CP 2012-1:
1974

Incorporating Amendment Nos. 1 and 2

Code of Practice for

Foundations for machinery —

Part 1: Foundations for reciprocating machines

Confirmed
January 2010

UDC 69.021.15:624.159.11:62 – 218:62 – 12

Code drafting sub-committee CVCP/4/7 Foundations for machinery

	Representing:
Mr J Calderwood (*Chairman*)	
Mr J A Williams	Association of Consulting Engineers
Mr J Calderwood Mr E F Crawley Mr J H Hayward	British Internal Combustion Engine Manufacturers
Mr H Watson	Power Generation Association
Mr M R Hollington	Cement and Concrete Association
Mr R A Vaughan	Diesel Engineers' and Users' Association
Mr D L McKie	Electricity Supply Industry in England and Wales
Mr P R Carver Mr J E den Tieter	Engineering Equipment Users' Association
Mr P Sturgess	Federation of Civil Engineering Contractors
Mr A C Meigh Mr D B O'Neill	Institution of Civil Engineers
Mr D G M Roberts	Institution of Public Health Engineers
Mr C R J Fleming Mr K O Pook	Department of the Environment
Mr P B Edwards	Institution of Structural Engineers
Mr D A Gillespie	Co-opted
Mr R Harrison	British Standards Institution

Code drafting panel CVCP/4/7/1 Machinery foundation

	Representing:
J Calderwood (*Chairman*)	
Mr E F Crawley Mr J H Hayward	British Internal Combustion Engine Manufacturers' Association
Mr P B Edwards	Institution of Structural Engineers
Mr K O Pook	Nominated by CVCP/4/7
Mr R B Croft	Co-opted
Mr D A Gillespie	Co-opted
Mr B O Skipp	Co-opted
Mr R Harrison	British Standards Institution

This Code of Practice, having been approved by the Codes of Practice Committee for Civil Engineering, was published under the authority of the Executive Board on 30 August 1974

The following BSI references relate to the work on this code:
Committee references CVCP/4/7 and CVCP/4/7/1
Draft for comment 71/11038

ISBN 0 580 08222 9

Amendments issued since publication

Amd. No.	Date of issue	Comments
1741	May 1975	
1938	April 1976	Indicated by a sideline in the margin

Contents

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

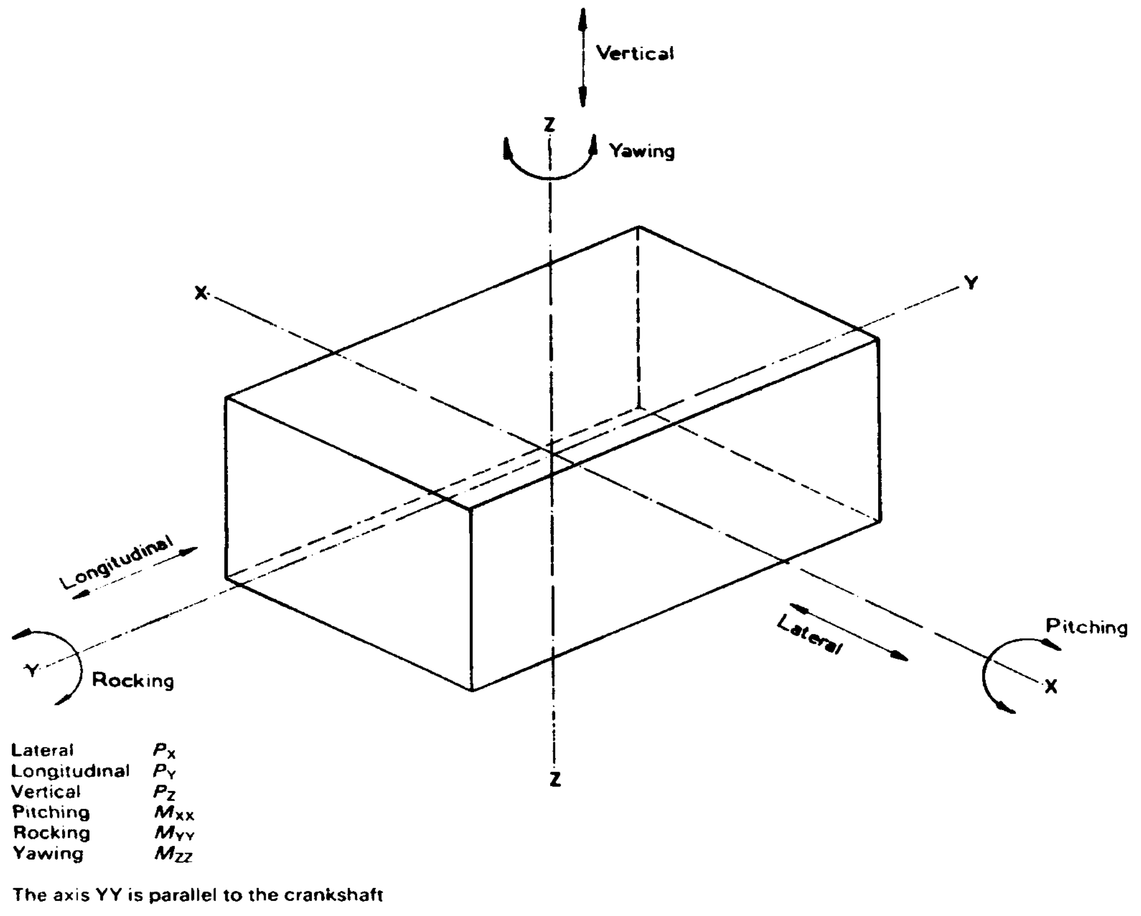


Figure 1 — System of axes and the six degrees of freedom

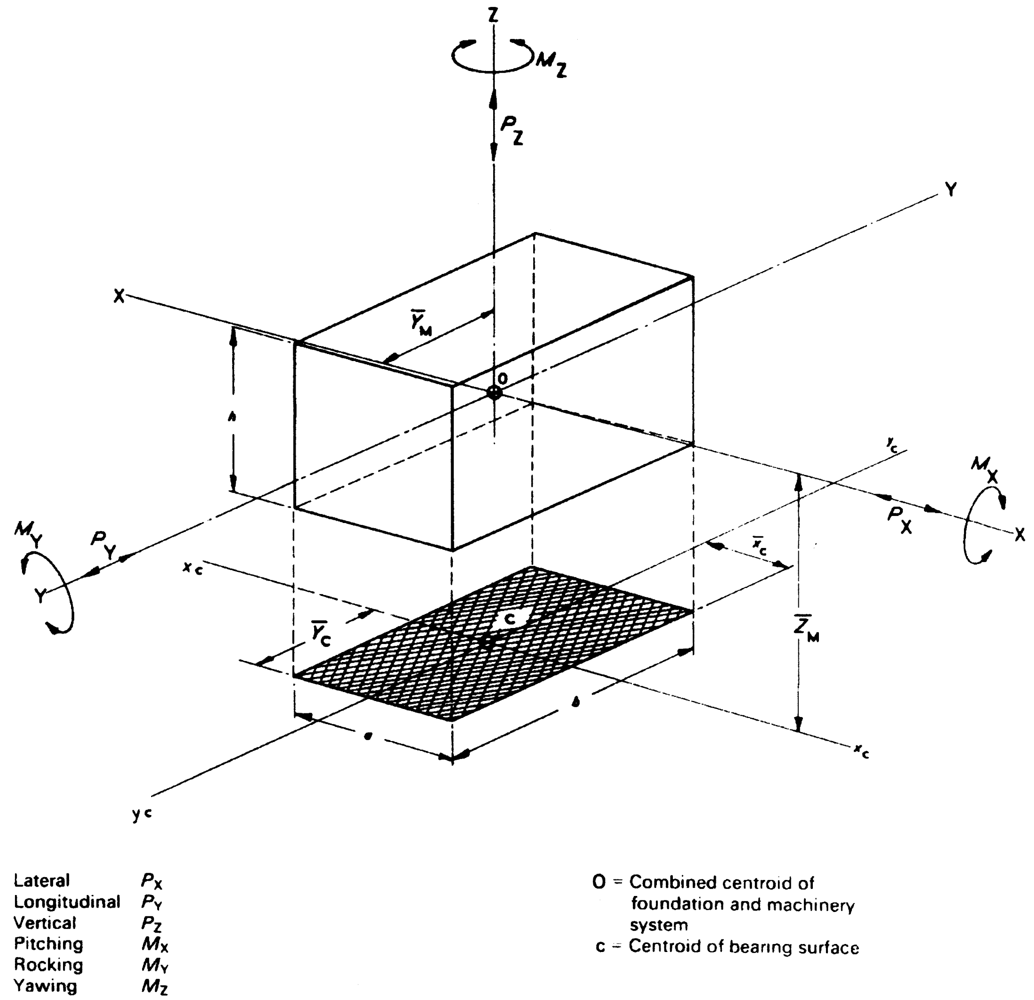


Figure 2 — Axes and co-ordinates

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 tests[1]. 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 tests[2)] 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 curves[1] 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 modulus[2].

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:

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

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

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

For installations of lesser importance:

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

or

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

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

$\frac{f_m}{f_n}$ or $\frac{f_p}{f_n}$ 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 bibliography[3].

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.

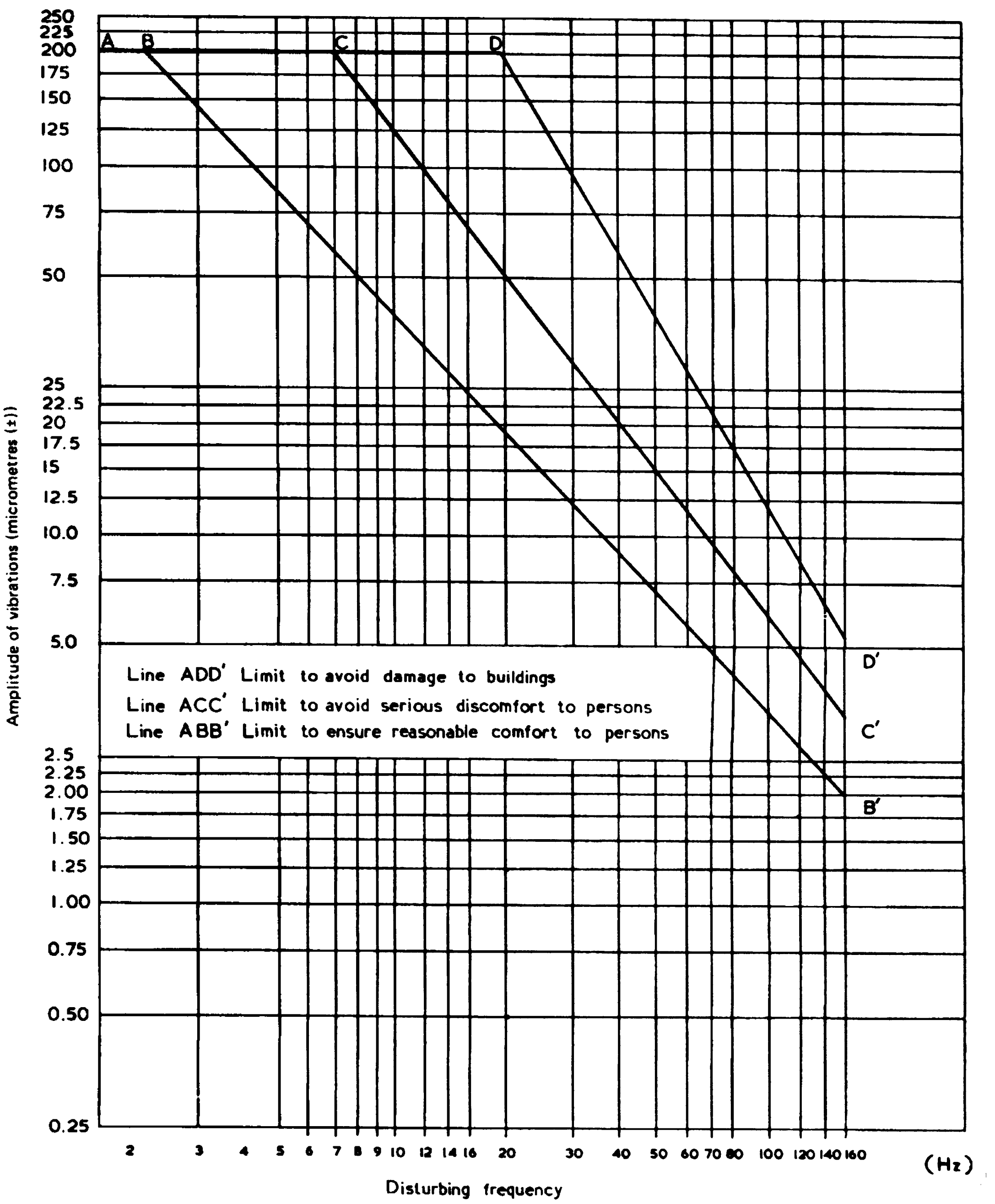
3.5.2 Empirical rules for the dimensions of concrete foundation blocks. The initial dimensioning of concrete foundation blocks which is largely based on empirical rules, should be regarded only as commencing data for the design of the foundation blocks but cases may occur where calculations show that 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.

