भारतीय मानक ब्यूरो
BUREAU OF INDIAN STANDARDS

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व्यापक परिचालन मसौदे

हमारा संदर्भ : सीईडी 43 /टी–61, टी-62 & टी-63 **17 अगस्त 2020**

तकनीकी समिति : मृदा एवं नींव इंजीनियरी विषय समिति, सीईडी 43

प्राप्तकर्ता :

1 सिविल इंजीनियरी विभाग परिषद् के रूचि रखने वाले सदस्य

2 मृदा एवं नींव इंजीनियरी विषय समिति, सीईडी 43 एवं आईएस 2974 (भाग 1 से 5) के पुनरीक्षण के लिए मसौदे तैयार करने के लिए तदर्थ पैनल, सीईडी 43:P8 के सभी सदस्य

3 रूचि रखने वाले अन्य निकाय

महोदय/महोदया,

निम्नलिखित मसौदे संलग्न है :

प्रलेख संख्या	शीर्षक
सीईडी 43 (12408)WC	**मशीनों की नींव का डिज़ाइन एवं निर्माण - रीति संहिता: भाग 1 सामान्य प्रावधान का भारतीय मानक मसौदा [IS 2974 (भाग 1 से 5) का पुनरीक्षण]** **(आई सी एस संख्या: 93.020)**
सीईडी 43 (13116)WC	**मशीनों की नींव का डिज़ाइन एवं निर्माण - रीति संहिता: भाग 2 ब्लॉक नींव का भारतीय मानक मसौदा [IS 2974 (भाग 1 से 5) का पुनरीक्षण]** **(आई सी एस संख्या: 93.020)**
सीईडी 43 (13264)WC	**मशीनों की नींव का डिज़ाइन एवं निर्माण - रीति संहिता: भाग 3 फ्रेम नींव का भारतीय मानक मसौदा [IS 2974 (भाग 1 से 5) का पुनरीक्षण]** **(आई सी एस संख्या: 93.020)**

कृपया इन मानक के मसौदों का अवलोकन करें और अपनी सम्मतियाँ यह बताते हुए भेजें कि यदि ये मानक के रूप में प्रकाशित हो तो इन पर अमल करने में आपके व्यवसाय अथवा कारोबार में क्या कठिनाइयाँ आ सकती हैं ।

सम्मतियाँ भेजने की अंतिम तिथि: **15 अक्टूबर 2020**.

सम्मति यदि कोई हो तो कृपया **ईमेल आईडी, madhurima@bis.gov.in** पर संलग्न फोर्मेट में भेजें।

यदि कोई सम्मति प्राप्त नहीं होती है अथवा सम्मति में केवल भाषा संबंधी त्रुटि हुई तो उपरोक्त प्रलेखों को यथावत अंतिम रूप दिया जाएगा । यदि सम्मति तकनीकी प्रकृति की हुई तो विषय समिति के अध्यक्ष के परामर्श से अथवा उनकी इच्छा पर आगे की कार्यवाही के लिए विषय समिति को भेजे जाने के बाद प्रलेखों को अंतिम रूप दे दिया जाएगा ।

ये प्रलेख भारतीय मानक ब्यूरो की वैबसाइट **www.bis.gov.in** पर भी उपलब्ध है

धन्यवाद ।

भवदीय,

(संजय पंत)
प्रमुख (सिविल इंजीनियरी)

संलग्न : उपरिलखित

भारतीय मानक ब्यूरो
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DRAFTS IN WIDE CIRCULATION

DOCUMENT DESPATCH ADVICE

Reference	Date
CED 43/T- 61, T- 62 &T- 63	17 August 2020

TECHNICAL COMMITTEE:

Soil and Foundation Engineering Sectional Committee, CED 43

ADDRESSED TO:

1. All Members of Civil Engineering Division Council, CEDC
2. All Members of Soil and Foundation Engineering Sectional Committee, CED 43 and the Adhoc Panel for Preparation of Drafts for Revision of IS 2974 (Parts 1 to 5), CED 43:P8
3. All other interests

Dear Sir/Madam,

Please find enclosed the following drafts:

Doc No.	Title
CED 43 (12408)WC	**Draft Indian Standard Design and Construction of Machine Foundations — Code of Practice: Part 1 General Provisions [Revision of IS 2974 (Parts 1 to 5)]** **(ICS No. 93.020)**
CED 43 (13116)WC	**Draft Indian Standard Design and Construction of Machine Foundations — Code of Practice: Part 2 Block Foundations [Revision of IS 2974 (Parts 1 to 5)]** **(ICS No. 93.020)**
CED 43 (13264)WC	**Draft Indian Standard Design and Construction of Machine Foundations — Code of Practice: Part 3 Frame Foundations [Revision of IS 2974 (Parts 1 to 5)]** **(ICS No. 93.020)**

Kindly examine the draft standards and forward your views stating any difficulties which you are likely to experience in your business or profession, if these are finally adopted as National Standards.

Last Date for comments: 15 October 2020.

Comments if any, may please be made in the format as given overleaf and mailed to the email id, **madhurima@bis.gov.in**.

In case no comments are received or comments received are of editorial nature, you will kindly permit us to presume your approval for the above document as finalized. However, in case comments of technical nature are received, then it may be finalized either in consultation with the Chairman, Sectional Committee or referred to the Sectional Committee for further necessary action if so desired by the Chairman, Sectional Committee.

The documents are also hosted on BIS website, **www.bis.gov.in**.

Thanking you,

Yours faithfully,

(Sanjay Pant)
Head (Civil Engg.)

Encl: as above

FORMAT FOR SENDING COMMENTS ON BIS DOCUMENTS

(Please use A4 size sheet of paper only and type within fields indicated. Comments on each clause/subclause/table/fig etc. be started on a fresh box. Information in column 5 should include reasons for the comments, and those in column 4 should include suggestions for modified wording of the clauses when the existing text is found not acceptable. Adherence to this format facilitates Secretariat's work) {Please e-mail your comments to **madhurima@bis.gov.in** }

DOC. NO.	**Doc: CED 43 (13116)**
TITLE	**Draft Indian Standard Design and Construction of Machine Foundatio — Code of Practice: Part 2 Block Foundations [Revision of IS 2974 (Parts 1 to 5)] (ICS No. 93.020)**
LAST DATE OF COMMENTS	**15 October 2020**
NAME OF THE COMMENTATOR/ ORGANIZATION	___________________________

Sl. No. (1)	**Clause/Sub-clause/Para No. (2)**	**Comments/Suggestions (3)**	**Modified Wording of the Clause (4)**	**Reasons/ Justifications for the Proposed Changes (5)**

Doc: CED 43 (13116)
August 2020

BUREAU OF INDIAN STANDARDS

DRAFT FOR COMMENTS ONLY

DESIGN AND CONSTRUCTION OF MACHINE FOUNDATIONS — CODE OF PRACTICE

PART 2 BLOCK FOUNDATIONS

[*Revision of* IS 2974 (Parts 1 to 5)]
ICS 93.020

Soil and Foundation Engineering Sectional Committee, CED 43	Last date for Comment: **15 October 2020**

FOREWORD

(*Formal clauses to be added later*)

Installation of heavy machinery has assumed increased importance in the wake of the vast programme of industrial development in the country. The overall foundation design of such machines shall have to be in accordance with the dynamic requirements of machine, and foundation and soil, besides special requirements of the machine as laid down by machine manufacturer. It was well realized that the dynamic soil parameters underneath the foundations play a significant role in achieving the said objective. It is to serve this purpose that, IS 2974 'Code of practice for design and construction of machine foundations' was published in five parts covering foundations for host of machines, thereby meeting development needs of the country. The various parts of the Code were published and revised as per the details given below:

	Various Parts	*First published in*	*Subsequently revised in*
Part 1	Foundations for reciprocating type machines	1964	1969 and then in 1982
Part 2	Foundations for impact type machines	1966	1980
Part 3	Foundations for rotary type machines (Medium and high frequency)	1967	1975 and then in 1992
Part 4	Foundations for rotary type machines of low frequency	1968	1979
Part 5	Foundations for impact machines other than hammer (Forging and stamping press), pig-breaker, drop crusher and jolter	1970	1970 and then in 1987

Over the years, improvement in manufacturing technology has provided machines of higher ratings with better tolerances and controlled behaviour. The increased dependence of society provides no room for failure and demands equipment and systems with higher performance reliability. To ensure satisfactory performance of machines and to minimize machine downtime on account of malfunction/unsatisfactory performance, foundations for these machines have to be specially designed taking into consideration the impact of vibration on the foundations as well as on the adjoining structures. Thus, for satisfactory performance, every machine, be it small or large, does require detailed vibration analysis providing insight into the dynamic behaviour of machine-foundation system including their associated components.

