भारतीय मानक

Indian Standard

IS 1893 (Part 4) : 2024

संरचनाओं के भूकंपरोधी डिज़ाइन के लिए मानदंड

भाग 4 औद्योगिक संरचनाएँ और चट्टा टाइप संरचनाएँ

(दूसरा पुनरीक्षण)

Criteria for Earthquake Resistant Design of Structures

Part 4 Industrial Structures and Stack-Like Structures

(*Second Revision*)

ICS 91.120.25

भारतीय मानक ब्यूरो
BUREAU OF INDIAN STANDARDS
मानक भवन, 9 बहादुर शाह ज़फर मार्ग, नई दिल्ली - 110002
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI - 110002
www.bis.gov.in www.standardsbis.in

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FOREWORD

This Indian Standard (Part 4) (Second Revision) was adopted by the Bureau of Indian Standards, after the draft finalized by the Earthquake Engineering Sectional Committee had been approved by the Civil Engineering Division Council.

India is prone to strong earthquake shaking, and hence earthquake resistant design is essential. Structures designed as per this standard are expected to sustain damage during strong earthquake ground shaking. IS 1893 'Recommendations for earthquake resistant design of structures' was first published in 1962, and revised in 1966, 1970, 1975 and 1984. Further, in 2002, the Committee decided to present the provisions for different type of structures in separate parts, to keep abreast with rapid developments and extensive research carried out in earthquake-resistant design of various structures.

Considering the state of knowledge available then and in order to update this standard, the Committee had decided to cover the provisions for different types of structures in separate parts. This standard was therefore split into parts. The other parts in this series are:

Part 1 General provisions and buildings
Part 2 Liquid retaining tanks
Part 3 Bridges and retaining walls
Part 5 Dams and embankments (to be formulated)
Part 6 Base isolated buildings

Clauses **1** to **6** of Part 1 of the standard represent general provisions that are applicable to all types of structures covered in Parts 2 to 6 (*including those under preparation*). The general provisions that are applicable specifically to industrial structures and stack-like structures, have also been provided in these clauses.

Part 4 of the standard was first published as a separate one in 2005 in which provisions on earthquake resistant design for industrial structures including stack-like structures were covered respectively in Sections 1 and 2. Thereafter, the Part 4 was revised in 2015, in which design spectrum was included, detailed categorization of industrial structures was incorporated; and special design consideration for RCC stacks were included. This revision is based on the earthquake hazard and seismic zone map as specified in IS 1893 (Part 1) : 2016.

In this second revision, the following significant changes have been incorporated:

a) Definitions of various terms related to earthquake engineering and industrial structures have been incorporated;
b) Design spectrum for industrial structures (Section 1) and stack-like structures (Section 2) has been updated and included in Annex C;
c) Importance factor for Category 3 structures has been modified to be consistent with IS 1893 (Part 1);
d) Maintenance specific imposed load (MSIL) has been introduced to address long maintenance periods where the loads as well as structural configuration may be different from those considered under other conditions;
e) Industrial structures have been categorized in details, and the erstwhile Table 6 has been expanded in to three new Tables 6, 7 and 8, and separately describes industrial structures, stack-like structures, and equipment/piping, respectively;
f) Effect of masonry infill walls and stiffness considerations for RCC structures have been included;
g) Considerations for temporary structures or facilities are brought under the purview of this standard;
h) Specific provisions for the following have been included:

   1) Ground supported vertical cylindrical tanks,
   2) Structural considerations during maintenance,
   3) Anchorages,
   4) Structure supporting cranes,
   5) Bunkers and silos, and
   6) Pre-engineered steel structures.

(*Continued on third cover*)

Indian Standard

CRITERIA FOR EARTHQUAKE RESISTANT DESIGN OF STRUCTURES

PART 4 INDUSTRIAL STRUCTURES AND STACK- LIKE STRUCTURES

(Second Revision)

1 SCOPE

1.1 All industrial structures and stack-like structures other than nuclear installations shall be designed and constructed to resist the earthquake effects in accordance with the requirements and provisions of this standard. This standard describes the procedures for earthquake resistant design and provides the procedure of estimating the earthquake forces for design of such structures.

1.2 Provisions for earthquake resistant design of equipment and piping (including the seismic qualification of equipment) are under development. Till such time they are published, this standard (Part 4) shall remain applicable.

1.3 In Seismic Zones II and III, temporary structures such as scaffolding, temporary excavations, structures or equipment needed during a scheduled shutdown or maintenance period, structures erected to temporarily support heavy equipment and other facilities of industrial structures during construction and are meant for a limited-time use not exceeding one year need not be designed for earthquake forces.

1.4 In Seismic Zones IV and V, these temporary structures (as in **1.3**) shall be designed as Category 4 structures. The drift limitation provisions of Category 4 structures need not be applied to design of temporary structures.