3) To ensure reasonable stability in the case of vertical machines, the total width of the foundation (measured at right angles to the crankshaft) should be at least equal to the distance from the centre of the shaft to the bottom of the foundation. In the case of horizontal machines where the cylinders are arranged laterally the width should be greater.

4) The proportions of the foundation block should be such as to ensure stability against rocking.



NOTE These limits do not include any factors of safety (**3.4.7**).

Figure 3 — Amplitude limits of foundation block

3.5.3 Final design of foundation blocks. The final dimensions of a concrete foundation should be derived from vibration calculations and should take into account:

1) the dimensions of foundations by empirical rules;

2) the bearing pressure due to the dead and imposed load;

3) the natural frequencies of the system for vertical, longitudinal, lateral, rocking, yawing and pitching motions;

4) the relationship between the exciting frequency and the natural frequency of the foundation soils system;

5) the calculated amplitudes in the various modes;

6) the influence of underlying substrata, where they are of different types to the surface soil, and the effect of the ground water, when at a high level, on the machines and foundations; and

7) the effects of transmission of heat from the machine to the foundation block.

To simplify calculations, the planes of action of the forces imposed by the machines should, if possible, be parallel with one of the principal planes of inertia and be concentric with the axes of the foundation block.

Working drawings should be prepared and should clearly specify the working tolerances of accuracy required in the finished work.

Appendix A gives a design procedure, based on Barkan, for an undamped system. Although damping has been omitted in this example, there may be circumstances where it could well be taken into account.

3.5.4 Fixing of machines to foundation block. Where the machine is to be fixed rigidly to the concrete foundation, anchor bolts may be concreted into the foundation block in positions corresponding to holes in the base of the machine. It should be noted that the anchor bolts should be capable of meeting the conditions mentioned in **3.2.3.3**.

Alternatively, the machine may be fixed to the foundation block by means of bolts passing through the block, fastened by nuts and bearing assemblies inserted into specially formed access points.

Packers, wedges, shims or levelling screws should be used to bring the machine to its proper height and level, ensuring that the loads are distributed evenly over the levelling points used in the assembly. It is important that any instructions issued by machine manufacturers regarding levelling procedure and method of placing packers on the concrete be strictly followed.

The position and type of anchor bolts for securing the base of the machine to the foundation block should be taken into account when arriving at the dimensions for the block.

The holes in the foundation block to receive the anchor bolts should not be too large and there should be at least 75 mm of concrete between the periphery of the hole and any external surface. Wherever possible, holes should be wedge-shaped in form, the narrow part of the wedge being at the top.

The bolts should be set in the block so that they can be adjusted in all directions during aligning and levelling of the machinery. The length of the anchor bolts to be embedded into a foundation block should be such that sufficient anchorage is provided. Where a plain hexagon-headed bolt is used, its embedded length should be at least 30 times its diameter. The use of anchor plates or alternative devices may be adopted where desirable and the length of the bolt may be reduced accordingly, subject always to a sufficient length of embedment to ensure that there is no failure in the concrete itself.

Expanded type anchor bolts which impart a pressure to the walls of the hole in the foundation block may also be used, but in these cases the holes should not be too near to the external surfaces of the concrete or to each other, and reinforcement around the bolt hole in the foundation block should be provided to withstand bursting of the concrete.

3.5.5 Reinforced concrete for foundation blocks. Stresses should be calculated in accordance with the laws of mechanics and the recognized general principles relating to the design of reinforced and prestressed concrete. The requirements of CP 114 and CP 115 apply as appropriate in the design of the foundation blocks.

The strength of the concrete blocks may be assessed by the commonly employed elastic theory which makes the further assumption that steel and concrete are elastic within the range of the permissible stresses given in Clauses **303** and **304** of CP 114 and that the modular ratio is equal to 15. Alternatively, the load factor method described in Clauses **306** and **322** of CP 114 may be adopted where the basic requirement is that there should be a suitable load factor taking into account the dynamic forces.

The minimum strength of the concrete used in reinforced concrete block foundations should be as given in Table 1.

Table 1 — Strength requirements of concrete for block foundations

Nominal mix	Cube strength within 28 days after mixing		Cube strength within 7 days after mixing	
	Preliminary test	Works test	Preliminary test	Works test
1 : 2 : 4	N/mm^2 28	N/mm^2 21	N/mm^2 18.7	N/mm^2 14

Concrete strength in excess of the minimum strength may be used and should be in accordance with the requirements of CP 114.

3.5.6 Pile foundations. Foundation blocks incorporating end-bearing or friction piles may be considered in cases where there is need to make a significant change in frequency in one or more modes of vibration or where piles are required to support the dead loads.

Piles may affect the lowest natural frequencies of a foundation block, as compared to one placed directly on the natural soil, in the following manner:

1) increase the natural frequency in the vertical, rocking, pitching and possibly, the longitudinal modes of vibration;

2) decrease the natural frequency in the lateral and yawing modes of vibration depending upon the level of the stratum providing restraint to the piles.

An end-bearing pile is one which relies mainly on the end bearing for its load carrying properties, the amount of soil which participates in the vibration of the foundation block is therefore small in most cases.

A friction pile is one which relies mainly on frictional resistance between the pile surface and surrounding soil to transmit the entire load. Because vibration tends to destroy the frictional resistance established in granular soils, it is important to ensure that for the vertical, rocking and pitching modes the criteria laid down in **3.4.2** are adhered to.

Where raking piles are included, an increase in the lateral or longitudinal stiffness of the foundation blocks will result depending upon the direction of rake.

Pile caps, where used as a foundation block, should be of such a size as to meet all design criteria, and be not less than 0.6 m thick or one-tenth of the maximum width, whichever is the greater.

Where it is necessary to calculate the horizontal natural frequency of a piled foundation reference may be made to "Foundation soil and machine foundations"[1].

3.5.6.1 *Circumstances requiring piled foundations*. When a raft foundation is unsuitable it may be desirable to support the foundation block on piles. The most usual reasons for this situation are as follows.

1) When the pressure on the soil under the raft is greater than its maximum safe bearing capacity.

2) When a raft foundation, sized by the criteria in **3.5.2**, is found to be subject to resonance; or when an increase in the mass of the block is either unduly wasteful in material or ineffective due to the danger of resonance in other modes.

3) When a raft foundation is low tuned by one mode and high tuned by another, and the desirable frequency ratios of 0.5 and 2.0 cannot be maintained simultaneously.

4) When the amplitudes of movement of a raft foundation are in excess of their permissible values.

5) Piles should usually be employed when ground water is within $\frac{1}{2}B$ of the underside of the base, and they may be advisable if found within a distance of $2B$. (B is the breadth of the foundation.)

6) Piles should be used if a rigid strata is found within $1\frac{1}{2}B$ below the base in the case of level strata, or $2B$ if the strata is uneven and they may be desirable when the strata is found at somewhat greater depths.

However, vibrations can still propagate from the rock into the surrounding structures, and it may ultimately prove necessary to use anti-vibration mountings.

7) Piled foundation should be used when a raft foundation is liable to suffer a differential settlement in the order of 8 mm.

8) Piles may be used to minimize the effect of ground borne vibration on surrounding foundations and equipment. This is particularly important when these are within a distance of 50 m from the machine block and when the soil is sand of medium to low density. The effect on sensitive equipment should be considered to a distance of 200 m.

3.5.6.2 *Methods of assessing frequencies and amplitudes*. All systems of analysing the behaviour of piled foundations on which the piles are constructed monolithically with the base, are dependant on the estimation of the vertical and horizontal pile stiffnesses. The most reliable methods available for determining these require site investigations, either involving load tests or measurements of ultrasonic pulse velocities.

3.5.6.3 *Measurements of pile stiffnesses from in-situ pile tests*. Vertical pile tests should be carried out under the anticipated static working loads. To determine a measure of the dynamic load-deflection characteristics the load should be oscillated about this mean load by the amplitude of load reversal likely under operating conditions, but under small amplitudes of load oscillation a load of 1 tonne should be taken.

When the oscillation is conducted at slow speed (using jacks etc.) the oscillation of load should be repeated seven times, or until a final elastic load/deflection characteristic has been achieved.

Horizontal pile tests may similarly be conducted, but these may prove difficult to arrange for simple installation.

When the oscillation is carried out below the operating speed it is possible that the stiffness of the system will be underestimated, as although the test may utilize an *E*-value within 20 % of the correct dynamic *E*-value the pile will be effectively fixed at a greater depth and consequently the tests will underestimate the true stiffness.

For this reason with important installations in granular soils the test piles should be resonated at the operating frequency to assess whether the friction between the soil and the pile is destroyed by the oscillation. It is likely that a high proportion of this friction will remain if the exciting frequencies differ from the natural frequency of the foundation and the natural frequency of the soil by satisfactory margins.

3.5.6.4 *Deduction of pile stiffnesses from in situ soil tests*. The pile stiffness can be estimated from various parameters measured in a conventional soils investigation.

The vertical pile stiffness of the piles can be reliably estimated from the dynamic elastic modulus as given in CP 110 and, if the pile is end bearing on a rock of an *E*-value greater than 3 000 N/mm^2 [3)], they may be considered to be fixed at the base. When this is not the case the elastic deflection of the underlying strata should be allowed for.