Further, failure data collected over the years from field tests on wide variety of machines and their foundations provides clear indicator that the existing design philosophy needs a re-look and suggests host of changes to be incorporated in the codes covering various design and construction aspects of the foundations. In view of the above as well as the recent developments reported globally on this subject, it has been felt that the provisions regarding the design and construction of machine foundations should be further revised.

To cater to these objectives, it was decided to revise and restructure various Parts of IS 2974 to meet the current demand of satisfactory performance of machines with no room for failure. While restructuring these, it was decided to address the code foundation-wise rather than machine-wise except foundations for impact and impulsive load machines, that is, hammers and presses, where it necessarily has to be machine-wise. This would also avoid any overlapping of the provisions between different Parts of the codes for similar foundation types and bring clarity in design and construction of the foundation. Accordingly, the revised standard is being brought out in following eight parts, first five being brought out in the first phase and remaining three parts in subsequent phase:

Part 1 General provisions
Part 2 Block foundations
Part 3 Frame foundations
Part 4 Foundations for hammers and presses
Part 5 Foundation for machines (excluding hammers and presses) supported on vibration isolation system
Part 6 Machines supported on super structures
Part 7 Machines supported on strip footings
Part 8 Machines supported on common mat/raft.

This standard (Part 2) deals with specific provisions relating to design and construction of reinforced cement concrete (RCC) rigid block foundations for the installation of rotary and reciprocating machine (motors, pumps, compressors, fans and blowers, crushing mills, motor generators, rolling mill stands, etc.). For the general provisions, Part 1 of the standard shall be referred.

Further, in the design and construction of foundations for all the machines, a proper coordination between the different branches of engineering, including those dealing with erection and commissioning is essential. Coordinated efforts by the different branches would result in satisfactory performance, convenience of operation, economy and a good general appearance of the complete unit.

The main unit with all its auxiliaries and adjacent piping must be provided for, when making the foundation plans and all the details should be well worked out, before going ahead with the design.

In the preparation of this standard, due weightage has been given to international coordination among the standards and practices prevailing in different countries in addition to relating it to the practices in the field of this country.

For deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis shall be rounded off in accordance with IS 2:1960 ‘Rules for rounding off numerical values (*revised*)’. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

BUREAU OF INDIAN STANDARDS

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DESIGN AND CONSTRUCTION OF MACHINE FOUNDATIONS — CODE OF PRACTICE

PART 2 BLOCK FOUNDATIONS
[*Revision of* IS 2974 (Parts 1 to 5)]
ICS 93.020

Soil and Foundation Engineering Sectional Committee, CED 43	Last date for Comment: **15 October 2020**

1 SCOPE

1.1 This standard deals with design and construction of rigid block foundations in reinforced concrete for supporting the following types of machines:

a) Rotating machines, such as motors, pumps, fans and blowers.
b) Reciprocating machines, such as compressors and pump-displacement type, steam engines, diesel engines.
c) Miscellaneous machines, such as rolling mills, crushing mills like gyratory crusher, jaw crusher, roll crusher (single roll and double roll), hammer crusher, ball mills and tube mills.

NOTE — For detailed description of each type of machines covered in this Part of the standard, IS 2974 (Part 1) may be referred to.

1.2 Combined block foundations are not covered in the standard [*see* **4(b)**].

1.3 This standard shall be considered applicable to all industries as listed in IS 2974 (Part 1).

1.4 IS 2974 (Part 1) is a necessary adjunct to this standard.

2 REFERENCES

The Indian Standards given below contain provisions which through reference in this text, constitute provision of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the standards.

IS No.	*Title*
IS 456:2000	plain and reinforced concrete — Code of practice (*fourth revision*)
IS 875	Code of practice for design loads (other than earthquake) for

	buildings and structures
(Part 1):1987	Part 1 Dead loads − Unit weights of building material and stored materials (*second revision*) (Incorporating IS:1911-1967)
(Part 2):1987	Part 2 Imposed loads (*second revision*)
(Part 3): 2015	Part 3 Wind loads (*third revision*)
(Part 4):1987	Part 4 Snow loads (*second revision*)
(Part 5):1987	Part 5 Special loads and load combinations (*second revision*)
IS 1893(Part 4):2015	Criteria for earthquake resistant design of structures: Part 4 Industrial structures including stack-like structures (*first revision*)
(Part 1):2016	Part 1 General provisions and buildings (*sixth revision*)
IS 2911 (Parts 1 to 4):2010	Design and construction of pile foundations — Code of practice
IS 2974 (Part 1): ****	Design and construction of machine foundations — Code of practice: Part 1 General provisions (*under preparation*)
IS 2974 (Part 7):****	Design and construction of machine foundations — Code of practice: Part 7 Machines supported on strip footings (*under preparation*)
IS 6403:1981	Code of practice for determination of bearing capacity of shallow foundations (*first revision*)

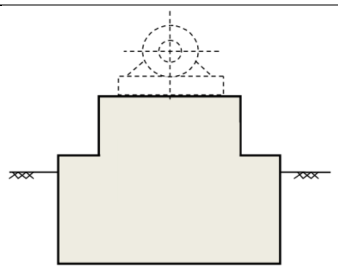
3 TERMINOLOGY

For the purpose of this standard, the terminologies given in IS 2974 (Part 1) shall apply.

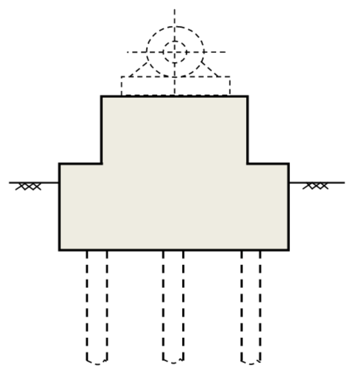
4 TYPES OF BLOCK FOUNDATIONS

Block foundations are commonly provided for supporting reciprocating machines, rotary machines, pumps, blowers, fans, etc., located close to grade. Based on the geometry, the block foundations can be classified as,

a) *Solid block foundation* — The Solid block foundations generally consist of reinforced concrete blocks, and are generally designed as rigid block. The solid block foundation, depending upon the geotechnical conditions, may be founded directly on soil [*see* Fig. 1(a)] or on pile group [*see* Fig. 1(b)].



1A Block foundation supported on soil



1B Block foundation supported on pile group

Fig. 1 Types of Solid Block Foundation

b) *Combined block foundation* — Combined blocks (*see* Fig. 2) are used to support closely spaced machines, and are supported on a single mat foundation. Such foundations are not covered by this standard.

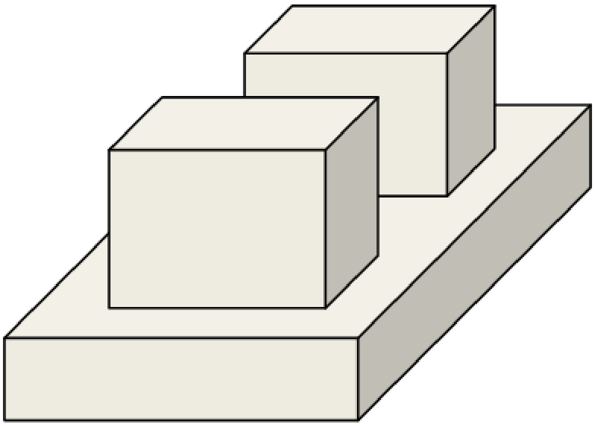


Fig. 2 Combined Block Foundation

c) *Hollow block foundation* (*cellular foundation*) — Hollow block foundations (*see* Fig. 3) may be used in special cases where it becomes necessary to reduce the mass of the block for obtaining satisfactory dynamic response.