1.5 Temporary facilities or structures that may be in service for longer than one year shall be designed as permanent structures as per the provisions of this standard in all seismic zones.

1.6 This standard does not deal with the construction features relating to earthquake resistant design in non-industrial buildings and structures. For guidance on earthquake resistant construction of these structures, reference may be made to the following standards: Other parts of IS 1893, IS 4326, IS 13827, IS 13828, IS 13920, IS 13935 and IS 15988.

1.7 This standard shall be considered applicable to structures of all industries, including those listed below, unless exclusively noted otherwise:

a) Process industries;
b) Power plants;
c) Petroleum, fertilizers, chemical and petro-chemical industries;
d) Steel, copper, zinc, and aluminum plants;
e) Pharmaceutical plants;
f) Cement industries;
g) Automobile industries;
h) Sugar and alcohol industries;
j) Glass and ceramic industries;
k) Textile industries;
m) Foundries;
n) Electrical, electronic and semi-conductor industries;
p) Consumer product industries;
q) Water treatment plants, effluent treatment plants and sewage treatment plants;
r) Leather industries;
s) Off-shore structures, marine/port and harbour structures;
t) Mills of various plants;
u) Information technology, data processing centers and communication industries;
v) Pulp and paper industries; and
w) Food processing and packaging plants.

1.8 In addition to the above, the standard is applicable to the following structures, which are classified as stack-like structures:

a) Natural draught cooling towers and prilling towers;
b) Transmission and communication towers and masts, including those mounted on buildings;
c) Chimneys and stack-like structures;
d) Steel tubular support structures for onshore wind turbine generator systems;

e) Silos (including parabolic silos);

f) Support structures for refinery columns including distillation columns; and

g) Pressure vessels and chemical reactor columns.

1.9 For nuclear installations, reference shall be made to the applicable safety standards.

2 REFERENCES

The standards listed in Annex A contain provisions, which, through reference in this text, constitute provisions 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 these standards.

3 TERMINOLOGY

Terminology given under **3** of IS 1893 (Part 1) shall apply to this standard as well. In addition, the following terms shall also apply to this standard. For definition of terms pertaining to soil mechanics and soil dynamics, reference may be made to IS 2809 and IS 2810, and for definition of terms pertaining to 'loads', reference may be made to IS 875 (Parts 1 to 5).

3.1 Damping — The effect of internal friction, inelasticity of material, slipping, sliding, etc, in reducing the amplitude of oscillation.

3.1.1 *Critical Damping* — The damping beyond which the free vibration motion will not be oscillatory.

3.1.2 *Damping Ratio* — A fraction of critical damping.

3.2 Design Vertical Acceleration Coefficient (A_v) — Design seismic acceleration spectral value of vertical ground motion that shall be used for design of structures, wherever appropriate.

3.3 Earthquake Ground Motion — The characteristics (intensity, duration, frequency content, etc) of seismic ground vibrations expected at any site depend on magnitude of earthquake, its focal depth, epicentral distance, characteristics of the path through which the seismic waves travel, and soil strata on which the structure is founded. The random earthquake ground motions, which cause the structure to oscillate, can be resolved in any three mutually perpendicular directions. The predominant direction of ground vibration is usually horizontal.

3.4 Epicenter — The geographical point on the surface of earth vertically above the point of origin of the earthquake.

3.5 Epicentral Distance — The distance on the ground surface between an observer or site and the epicenter.

3.6 Focal Depth — The distance between the epicenter and the focus.

3.7 Focus — The point inside the earth where the elastic waves due to earthquake originate causing shaking of ground.

3.8 Magnitude — A number that characterizes the relative size of an earthquake.

3.9 Modal Response History (MRH) Analysis — The solution methods for linear response history analysis procedure wherein the decoupled equations are solved to obtain modal responses, and after the solution, the modal responses are combined together.

3.10 Mode Shape — A characteristic deflected shape of a structure under free vibration corresponding to a specific natural frequency of the system, also known as an Eigen vector.

3.11 Mode Shape Coefficient — The element φ_{ik} is called the mode shape coefficient associated with degree of freedom i, when the structure is oscillating in mode k.

3.12 Principal Directions — Two mutually perpendicular horizontal directions in plan and the vertical direction of the structure along which the majority of force resisting system is oriented.

3.13 Seismic Mass — Seismic weight W divided by acceleration due to gravity, g.

3.14 Seismic Waves —— When an earthquake occurs, seismic waves are produced which are classified into two groups: body waves, which travel through the earth in all directions and to all depths, and surface waves, whose propagation is limited to a volume of rock within a few seismic wavelengths of the earth's surface.

3.15 Seismic Weight — Total dead load plus appropriate specified imposed load. The imposed load includes the weight of the contents for vessels, tanks, hoppers, equipment and containers.

4 TERMINOLOGY FOR INDUSTRIAL STRUCTURES

For the purpose of earthquake resistant design of industrial structures in this standard, the following definitions shall apply.

