc., which may be adversely affected by ground vibrations.

The finished design may take the form of a monolithic reinforced concrete block of appropriate size and mass to have satisfactory static and dynamic characteristics where resting on the natural supporting ground. Where this proves either impossible or impracticable it will be necessary to use anti-vibration mountings, to consolidate the sub-soil by mechanical or chemical means, or to adopt a piled foundation.

3.2 Data to be provided by machine manufacturer

The manufacturer should provide the information as outlined in 3.2.1 to 3.2.3.

3.2.1 General. A brief description of the prime mover and driven machinery should be provided, including:

- 1) description of driving and driven machinery;
- 2) operating speed or speed range;
- 3) number and arrangement of cylinders;
- 4) maximum rated output;
- 5) gearbox ratio where applicable; and
- 6) maximum operating temperature in the bases of the machines.

3.2.2 For static design

3.2.2.1 A loading diagram should be provided illustrating component masses and positions of centres of gravity relative to the three principal axes of the machinery to be mounted on the block.

3.2.2.2 A detailed drawing showing the position and size of mounting feet and details of holding-down bolts should be prepared.

3.2.2.3 A detailed drawing should be prepared giving dimensions of a block foundation of minimum size to satisfy the installation of machinery including the ancillary equipment, where necessary, and including information on discontinuities such as sumps and wells.

3.2.3 For dynamic design

3.2.3.1 Details of out-of-balance forces and couples should be given, together with associated frequencies for all possible modes of vibration for driving and driven machinery. These include:

- 1) external forces;
- 2) external primary couples;
- 3) external secondary couples; and
- 4) harmonic torques.

3.2.3.2 Mass moments of inertia of driving and driven machine about the three principal axes should be indicated.

3.2.3.3 Additional information relating to specific machines, such as that listed below, should be provided where relevant and significant.

- 1) Loads due to dynamic short circuit conditions. These are of the order of 10 times full load torque.

- 2) Loads due to faulty synchronizing condition where due consideration should be given to the possibility of faulty synchronizing with any other machine or combination of machines. With standard alternators these can be of the order of 13 to 15 times full load torque; with certain special types of alternator (e.g. those designed for starting very large motors) they may be as high as 20 times full load torque.
- 3) Loads due to “out-of-step” running between the machine and other machines.
- 4) Loads due to hydraulic, thermal or surge effects from pumps or compressors.
- 5) Loads due to an abnormal sudden stoppage.

The magnitude of the effects in 3) and 4) are unlikely to exceed those in 1) or 2) but they should be investigated.

3.2.3.4 Where it is found necessary to use anti-vibration mountings, as described in **3.5.8**, the civil or structural engineer and machine manufacturer should jointly discuss the type and position of these mountings.

3.2.3.5 Any further data requested by the civil or structural engineer for the foundation design should be provided.

3.3 Data on ground and site conditions

3.3.1 Site investigation. Methods of investigation should, in general, comply with the requirements of BS 1377, CP 2001 and CP 2004. However, there are particular requirements for dynamic investigations which are not covered and **3.3.2** to **3.3.6** inclusive outline investigation requirements.

The site investigation for a vibrating machine should ideally give information to a depth at least three times the expected mean plan dimension of the foundation which can be taken as the square root of the expected area.

However, where a well defined stratum of known characteristics is proved, and it is known that this extends to more than a depth of three times the mean dimension below foundation level, the depth of exploration may be reduced.

3.3.2 Soil properties to be determined. Qualitative information concerning the behaviour of the foundation under dynamic loading can be obtained from a knowledge of the relative density and particle size distribution of granular soils and of index properties and shear strength of cohesive soils.

In the methods outlined below for prediction of foundation behaviour, some form of elastic modulus is required, either the shear modulus, G , the compression modulus, E , with or without Poisson's ratio or some equivalent. The bulk density is also required. Depending on the importance of the installation, elastic parameters may be assessed from other data, or may be measured directly, preferably in situ.