Horizontal pile stiffnesses may be estimated from the knowledge of the dynamic modulus of the soil, Poisson's ratio and the ratio between the characteristic (i.e. operative) pile length to pile diameter. The characteristic length may in turn be estimated from the dynamic modulus of the soil, the pile width and the pile stiffness. The method of calculation assumes that the pile is supported in an end bearing, and that the resistance to horizontal movement is caused by the soil of the uppermost strata. The error of applying this procedure to piles supported by friction is not considerable.

3.5.6.5 *General considerations*. When the horizontal pile stiffness cannot be determined satisfactorily it is preferable to provide raking piles and account should be taken of any resulting reduction in stiffness on the rocking mode.

Consideration should be given to the interaction of closely spaced friction piles (see Barkan). The interaction is not the same as under static loading.

With concrete piles reinforcement should extend from the piles into the base.

Allowance should be made for the fact that the upper end of the piles may be free under test conditions, but under operating conditions they may be largely fixed. Failure to take account of this can lead to a four-fold error in estimating the stiffness of the system.

The mass of soil participating with a foundation supported on end bearing piles may be assumed to be the same as for a raft foundation. With friction piles a greater soil mass is involved although no accurate methods of determining it are available. Failure to take account of the soil mass and inertias will result in errors in the case of end bearing piles in the order of 30 % for vibration in the vertical mode, 20 % in the rocking mode, 10 % in the yawing mode and 5 % in both the translational modes.

3.5.6.6 *Compaction of ground by pile driving*. Piles may be used to compact the ground to improve the bearing capacity under a raft foundation. In these circumstances, the piles should not be in contact with the underside of the base and calculations are made on the assumption of a homogeneous soil mass.

[3)] 1 N/mm^2 = 1 MPa

3.5.7 Minimum reinforcement in block foundations. The requirements of CP 114 as regards minimum reinforcement should apply in all reinforced elements of concrete foundations. These minimum requirements should be given special consideration because of the dynamic effects arising in machine foundations. The following points should therefore be borne in mind.

1) The ends of mild steel reinforcing bars should always be hooked, irrespective of whether they are designed for tension or compression.

2) Reinforcement should be used at all faces.

3) The position of reinforcement should be such as to take into consideration flexural stresses, shrinkage stresses and deformation resulting from temperature changes.

4) Reinforcement should be provided around all pits and openings.

5) If the foundation is over 1 m thick, shrinkage reinforcement should be provided spaced approximately 600 mm in three directions (cube reinforcing with minimum bar diameter of 16 mm).

Notwithstanding the minimum reinforcement requirements for the concrete block foundations, where the concrete is subject to tension or bending arising from flexural oscillations, the reinforcement required should be arrived at by calculation. The minimum reinforcement in a concrete block should consist of bars at least 16 mm diameter spaced at 300 mm centre to centre, extending both vertically and horizontally near all the faces of the foundation block. Figure 4 shows typical examples of reinforcement. Where expanding type holding bolts are to be used, the reinforcement should be positioned to allow the drilling of the holes.

3.5.8 Anti-vibration mountings. Where it is found to be impracticable to design a foundation consisting of a simple concrete block resting on the natural soils to give satisfactory dynamic characteristics, it may be possible to reduce the transmitted vibrations to acceptable levels by means of anti-vibration mountings.

Depending upon the nature of the machinery and the installation, the anti-vibration mountings may be utilized:

1) between the machinery and its foundation;

2) between a foundation block and a supporting foundation.

The former arrangement is generally suitable where the out-of-balance forces are not severe and it should be noted that the natural frequencies of the system will be modified to a degree which depends upon the resilience, design and position of the anti-vibration mountings. The latter course may be used where it is necessary to increase the moments of inertia so that frequencies and amplitudes may be modified to acceptable limits.

Selection of the type of anti-vibration mounting should take into account the environmental conditions as well as the data listed in **3.2** and arrangements should be made to maintain accurate alignment of the machinery whilst deflections are taking place in the anti-vibration mountings.

3.5.8.1 *Types of mounting*. The many forms of commercially available anti-vibration mountings can be classified broadly as follows.

1) *Unit mountings*. [System 1) in **3.5.8**]. Unit mountings may utilize a spring support consisting of either a steel spring, with the addition of some damping device, or rubber which may be loaded in compression, shear or a combination of compression and shear. Variants of this unit may employ adjustable damping or snubbing devices to avoid excessive movement when running through a critical speed. Transmissibility can thus be kept to a low level whilst movement can be maintained within acceptable limits. Alternative suspension media may be used in unit mountings, for example, pressurized air springs and viscous devices.

2) *Area mountings*. [System 2) in **3.5.8**]. The simple form of the area-mounting type of installation consists of a carpet of resilient material upon which the foundation block is cast. Many proprietary examples are available and selection may be made from a wide range of cork, agglomerated cork, felt and rubber products.

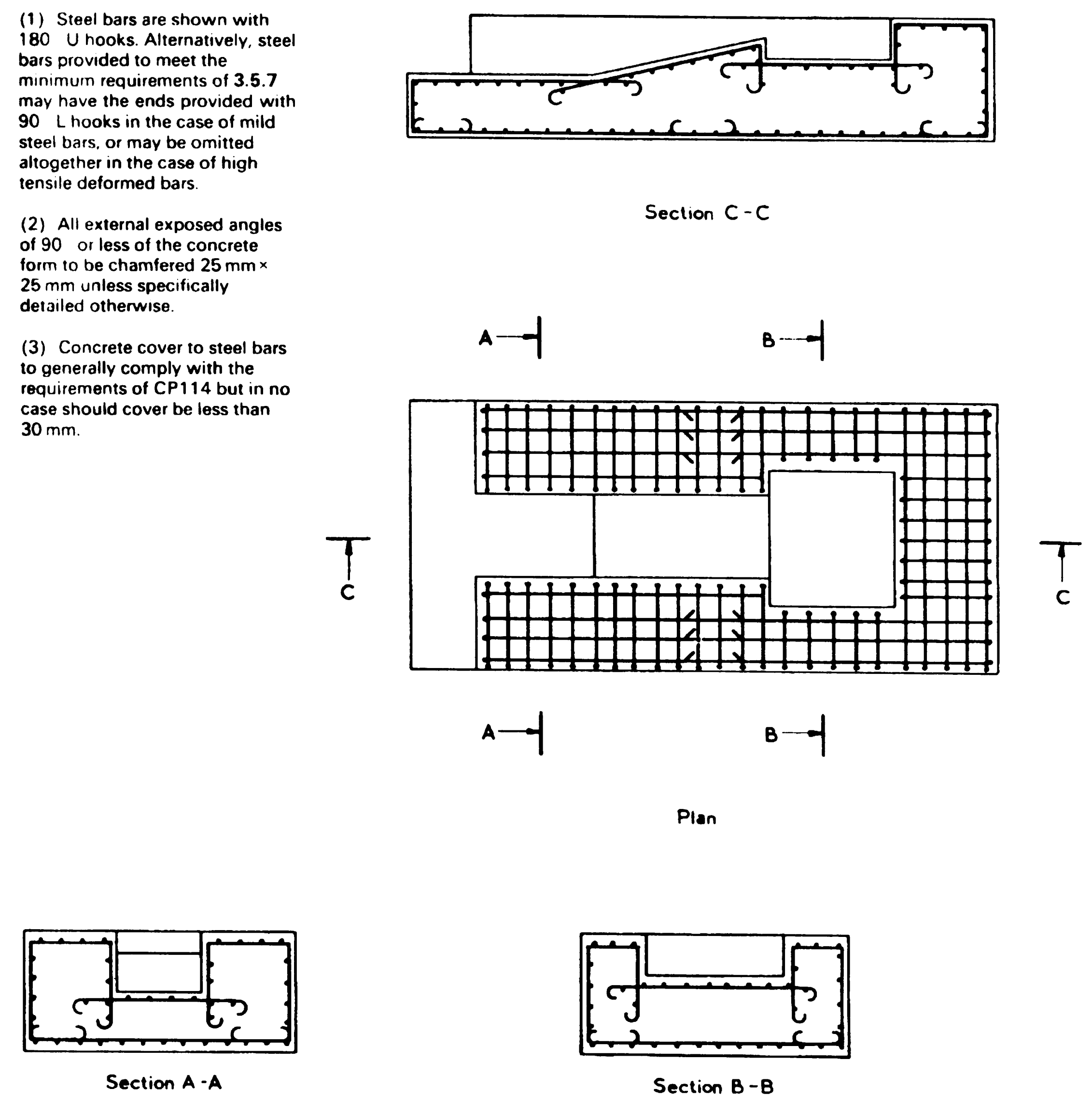


Figure 4 — Typical minimum reinforcement details

The types of carpet which are commercially available naturally possess different properties but, in general terms, those with continuous structures and uniform densities may be considered to be effective in isolating the higher frequencies only.

Some proprietary forms of rubber area mounting are manufactured with moulded profiles which result in a lower stiffness. This gives an improved effectiveness at lower frequencies and hence the isolation achieved extends over a wider frequency range. In cases where it is required to achieve a lower frequency than normally obtained, more than one layer of area mounting may be used, together with steel plates interposed between the layers.

3) *Foundation block suspension*. [System 2) in **3.5.8**]. Foundation block suspension is an alternative method of isolating a foundation block from a supporting foundation. The block together with all the machinery is suspended by utilizing leaf or coil springs or some equivalent form of resilient support.

Where resilient mountings are employed, movement of the machinery will result from dynamic effects. Accordingly, the maximum amplitudes should be calculated so that all connecting services (e.g. cables, water, oil, exhaust and compressed air pipes) may be provided with adequate flexibility. Careful consideration should be given to those amplitudes which occur when the machine is passing through critical speeds.

Further, allowance should be made for settlement, creep or fatigue which may occur over a long period within the elastic medium employed in the mounting.

3.5.9 Working drawings. After completion of the design, the working drawings should be submitted to the machine manufacturer for approval.

4 Work on site

4.1 Technical control of foundation construction

4.1.1 Appointment of supervising engineer. The construction of the foundations for machinery should be under the control of an experienced supervising engineer appointed by the purchaser.

The supervising engineer may be a representative of the civil or structural engineer responsible for the design of the foundation or a specialist technical adviser experienced in this type of work.

4.1.2 Duties of the supervising engineer. The duties, responsibilities and authority of the supervising engineer should be clearly defined in writing before the commencement of work on site and made known to all concerned.

These duties should include the following.

1) Examining and approving in conjunction with the civil or structural engineer the contractor's proposed methods of construction and programme of works.

2) Ensuring that the contractor's agreed methods of working are carried out and that the final permanent works are in accordance with the design and the specification and conform to the correct lines and levels.

3) Supervising and recording any tests which may have to be carried out at the site and inspecting raw materials at their source.

4) Preparing and submitting at predetermined intervals, regular reports recording the progress of the work and constituting a detailed history of the work of construction. These reports should be made available to the contractors.

5) Recording and checking the progress of the work in comparison with the programme in order to secure the completion of each section of the work by the programme date. Any delay should be reported immediately and in subsequent progress reports.

6) Recording upon the working drawings, or upon drawings prepared for that purpose, the character of the strata encountered in the excavation, the actual level and character of the soil at foundation level, the standing level of any ground water and details of any agreed deviations from the working drawings which may require to be made during the execution of the work. Any significant deviation from the design assumptions should be reported immediately to the civil or structural engineer.