4.1 Base — The level at which inertial forces generated in the buildings are considered to be transferred to the ground through the foundation. For buildings with basements, it is considered at the bottommost basement level.

4.2 Base Dimension — Dimension (in metre) of the base of the structure along a direction of earthquake ground shaking.

4.3 Centre of Mass — The point through which the resultant of the inertia force of a system acts during earthquake shaking. This point corresponds to the centre of gravity of masses of system.

4.4 Centre of Resistance — The point through which the resultant of the restoring forces in the structural elements of a system acts in that storey.

4.5 Combined Structures — A structure with lateral load resisting elements constructed from a combination of reinforced or prestressed concrete and structural steel.

4.6 Height of Structure (h) — The difference in levels between its base and its highest level. For pitched or sloped roofs, the height of structure is from the base to the average height of the roof.

4.7 Maintenance Specific Imposed Load (MSIL) — Load imposed on a specified floor area for maintenance and repair operations. MSIL shall include but not limited to the load due to maintenance equipment, staging, increased imposed load due to personnel and their equipment, etc. MSIL shall also duly account for the effect of non-uniform distribution of the load and influence of factors such as impact, if applicable.

4.8 Nonstructural Elements — Systems and components attached to the floors and walls of an industrial structure that are not part of its main load-bearing structural system.

4.9 Primary System — The building or non-building structure supporting the secondary system.

4.10 Secondary System — Structures, systems, equipment and components supported on the primary system.

4.11 Soil-Structure Interaction — Effect by which structure and surrounding soil mutually affect their overall response.

5 SYMBOLS

The symbols and notations applicable to both Sections 1 and 2 are given as under:

A	Area of cross-section at the base of the structural shell
A_h	Design horizontal seismic coefficient
A_v	Design vertical seismic coefficient
b_i	Floor plan dimension of floor i, perpendicular to direction of force
c	Index for closely spaced modes
CQC	Complete quadratic combination method
C_T	Coefficient depending upon the slenderness ratio of the structure
C_v	Coefficient of shear force depending on slenderness ratio, k
DL	Dead load
D_m	Distribution factors for moment
D_{max}	Maximum lateral deflection
D_v	Distribution factors for shear
d	Thickness of pile cap, raft or open foundation
EL	Earthquake load

EL_x	Response quantity due to earthquake loads in X-direction
EL_Y	Response quantity due to earthquake loads in Y-direction
EL_Z	Response quantity due to earthquake loads in Z-direction
E_p	Modulus of elasticity of pile material
E_s	Modulus of elasticity of material of the structural shell
e_{di}	Design eccentricity at floor, i
e_{si}	Static eccentricity at floor, i
F_i	Lateral force at level, i
G	Shear modulus of soil = ρV_s^2
g	Acceleration due to gravity
h	Height of structure above the base
$\bar{h}$	Height of centre of gravity of structure above base
I	Importance Factor
IL	Imposed loads
I_m	Moment of inertia of pile section
k	Slenderness ratio
K_h	Horizontal stiffness
K_τ	Rocking stiffness
$\{M\}$	Mass matrix of the structural system
M_F	Total mass of all the equipment that are flexibly mounted (using isolators) at different locations in the structure
M_k	Modal mass of mode, k
$[M_p]$	Mass matrix of the primary system
M_{PS}	Total mass of the primary system (structural system) on which the secondary system is supported
M_R	Total mass of all the equipment that are rigidly mounted at different locations in the structure
M_S	Total mass of the secondary system
$MSIL$	Maintenance specific imposed load
N	Standard penetration test value (SPT Value) of the soil
n	Number of levels of lumped weight or floors of the structure
n_m	Number of modes
n_p	Number of piles
p_{ij}	Cross-modal correlation co-efficient
R	Response reduction factor
R_1	Response reduction factor for structure 1

R_2	Response reduction factor for structure 2
r	Number of modes being considered
r_e	Radius of gyration of the structural shell at the base section
r_o	Radius of circular raft foundation
r_s	Mean radius of structural shell
$SIDL$	Super imposed dead loads
$SRSS$	Square root of sum of squares
$\frac{S_a}{g}$	Spectral acceleration coefficient
$\left(\frac{S_a}{g}\right)_{ss}$	Site-specific spectral acceleration coefficient
T	Undamped natural period of vibration of the structure
T_l	Characteristic length of pile
$\{U_b\}$	Influence vector (displacement vector) of the structural system
V_B	Design seismic base shear
$\overline{V_B}$	Design seismic base shear estimated using approximate fundamental period as per IS 1893 (Part 1)
V_{BB}	Seismic base shear for bare frame model
V_{BI}	Seismic base shear for infilled frame model
V_s	Shear wave velocity of the medium
W_i	Seismic weight of floor i; Weight at level i
W_t	Total weight of the structure including weight of lining and contents above the base
Z	Seismic zone factor
Δ_{sep}	Separation between adjacent units
Δ_1	Elastic displacement for structure 1
Δ_2	Elastic displacement for structure 2
δ	Maximum value of deflection
δ_i	Lateral displacement at level i
δ_x, δ_y, δ_z	Maximum value of deflection in X, Y, Z direction respectively
ρ	Mass density of soil
φ_j	Normalized mode shape of mode j
φ_{ik}	Mode shape coefficient at floor i, in mode, k
φ_{ci}	Mode vector value from the primary system's modal displacement at the location where the secondary system is connected
Γ_j	Participation factor for mode j
λ^*	Peak response quantity due to closely spaced modes only