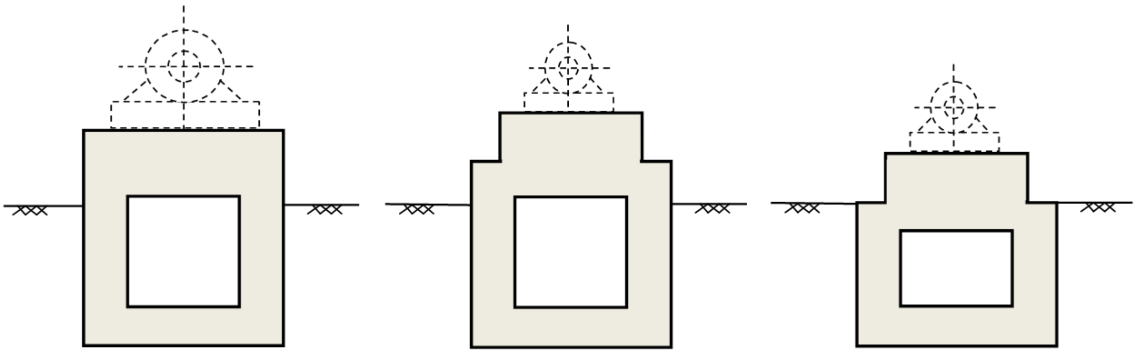


Fig. 3: Hollow Block Foundations

5 SYSTEM DATA

5.1 Machine Data

5.1.1 The necessary machine data required for the design of block foundation for supporting different types of machines as given in **7** of IS 2974 (Part 1) shall be obtained from the machine manufacturer.

5.1.2 Details of piping connected to machine up to their first support point/first bellow point shall be provided for considering mass effect.

5.2 Foundation Data

5.2.1 Machine layout showing footprint dimensions, levels, machine centerlines, details of openings, trenches, notches, pedestals, inserts/embedments, extent of machine sole plate/grout area, etc., shall be provided by machine manufacturer/supplier.

5.2.2 Layout of ducting, cabling, etc, within foundation area as well as their supporting details shall also be provided by machine manufacturer/supplier.

5.2.3 *Foundation Material*

Block foundation is made of reinforced cement concrete (RCC). The minimum grade, material properties and permissible stresses of the concrete and reinforcement for the design of block foundation shall be as per **8** of IS 2974 (Part 1).

5.3 Geotechnical Data

The block foundations are generally provided with one of the following types of base support conditions:

a) Directly on soil; or
b) Piles.

5.3.1 *Permissible Soil Bearing Pressure/Safe Pile Capacity*

For block foundation directly supported over soil, the net allowable bearing pressure under static loading shall be determined in accordance with IS 6403. In case of block foundation supported on pile, safe load capacity of piles shall be determined as per IS 2911.

5.3.2 *Dynamic Soil/Pile Parameters*

The dynamic soil/pile parameters required for design of block foundation shall be evaluated as per IS 2974 (Part 1).

6 DESIGN CRITERIA

6.1 Steps for Design

Design of block foundations for machines generally involves the following steps:

a) Obtain the system data (machine data, foundation data, geotechnical data) required for design of the foundation as per **5**;
b) Foundation sizing;
c) Static analysis for checking the soil bearing pressure/pile load;
d) Free vibration analysis for evaluating natural frequencies;
e) Forced vibration analysis to evaluate the amplitudes of vibration;
f) Static analysis for strength design; and
g) Details of miscellaneous features such as bolting, grouting, etc.

6.2 Foundation Rigidity

6.2.1 A solid block foundation shall be considered as rigid, provided the thickness *T* of the foundation block is greater than 0.4, *L*, where *L* is the greater plan dimension of the foundation.

6.2.2 A hollow block foundation shall be considered as rigid, if the first natural frequency of each panel of the hollow block is more than 1.3 times the highest operating speed of the machine. The minimum thickness of each panel shall be 300 mm. These hollow blocks shall not be filled with any material. Further, air vents shall be provided in the portion above ground level to relieve the entrapped air. Due care shall be taken to avoid water entry in to the hollow part through these air vents.

6.2.3 If the conditions as given in **6.2.1** and **6.2.2** are not met, then the type of foundation under consideration (solid or hollow) becomes flexible foundation, and IS 2974 (Part 7) shall be referred for such foundations.

6.3 Permissible Bearing Pressure

The permissible bearing pressure on soil/load on the heaviest loaded pile shall be as specified in **9.5** of IS 2974 (Part 1).

6.4 Permissible Settlement

The total permissible settlement shall be as specified in **4.3.7** of IS 2974 (Part 1).

6.5 Permissible Amplitude of Vibration

Permissible amplitudes of vibration shall be as specified in **10.2** of IS 2974 (Part 1). In case machine manufacturer's recommended permissible amplitudes are more stringent than those given in Part 1, the same shall be complied with.

7 SIZING OF FOUNDATION BLOCK

7.1 Preliminary Sizing

For initial dimensioning of the foundation, the following empirical rules shall be followed:

a) Minimum dimensions of the block shall be such to accommodate the foot print of the machine. In addition, sufficient area for maintenance of the machine shall be provided.
b) The shape of the block below the ground level should preferably be rectangular/circular, as dictated by machine layout. However, in special cases, deviation may be taken.
c) For foundation directly supported over soil or supported over the piles, the weight of block foundation shall be about 3 times the supported machine weight for a rotating type machine, and 5 times for reciprocating type machine. However, detailed dynamic design will govern the final weight of the block.
d) The foundation eccentricity along lateral (*X* and *Z*) directions shall not exceed 5 percent of the foundation base area dimensions in respective direction.

e) While sizing the foundation, it should be ensured that the resultant of lateral and vertical loads fall within the middle third of the foundation base to avoid the uplift. It is required primarily for lateral forces like earthquake.
f) While sizing the foundation, care should be taken to see that the vertical natural frequency (first vertical mode of vibration) of the machine-foundation-soil system shall be at least 20 percent away from the machine operating speed range.

7.2 Requirement of Pile Foundations

Whether foundation is to be supported directly over soil or on piles is governed by geotechnical considerations. However, piles can also be provided to support the blocks, when the amplitudes of vibration of the block foundation under operation are in excess of their permissible values or the effect of ground borne vibration on surrounding foundations and equipment is to be minimized.

8 DYNAMIC ANALYSIS

Dynamic analysis of the machine-foundation-soil system shall be carried out to ensure that the dynamic response of the foundation under operating conditions are within the permissible limits (*see* **6.5**). These shall be assessed by performing the following analyses:

a) Free vibration analysis, and

b) Forced vibration analysis.

The dynamic analysis shall be carried out either by manual method or finite element method as given in **8.3** and **8.4** respectively.

8.1 Modeling for Dynamic Analysis

8.1.1 All those elements/components that have mass/stiffness shall be included in the model. All the connected piping up to first support point/first bellow point shall also be included in the model for their mass effect only.

8.1.2 *Spring Coefficients for Soil Support*

The soil supporting medium shall be idealized as six elastic springs,3 translational and 3 rotational. These spring stiffnesses, that is, vertical stiffness (k_y), horizontal/sliding (k_x, k_z), rocking (k_θ, k_ϕ), and torsional (k_ψ) shall be computed as per IS 2974 (Part 1).

8.1.3 *Spring coefficients for Pile Support*

The effective pile stiffness (six elastic springs) including the influence of pile group effect shall be evaluated by following the provisions in IS 2974(Part 1).

8.1.4 *Effect of Embedment*

Generally block foundations are embedded into the soil for some depth. Since the embedment effect will lead to increased damping, which in turn result in reduced vibration amplitudes, it is suggested to ignore this effect in foundation response computation.

8.1.5 *Damping Ratio*

The damping ratio shall be taken as specified in IS 2974 (Part 1).