3.3.3 Investigation methods for granular soils. An assessment of the elastic properties of granular soils can be made from a knowledge of relative density and particle size distribution. For the measurement of relative density it is necessary to determine the natural density of the soil and to compare this with the values of maximum and minimum density obtained from laboratory tests on whole samples. The natural density may be obtained from measurements on undisturbed samples from trial pits or borings. It should be noted, however, that elaborate sampling methods are required and considerable care is needed to avoid significant sample disturbance in saturated fine-grained materials. For some granular materials reconstitution to in situ density and the measurement of the dynamic shear modulus and using laboratory resonance column methods is possible. Furthermore, it may be virtually impossible to obtain undisturbed samples of granular materials containing gravel-size particles. Alternatively, the natural density may be measured in situ using nuclear probes.

In situ testing methods can also be used; for example static sounding tests give data from which an approximate assessment of elastic modulus can be made. More direct measurements can be obtained from plate loading tests or other similar tests¹⁾. In addition, a crude assessment of relative density may be obtained from the results of standard penetration tests. Dynamic tests can also be carried out, as described in **3.3.6**.

¹⁾ Such as the use of a device, available commercially under the trade name Pressuremeter, with which a borehole can be radially dilated and the pressure-deformation relation used to derive a modulus for the ground.

3.3.4 Investigation methods for cohesive soils. For cohesive soils it is often possible to obtain relatively undisturbed specimens by sampling in boreholes and these can be used in the laboratory to carry out compression tests in which the elastic parameters can be measured. However, it should be borne in mind that even a very small degree of sample disturbance will lead to under-estimating the elastic modulus. If samples can be obtained in the form of hand-cut blocks from pits, then the chance of disturbance is less and a more representative value of the elastic modulus can be obtained. The laboratory techniques to be used for these determinations may be specialized, in some cases involving cyclic loading; in the case of soft cohesive soil, consolidation tests should be carried out in the laboratory in addition to compression tests.

For in situ testing of cohesive soils, the use of plate loading tests or similar tests²⁾ will again give a measure of the elastic modulus. Dynamic testing in situ may also be carried out as described in 3.3.6.

3.3.5 Investigation methods for other soils. Soils may be encountered which may not fall into the simple categories given above, for example residual soils, silts and soft rocks. The method of testing will have to be related to the particular nature of the soils involved, but in each case it should be directed to measuring or assessing reliably the elastic parameters.

3.3.6 Dynamic investigations. The use of small vibrators for in situ determinations of dynamic parameters is desirable. Care should be taken to ensure that the vibrators have a resultant unbalanced vertical force, that they are well bedded into the soil to be tested and that the static load they impose should be high enough to resist any tendency to “jump” off the ground during operation. It is possible to derive a dynamic shear modulus and damping factor from the amplitude frequency curves¹ by varying the frequency of the applied dynamic force and measuring the amplitude both at the vibrator itself and in the adjacent soil.

Alternatively, the resonant frequency for different static masses of vibrator can be identified using amplitudes comparable to those allowable for the full size foundation when it is possible to deduce the value of shear modulus².

Study of the surface waves at varying distances from the vibrator can reveal variations in properties with depth.

It is also possible to obtain a value of shear modulus by a pulse method consisting of a source of both shear (S) wave and compression (P) wave and detectors of horizontal and vertical motion such as a suitably designed seismometer. A permanent record of the complete pulse should be obtained for both S and P waves permitting clear identification. This technique depends upon generation of sufficient shear wave energy and upon the axiality of response of the orientated detectors.

3.4 Design criteria

3.4.1 General. All machine foundations should satisfy two fundamental criteria: that resonance does not occur between the frequencies of the pulsating loads and the natural frequencies of the foundation/soil system and also that the amplitude of any vibration does not exceed safe limits. Whilst these two factors are to some extent interlinked, in that near resonance can lead to excessive amplitude, it is usual to consider them separately. Design criteria based on frequency and amplitude limits can be classed as follows:

- 1) limits set by the possibility of damage or uneconomic wear to machinery or associated equipment or both;
- 2) limits set by the possibility of damage to buildings or structures;
- 3) limits of structural-borne vibrations to ensure comfort of persons; and
- 4) limits set by possibility of disturbance of ground resulting in unacceptable settlement of foundation.