λ	Peak response due to all modes considered
λ_c	Peak response quantity in closely spaced modes, *c*
λ_i	Response quantity of mode *i*
λ_j	Response quantity of mode *j*
λ_k	Peak response of quantity in mode *k*
ζ	Modal damping ratio
η_h	Modulus of sub-grade reaction of soil in horizontal direction
v	Poisson's ratio of soil
ω_i	Circular natural frequency, in mode *i*
ω_j	Circular natural frequency, in mode *j*

6 GENERAL PRINCIPLES AND DESIGN CRITERIA

6.1 General Principles

6.1.1 *Inertia Forces*

Earthquake generated inertia forces shall be considered in both horizontal and vertical directions in design and shall be used appropriately for structural floors supporting equipment, machinery and piping. Effects of earthquake-induced vertical shaking can be significant for overall stability analysis of structures, especially in structures: (a) with large spans, and (b) those in which stability is a criterion for design. Reduction in gravity force due to vertical ground motions can be detrimental particularly in prestressed horizontal members, cantilevered members, and gravity structures. Hence, special attention shall be paid to effects of vertical ground motion on prestressed or cantilevered beams, girders, and slabs.

6.1.2 The response of a structure to ground vibrations depends on soil strata, its foundation type, materials, form, size, its mode of construction, duration and characteristics of ground motion. This standard specifies design forces for structures founded on rocks or soils, which do not settle, liquefy or slide, due to loss of strength during earthquake ground vibrations.

6.1.3 Actual ground accelerations that are experienced during earthquakes by structures are much stronger than the design accelerations specified in the standard. Consequently, these are likely to experience inelastic deformations. Ductility arising from inelastic material behaviour with appropriate design and detailing, and over strength resulting from the additional reserve strength in structures over and above the design strength, are relied upon to account for the differences in actual and design lateral forces. In other words, earthquake resistant design as per this standard relies on inelastic behaviour of structures. But, the maximum ductility that can be realized is limited. Therefore, all structures shall be designed for at least the minimum design lateral force specified in this standard.

6.1.4 Members and connections of reinforced and prestressed concrete members shall be designed (as per IS 456 and IS 1343) to ensure that premature failure does not occur due to shear or bond. Some provisions for appropriate ductile detailing of RC members are given in IS 13920. Members and their connections of steel structures shall be designed and detailed such that high ductility is obtained in the structure, thereby avoiding premature failure due to elastic or inelastic buckling of any type. Some provisions for appropriate ductile detailing of steel members are given in IS 800 and IS 18168.

6.1.5 Soil-structure interaction refers to effects of flexibility of supporting soil-foundation system on the response of structure. It shall not be considered for structures supported on rock or rock-like material at shallow depth.

6.1.6 Equipment and other mechanical systems and machinery, which are supported at various floor levels of the structure, will be subjected to different motions at their support points. In such cases, it may be necessary to obtain floor response spectra for analysis and design of equipment. For example, containers and vessels of hazardous or toxic materials with solids, liquids, or gases, shall be analyzed using applicable floor response spectra. Specialist literature shall be referred for generation of floor response spectra.

6.1.7 The design force specified in this standard shall be considered in each of the two principal horizontal directions and in vertical direction of the structure.

6.2 Assumptions and Considerations

The following assumptions and considerations have been made in this standard for earthquake resistant design of structures:

a) Earthquake ground motions are complex and irregular, consisting of several frequencies and of varying amplitudes each lasting for a small duration. Therefore, usually, resonance of the type as visualized under steady-state sinusoidal excitations will not occur, as it would need time to build up such amplitudes. But, there are exceptions where resonance-like conditions have been seen to occur between long distance waves and tall structures founded on deep soft soils;

b) Earthquake is not likely to occur simultaneously with high wind, maximum flood, or maximum sea waves;

c) Maintenance specific imposed loads (MSIL) shall be considered only when the maintenance duration is longer than 10 days. When the maintenance duration is less than 10 days, MSIL need not be combined with earthquake forces, but shall be separately considered as a super imposed load in the structural design; and

d) The values of elastic modulus of materials, where required, shall be those for static analysis [as per IS 456, IS 800, IS 1343, IS 1905, IS 4998 and IS 2974 (Parts 1 to 5)], unless a more definite values are available for use in dynamic conditions.