8.1.6 *Mass*

The model shall include masses of all elements (self-weight of foundation, machine, miscellaneous accessories, etc at respective centre of masses.

8.1.7 *Dynamic Forces*

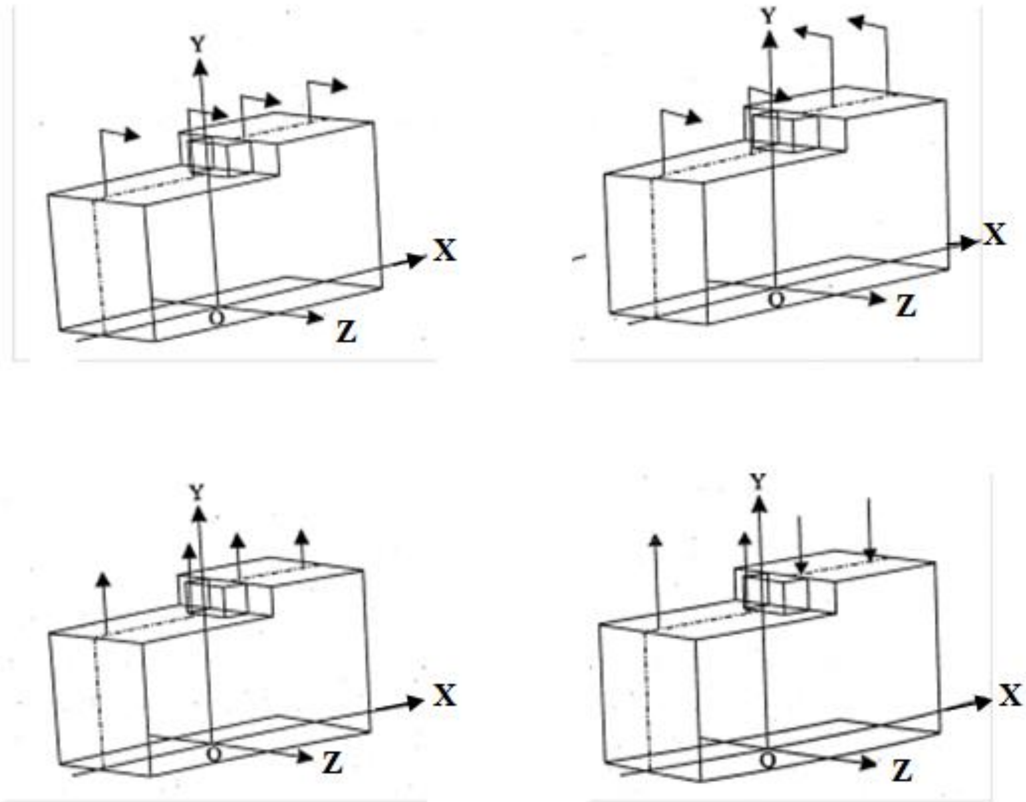
8.1.7.1 The dynamic forces generated due to unbalanced masses are to be supplied by the manufacturer of the machine as per the data requirement listed IS 2974 (Part 1). In the event of non-availability of data from the manufacturer, the same can be approximately estimated as per the guidelines in Annex B of IS 2974 (Part 1).

8.1.7.2 The dynamic forces shall be applied only at respective bearing locations.

8.1.7.3 The dynamic forces shall be applied simultaneously at all bearing locations. In case there is a constraint by the software, these shall be applied one at a time, and overall response shall be computed by combining individual response using SRSS (square root of sum of squares).

8.1.7.4 In case of reciprocating machines, the overall foundation response shall be calculated by adding the vibration amplitude due to both primary and secondary (at multiples of operating frequency) reciprocating loads.

8.1.7.5 For rotary machines, the unbalanced forces (drive machine and driven machine) in horizontal (direction perpendicular to the axis of rotation) as well as vertical direction (one at a time) shall be applied both in-phase and out-of-phase as shown in Fig 4.



4A In-phase Bearing Locations 4B Out-of-phase Bearing Locations

Fig. 4 Dynamic Unbalanced Forces at Bearing Locations

8.2 Dynamic Response

8.2.1 The dynamic response shall be computed either in terms of velocity, in mm/s or in terms of displacement, in microns or both, as the case may be.

8.2.2 The response amplitude shall be evaluated at,

a) Machine bearing locations;
b) Base of bearing pedestals;
c) Corners of foundation block at top surface; and
d) Top of raised pedestals, if any.

8.3 Dynamic Analysis by Manual Method

Dynamic analysis by manual method is applicable only for rigid block foundation. Manual method shall not be used for flexible block foundations (*see* **6.2.3**).

8.3.1 Dynamic analysis by manual method is applicable in cases where the machine-foundation system can be idealized as a spring-mass system. Following criteria shall be satisfied for analysis by manual method:

a) The foundation block is rigid, meeting the rigidity criteria specified in **6.2**.
b) All projected parts/ elements of the foundation like raised pedestals, cantilever projection, etc shall be sized such that the 1st frequency of these parts in bending/compression mode is higher than the highest rigid body mode (6th mode) of the main foundation block. In addition, the natural frequencies of these projected elements shall be ± 20 percent away from machine operating speed/speeds. To satisfy this criterion, the following shall be met:

$$3.23\times10^{-6}\,\frac{b\sqrt{E}}{L^2} < 0.8\,f_{\mathrm{m}} \quad \text{or} \quad 3.23\times10^{-6}\,\frac{b\sqrt{E}}{L^2} > 1.2\,f_{\mathrm{m}}$$

$$3.23\times10^{-6}\,\frac{D\sqrt{E}}{L^2} < 0.8\,f_{\mathrm{m}} \quad \text{or} \quad 3.23\times10^{-6}\,\frac{D\sqrt{E}}{L^2} > 1.2\,f_{\mathrm{m}}$$

where

b and *D* = cross-sectional dimensions of the projected element, in m;
L = span/height of the projected element, in m;
E = modulus of elasticity of the projected element, in MPa; and
f_{m} = operating frequency of the machine, in Hz.

8.3.2 Dynamic analysis by manual method includes determination of center of mass of the machine-foundation system, center of area of contact of foundation with the soil and transformation of the oscillating forces at the centroid of the base area.

8.3.3 *Free Vibration Analysis*

Free vibration analysis shall be carried out to evaluate the natural frequencies of the block and the corresponding modes. The equation of dynamic equilibrium for free vibration is,

$$M_{\ddot{x}} + C_{\dot{x}} + K_{x} = 0$$

where *M, C* and *K* are the mass, damping and stiffness of the machine-foundation-support system.

The natural frequency of the foundation system corresponding to each vibration mode shall be computed as per Annex A.

8.3.4 *Forced Vibration Analysis*

General equation of motion for forced vibration subjected to harmonic loading is,

$$M_{\ddot{x}} + C_{\dot{x}} + K_{x} = F_0 \sin \omega_{\mathrm{m}} t$$

where, F_0 is the amplitude of the excitation force (harmonic force) and$\omega_{\mathrm{m}}$is operating frequency/frequencies of machine, in rad/s.

The amplitude of vibration of the foundation block due to unbalanced machine forces in different direction shall be computed as per Annex A.

8.4 Analysis by FEM

Dynamic analysis by finite element method (FEM) is applicable both for rigid as well as flexible block foundations. Although machine foundations can be analyzed using equations, it becomes often more complicated and impractical when the foundation system becomes more complex. This necessitates the use of advanced computational techniques like FE analysis.