7) Inspecting and checking the completed work and recording the finished dimensions and levels of the foundation.

8) Obtaining from the machinery contractor his agreement in writing, before installation of machinery commences, that the dimensions and levels of the concrete foundation, together with the positions and levels of all embedded parts and assemblies, so recorded are within permissible tolerances of the requirements insofar as the erection of machinery is concerned.

4.2 The responsibilities of the civil engineering contractor

4.2.1 Information to be supplied by the civil engineering contractor. The responsibilities of the civil engineering contractor should include an obligation to provide and submit the following information, prior to the commencement of the work, to the civil or structural engineer responsible for the design of the foundation.

1) A construction programme for the whole of the works. In this programme the period of time between the completion of construction and the commencement of machinery erection should be as long as practicable and in no case be less than one month so as to minimize the effects of shrinkage and creep movements on machine alignment.

2) Details of the concrete mix to be used in the construction of the foundation. The mix should be designed and tested in accordance with the requirements of CP 114 or CP 115.

3) Details of the position of any construction joints required to be provided in the construction of the foundation, together with proposals for the method of forming the joints and of continuing the work.

4) Details of materials and methods the contractor proposes to use for the protection and curing of the concrete.

4.2.2 Setting out. The civil engineering contractor should be responsible for the proper setting out of the works and for the correctness in accordance with the working drawings of the positions, levels, dimensions and alignment of the foundation.

4.2.3 Inspection of stages of work. The civil engineering contractor should also be responsible for advising the supervising engineer when the following stages of the work have been reached and are ready for inspection.

1) The excavation and preparation of the soil to receive the concrete foundation.

2) The fixing of formwork and steel reinforcement and fixed parts to be embedded.

3) The fixing or placing of specified resilient anti-vibration mountings or materials.

The contractor should not proceed with the work of construction beyond each of the foregoing stages until he receives written approval from the supervising engineer.

4.3 Workmanship

4.3.1 Workmanship generally. Workmanship on site should generally comply with the relevant clauses of CP 2004, CP 114 and CP 115.

4.3.2 Continuity of work. Foundation blocks should be cast preferably in a single continuous operation. Where construction joints are specified and shown on the working drawing or agreed with the civil or structural engineer the concrete in each monolith between construction joints should be completed without interruption.

Consideration should however be given to the need for reducing to acceptable values the heat of hydration and the rate of its development and also to the difference between the maximum temperature of the concrete during curing and the minimum ambient temperature.

The civil engineering contractor should organize his work and supplies of materials to ensure the reliability of the continuity of concrete work in accordance with the stipulated requirements.

In the event that an unforeseen interruption in the concreting occurs, the resulting unavoidable joint should be considered as a construction joint and treated in the same way as construction joints shown on the working drawings or as may be ordered by the supervising engineer.

4.3.3 Embedded parts. The method to be employed for fixing the machine to its foundation will have been determined by agreement between the machine manufacturer and the civil or structural engineer responsible for the design of the foundation and should be shown in detail on the working drawings together with a clear demarcation between the limits of supply of the contractors concerned.

The machine manufacturer should be responsible for supplying and delivering to site in due time all steel bearers, seating plates, frames and fixing bolt assemblies which are required under the terms of the contract and which are necessary for erecting and fixing the machine to the foundation and which require to be set and embedded during the construction of the concrete block foundation.

The civil engineering contractor should be responsible for placing and fixing the parts to be embedded in the correct positions and levels and to fix them in such a way that they cannot be displaced during the pouring, tamping and vibration of the concrete. They may be fixed to the reinforcement steel by welding or wiring, or they may be fixed to the formwork.

The work of embedding, grouting, packing and filling should be in accordance with the stipulated requirements. If this work is carried out by the civil engineering contractor as and when required by the machinery erection contractor, it should be according to the instructions of the supervising engineer.

All necessary precautions should be taken to avoid the possibility that the machine will be disturbed or displaced during filling, grouting and embedding operations.

4.3.4 Dry packing. Where dry packing is specified for filling and pinning up to the underside of seating plates, bedplates or steel bearers, it should comprise a cement mortar consisting of one part of Portland cement and two parts of sharp clean sand, by volume, mixed with water to a consistency equivalent to moist earth.

The quantity of water to be added is best found by experiment and will vary according to the grading of the sand and the amount of moisture already contained in the sand. The final mix should, however, have a water/cement ratio not greater than necessary to hydrate the cement and allow it to be packed into position.

A sample of the mix clenched tightly in the hand should not squeeze out excess moisture and when the hand is opened the sample should retain its form and break cleanly without crumbling. The palm of the hand should be moist but not wet.

The space to be provided between the top surface of the concrete and the underside of seating plates, bedplates and steel bearers to be dry packed, normally should be approximately 50 mm.

Areas to be dry packed should have formwork on three sides, the direction for inserting the dry pack from the fourth side being chosen for maximum convenience during packing.

The dry pack should be inserted in small quantities at a time, each portion being rammed before the next is inserted. Ramming should be carried out either by a suitably sized hardwood rod and mallet or by a metal rod. Power ramming should not be used because of the development of excess pressure likely to distort or displace machine parts.

Dry packing should be placed and compacted within a period not exceeding one hour after mixing.

4.3.5 Cement grout. Cement grout used for filling or embedding should consist of one part of Portland cement and two parts of clean sharp sand mixed to a moist consistency sufficient to facilitate the grout being fully worked under all seatings. A quick setting cement should not be used.

Additives may be employed to give non-shrink properties to cement grout. In this case the ratio of cement to sand may be varied and the instructions of the additive manufacturer should be closely followed.

Alternatively, where a proprietary non-shrink grout is used, it should be mixed and placed in accordance with manufacturer's instructions.

Cement grout should be placed within a period commensurate with the type of cement used but not exceeding one hour from the time of mixing.

4.3.6 Synthetic resin grout. Synthetic resins in the epoxide group, when compounded into a suitable paste or mortar form, may be employed as an alternative for either dry packing or cement grout, for the purposes of filling and embedding under the machinery bedplates and around fixing assemblies, provided that satisfactory conditions will exist on site to allow a satisfactory rate of curing, and that the underside of the machinery bedplate in contact with the resin compound has been prepared so as to permit the removal of the bedplate from the foundation at some later date.

The use of synthetic resin compounds may suggest a possibility of reducing the dimension of the space normally allowed for grouting when using cement compounds.

Synthetic resin compounds should be used for these purposes strictly in accordance with the manufacturer's instructions and only in cases where approval for their use, together with any resultant reduction in grouting clearances, has been agreed with the machinery manufacturer.

4.3.7 Grouting. Particular attention should be given to the following points concerning the work of grouting.

1) All metallic and concrete surfaces should be thoroughly cleaned and washed so as to remove all dirt, oil, grease, loose particles and cement laitance. The concrete surfaces should be roughened and saturated with clean water and kept wet for at least 24 h and all surplus water removed and surfaces cleaned oil free with compressed air immediately before commencement of grouting.

2) The arrangement of the bases and proposed method of placing cement grout should be checked in order to determine if additional provisions require to be made in order to avoid trapping air. Air relief holes should be provided if required.

3) Forms should be high enough to provide a head of grout on all sides which should be at least 150 mm high on the side from which cement grout is to be poured. Forms should be placed with sufficient clearance to the edges of the bases to enable the grout to be properly worked into position.

4) Forms should be strong and secure and well caulked to prevent leakage. The cement grout should be poured from one side to avoid forming air pockets and be carried out continuously without interruption so that the filling is continuous and dense.

5) On completion of the curing of the grout underfill the machine should be finally checked to ensure that its alignment is acceptable.

6) Exposed surfaces of grout and concrete should be prepared and given two coats of an oil and alkali resistant coating.

7) Specific measures are to be stipulated on the working drawings to ensure that mortar and grout materials do not enter the spaces from which such materials are to be excluded e.g. the space between the top of the concrete foundation and the sides and bottom of the bases of the machinery, the spaces between the bolts and the clearance holes through which they pass both in the bases of the machinery and in the foundation.

4.4 Testing and measurement of vibrations

4.4.1 Introduction. Testing of a foundation block prior to the initial running of the machinery may, where warranted, be carried out to determine the natural frequency in appropriate modes and the amplitudes due to the dynamic forces which could be operative in either normal running or special emergency conditions.

4.4.2 Excitation. An electromagnetic or hydraulic vibrator should be mounted upon the block to excite it in the same mode of vibration to that expected from the operating machinery.

The operating machinery should be installed prior to these tests. The amplitudes of motion which can be induced with a scaled down disturbing force will be significantly smaller than those which would be expected in the operation of the machine. Allowance may have to be made for the non-linearities of soil response.

4.4.3 Measurements. The vibrations should be measured by transducers having a linear response over the range 2 Hz to 200 Hz. The accuracy of the transducers should be better than 10 % and they should respond to a uniaxial motion with not more than 10 % cross sensitivity.

The transducers may be of the velocity sensitive type commonly called geophones or piezoelectric accelerometers, provided that they cover the range of frequencies with the required sensitivity.

The mountings for such transducers should be firm. It is not satisfactory merely to rest the transducers on the block, or to hold them against the sides by hand.

The position and orientation of the vibration transducers should be such as to give a picture of the block motion in space and time. Transducers should preferably be placed on the extremities of the uppermost surface of the block and as near as possible to the axes X and Y (see Figure 2).

Transducers should be capable of measuring vibrations in three directions; one vertical and two horizontal, parallel to axes X and Y.

In order to gain a full picture of the behaviour of a block it is necessary to record from all detectors simultaneously and this requires multiple channel recorders or some other appropriate data recording equipment. However, in the case of small installations it may be acceptable to measure from each position on a single channel using a meter indication of the root mean square or peak-peak vibration parameters of velocity, displacement or acceleration if the frequency of the disturbing force is known. A number of these devices is available on the market.

It is preferable, however, to use equipment which gives an immediate record of frequency of a vibration particularly during studies on the response on running up through a critical speed.

Appendix A Step-by-step design procedure

A.1 General

There are varying methods of design for reinforced concrete foundations for reciprocating machinery.

Reference to the bibliography will assist the designer in the choice of method of design. The method of design illustrated in this Appendix is based on proposals made by D.D. Barkan[4].

A.2 Symbols and units

See Figure 2.

Symbol		Unit
A	Area of foundation base (i.e. $A = a \times b$).	m^2
A_X	Amplitude of horizontal vibrations parallel to axis XX.	m
A_Y	Amplitude of horizontal vibrations parallel to axis YY.	m
A_Z	Amplitude of vertical vibrations.	m
$A_{\phi X}$	Amplitude of angular vibrations about axis XX (i.e. pitching).	rad
$A_{\phi Y}$	Amplitude of angular vibrations about axis YY (i.e. rocking).	rad
$A\phi_Z$	Amplitude of angular vibrations about axis ZZ (i.e. yawing).	rad

NOTE All amplitudes are ±, i.e. from mean position.