6.3 Increase in Permissible Stresses

6.3.1 *Increase in Permissible Stress in Materials*

When earthquake forces are considered along with other design forces using the working stress method of design, the permissible stresses in materials may be increased by one-third. But, in case of steels having a definite yield stress, the stress shall be limited to the yield stress. For steels without a definite yield point, the stress shall be limited to 80 percent of the ultimate strength or 0.2 percent proof stress, whichever is smaller. In prestressed concrete members, the tensile stress in the extreme fibres of the concrete shall be limited to two-third of the modulus of rupture of concrete. When using the limit state method of design, increase in permissible stresses in materials is not allowed.

6.3.2 *Increase in Allowable Net Bearing Pressure on Soils in Design of Foundations*

When earthquake forces are included, the net allowable bearing pressure in soils shall be increased as per Table 1A, depending on type of soil.

In soil deposits consisting of submerged loose sands and soils falling under classification SP with corrected standard penetration test values *N*, less than 15 in Seismic Zones III, IV and V and less than 10 in Seismic Zone II, the shaking caused by earthquake ground motion may cause liquefaction or excessive total and differential settlements. For specific sites, study should be conducted to determine its liquefaction potential on need basis. Specialist literature may be referred to assess liquefaction potential. Such sites should preferably be avoided while locating new settlements or important projects. Otherwise, this aspect of the problem needs to be investigated and appropriate methods of compaction or stabilization adopted to ac h ieve suitable values as indicated in Note 4 of Table 1A.

Alternatively, deep pile foundation may be provided and taken to depths well into the layer, which is not likely to liquefy. Also, marine clays and other sensitive clays are known to liquefy due to collapse of soil structure and will need special treatment according to site condition (*see* Table 1A and Table 1B).

Table 1A Percentage Increase in Net Allowable Bearing Pressure and Skin Friction of Soils

(*Clause* 6.3.2)

Sl No.	Soil Type	Percentage Increase Allowable
(1)	(2)	(3)
i)	*Type* A — Rock or hard soils	50
ii)	*Type* B — Medium or stiff soils	25
iii)	*Type* C — Soft soils	0

Table 1A (*Concluded*)

Sl No.	Soil Type	Percentage Increase Allowable
(1)	(2)	(3)

NOTES

1 The net allowable bearing pressure shall be determined in accordance with IS 6403 or IS 8009.
2 Only corrected values of *N* shall be used.
3 If any increase in net allowable bearing pressure has already been permitted for forces other than seismic forces, the total increase in allowable bearing pressure when seismic force is also included shall not exceed the limits specified above.
4 The desirable minimum corrected field values of *N* are as follows:

Sl No.	*Seismic Zone*	*Depth Below Ground Level* (*m*)	*N Values* (*Corrected*)	*Remarks*
(1)	(2)	(3)	(4)	(5)
i)	III, IV and V	≤ 5 ≥ 10	15 25	For values of depths between 5 m and 10 m, linear interpolation is recommended.
ii)	II	≤ 5 ≥ 10	15 20	

If soils of lower *N* values are encountered than those specified above, then suitable ground improvement techniques shall be adopted to achieve these values. Alternately, deep pile foundations should be used, which are anchored in stronger strata, underlying the soil layers that do not meet the requirement.

5 Piles should be designed for lateral loads neglecting lateral resistance of those soil layers (if any), which are liable to liquefy.

6 Indian Standards IS 1498 and IS 2131 may be referred for soil notation, and corrected *N* values shall be determined by applying correction factor C_N for effective overburden pressure σ'_{vo} using relation $N = C_N N_1$, where $C_N = \sqrt{P_a/\sigma'_{vo}} \leq 1.7$, P_a is the atmospheric pressure and N_1 is the uncorrected SPT value for soil.

7 While using this table, the value of *N* to be considered shall be determined as below:

a) Isolated footings — weighted average of *N* of soil layers from depth of founding, to depth of founding plus twice the breadth of footing;
b) Raft foundations — weighted average of *N* of soil layers from depth of founding, to depth of founding plus twice the breadth of raft;
c) Pile foundation — weighted average of *N* of soil layers from depth of bottom tip of pile, to depth of bottom tip of pile plus twice the diameter of pile;
d) Group pile foundation — weighted average of *N* of soil layers from depth of bottom tip of pile group, to depth of bottom tip of pile group plus twice the width of pile group; and
e) Well foundation — weighted average of *N* of soil layers from depth of bottom tip of well, to depth of bottom tip of well plus twice the width of well.

For determining the type of soil, soils shall be classified in 4 types as given in Table 1B.