8.4.1 *Modeling for Dynamic Analysis by FEM*

a) *Foundation block* — The foundation block shall preferably be modeled using first/higher order 3D solid elements. The model shall include all openings/cutouts, cantilever projections, raised pedestals, etc., unless considered insignificant. At least three elements shall be modeled in any direction of the block. A typical FE model using 3D solid element is shown in Fig. 5.

b) *Supporting media* — The soil/pile stiffness calculated as per **8.1** shall be modeled using linear 3D spring elements applied at the bottom of the foundation.

   i) In case of foundation directly supported on soil, soil can be modeled as a set of three translational and three rotational springs attached at the centre of gravity (CG) of the base area. Alternatively, three translational springs distributed over the base can also be used. It may be noted that, this type of modeling will result in upper bound of the rotational frequency.

   ii) In case of foundation supported on pile group, the three translational springs (taking group action of pile into account) shall be located at the respective pile location.

iii) While connecting soil rotational springs to the foundation modeled using solid elements, proper care must be taken to avoid degree of freedom incompatibility between solid elements and spring elements.

c) The mass of the rotating or any other equipment on the foundation shall be modeled at their respective centers of gravity and shall be connected to the foundation top at appropriate locations by massless rigid links, preferably by master-slave concept.

d) The FE model results shall be validated using simple manual calculation to avoid gross error in modeling.

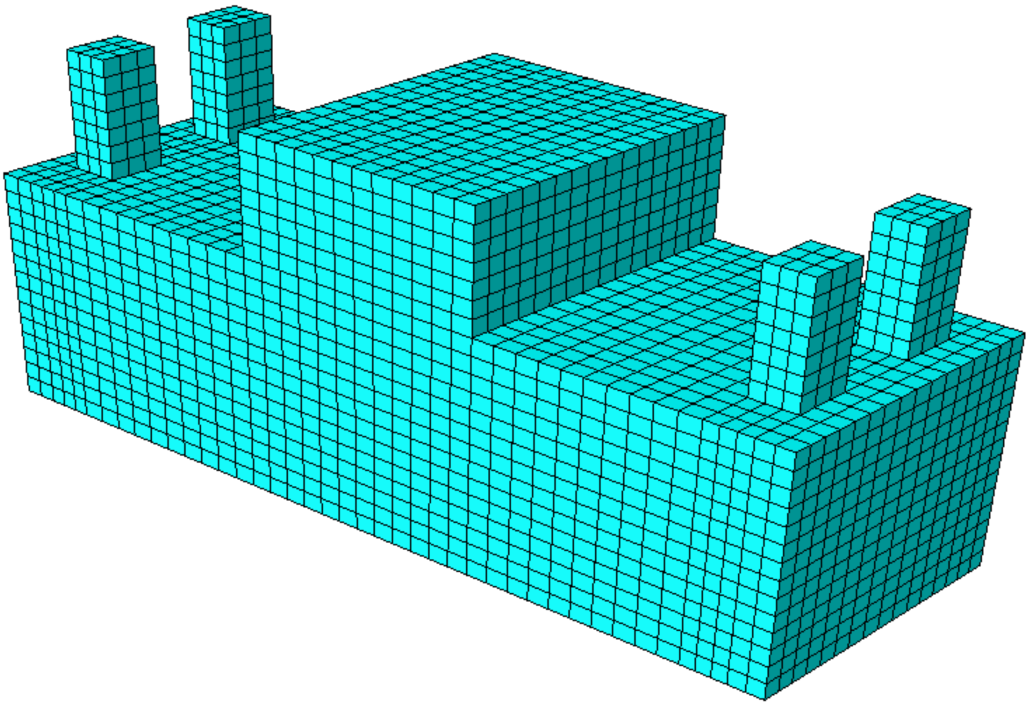


Fig. 5 Typical Finite Element Model of a Solid Block Foundation

8.4.2 *Free Vibration Analysis*

Free vibration analysis based on Eigen solution shall be carried out to extract the natural frequencies of machine-foundation system. The results shall be used to check whether the vertical natural frequency of the foundation system is sufficiently away from the operating frequency of the machine. In case the criteria as above is not satisfied, this is an indication that foundation needs re-sizing.

8.4.3 *Forced Vibration Analysis*

a) A steady state harmonic response analysis shall be performed to obtain the steady state amplitude of vibration due to various design unbalanced loads caused by the vibrating machine.

b) The analysis shall be carried out over a forcing frequency range within ±20 percent of the machine operating frequency.

c) Either direct integration technique or a mode superposition technique may be used.

d) When modal superposition procedure is used, atleast all modes within 1.2 times the highest operating frequency shall be included while performing the dynamic analysis.

8.4.4 *Modeling Damping*

Damping can be specified as constant for all modes or selectively changed for each mode in case of mode based dynamic analysis. For direct integration technique, Rayleigh damping can be considered. In case of Rayleigh damping, the constants shall be chosen appropriately so that the damping applied within the range of frequency of interest is less than the applicable damping of the foundation system.

9 STRENGTH ANALYSIS

9.1 Analysis of the foundation shall be performed to achieve the following:

a) Computation of pressure transmitted to the soil;
b) Analysis of stress within the foundation block; and
c) Stress analysis of separate units of the foundation, such as units weakened by openings, cantilevers and others.

The analysis may be performed using FEM or manual methods (wherever applicable)

9.2 Modeling for Strength Analysis

a) The same model used for dynamic analysis can also be used for strength analysis.
b) The loads and load combination to be considered for strength analysis shall be as per **9.2.1** and **9.2.2**.

9.2.1 *Load Cases*

9.2.1.1 *Dead loads* (DL)

The dead loads shall include the weight of,

a) Foundation block (including all the projected elements);
b) Machine (drive machine, driven machine, bearing pedestals, coupling, gear box, base frame, etc), excluding the weight of gas or liquid in the machine; and
c) Pipes and valves up to first anchor point/bellow.

9.2.1.2 *Imposed loads* (IL)

Imposed load of 10kN/m^2 around the machine frame shall be considered.

9.2.1.3 *Operating Loads* (OL)

Static operating weights: It includes the weight of gas or liquid in the machine during normal operation and forces, such as the drive torque developed by some machine between the drive mechanism and driven machine.

9.2.1.4 *Wind loads* (WL)

Wind load on the surface area of the machine, auxiliary equipment, pipes is based on the wind speed at the site location and shall be calculated as per IS 875.

9.2.1.5 *Seismic force* (EL)

Seismic forces shall be computed as per IS 1893 (Part 4).

9.2.1.6 *Equivalent static machine dynamic loads* (ESL)

The dynamic load (equivalent static load) due to rotating parts shall be applied at respective bearing locations.

For crusher, 5 times the load due to machine on the crushing element shall be considered.

For pumps, 3 times the weight of the pump shall be considered.

For motor generators and motor drives, dynamic factor of 2 shall be applied to the load due to machine itself.

9.2.1.2 *Force due to emergency/faulted conditions* (FL), (if applicable)

The forces due to malfunction of machine components such as,

a) Short circuit loads for motor/generator (SCF);
b) Forces due to loss of moving parts like blade, hammer, fins, etc (LBL);
c) Bowed rotor forces (BRF); and
d) Bearing failure load (BFL).

9.2.1.3 *Thermal Loads (TL) (if any)*

The temperature variation causes sliding at the support points due to expansion and contraction. The thermal forces on the foundation generally balance out being of equal and opposite sign. However, they govern the design of the anchor bolts, pedestal and the grouting system. For estimating the loads acting through the sole plate, friction coefficient varying from 0.2 to 0.5 may be used.

9.2.2 *Load Combinations*

9.2.2.1 *Load combinations for working stress method of design and for serviceability limit state*

a) Operating condition

DL + IL + OL±ESL + TL

b) Emergency load condition

i) Short circuit condition

DL+ IL+ OL ±ESL+ TL± SCF

ii) Loss of blade unbalance/bowed rotor

DL+ IL+ OL+ TL ± LBL/BRF

iii) Bearing failure condition

DL+ IL+ OL + TL ± BFL

c) Environmental condition

DL+ IL + OL ±ESL+TL±EL/WL

9.2.2.2 *Load Combinations for Limit State Method*

a) Erection/Maintenance condition

1.5 [DL+IL+EML]

b) Operating condition

1.5 [DL + IL + OL ±ESL + TL]

c) Emergency load condition

i) Short circuit condition
1.2[DL + IL + OL ±ESL + TL ± SCF]

ii) Loss of blade unbalance / Bowed rotor
1.2[DL+IL+OL+TL ± LBL/BRF]

iii) Bearing failure condition
1.0 [DL+IL+OL+TL ± BFL]

d) Environmental condition

1.2[DL+IL+OL±ESL+TL±EL/WL]

1.5[DL ± EL/WL]

NOTES

1 Reversible nature of dynamic load and frictional loads shall be considered.
2 Effects due to vertical earthquake load may be neglected.