The various criteria for the ratio of operating frequencies to natural frequencies are given in 3.4.2. Amplitude limits corresponding to the four classes set out above will be found under their respective headings in 3.4.3 to 3.4.6 inclusive. The limits quoted therein are the maximum permissible resultant amplitudes of vibration of any part of the foundation block.

²⁾ Such as the use of a device, available commercially under the trade name Pressuremeter, with which a borehole can be radially dilated and the pressure-deformation relation used to derive a modulus for the ground.

3.4.2 Frequency ratio. The frequency ratio is defined as:

$$\frac{f_m}{f_n} = \frac{\text{frequency of disturbing moment}}{\text{natural frequency of vibrations of foundation block and machinery system}}$$

OR

$$\frac{f_p}{f_n} = \frac{\text{frequency of disturbing force}}{\text{natural frequency of vibrations of foundation block and machinery system}}$$

Wherever possible the highest significant disturbing frequency should be lower than the natural frequency. For important installations, the frequency ratio should be such that:

$$\frac{f_m}{f_n} \text{ or } \frac{f_p}{f_n} \text{ is less than 0.5.}$$

Where this is not possible, the lowest significant disturbing frequency should be such that:

$$\frac{f_m}{f_n} \text{ or } \frac{f_p}{f_n} \text{ is greater than 2.}$$

For installations of lesser importance:

$$\frac{f_m}{f_n} \text{ or } \frac{f_p}{f_n} \text{ should be less than 0.6}$$

OR

$$\frac{f_m}{f_n} \text{ or } \frac{f_p}{f_n} \text{ should be greater than 1.5.}$$

Where the machine is connected to the foundation by means of low frequency resilient anti-vibration mountings:

$$\frac{f_m}{f_n} \text{ or } \frac{f_p}{f_n} \text{ should be greater than 3.}$$

Whilst the above criteria should be applied to all possible modes of vibration, it may be necessary to operate closer to resonance for some minor modes, in which case consideration should be given to the resulting amplitudes. In cases where, for any mode, disturbing frequency is higher than natural frequency, consideration of amplitude at resonance will be required since the unit will pass through resonance during running up; this factor should be given particular consideration in the case of reciprocating machines, with a small number of cylinders, on resilient anti-vibration mountings.

Even though the machine may be balanced, minor disturbing forces can occur due to manufacturing tolerances and other causes and, for sensitive installations, the frequencies arising from these may have to be taken into account.

Effectively two kinds of damping may be operative, that due to radiation of energy away from the foundation block and that due to dissipation processes in the soil. The first kind is a function of block mass and geometry differs for different modes and is independent of soil elastic properties. The second kind is a property of the soil. Guidance on the significance of these factors can be obtained from the bibliography³.

3.4.3 Limitation of vibration amplitude to avoid damage to machinery. Where the manufacturer of the machinery has prescribed a maximum amplitude of vibration of the foundation to avoid damage to machinery, this limiting amplitude should not be exceeded. Where no specific limit has been given by the machine manufacturer it may be taken that a foundation satisfying the other amplitude criteria will provide a satisfactory base for the machinery.

3.4.4 Limitation of vibration amplitude to avoid damage to buildings. In fixing the permissible amplitude, consideration should be given to neighbouring buildings and structures and to the machines and apparatus they contain. From data currently available it appears that damage in neighbouring buildings due to resonance will be negligible if the amplitude vibration of the foundation is less than 200 μm at frequencies below 20 Hz. Where the disturbing frequency exceeds 20 Hz, a lower permissible amplitude may be necessary for certain installations, when a value corresponding to the frequency may be read off line ADD' of Figure 3.