Table 1B Classification of Types of Soils for Determining Percentage Increase in Net Bearing Pressure and Skin Friction

(*Clauses* 6.3.2 *and* 17.1)

Sl No.	**Soil Type**	**Remarks**
(1)	(2)	(3)
i)	Type A Rock or hard soils	Well graded gravel (GW) or well graded sand (SW) both with less than 5 percent passing 75µm sieve (fines); Well graded gravel-sand mixtures with or without fines (GW-SW); Poorly-graded sand (SP) or clayey sand (SC), all having *N** above 30; and Stiff to hard clays with *N* above 30
ii)	Type B Medium or stiff soils	Poorly graded sands or poorly graded sands with gravel (SP) with little or no fines having *N* between 10 and 30; a Stiff to medium stiff fine-grained soils, like silts of low compressibility (ML) or clays of low compressibility (CL) having *N* between 10 and 30.

Table 1B (*Concluded*)

Sl No.	Soil Type	Remarks
iii)	Type C Soft soils	All soft soils other than SP with *N*<10. The various possible soils are: a) Silts of intermediate compressibility (MI); b) Silts of high compressibility (MH); c) Clays of intermediate compressibility (CI); d) Clays of high compressibility (CH); e) Silts and clays of intermediate to high compressibility (MI-MH or CI-CH); f) Silt with clay of intermediate compressibility (MI-CI); and g) Silt with clay of high compressibility (MH-CH).
iv)	Type D Unstable, collapsible, liquefiable soils	Requires site-specific study and special treatment according to site condition (*see* **6.3.2**).

7 DESIGN SPECTRUM

7.1 For design of structures falling under Categories 1 and 2, site-specific seismic spectra shall be evaluated. The effects of earthquake base excitation for design, shall be estimated based on the principles of probabilistic earthquake hazard assessment as well as on the principles of deterministic earthquake hazard assessment. The envelope of the two methods shall be considered as the site-specific spectra.

The effects of standard design spectra as per **7.3.2**, shall be taken as minimum for design of structures. The effects of the site-specific spectrum shall not be taken less than those arising out of the design spectrum specified in this standard.

7.2 For design of structures falling under Categories 3 and 4, where site-specific studies are not carried out, the effects of design spectrum specified in this standard with correction for zone factor and modifications as per **7.3.2** shall be adopted.

7.3 Design Horizontal Seismic Coefficient

The horizontal seismic coefficient A_h shall be estimated using the natural period T, described as below.

7.3.1 When using site-specific spectrum, (site-specific spectra shall be generated for an earthquake with probability of exceedance of 10 percent in 50 years), the design horizontal seismic coefficient A_h shall be estimated as:

$$A_h = \left(\frac{S_a}{g}\right)_{SS} \frac{I}{R}$$

where

$\left(\frac{S_a}{g}\right)_{SS}$ = Site-specific spectral acceleration coefficient denoting peak response acceleration corresponding to fundamental natural period, T of the structure;

I = Importance factor as per Table 3; and

R = Response reduction factor as per Table 4.

7.3.2 When using design spectrum given in this standard, the design horizontal seismic coefficient A_h shall be estimated as:

$$A_h = \frac{Z}{2}\left(\frac{S_a}{g}\right)\frac{I}{R}$$

where

Z = Seismic Zone Factor given in given in Table 13 [Seismic Zone Factors for some important towns are listed in Annex E of IS 1893 (Part 1)];

$\left(\frac{S_a}{g}\right)$ = Spectral acceleration coefficient for different soil types, normalized with peak ground acceleration, as given in Fig. 1 (Annex C), corresponding to fundamental natural period, T of structure. These values are for 5 percent damping. Multiplying factors for obtaining the spectral values for other damping values are given in Table 14 (Annex B);

*Here *N* is the corrected standard penetration test value after ground improvement if required.

I = Importance factor given in Table 3;

R = Response reduction factor given in Table 4; and

T = Natural period of the structure (*see* **9.3** and **14**).

Ratio $\left(\frac{I}{R}\right)$ shall, in no case, be larger than 1.0.

7.4 Design Vertical Seismic Coefficient

Design vertical seismic coefficient $A_{\rm v}$ shall be in accordance with **6.4.6** of IS 1893 (Part 1).

SECTION 1 INDUSTRIAL STRUCTURES

8 DESIGN CRITERIA

8.1 Categorization of Structures

8.1.1 To perform well in an earthquake, industrial structures shall possess adequate strength, stiffness and ductility.

8.1.2 Industrial structures shall be classified into the following 4 categories:

a) Category 1

i) Structures, whose failure (including failure due to hazard of fire, explosion or air and water poisoning) can cause conditions that can lead directly or indirectly to extensive loss of life/property to population at large in the areas adjacent to the industrial facility, or

ii) Structures that support components and equipment whose failure can cause conditions that can lead directly or indirectly to extensive loss of life/property to population at large in the areas adjacent to the industrial facility.

b) Category 2

i) Structures not falling in Category 1, whose failure can cause conditions that can lead directly or indirectly to extensive damage (including due to consequent fire hazards) within the industrial facility, or

ii) Structures in industrial facilities, which are required to handle emergencies immediately after an earthquake, such as hospitals, communication facilities etc. are also included under this category, or

iii) Structures that support components and equipment that do not fall in Category 1 and whose failure can cause conditions that can lead directly or indirectly to extensive damage (including due to consequent fire hazards) within the industrial facility.

c) Category 3

i) High monetary value structures or structures housing expensive plant, machinery or equipment, and not falling in Categories 1 and 2, or

ii) Structures that support high monetary value components and equipment that do not fall in Categories 1 and 2.

d) Category 4

All other structures, components and equipment not included in Categories 1, 2 and 3.