10 CONCRETEBLOCK FOUNDATION DESIGN

10.1 Method of Design

10.1.1 Foundation shall be designed by limit state method or working stress method in accordance with IS 456.

10.1.2 When working stress method of design is adopted, permissible stresses in concrete and steel for emergency and environmental conditions shall be appropriately increased in accordance with **8** of IS 2974 (Part 1).

10.2 Reinforcement

10.2.1 Minimum reinforcement in the concrete block shall be not less than 25 kg/m^3. For machines requiring special design considerations of foundations, like machines pumping explosive gases, the reinforcement shall be not less than 40 kg/m^3.

10.2.2 *Reinforcement Detailing*

The following points shall be considered while arranging the reinforcements:

a) Reinforcement shall be provided on all faces, both ways. The minimum diameter of reinforcement in the block shall be 12 mm and the maximum spacing shall be 200 mm centre to centre, both ways on all the faces of the foundation block.

b) If the height of main foundation block exceeds one meter, one additional layer of reinforcement of 12 dia @ 300 c/c (both ways) shall be placed at every 1000 mm or less. This additional reinforcement shall be part of design steel/minimum steel.

c) The secondary shrinkage reinforcement as per **10.2.3 (b)** may be replaced by providing steel fibres of short lengths up to 60 mm and of aspect ratio of 80, inside the mass randomly in accordance with IS 456. Minimum recommended dosages of steel fibres should be either as given below or as recommended by the supplier:

Aspect Ratio	*Length* *mm*	*Diameter* *mm*	*Dosage* *kg/m^3*	*Fibre Type /Remarks*
80	60	0.75	10	Glued Hooked End
65	60	0.90	15	Glued Hooked End

d) Reinforcement shall be provided around all pits and openings as per **12.2.3** of IS 2974 (Part 1).

e) The minimum cover to concrete shall be as given below:

i) 75 mm at the bottom
ii) 50 mm at the top and on the sides

11 CONSTRUCTION ASPECTS

The construction aspects such as provision of construction joint, mass concreting, concreting in extreme weather, grouting, etc. shall be as per **12** of IS 2974 (Part 1).

ANNEX A

(*Clauses*, 8.3.3 *and* 8.3.4)

DYNAMIC ANALYSIS OF MACHINE-FOUNDATION-SOIL SYSTEM BY MANUAL METHOD

A-1 MATHEMATICAL IDEALIZATION

For the purpose of dynamic analysis, the machine-foundation-soil system can be mathematically idealized as single mass system with six linear springs (3 translations and 3 rotations) as shown in Fig. 6. The point O represents the CG of base area of foundation in contact with the soil and point C represents combined centroid of machine-foundation system.

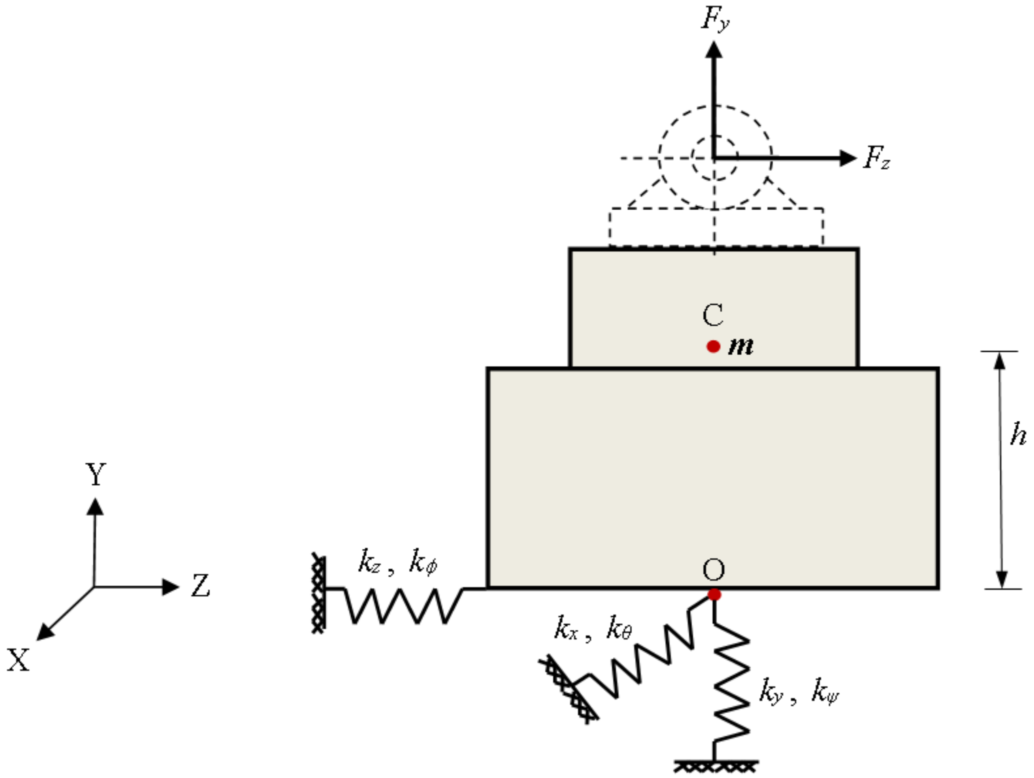


Fig. 6 Mathematical Idealization of a Typical Block Foundation

A-2 NOTATIONS

Symbol	*Units*	*Description*
m	kg	Total mass of machine and foundation
h	m	Height of overall centroid C from O
M_{mx}	kg m^2	Mass moment of inertia about X-axis at point C
M_{my}	kg m^2	Mass moment of inertia about Y axis at point C
M_{mz}	kg m^2	Mass moment of inertia about Z axis at point C
M_{mox}	kg m^2	Mass moment of inertia about X axis at point O
M_{moy}	kg m^2	Mass moment of inertia about Y axis at point O
M_{moz}	kg m^2	Mass moment of inertia about Z axis at point O
A	m^2	Foundation base area in contact with soil
I_{xx}	m^4	Moment of Inertia of foundation base area about X
I_{yy}	m^4	Moment of Inertia of foundation base area about Y
I_{zz}	m^4	Moment of Inertia of foundation base area about Z
k_x	N/m	Translational soil stiffness along X
k_y	N/m	Translational soil stiffness along Y

k_z	N/m	Translational soil stiffness along Z
k_θ	Nm/rad	Rotational soil stiffness about X
k_ψ	Nm/rad	Rotational soil stiffness about Y
k_ϕ	Nm/rad	Rotational soil stiffness about Z
ω_n	rad/sec	Natural frequency of the machine-foundation system
ω_m	rad/sec	Operating circular frequency/frequencies of machine
F_{ox}, F_{oy}, F_{oz}	N	Forces at point O along X, Y and Z direction
$M_{o\theta}$, $M_{o\psi}$, $M_{o\phi}$	N m	Moments about X, Y and Z axis at point O
ζ		Damping ratio
x_f, y_f, z_f	micron	Maximum amplitude of vibration at foundation top in X, Y and Z direction
L, B, H	m	Dimension of foundation block in X, Z and Y direction

A-3 FREE VIBRATION ANALYSIS

The machine foundation system undergoes six modes of vibration, that is, two uncoupled modes (vertical and torsional motion) and four coupled modes (translation and rocking about horizontal axes, *X* and *Z*). The natural frequencies corresponding to these six modes of vibration shall be computed manually using the equations given below.

a) Motion along *Y* direction (Vertical)

$$\omega_{ny} = \sqrt{\frac{k_y}{m}}$$

b) Motion about *Y* direction (Torsional)

$$\omega_{n\psi} = \sqrt{\frac{k_\psi}{M_{moy}}}$$

The torsional mode is always uncoupled.