Cr	Barkan's soil coefficient of elastic uniform shear.	N/m^3
Cu	Barkan's soil coefficient of elastic uniform compression.	N/m^3
Cs	Barkan's soil coefficient of non-uniform shear.	N/m^3
$C\phi$	Barkan's soil coefficient of non-uniform compression.	N/m^3
Pb	Maximum allowable bearing pressure on soil.	kN/m^2
$I_{XX(E)}$	Mass moment of inertia of engine about its centre of gravity with respect to XX axis.	kg m^2
$I_{YY(E)}$	Mass moment of inertia of engine about its centre of gravity with respect of YY axis.	kg m^2
$I_{ZZ(E)}$	Mass moment of inertia of engine about its centre of gravity with respect to ZZ axis.	kg m^2
$I_{XX(A)}$	Mass moment of inertia of driven machine about its centre of gravity with respect to XX axis.	kg m^2
$I_{YY(A)}$	Mass moment of inertia of driven machine about its centre of gravity with respect to YY axis.	kg m^2
$I_{ZZ(A)}$	Mass moment of inertia of driven machine about its centre of gravity with respect to ZZ axis.	kg m^2
$I_{XX(F)}$	Mass moment of inertia of foundation block about its centre of gravity with respect to XX axis.	kg m^2
$I_{YY(F)}$	Mass moment of inertia of foundation block about its centre of gravity with respect to YY axis.	kg m^2
$I_{ZZ(F)}$	Mass moment of inertia of foundation block about its centre of gravity with respect to ZZ axis.	kg m^2
f_n	Natural frequency of linear vibrations of foundation and machinery system.	rad/s
f_p	Frequency of disturbing force.	rad/s
f_m	Frequency of disturbing moment.	rad/s

Symbol		Unit
$f_{n\phi}$	Natural frequency of rocking, pitching and yawing vibrations of a foundation and machinery system.	rad/s

NOTE rad/s × 60/2π = vibration/min.

$I_{x(c)}$	Second moment of area of foundation bearing surface with respect to axis x_cx_c which passes through its own centroid, c, and is parallel to the axis of rotation XX (i.e. $I_{x(c)} = ab^3/12$).	m^4
$I_{y(c)}$	Second moment of area of foundation bearing surface with respect to axis y_cy_c which passes through its own centroid, c, and is parallel to the axis of rotation YY (i.e. $I_{y(c)} = a^3b/12$).	m^4
$I_{z(c)}$	Second moment of (polar) area of foundation bearing surface with respect to a vertical axis which passes through its own centroid, c, and is perpendicular to the x_cx_c and y_cy_c axes (i.e. $I_{z(c)} = I_{x(c)} + I_{y(c)}$).	m^4
I_{XX}	Mass moment of inertia of foundation and machinery system with respect to axis XX through their combined centre of gravity, O.	kg m^2
I_{YY}	Mass moment of inertia of foundation and machinery system with respect to axis YY through their combined centre of gravity, O.	kg m^2
I_{ZZ}	Mass moment of inertia of foundation and machinery system with respect to axis ZZ through their combined centre of gravity, O.	kg m^2
$I_{x(c)x(c)}$	Mass moment of inertia of foundation and machinery with respect to axis x_cx_c defined as in $I_{x(c)}$ above (i.e. $I_{x(c)x(c)} = I_{XX} + m\bar{Z}_M^2$).	kg m^2
$I_{y(c)y(c)}$	Moment of inertia of foundation and machinery system with respect to axis y_cy_c defined as in $I_{y(c)}$ above (i.e. $I_{y(x)y(c)} = I_{YY} + m\bar{Z}_M^2$).	kg m^2
m	Mass of foundation and machinery system.	kg
m_e	Mass of engine.	kg
m_a	Mass of driven machine.	kg
m_f	Mass of foundation block.	kg
g	Acceleration due to gravity (9.81 m sec^{-2}).	m sec^{-2}
r_1	Ratio $I_{XX}/I_{x(c)x(c)}$.	
r_2	Ratio $I_{YY}/I_{y(c)y(c)}$.	
P_X	External out of balance horizontal force in projection of axis XX.	N
P_Y	External out of balance horizontal force in projection of axis YY.	N
P_Z	External out of balance vertical force.	N
M_X	Unbalanced moment about XX axis resulting from inertia forces and torques, external existing torques and external out of balance forces.	N m
M_Y	Unbalanced moment about YY axis.	N m
M_Z	Unbalanced moment about ZZ axis.	N m
$\bar{Y}_M$	Distance to centre of gravity of foundation and machinery system from the end of the block.	m
$\bar{Y}_E$	Distance to centre of gravity of engine from the end of the block.	m
$\bar{Y}_D$	Distance to centre of gravity of driven machinery from the end of the block.	m
$\bar{Y}_F$	Distance to centre of gravity of foundation block from end of the block.	m

Symbol		Unit
$\bar{Y}_C$	Distance to centroid of foundation base area from the end of the block.	m
$\bar{Z}_E$	Distance to centre of gravity of engine from the base of the foundation block.	m
$\bar{Z}_A$	Distance to centre of gravity of driven machinery from the base of the foundation block.	m
$\bar{Z}_F$	Distance to centre of gravity of foundation block from the foundation base.	m
$\bar{Z}_M$	Distance to centre of gravity of foundation and machinery system from the base of the foundation block.	m
e_y	Percentage eccentricity of centre of gravity of foundation and machinery system related to the centroid of the foundation base area, i.e. $$e_y = \frac{\bar{Y}_C - \bar{Y}_M}{b} \times 100.$$	%

A.3 Basis of design method

The use of Barkan's simple theory[4] should not give rise to errors of greater than 10 % in the resonant frequency for typical foundations where the effective mass of soil participation is not greater than 23 % of the mass of the foundation plus machine.

The soil characteristics are expressed in terms of Cu, Cϕ, Cr and Cs, and an allowable bearing pressure Pb. It is assumed that the designer will obtain data for these characteristics either from ground investigations or from published data[4] relative to the ground conditions.

A.4 Step-by-step design method

A.4.1 General. (from **3.2.1**) Determine

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.
6) Maximum operating temperature in the bases of machines.

A.4.2 Static design (from **3.2.2**). Determine

1) Loading diagram for machinery components.
2) Centres of gravity relative to the three principal axes of the machinery to be mounted on block.
3) Position and size of mounting feet and holding down bolts.
4) Minimum size of foundation block to suit machinery and components.
5) Details of discontinuities in block such as sumps and wells etc.

A.4.3 Dynamic design (from **3.2.3**). Determine

1) Details of out of balance forces and couples: for external forces P_Z, P_X, P_Y; for external primary and secondary couples M_Z, M_X; for harmonic torques M_Y.
2) Moments of inertia of engine and driven machinery:
   a) Moments of inertia of engine about:
      XX axis (pitching) = $I_{XX(E)}$
      YY axis (rocking) = $I_{YY(E)}$
      ZZ axis (yawing) = $I_{ZZ(E)}$
   b) Moments of inertia of driven machine:
      XX axis (pitching) = $I_{XX(A)}$
      YY axis (rocking) = $I_{YY(A)}$

ZZ axis (yawing) = $I_{ZZ(A)}$

c) Loads due to dynamic short circuit conditions.

d) Loads due to faulty synchronizing conditions.

e) Loads due to “out of step” running between machines.

f) Loads due to hydraulic, thermal or surge effect from machinery.

g) Loads due to an abnormal sudden stoppage.

h) Details of anti-vibration mountings if specified.

i) Any further details for design of foundation block.

A.4.4 Amplitude limits (from **3.4.3** to **3.4.6**). Determine the maximum permissible amplitude and frequency of vibration at which the machine will operate satisfactorily.

A.4.5 Soil properties (from **3.3.2**). Determine

1) Soil characteristics Cr, Cu, Cϕ, Cs and Pb appropriate to the geometry of the foundation.

2) *mg*.

3) Applied pressure on soil from foundation block, *mg*/*A*. Check that mg/A < Pb

A.4.6 *Centre of gravity and stability*

1) Determine centre of gravity of foundation block, i.e. $\bar{Y}_F$ and $\bar{Z}_F$.

2) Determine centre of gravity of foundation and machinery system, i.e. $\bar{Y}_M$ and $\bar{Z}_M$.

3) Check that the ratio of foundation mass/machine mass satisfies **3.5.2** 1).

4) Check that the centre of gravity of foundation and machinery system in relation to the centroid of foundation area in contact with the soil satisfies **3.5.2** 2) i.e. e_y.

5) Check that the width of foundation in relation to height of centre of crankshaft above base of foundation satisfies **3.5.2** 3).

6) Check the stability of foundation against overturning in accordance with conditions set out in **3.2.3.3** and also **3.5.2** 4).

A.4.7 *Moments of inertia and area*

1) Determine mass moment of inertia of foundation and machinery system with respect to axis XX through their combined centre of gravity, i.e. I_{XX}.

2) Determine mass moment of inertia of foundation and machinery system with respect to axis YY through their combined centre of gravity, i.e. I_{YY}.

3) Determine mass moment of inertia of foundation and machinery system with respect of axis ZZ through their combined centre of gravity, i.e. I_{ZZ}.

4) Determine mass moment of inertia of foundation and machinery system with respect to axis x_cx_c passing through the centroid of the bearing surface and parallel to the axis of rotation XX, i.e. $I_{x(c)x(c)}$.

5) Determine mass moment of inertia of foundation and machinery system with respect to axis y_cy_c passing through the centroid of the bearing surface and parallel to the axis of rotation YY, i.e. $I_{y(c)y(c)}$.

6) Establish ratio $r_1 = I_{XX}/I_{x(c)x(c)}$.

7) Establish ratio $r_2 = I_{YY}/I_{y(c)y(c)}$.

8) Determine second moment of area of foundation bearing surface with respect to axis x_cx_c defined as in 4) above, i.e. $I_{x(c)}$.

9) Determine second moment of area of foundation bearing surface with respect to axis y_cy_c defined as in 5) above, i.e. $I_{y(c)}$.

10) Determine second polar moment of area of foundation bearing surface with respect to the axis passing through the centroid of base area in contact with the soil, i.e. $I_{z(c)}$.

A.4.8 Frequencies and amplitudes. Determine natural frequencies and amplitudes of vibration.

Although the system being considered has six degrees of freedom it may only vibrate in four different ways or modes. Rotation about the XX axis does not usually take place independently of translation along the YY axis; i.e. pitching and longitudinal vibrations normally occur simultaneously. Rotation about the YY axis does not usually take place independently of translation along the XX axis; i.e. rocking and lateral vibrations normally occur simultaneously. Each of these modes of vibration has two natural frequencies, i.e. the principal natural frequencies, which are derived from the natural frequencies of the individual degrees of freedom of the mode.

The other two modes of this system are vertical vibrations and yawing vibrations.

A.4.8.1 *The pitching and longitudinal mode*

A.4.8.1.1 *Natural frequencies*

For rotation about XX: $f_{n\phi(X)}{}^2 = C\phi \dfrac{I_{x(c)}}{I_{x(c)x(c)}}$

For translation along YY: $f_{n(Y)}{}^2 = \dfrac{C\tau A}{m}$

Principal natural frequencies, f_{n1} and f_{n2}:

$f_n{}^4 - \dfrac{(f_{n\phi(X)}{}^2 + f_{n(Y)}{}^2)f_n{}^2}{r_1} + \dfrac{f_{n\phi(X)}{}^2 f_{n(Y)}{}^2}{r_1} = 0$ yields f_{n1} and f_{n2} for pitching and longitudinal modes.