3.4.5 Limitation of vibration amplitude to avoid discomfort of persons. For low speed machines, it is unlikely that foundations which satisfy 3.4.4 will produce vibrations of sufficient amplitude to be disturbing to persons. For higher speed machines or where there are particular reasons to avoid discomfort to personnel working nearby, a lower permissible amplitude may be necessary and an appropriate figure, corresponding to the operating frequency and to the degree of protection required, may be taken off Figure 3.

3.4.6 Limitation of vibration amplitude to avoid settlement of machine foundation. For many soil types, foundations for low speed machines designed to a limiting amplitude of 200 μm will not suffer undue settlement due to dynamic loads. In some soils, particularly loose sands and silts in conjunction with a high water table, significant settlement may occur. The present state of knowledge of this subject does not permit a limiting amplitude to be given but where the civil or structural engineer considers that the soil profile is such that a serious risk of excessive settlement exists, he should arrange to consolidate the soil underneath the foundation, or to transfer the load to a more satisfactory soil stratum and depth, or to provide a semi-buoyant or fully buoyant foundation.

3.4.7 Factors of safety. The various limits given in 3.4.3 to 3.4.6 are absolute values and contain no factors of safety. The final design of the foundation should, therefore, have computed values of amplitude less than those figures. No clear guidance can be given on the factor of safety to be applied in any given case because this will depend upon the refinement of the computations and the reliability of the soils data used, but in general the computed amplitudes should not be more than two-thirds of the allowable figures (factor of safety of 1.5).

3.5 Concrete foundation design

3.5.1 General conditions. Concrete foundations for reciprocating machines are usually in block form with openings, recesses, channels and holding-down boltholes according to the structure of the machine and associated equipment. Both the foundation and machine are usually regarded as a single body supported by an elastic underlay (which may be the sub-soil or a resilient mounting). The concrete foundation system, whether supported on the ground or resting on resilient mountings, is subject to oscillations at determinable frequencies in six degrees of freedom, i.e. lateral, vertical, longitudinal, rocking, yawing and pitching, acting separately or in various combinations (see Figure 1).

The natural frequencies of the foundations due to rocking, yawing and pitching are specially influenced by the dimensions of the foundation itself; thus for shallow foundations the natural rocking frequency will be nearly the same as the vertical frequency and for high and deep foundations it will be much lower. The design of the foundations should take into consideration the whole of the data required to be supplied by the machine manufacturer in accordance with 3.2. Pile foundations may be used in special cases where the soil conditions are unsuitable to support block foundations, or when the natural frequency of block foundations needs to be raised in cases where it is impossible to alter dimensions or when amplitudes or settlement, or both, need to be reduced.

Cellular foundations may be used in special cases where it is necessary to maintain the rigidity of a block foundation but with mass saving in terms of concrete. Wherever possible, means should be provided in cellular foundations to add mass by filling the voids in order to adjust the natural frequency of the foundation block, where necessary, but this should not be undertaken without considering the effects of additional settlement arising from the additional mass. In the case of cohesionless soils, consideration should be given to making provision for chemical consolidation in order to modify the sub-soil stiffness.

3.5.2 Empirical rules for the dimensions of concrete foundation blocks. The initial dimensioning of concrete foundation blocks which is largely based on empirical rules, should be regarded only as commencing data for the design of the foundation blocks but cases may occur where calculations show that foundations not complying with these criteria are wholly satisfactory. The empirical rules are as follows.

- 1) The mass of the foundation should be greater than that of the plant.
- 2) In order to obtain uniform settlement of the foundation, it is recommended that the common centre of gravity of the system (i.e. of the foundation and machine) is located as near as possible to the same vertical line as the centroid of the foundation area in contact with the soil. In any case the eccentricity in the distribution of masses should not exceed 5 % of the length of the side of the contact area. In addition, the centre of gravity of the machine and foundation system should if possible be below the top of the foundation block.