c) Motion in *XY* Plane (Translation along *X* and Rocking about *Z*)

$$\omega_{n1}^2 = \frac{1}{2\gamma_z}\left[\left(\omega_{n\varphi}^2 + \omega_{nx}^2\right) - \sqrt{\left(\omega_{n\varphi}^2 + \omega_{nx}^2\right)^2 - 4\gamma_z\ \omega_{n\varphi}^2\omega_{nx}^2}\right]$$

$$\omega_{n2}^2 = \frac{1}{2\gamma_z}\left[\left(\omega_{n\varphi}^2 + \omega_{nx}^2\right) + \sqrt{\left(\omega_{n\varphi}^2 + \omega_{nx}^2\right)^2 - 4\gamma_z\ \omega_{n\varphi}^2\omega_{nx}^2}\right]$$

where

$$\gamma_z = \frac{M_{mz}}{M_{moz}},\ \omega_{nx}{}^2 = \frac{k_x}{m},\ \omega_{n\phi}{}^2 = \frac{k_\phi}{M_{moz}}$$

d) Motion in *ZY* Plane (Translation along *Z* and Rocking about *X*)

$$\omega_{n3}^2 = \frac{1}{2\gamma_x}\left[\left(\omega_{n\theta}^2 + \omega_{nz}^2\right) - \sqrt{\left(\omega_{n\theta}^2 + \omega_{nz}^2\right)^2 - 4\gamma_x\ \omega_{n\theta}^2\omega_{nz}^2}\right]$$

$$\omega_{n4}^2 = \frac{1}{2\gamma_x}\left[\left(\omega_{n\theta}^2+\omega_{nz}^2\right)+\sqrt{\left(\omega_{n\theta}^2+\omega_{nz}^2\right)^2-4\gamma_x\ \omega_{n\theta}^2\omega_{nz}^2}\ \right]$$

where

$$\gamma_x = \frac{M_{mx}}{M_{mox}}\ ,\ \omega_{nz}{}^2 = \frac{k_z}{m}\ ,\ \omega_{n\theta}{}^2 = \frac{k_\theta}{M_{mox}}$$

A-4 Forced Vibration Analysis

Forced vibration analysis is carried out to obtain the foundation response due to unbalanced forces of the machine. The foundation response is calculated at point O after transferring the machine unbalanced forces to this point. F_{ox}, F_{oy}, F_{oz} are the force components, and $M_{o\theta}$, $M_{o\psi}$, $M_{o\phi}$are the moment components of unbalanced forces (sinusoidal) acting at point O.

The response shall be calculated manually using the equations given below for damped or undamped cases. When the natural frequencies of the foundation system are in resonance with the operating speed of the machine, equations with damping shall be used to compute the response (*see* **A-4.2**). For all other cases, response can be computed using undamped equations.

A-4.1 Vibration Amplitude (Undamped Case)

a) *Amplitude for vertical motion (along Y direction)*

$$y_0 = \delta_y \frac{1}{\left|\left(1-\beta_y{}^2\right)\right|}$$

where

$$\delta_y = \frac{F_{oy}}{k_y}\ ,\ \beta_y = \frac{\omega_m}{\omega_{ny}}$$

b) *Amplitude for torsional motion (about Y direction)*

$$\psi_0 = \delta_\psi \frac{1}{\left|\left(1-\beta_\psi{}^2\right)\right|}$$

where

$$\delta_\psi = \frac{M_{o\psi}}{k_\psi}\ ,\ \beta_\psi = \frac{\omega_m}{\omega_{n\psi}}$$

c) *Amplitude for translation along X direction and rocking about Z direction (coupled mode*)

The amplitude can be calculated by considering one force (either F_{ox} or $M_{o\phi}$) acting at a time.

1) *Applied dynamic force F_{ox} sin($\omega_m t$)*

$$x_0 = \delta_x \frac{\left(1-\beta_\phi^2\right)}{\left(1-\beta_1^2\right)\left(1-\beta_2^2\right)}$$

$$\phi_0 = -\delta_x \frac{mh}{M_{moz}} \frac{\beta_\phi^2}{\left(1-\beta_1^2\right)\left(1-\beta_2^2\right)}$$

2) *Applied dynamic moment $M_o$sin ($\omega_m t$)*

$$x_0 = -h\delta_\phi \frac{\beta_x^2}{\left(1-\beta_1^2\right)\left(1-\beta_2^2\right)}$$

$$\phi_0 = \delta_\phi \frac{\left(1-\beta_x^2\right)}{\left(1-\beta_1^2\right)\left(1-\beta_2^2\right)}$$

where

$\delta_x = \frac{F_{ox}}{k_x}$, $\delta_\phi = \frac{M_{o\phi}}{k_\phi}$, β_x and β_ϕ are frequency ratios corresponding to natural frequencies ω_{nx} and $\omega_{n\phi}$, β_1 and β_2 are frequency ratios corresponding to natural frequencies ω_{n1} and ω_{n2}.

d) Amplitude for translation along Z direction and rocking about X direction (coupled mode).

The amplitude can be calculated by considering one force (either F_{oy} or $M_{o\theta}$) acting at a time.

1) *Applied dynamic force F_{oz} sin($\omega_m t$)*

$$z_0 = \delta_z \frac{\left(1-\beta_\theta^2\right)}{\left(1-\beta_3^2\right)\left(1-\beta_4^2\right)}$$

$$\theta_0 = \delta_z \frac{mh}{M_{mox}} \frac{\beta_\theta^2}{\left(1-\beta_3^2\right)\left(1-\beta_4^2\right)}$$

2) *Applied dynamic moment $M_{o\phi}$sin($\omega_m t$)*

$$z_0 = h\delta_\theta \frac{\beta_z^2}{\left(1-\beta_3^2\right)\left(1-\beta_4^2\right)}$$

$$\theta_0 = \delta_\theta \frac{\left(1-\beta_z^2\right)}{\left(1-\beta_3^2\right)\left(1-\beta_4^2\right)}$$

where

$\delta_z = \frac{F_{oz}}{k_z}$, $\delta_\theta = \frac{M_{o\theta}}{k_\theta}$, β_z and β_θ are frequency ratios corresponding to natural frequencies ω_{nz} and $\omega_{n\theta}$, β_3 and β_4 are frequency ratios corresponding to natural frequencies ω_{n3} and ω_{n4}.

A-4.2 Vibration Amplitude (Damped Case)

The foundation is considered to be in resonance, whenever the natural frequency corresponding to a specific mode lies within ±20 percent of normal operating speed of the machine. Under such situation, amplitude of vibration shall be calculated as below considering damping.

a) *Amplitude for vertical motion (along Y direction)*

$$y_0 = \delta_y \frac{1}{\sqrt{\left(1-\beta_y{}^2\right)^2 + \left(2\beta_y\zeta\right)^2}}$$

b) *Amplitude for torsional motion (about Y direction)*

$$\psi_0 = \delta_\psi \frac{1}{\sqrt{\left(1-\beta_\psi{}^2\right)^2 + \left(2\beta_\psi\zeta\right)^2}}$$

c) *Amplitude for translation along X direction and rocking about Z direction (coupled mode)*

The amplitude can be calculated by considering one force (either F_{ox} or $M_{o\phi}$) acting at a time.

1) *Applied dynamic force*, $F_{ox}\sin(\omega_m t)$

i. Resonance with natural frequency f_1 ($0.8<\beta_1<1.2$)

$$x_0 = \delta_x \frac{\left(1-\beta_\phi{}^2\right)}{\left(1-\beta_2{}^2\right)\sqrt{\left(1-\beta_1{}^2\right)^2 + \left(2\beta_1\zeta\right)^2}}$$

$$\phi_0 = -\delta_x \frac{mh}{M_{moz}} \frac{\beta_\phi{}^2}{\left(1-\beta_2{}^2\right)\sqrt{\left(1-\beta_1{}^2\right)^2 + \left(2\beta_1\zeta\right)^2}}$$

NOTE—If term $\left(1-\beta_1{}^2\right)$ is negative then term $\sqrt{\left(1-\beta_1{}^2\right)^2 + \left(2\beta_1\zeta\right)^2}$ should also be negative.

ii. *Resonance with natural frequency,* f_2 ($0.8<\beta_2<1.2$)

$$x_0 = \delta_x \frac{\left(1-\beta_\phi{}^2\right)}{\left(1-\beta_1{}^2\right)\sqrt{\left(1-\beta_2{}^2\right)^2 + \left(2\beta_2\zeta\right)^2}}$$

$$\phi_0 = -\delta_x \frac{mh}{M_{moz}} \frac{\beta_\phi{}^2}{\left(1-\beta_1{}^2\right)\sqrt{\left(1-\beta_2{}^2\right)^2 + \left(2\beta_2\zeta\right)^2}}$$

NOTE— If term $\left(1-\beta_2{}^2\right)$ is negative then term $\sqrt{\left(1-\beta_2{}^2\right)^2 + \left(2\beta_2\zeta\right)^2}$ should also be negative.