Determine frequency ratios $\dfrac{f_{m(X)}}{f_{n1}}, \dfrac{f_{m(X)}}{f_{n2}}, \dfrac{f_{p(Y)}}{f_{n1}}, \dfrac{f_{p(Y)}}{f_{n2}}$.

Check that the recommendations of **3.4.2** are satisfied.

A.4.8.1.2 *Amplitudes*

1) Due to an exciting force P_Y:

$$A_{Y(p)} = \frac{(C\phi I_{x(c)} - mg\bar{Z}_M + C\tau A\bar{Z}_M{}^2 - I_{XX} f_{p(Y)}{}^2)P_Y}{\Delta P}$$

$$A_{\phi X(p)} = \frac{C\tau A\bar{Z}_M P_Y}{\Delta P}$$

where

$\Delta P = mI_{XX}(f_{n1}{}^2 - f_{p(Y)}{}^2)(f_{n2}{}^2 - f_{p(Y)}{}^2)$

2) Due to an exciting moment M_X:

$$A_{Y(m)} = \frac{C\tau A\bar{Z}_M M_X}{\Delta M}$$

$$A_{\phi X(m)} = \frac{(C\tau A - m f_{m(X)}{}^2) M_X}{\Delta M}$$

where

$\Delta M = mI_{xx}(f_{n1}{}^2 - f_{m(X)}{}^2)(f_{n2}{}^2 - f_{m(X)}{}^2)$

Determine $A_Y = A_{Y(p)} + A_{Y(m)}$ and $A_{\phi X} = A_{\phi X(p)} + A_{\phi X(m)}$

Determine the maximum horizontal displacements at base of foundation block, A_b, and at top of foundation block, A_t.

$A_b = A_Y + \bar{Z}_M A_{\phi X}$
$A_t = A_Y + (h - \bar{Z}_M) A_{\phi X}$

Check that the recommendations of **3.4.3** to **3.4.6** are satisfied.

A.4.8.2 *The rocking and lateral mode*

A.4.8.2.1 *Natural frequencies*

For rotation about YY: $f_{n\phi(Y)}^2 = C\phi \dfrac{I_{y(c)}}{I_{y(c)y(c)}}$

For translation along XX: $f_{n(X)}^2 = Cr \dfrac{A}{m}$

Principal natural frequencies, f_{n1} and f_{n2}:

$$f_n^4 - \frac{(f_{n\phi(Y)}^2 + f_{n(X)}^2) f_n^2}{r_2} + \frac{f_{n\phi(Y)}^2 \cdot f_{n(X)}^2}{r_2} = 0$$ yields f_{n1} and f_{n2} for rocking and lateral modes.

Determine frequency ratios $\dfrac{f_{m(Y)}}{f_{n1}}, \dfrac{f_{m(Y)}}{f_{n2}}, \dfrac{f_{p(X)}}{f_{n1}}, \dfrac{f_{p(X)}}{f_{n2}}$

Check that the recommendations of **3.4.2** are satisfied.

A.4.8.2.2 *Amplitudes*

1) Due to an exciting force P_x:

$$A_{X(p)} = \frac{(C\phi I_{y(c)} - mg \bar{Z}_M + CrA \bar{Z}_M^2 - I_{YY} f_{p(X)}^2) P_X}{\Delta P}$$

$$A_{\phi Y(p)} = \frac{CrA \bar{Z}_M P_X}{\Delta P}$$

where

$\Delta P = m I_{YY} (f_{n1}^2 - f_{p(X)}^2)(f_{n2}^2 - f_{p(X)}^2)$

2) Due to an exciting moment M_Y:

$$A_{X(m)} = \frac{CrA \bar{Z}_M M_Y}{\Delta M}$$

$$A_{\phi Y(m)} = \frac{(CrA - m f_{m(Y)}^2) M_Y}{\Delta M}$$

where

$\Delta M = m I_{YY} (f_{n1}^2 - f_{m(Y)}^2)(f_{n2}^2 - f_{m(Y)}^2)$

Determine $A_X = A_{X(p)} + A_{X(m)}$ and $A_{\phi Y} = A_{\phi Y(p)} + A_{\phi Y(m)}$

Determine maximum horizontal displacements at base of foundation block, A_b, and top of foundation block, A_t.

$$A_b = A_X + Z_M A_{\phi Y}$$
$$A_t = A_X + (h - \bar{Z}_M) A_{\phi Y}$$

Check that the recommendations of **3.4.3** to **3.4.6** are satisfied.

A.4.8.3 *The vertical mode*

A.4.8.3.1 *Natural frequency*

For translation along *ZZ*: $f_{n(Z)}^2 = \dfrac{CuA}{m}$

Determine frequency ratio $\dfrac{f_{p(Z)}}{f_{n(Z)}}$

Check that the recommendations of **3.4.2** are satisfied.

A.4.8.3.2 *Amplitudes*

Determine $A_Z = \dfrac{P_Z}{m({f_{n(Z)}}^2 - {f_{p(Z)}}^2)}$

Check that the recommendations of **3.4.3** to **3.4.6** are satisfied.

A.4.8.4 *The yawing mode*

A.4.8.4.1 *Natural frequency*

For rotation about ZZ: ${f_{n\phi(Z)}}^2 = \dfrac{Cs\, I_{Z(c)}}{I_{ZZ}}$

Determine frequency ratio $\dfrac{f_{m(Z)}}{f_{n\phi(Z)}}$

Check that the recommendations of **3.4.2** are satisfied.

A.4.8.4.2 *Amplitude*

Determine $A_{\phi Z} = \dfrac{M_Z}{I_{ZZ}({f_{n\phi(Z)}}^2 - {f_{m(Z)}}^2)}$

Determine maximum horizontal displacements at two ends of foundation block, A_L and A_R.

$A_L = \bar{Y}_M A_{\phi Z}$

$A_R = (b - \bar{Y}_M)\, A_{\phi Z}$

Check that the recommendations of **3.4.3** to **3.4.6** are satisfied.

Appendix B Design of a foundation block for machine with out of balance forces and moments

B.1 Introduction

This numerical example is inserted as an aid to the method of design, worked as Appendix A to the Code. An actual installation has been taken for the purpose of this example but attention is drawn to the fact that an individual example cannot cover every aspect of machinery foundations design. For details of foundation block considered see Figure 5.

For the sake of simplicity and clarity the inertia of the soil participation has been neglected but in certain circumstances it may be necessary for the designer to take this into account.

NOTE Certain figures have been modified in order to create significant vibrations.

B.2 Calculations

B.2.1 ***General*** (see **3.2.1**)

1) Engine is a turbo-charged two stroke cycle engine.

Bore = 0.36 m

Stroke = 0.47 m

Driven machine is an alternator.

2) Operating speed is 10 Hz (600 rev/min).

3) Five cylinder in-line unit.

4) Maximum rated output is 2 600 kW.

5) Not applicable.

6) Not applicable.