8.1.3 Typical categorization of industrial structures is given in Tables 6, 7 and 8. These are applicable for design of equipment, as well as its supporting structure and their foundation.

NOTES

1 The term failure used in the definition of categories implies loss of function and these structures, components and equipment may not experience complete collapse.

2 Pressurized equipment where cracking can lead to rupture may be categorized based on the severity of consequences of rupture.

3 Mixed use of structures where components of more than one category are present, the entire structure shall comply with the requirement of the most stringent category.

8.2 Design Loads

8.2.1 *Dead Load* (*DL*)

The dead loads shall be taken as per IS 875 (Part 1).

8.2.2 *Super Imposed Dead Loads* (*SIDL*)

Industrial structures contain equipment and associated fluids, bulk materials, auxiliaries and accessories, which are mounted permanently on the structures. These loads shall be taken in accordance with equipment specifications.

NOTES

1 These loads may be provisional, that is, during service, some of SIDL (or at some locations) may be smaller or negligible. Such variations should be accounted in the design of individual members.

2 Equipment supported on a structure can have multipleoperational scenarios such as empty, partially full and full. These operational scenarios may result in mass irregularities that shall be duly accounted for. In case of multiple equipment supported on a structure, various possible combinations of operational conditions shall be considered.

8.2.3 *Imposed Loads* (*IL*)

These shall be taken as per IS 875 (Part 2).

8.2.4 *Maintenance Specific Imposed Loads* (*MSIL*)

These shall be taken as per **4.7**.

8.2.5 *Earthquake Loads* (*EL*)

Earthquake force estimation, analysis, and design for various categories of structures shall comply with Table 2.

8.2.6 *Other Loads*

Whenever loads and load effects due to temperature changes, soil and hydrostatic pressures, accidental loads etc. are to be considered in the design of industrial structures, the same shall be as per IS 875 (Part 5).

8.3 Load Combinations

When earthquake loads are considered on a structure, the response quantities (namely member forces, displacements, storey forces, shears and base reactions) due to dead load (DL), imposed load (IL), super imposed dead loads (SIDL), maintenance specific imposed loads (MSIL), and design earthquake load (EL) shall be combined as per **8.3.1** and **8.3.2**.

8.3.1 *Partial Safety Factors for Limit State Design and Load Factors for Plastic Design of Steel Structures*

a) Partial Safety Factors for Loads in Limit State Design

In the limit state design of steel structures, load combinations shall conform to applicable clauses of IS 800.

b) Load Factors in Plastic Design

In the plastic design of steel structures, load combinations considered shall include:

1) $1.7(\mathrm{DL} + \mathrm{SIDL} + \mathrm{IL} + \mathrm{MSIL})$

2) $1.7(\mathrm{DL} + \mathrm{SIDL} + \mathrm{MSIL}) \pm 1.7\mathrm{EL}$

3) $1.3(\mathrm{DL} + \mathrm{SIDL} + \mathrm{IL} + \mathrm{MSIL} \pm \mathrm{EL})$

In these load combinations, MSIL shall be as per **6.2 (c)**, and IL shall not include erection loads and crane loads.

8.3.2 *Partial Safety Factors for Loads in Limit State Design of Reinforced Concrete and Pre Stressed Concrete Structures*

In the limit state design of reinforced and prestressed concrete structures, load combinations considered shall include:

a) $1.5(\mathrm{DL} + \mathrm{SIDL} + \mathrm{IL} + \mathrm{MSIL})$

b) $1.2(\mathrm{DL} + \mathrm{SIDL} + \mathrm{IL} + \mathrm{MSIL} \pm \mathrm{EL})$

c) $1.5(\mathrm{DL} + \mathrm{SIDL} + \mathrm{MSIL} \pm \mathrm{EL})$

d) $1.5(0.6\mathrm{DL} \pm \mathrm{EL})$

In these load combinations, MSIL shall be as per **6.2 (c)**, and IL shall not include erection loads and crane loads. Partial safety factor for load due to prestressing effect shall be as per IS 1343.

8.3.2.1 In industrial structures, the plan-wise distribution of mass and stiffness of the structural system may or may not be symmetrical about two lateral directions, that is, along X and Y directions in plan. When responses from the three earthquake components are to be considered, the response due to each component shall be combined as per **8.3.2.1.1** and **8.3.2.1.2**.