2) *Applied dynamic moment*, $M_{o\phi}\sin(\omega_m t)$

i) Resonance with natural frequency f_1($0.8<\beta_1<1.2$)

$$x_0 = -h\delta_\phi \frac{\beta_x^{\ 2}}{\left(1-\beta_2^{\ 2}\right)\sqrt{\left(1-\beta_1^{\ 2}\right)^2+\left(2\beta_1\zeta\right)^2}}$$

$$\phi_0 = \delta_\phi \frac{\left(1-\beta_x^{\ 2}\right)}{\left(1-\beta_2^{\ 2}\right)\sqrt{\left(1-\beta_1^{\ 2}\right)^2+\left(2\beta_1\zeta\right)^2}}$$

NOTE— If term $\left(1-\beta_1^{\ 2}\right)$ is negative then term $\sqrt{\left(1-\beta_1^{\ 2}\right)^2+\left(2\beta_1\zeta\right)^2}$ should also be negative.

ii) *Resonance with natural frequency, f_2*(0.8 <β_2<1.2)

$$x_0 = -h\delta_\phi \frac{\beta_x^{\ 2}}{\left(1-\beta_1^{\ 2}\right)\sqrt{\left(1-\beta_2^{\ 2}\right)^2+\left(2\beta_2\zeta\right)^2}}$$

$$\phi_0 = \delta_\phi \frac{\left(1-\beta_x^{\ 2}\right)}{\left(1-\beta_1^{\ 2}\right)\sqrt{\left(1-\beta_2^{\ 2}\right)^2+\left(2\beta_2\zeta\right)^2}}$$

NOTE — If term $\left(1-\beta_2^{\ 2}\right)$ is negative then term $\sqrt{\left(1-\beta_2^{\ 2}\right)^2+\left(2\beta_2\zeta\right)^2}$ should also be negative

d) Amplitude for translation along Z direction and rocking about X direction (coupled mode)

The amplitude can be calculated by considering one force (either F_{oz} or $M_{o\theta}$) acting at a time.

1) *Applied dynamic force, $F_{oz} \sin(\omega_m t)$*

i) Resonance with first natural frequency, f_3 (0.8<β_3<1.2)

$$z_0 = \delta_z \frac{\left(1-\beta_\theta^{\ 2}\right)}{\left(1-\beta_4^{\ 2}\right)\sqrt{\left(1-\beta_3^{\ 2}\right)^2+\left(2\beta_3\zeta\right)^2}}$$

$$\theta_0 = \delta_z \frac{mh}{M_{mox}} \frac{\beta_\theta^{\ 2}}{\left(1-\beta_4^{\ 2}\right)\sqrt{\left(1-\beta_3^{\ 2}\right)^2+\left(2\beta_3\zeta\right)^2}}$$

NOTE — If term $\left(1-\beta_3^{\ 2}\right)$ is negative then term $\sqrt{\left(1-\beta_3^{\ 2}\right)^2+\left(2\beta_3\zeta\right)^2}$ should also be negative.

ii) *Resonance with first natural frequency, f_4* (0.8<β_4<1.2)

$$z_0 = \delta_z \frac{\left(1-\beta_\theta^{\ 2}\right)}{\left(1-\beta_3^{\ 2}\right)\sqrt{\left(1-\beta_4^{\ 2}\right)^2+\left(2\beta_4\zeta\right)^2}}$$

$$\theta_0 = \delta_z \frac{mh}{M_{mox}} \frac{\beta_\theta^{\ 2}}{\left(1-\beta_3^{\ 2}\right)\sqrt{\left(1-\beta_4^{\ 2}\right)^2+\left(2\beta_4\zeta\right)^2}}$$

NOTE— If term $\left(1-\beta_4^{\ 2}\right)$ is negative then term $\sqrt{\left(1-\beta_4^{\ 2}\right)^2+\left(2\beta_4\zeta\right)^2}$ should also be negative.

2) *Applied dynamic moment*, $M_{o\phi}sin(\omega_m t)$

i) Resonance with natural frequency f_3 ($0.8<\beta_3<1.2$)

$$z_0 = h\delta_\theta \frac{\beta_z^2}{\left(1-\beta_4^2\right)\sqrt{\left(1-\beta_3^2\right)^2+\left(2\beta_3\zeta\right)^2}}$$

$$\theta_0 = \delta_\theta \frac{\left(1-\beta_z^2\right)}{\left(1-\beta_4^2\right)\sqrt{\left(1-\beta_3^2\right)^2+\left(2\beta_3\zeta\right)^2}}$$

NOTE — If term $\left(1-\beta_3^2\right)$ is negative then term $\sqrt{\left(1-\beta_3^2\right)^2+\left(2\beta_3\zeta\right)^2}$ should also be negative.

ii) *Resonance with natural frequency*, f_4 ($0.8<\beta_4<1.2$)

$$z_0 = h\delta_\theta \frac{\beta_z^2}{\left(1-\beta_3^2\right)\sqrt{\left(1-\beta_4^2\right)^2+\left(2\beta_4\zeta\right)^2}}$$

$$\theta_0 = \delta_\theta \frac{\left(1-\beta_z^2\right)}{\left(1-\beta_3^2\right)\sqrt{\left(1-\beta_4^2\right)^2+\left(2\beta_4\zeta\right)^2}}$$

NOTE— If term $\left(1-\beta_4^2\right)$ is negative then term $\sqrt{\left(1-\beta_4^2\right)^2+\left(2\beta_4\zeta\right)^2}$ should also be negative.

A-4.3 Amplitude at Foundation Top

Consider a foundation block of size *L, B* and *H* in *X, Z* and *Y* direction, respectively. The amplitude of vibration $x_0, y_0, z_0, \phi_0, \psi_0, \theta_0$ at point O (CG of the base area) due to unbalanced machine forces are obtained in the previous section. The amplitudes at centre and corners of foundation top are obtained as follows.

a) Amplitude at centre of foundation top

The maximum amplitude of vibration at centre of foundation top $\bar{x}_f, \bar{y}_f, \bar{z}_f$ in *X, Y* and *Z* direction can be calculated as

$$\bar{x}_f = \left|(x_0 + H\phi_0)\right|$$

$$\bar{y}_f = \left|y_0\right|$$

$$\bar{z}_f = \left|(z_0 - H\theta_0)\right|$$

b) Amplitude at corners of foundation top

The maximum amplitude of vibration at corners of foundation top, x_{fc}, y_{fc}, z_{fc} along *X, Y* and *Z* direction can be calculated as

$$x_{fc} = \left|\psi_0 \left(B/2\right)\right|$$

$$y_{fc} = \left|\theta_0 \left(B/2\right)\right| + \left|\phi_0 \left(L/2\right)\right|$$

$$z_{fc} = \left|\psi_0 \left(L/2 \right)\right|$$

c) Maximum amplitude of vibration at foundation top, x_f, y_f, z_f along *X*, *Y* and *Z* direction can be calculated as

$$x_f = (\bar{x}_f + x_{fc}) \times 10^{-6}$$

$$y_f = (\bar{y}_f + y_{fc}) \times 10^{-6}$$

$$z_f = (\bar{z}_f + z_{fc}) \times 10^{-6}$$