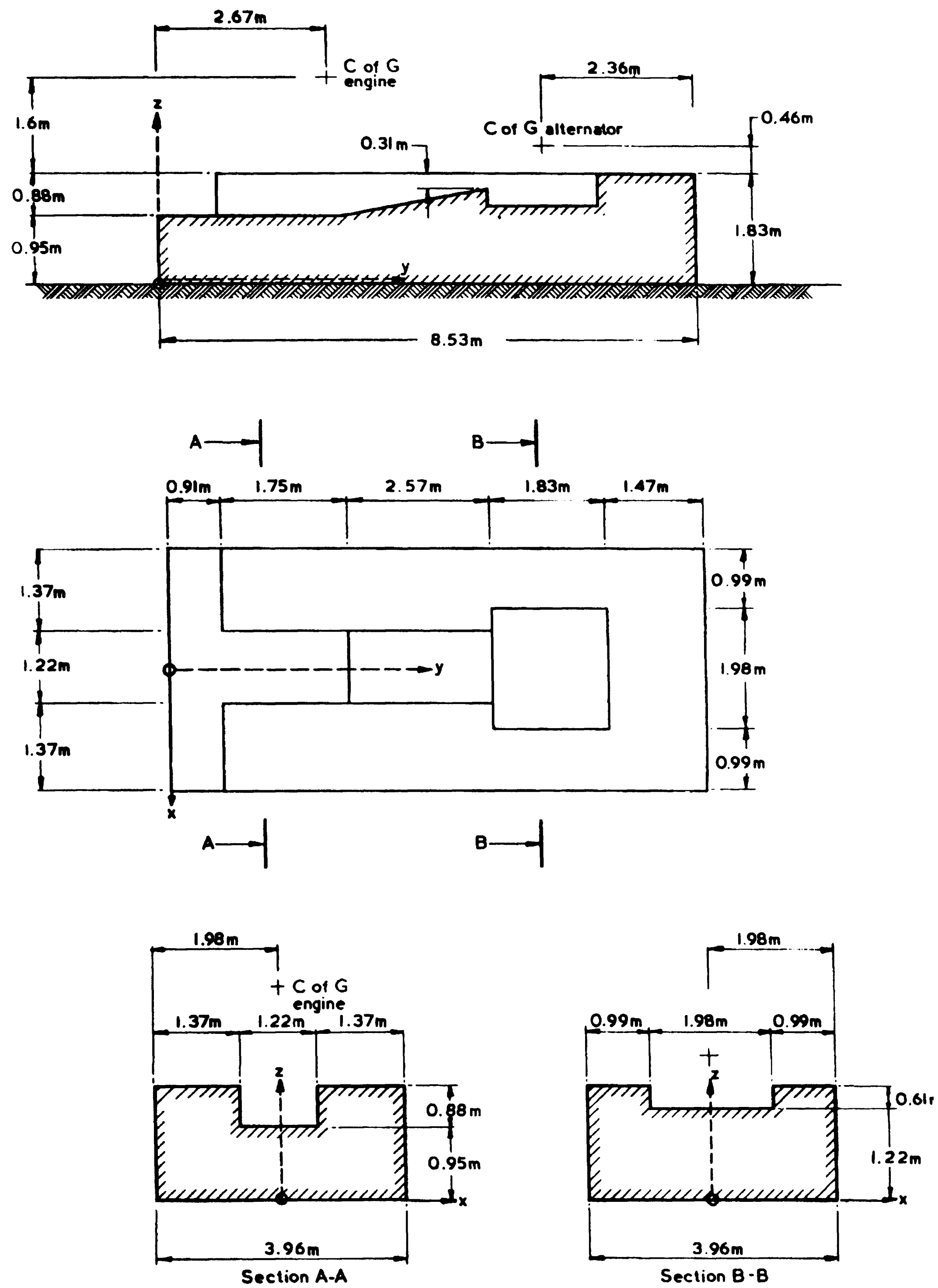


Figure 5 — Typical foundation block

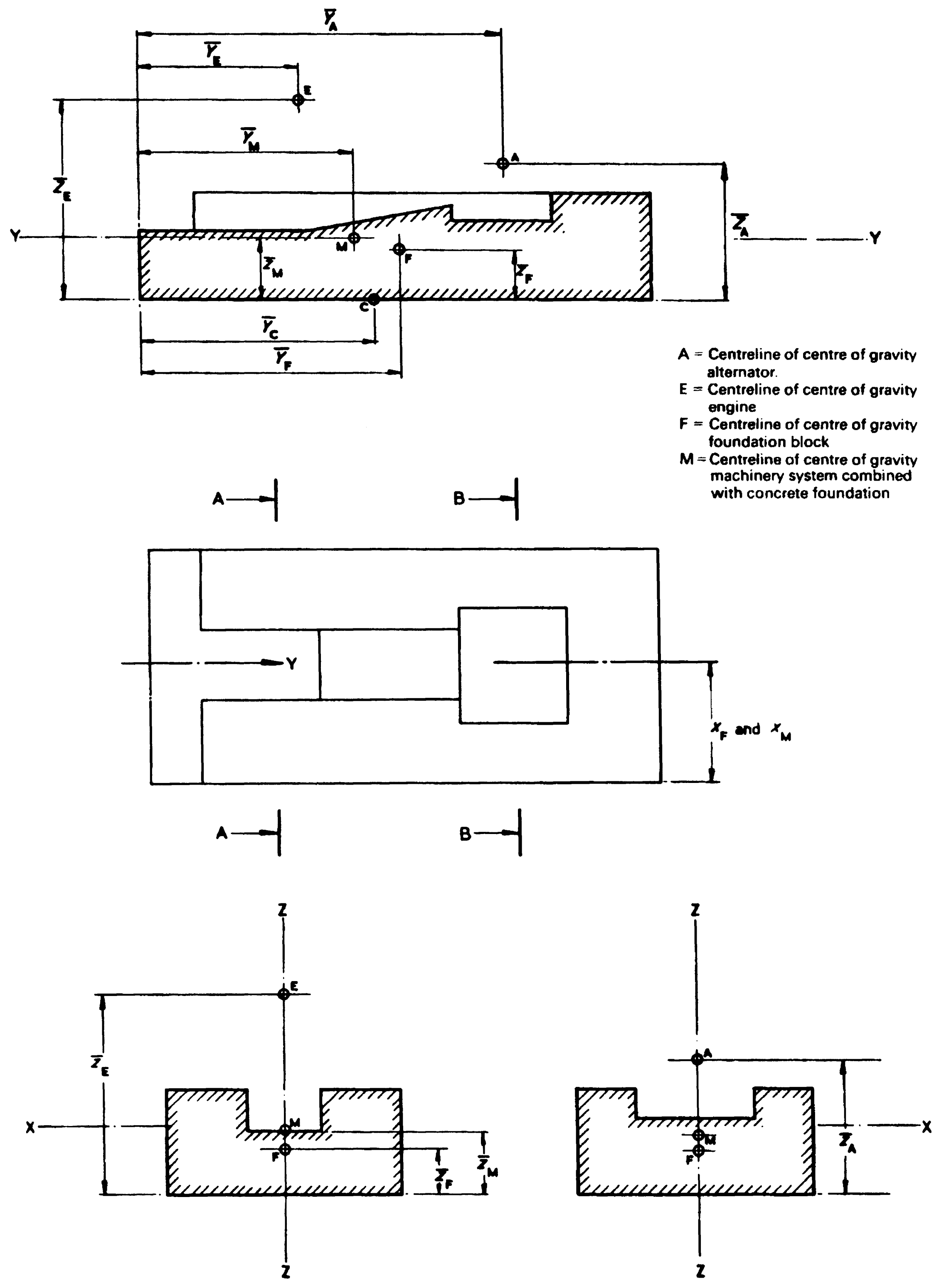


Figure 6 — Axes and co-ordinates of foundation block

B.2.2 ***Static design*** (see **3.2.2**)

1) Mass of engine = 28.4 t

Mass of alternator = 14.7 t

Mass of concrete block = 125 t

2) Positions of centres of gravity: see Figure 6.

3) Positions of mounting feet: not shown.

4) Dimensions of minimum block size: see Figure 5.

5) Details of discontinuities in block: see Figure 5.

B.2.3 ***Dynamic design*** (see **3.2.3**)

1) External forces: $P_X = P_Y = P_Z = 0$

External primary couples: $M_X = M_Z = 0$

External secondary couples: $M_Z = 7 \times 10^4$ N m

Frequency: 10 × 2 = 20 Hz

Harmonic torques: $M_Y = 1.6 \times 10^4$ N m at frequency 50 Hz

2) Moments of inertia of engine and driven machinery about the centre of gravity of the machinery system:

XX axis (pitching) = 250×10^3 kg m^2

ZZ axis (yawing) = 210×10^3 kg m^2

YY axis (rocking) = 62×10^3 kg m^2

3) Loads due to dynamic short circuit or faulty synchronizing conditions assumed to be 13 times full load torque.

4) Loads due to “out of step” running between machines assumed to be zero.

5) Loads due to hydraulic, thermal or surge effects from machinery assumed to be zero.

6) No anti-vibration mountings provided.

7) No further details provided.

B.2.4 ***Limitation of vibration amplitude*** (see **3.4.3** to **3.4.6**)

No amplitude limits specified.

B.2.5 ***Soil properties*** (see **3.3.2**)

1) From the work by Barkan[4] and assuming sand of medium density:

p.29, Tables 1 to 7:	Cu = 30×10^3 kN/m^3
p.33:	Cϕ = 52×10^3 kN/m^3
p.41:	Cr = 22×10^3 kN/m^3
	Cs = 28×10^3 kN/m^3
p.29:	Pb = 250 kN/m^2

2) $mg = (28.4 + 14.7 + 125) \times 9.807$ kN

mg = 1 650 kN

3) Applied pressure on soil = mg/A

= 1650/(8.53 × 3.96)

= 48.8 kN/m^2

Pb = 250 kN/m^2

mg/A < Pb

B.2.6 ***Centres of gravity and stability***

1) Centre of gravity of foundation block:

$\bar{Y}_F = 4.52$ m

$\bar{Z}_F = 0.82$ m

2) Centre of gravity of foundation and machinery system:

$\bar{Y}_M = 4.36$ m

$\bar{Z}_M = 1.39$ m

3) Ratio foundation mass/machine mass:

125/43.1 = 2.9

i.e. foundation mass is greater than machine mass and the rule given in **3.5.2** 1) is satisfied.

4) Centroid of foundation base area:

$Y_c = 4.26$ m

Eccentricity of centre of gravity of foundation and machinery system from the centroid of the foundation base area:

$$e_y = \frac{Y_M - Y_C}{b} = \frac{4.36 - 4.26}{8.53} \times 100 = 1.17\% < 5\%$$

i.e. the eccentricity does not exceed 5 % and the first rule given in **3.5.2** 2) is satisfied.

Height of top of foundation block is 1.83 m, which is greater than height of centre of gravity of foundation and machine, $\bar{Z}_M$, and the second rule given in **3.5.2** 2) is satisfied.

5) Height of crankshaft above top of foundation = 1 m.

Distance from bottom of foundation to centre of crankshaft = 1.83 + 1 = 2.83 m.

$$\frac{\text{Width of block}}{2.83} = \frac{3.96}{2.83} = 1.4$$

Therefore the rule given in **3.5.2** 3) is satisfied.

6) Stability against overturning:

Overturning torque = 13 × full load torque

Where full load torque is derived from the output at the alternator terminals,

i.e. 2600 kW = 2.6×10^6 J/s

$$\text{Torque} = \frac{\text{J/sec} \times 60}{2\pi \times \text{rev/min.}} = \frac{2.6 \times 10^6 \times 60}{6.28 \times 600} = 41.4\,\text{kNm}$$

Overturning torque = 13 × 41.4

= 538 kN m

For overturning about a bottom edge, stabilizing torque is provided by foundation and machine masses.

Stabilizing torque = mg × foundation width/2

$$= 1650 \times \frac{3.96}{2} = 3270 \text{ kN m}$$

Factor of safety against overturning = 6.08

Therefore the rule given in **3.5.2** 4) is satisfied.

B.2.7 ***Moments of inertia and area*** (see *Appendix C* for formula)

Moments of inertia of foundation and machine about:

1) axis XX, $I_{XX} = 11.08 \times 10^5$ kg m^2

2) axis YY, $I_{YY} = 3.20 \times 10^5$ kg m^2

3) axis ZZ, $I_{ZZ} = 11.8 \times 10^5$ kg m^2

Moments of inertia of foundation and machine about:

4) axis $x_c x_c$, $I_{x(c)x(c)} = 14.34 \times 10^5$ kg m^2

5) axis $y_c y_c$, $I_{y(c)y(c)} = 6.46 \times 10^5$ kg m^2

6) Ratio $r_1 = 0.772$

7) Ratio $r_2 = 0.495$

Second moment of area of foundation bearing surface with respect to:

8) axis $x_c x_c$, $I_{x(c)} = 205$ m^4

9) axis $y_c y_c$, $I_{y(c)} = 44$ m^4

10) axis $z_c z_c$, $I_{z(c)} = 249$ m^4

B.2.8 ***Natural frequencies and amplitudes of vibration***

B.2.8.1 *The pitching and longitudinal mode*

$P_Y = M_X = 0$ therefore no vibration occurs in this mode.

B.2.8.2 *The rocking and lateral mode*

B.2.8.2.1 *Natural frequencies*

For rotation about YY:

$$\begin{aligned} f_{n\phi(Y)}{}^2 &= C\phi \times I_{y(c)}/I_{y(c)y(c)} \\ &= 52 \times 10^6 \times 44.1/(6.46 \times 10^5) \\ &= 3.55 \times 10^3 \text{ (rad/s)}^2 \end{aligned}$$

For translation along XX:

$$\begin{aligned} f_{n(X)}{}^2 &= \mathrm{Cr} \times A/m \\ &= 22 \times 10^3 \times 8.53 \times 3.96/168.1 \\ &= 4.42 \times 10^3 \text{ (rad/s)}^2 \end{aligned}$$

Principal natural frequencies f_{n1} and f_{n2}:

$$f_n{}^4 - f_n{}^2\,(3.55 + 4.42)\,10^3/0.495 + 4.42 \times 3.55 \times 10^6/0.495 = 0$$

Therefore $f_{n1} = 117.5$ rad/s

Therefore $f_{n2} = 48.1$ rad/s

Frequency ratios:

$$\begin{aligned} f_{m(Y)}/\mathrm{f}_{n1} &= 50 \times 2\pi/117.5 \\ &= 2.65 \end{aligned}$$

$$\begin{aligned} f_{m(Y)}/f_{n2} &= 50 \times 2\pi/48.1 \\ &= 6.55 \end{aligned}$$

As these ratios are less than 0.5 or greater than 2.0, then the recommendation of **3.4.2** is satisfied.

B.2.8.2.2 *Amplitudes*

Amplitudes due to exciting moment M_Y:

For rotation about YY:

$$\begin{aligned} A_{\phi Y(m)} &= (\mathrm{Cr}\,A - m f_{m(Y)}{}^2)\, M_Y/\Delta M \\ &= 5.77 \times 10^{-7} \text{ rad} \end{aligned}$$

For translation along XX:

$$\begin{aligned} A_{X(m)} &= \mathrm{Cr} A Z_M M_Y/\Delta M \\ &= 3.74 \times 10^{-8} \text{ m} \end{aligned}$$

Amplitudes due to exciting force P_X:

$P_X = 0$

Therefore $A_{\phi Y(p)} = A_{X(p)} = 0$

Therefore $A_X = 3.74 \times 10^{-8}$ m = 0.0374 µm

$A_{\phi Y} = 5.77 \times 10^{-7}$ rad

Maximum horizontal displacements:

$$A_b = A_X + Z_M \times A_{\phi Y}$$
$$= 3.74 \times 10^{-8} + 1.39 \times 5.77 \times 10^{-7}$$
$$= 83.9 \times 10^{-8} \text{ m} = 0.839 \ \mu\text{m}$$

$$A_t = A_X + (-\overline{Z}_M)\ A_{\phi Y}$$
$$= 3.74 \times 10^{-8} + (1.83 - 1.39) \times 5.77 \times 10^{-7}$$
$$= 29.12 \times 10^{-8} \text{ m} = 0.291 \ \mu\text{m}$$

As these amplitudes do not exceed 200 µm, then the recommendations of **3.4.3** to **3.4.6** are satisfied.

B.2.8.3 *The vertical mode*

$P_Z = 0$ therefore no vibration occurs in this mode.

B.2.8.4 *The yawing mode*

B.2.8.4.1 *Natural frequency*

For rotation about ZZ:

$$f_{n\phi(Z)}^{\ 2} = \text{Cs}I_{z(c)}/I_{ZZ}$$
$$= 28 \times 10^6 \times 249 \times 1/(11.8 \times 10^5)$$
$$= 76.81 \text{ rad/s}$$

Frequency ratio:

$$f_{m(Z)}/f_{n\phi(Z)} = 20 \times 2\pi/76.81$$
$$= 1.64$$

This should be greater than 2.0, or greater than 1.5 for installations of lesser importance. Hence the recommendation of **3.4.2** is satisfied for installations of lesser importance only.

B.2.8.4.2 *Amplitude*

For rotation about ZZ:

$$A_{\phi Z} = M_Z/I_{ZZ}\ (f_{n\phi(Z)}^{\ 2} - f_{m(Z)}^{\ 2})$$
$$= 7 \times 10^4/11.8 \times 10^5\ (76.8^2 - 104.5^2)$$
$$= 1.18 \times 10^{-5} \text{ rad}$$

Maximum horizontal displacements:

$$A_L = Y_M \times A_{\phi Z}$$
$$= 4.36 \times 1.18 \times 10^{-5} \text{ m}$$
$$= 5.14 \times 10^{-5} \text{ m}$$
$$= 51.4 \ \mu\text{m}$$

$$A_R = (b - Y_M)\ A_{\phi Z}$$
$$= (8.53 - 4.36) \times 1.18 \times 10^{-5} \text{ m}$$
$$= 4.92 \times 10^{-5} \text{ m}$$
$$= 49.2 \ \mu\text{m}$$

As these amplitudes do not exceed 200 µm, then the recommendations of **3.4.2** to **3.4.6** are satisfied.

Appendix C Moments of inertia and area, of foundation block

Moments of inertia of engine, alternator and foundation:

1) $I_{XX} = (I_{XX(e)} + m_e R_{XX(e)}^2) + (I_{XX(a)} + m_{(a)} R_{XX(a)}^2) + (I_{XX(f)} + m_f R_{XX(f)}^2)$

2) $I_{YY} = (I_{YY(e)} + m_e R_{YY(e)}^2) + (I_{YY(a)} + m_a R_{YY(a)}^2) + (I_{YY(f)} + m_f R_{YY(f)}^2)$

3) $I_{ZZ} = (I_{ZZ(e)} + m_e R_{ZZ(e)}^2) + (I_{ZZ(a)} + m_a R_{ZZ(a)}^2) + (I_{ZZ(f)} + m_f R_{ZZ(f)}^2)$

NOTE R is the direct distance between the component C of G to the combined C of G.
For example, $R_{XX(E)}$ = Distance between C of G of engine and C of G of the foundation and machinery system about axis XX. (Distance between point E and point M in Figure 6.)

Moments of inertia of engine, alternator and foundation about foundation base:

4) about axis $x_c x_c$, $I_{x(c)x(c)} = I_{XX} + m\bar{Z}_M^2$

5) about axis $y_c y_c$, $I_{y(c)y(c)} = I_{YY} + m\bar{Z}_M^2$

6) r_1 = ratio $\dfrac{I_{XX}}{I_{x(c)x(c)}}$

7) r_2 = ratio $\dfrac{I_{YY}}{I_{y(c)y(c)}}$

Second moments of area of foundation bearing surface with respect to:

8) axis $x_c x_c$, $I_{x(c)} = \dfrac{ab^3}{12}$

9) axis $y_c y_c$, $I_{y(c)} = \dfrac{a^3 b}{12}$

10) axis ZZ, $I_{z(c)} = I_{x(c)} + I_{y(c)}$

Appendix D Bibliography

[1]ALPAN, I. Foundation soil and machine foundations. Israel Institute of Technology, Haifa.

[2]GROOTENHUIS, P. and AWOJOBI, A. O. The in-situ measurement of the dynamic properties of soil. *In*: Vibration in civil engineering. (ed. B.O. Skipp). London: Butterworths, 1966.

Describes field tests with vibrator and analysis based upon recent theoretical studies.

[3]RICHART, F. E. Jr. Foundation vibrations (Transactions Paper 3351). *Transactions of the American Society of Civil Engineers*. 1962: **127**(1), 863–898.

Design method outlined based upon elastic half space theory. Extensive bibliography and worked examples. Theory based on analyses by E. Reissner and T. Y. Sung.

[4]BARKAN D. D. Dynamics of bases and foundations. New York: McGraw-Hill, 1962. (Translated from Russian).

Extensive compilation of full scale experience. Criteria and design methods based upon simplification of elastic half space theory. Primary source, in conjunction with USSR design codes for other codes.

The following references are not referred to in the text but reference was made to them during preparation of this Part of this Code.

CONVERSE, F. J. Foundations subject to dynamic forces. *In*: Foundation engineering. (ed. G. A. Leonards) New York: McGraw-Hill, 1962.

Gives examples based upon semi-empirical analyses with concept of participating mass and modulus varying linearly with depth bases upon intuitive assumptions due to Pauw.

DUKE, C. M. Techniques for field measurement of shear wave velocity in soils. *Proceedings IV world conference on earthquake engineering*, Santiago de Chile. Vol. **III** p. A5 39–55.

EASTWOOD, W. Vibrations in foundations. *Struct. Eng*. 1953: **31**, 82–98.

Information on model pile behaviour.

FORSSBLAD, L. Investigations of soil compaction by vibration. Acta Polytechnica Scandinavia Civil and Building Construction Series No. 134. Stockholm : Royal Swedish Academy of Engineering Sciences, 1965.

Research on effect of vibration on internal friction are described. Laboratory and field tests discussed. Observations on nearby buildings were made and limits were suggested.

HSIEH, T. K. Foundation vibrations. *Proc. Inst. Civ. Eng*., **22**, 211–226.

Basic paper with mathematics used by Whitman in simplified method.

IRISH, K. and WALKER, W. P. Foundations for reciprocating machines. London: Concrete Publications, 1969.

Practical solutions to the design of raft, pile and massive foundations for reciprocating machinery.

JONES, R., LISTER, M. W. and THROWER, E. M. The dynamic behaviour of soils and foundations. *In*: Vibration in civil engineering. London: Butterworths, 1966.

Review paper with many references.

KER-WILSON, W. Vibration engineering. London: Charles Griffin, 1959.

Basically a mechanical engineering text with suggested criteria.

MAJOR, A. Vibration analysis and design of foundations for machinery and turbines. London: Colletts, 1962.

Basic text book deriving from Barkan's work but with many examples. A number of national codes are also listed which may be useful to the reader.

MOORE, P. J. A review of design method for machinery foundation. *Journal of the Institute of Engineers*. Australia, April-May, 1967.

NEWCOMB, W. G. Principles of foundation design for engines and compressors. Transactions of the American Society of Mechanical Engineers. Vol 7.

Empirical design procedures described and criteria given.

PAUW, A. A dynamic analogy for foundation soil systems. A.S.T.M. Special Tech. Pub. No. 156, 1952, p. 90–112.

See reference to work by Converse, 1962.

RAUSCH, E. Machine foundations and other dynamical problems in civil engineering. Dusseldorf: V.D.I. Verlog, 1959.

Basic text with engineering examples.

STEFFENS, R. J. Some aspects of structural vibrations. *In*: Vibration in civil engineering. London: Butterworths, 1966.

Review covering criteria affecting persons and structures. Extensive bibliography.

SUNG, T. Y. Vibrations in semi-infinite solids due to periodic surface loadings. A.S.T.M. Special Tech. Pub. No. 156, 1953, p. 35 68.

Basic mathematical text for response with assumed pressure distributions.

TSCHEBOTARIOFF, G. P. Performance records of engine foundations. Symposium on dynamic testing of soils. A.S.T.M. Special Tech. Pub. No. 156, 1954, p. 163 173.

Records and criteria given.

WHITMAN, Robert V. Analysis of foundation vibrations. *In*: Vibration in civil engineering. London: Butterworths, 1966. Describes large scale field tests and suggests design method based upon elastic half space theory but in terms of simple spring constants and effective participating soil mass.

IS. 2974. Indian Standard Code of Practice for design and construction of machine foundations. Part 1: Foundations for reciprocating type machines.

blank

Publications referred to

This Code of Practice makes reference to the following British Standard and Codes of Practice:

BS 1377, *Methods of testing soils for civil engineering purposes*.

CP 110, *The structural use of concrete*.

CP 110-1, *Design, materials and workmanship*.

CP 114, *Structural use of reinforced concrete in buildings*.

CP 115, *Structural use of prestressed concrete in buildings*.

CP 116, *Structural use of precast concrete*.

CP 2001, *Site investigations*.

CP 2004, *Foundations*.

BSI — British Standards Institution

BSI is the independent national body responsible for preparing British Standards. It presents the UK view on standards in Europe and at the international level. It is incorporated by Royal Charter.

Revisions

British Standards are updated by amendment or revision. Users of British Standards should make sure that they possess the latest amendments or editions.

It is the constant aim of BSI to improve the quality of our products and services. We would be grateful if anyone finding an inaccuracy or ambiguity while using this British Standard would inform the Secretary of the technical committee responsible, the identity of which can be found on the inside front cover. Tel: 020 8996 9000. Fax: 020 8996 7400.

BSI offers members an individual updating service called PLUS which ensures that subscribers automatically receive the latest editions of standards.

Buying standards

Orders for all BSI, international and foreign standards publications should be addressed to Customer Services. Tel: 020 8996 9001. Fax: 020 8996 7001.

In response to orders for international standards, it is BSI policy to supply the BSI implementation of those that have been published as British Standards, unless otherwise requested.

Information on standards

BSI provides a wide range of information on national, European and international standards through its Library and its Technical Help to Exporters Service. Various BSI electronic information services are also available which give details on all its products and services. Contact the Information Centre. Tel: 020 8996 7111. Fax: 020 8996 7048.

Subscribing members of BSI are kept up to date with standards developments and receive substantial discounts on the purchase price of standards. For details of these and other benefits contact Membership Administration. Tel: 020 8996 7002. Fax: 020 8996 7001.

Copyright

BSI
389 Chiswick High Road
London
W4 4AL