8.3.2.1.1 Where the plan-wise distribution of mass and stiffness of the structural system is not symmetrical about two plan (X and Y) directions, the response due to each component shall be combined such that when the maximum response from one component occurs, the responses from the other horizontal and vertical components are 30 percent of the corresponding maxima along those directions.

All possible combinations of the three components ($\mathrm{EL_X}$, $\mathrm{EL_Y}$, $\mathrm{EL_Z}$) including variations in sign (plus or minus) shall be considered. Thus, the response due to earthquake force (EL) shall be the maximum of the following:

$$\mathrm{EL} = \begin{cases} \mathrm{EL_X} \pm 0.3\,\mathrm{EL_Y} \pm 0.3\,\mathrm{EL_Z} \\ \mathrm{EL_Y} \pm 0.3\,\mathrm{EL_X} \pm 0.3\,\mathrm{EL_Z} \\ \mathrm{EL_Z} \pm 0.3\,\mathrm{EL_X} \pm 0.3\,\mathrm{EL_Y} \end{cases}$$

As an alternative to the above procedure, the response (EL) due to the combined effect of the three components can be obtained on the basis of square root of the sum of the squares (SRSS), as:

$$\mathrm{EL} = \sqrt{(\mathrm{EL_X})^2 \pm (\mathrm{EL_Y})^2 \pm (\mathrm{EL_Z})^2}$$

Table 2 Earthquake Force Estimation, Method of Analysis and Design for Various Categories of Structures

(*Clauses* 8.2.5 *and* 10.3.1)

Sl No.	Structure Category (*see* **8.1**)	Earthquake Force Estimation			Method of		Minimum Lateral Force (Percent of Seismic Weight W) for different Zones			
		Seismic Hazard Assessment Method	Damping Ratio	Method of Calculating Natural Period	Structural Analysis Method	Structural Design	II	III	IV	V
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(i)	1	Site-specific assessment as per **7.1**	5 percent for RC structures and 2 percent for steel structures (*see* **9.4**; **15** and Table 5)	(*see* **9.1**, **9.3**, **14.1** and **14.2**) Modal analysis with all stiffnesses of the lateral as well as vertical load resisting members and masses of the structures modeled (For preliminary natural period estimation, *see* **9.3.1**)	a) Linear for design, and b) Nonlinear response history analysis for verification of mechanism (*see* Note)	Limit state design as per IS 456 for RC structures and as per IS 800 and IS 18168 for steel structures	2.00	2.75	4.00	6.00
(ii)	2	Site-specific assessment as per **7.1**	-do-	-do-	Linear for design	-do-	1.50	2.00	3.00	4.50

Table 2 (*Concluded*)

Sl No.	**Structure Category** (*see* **8.1**)	**Earthquake Force Estimation**			**Method of**		**Minimum Lateral Force (Percent of Seismic Weight W) for different Zones**			
		Seismic Hazard Assessment Method	Damping Ratio	Method of Calculating Natural Period	Structural Analysis Method	Structural Design	II	III	IV	V
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(iii)	3	Site-specific assessment as per **7.1** or assessment as specified in **7.2**	-do-	-do-	-do-	-do-	1.25	1.75	2.50	3.75
(iv)	4	Site-specific assessment as per **7.1** or assessment as specified in **7.2**	-do-	-do-	-do-	-do-	1.00	1.50	2.00	3.00

NOTE — Specialist literature shall be referred for nonlinear response history analysis for verification of mechanism, wherever required.

8.3.2.1.2 Where the plan-wise distribution of mass and stiffness of the structural system is symmetrical about two plan (X and Y) directions, the structure shall be designed for the effects due to full design earthquake force in one horizontal plan direction at a time combined with those due to 30 percent of full earthquake force along the vertical (Z) direction.

Thus, the response due to earthquake force (EL) shall be the maximum of the following:

$$\mathrm{EL} = \begin{cases} \pm \mathrm{EL_X} \pm 0.3\ \mathrm{EL_Z} \\ \pm \mathrm{EL_Y} \pm 0.3\ \mathrm{EL_Z} \\ \pm \mathrm{EL_Z} \pm (0.3\ \mathrm{EL_X} \text{ or } \pm 0.3\ \mathrm{EL_Y}) \end{cases}$$

8.3.2.1.3 The combination procedures of **8.3.2.1.1** and **8.3.2.1.2** apply to the same response quantity (say, moment in a column about its major axis, or storey shear in a frame) due to different components of the ground motion. These combinations shall be made at the member force or stress level.

8.3.3 Other loads in accordance with **8.2.6** shall be combined as per IS 875 (Part 5).

8.4 Seismic Weight

8.4.1 *Seismic Weight of Floor*

Seismic weight of each floor is sum of its full dead load (DL), superimposed dead load (SIDL), percentage of imposed load (IL) as specified in IS 1893 (Part 1) and applicable maintenance specific imposed loads (MSIL) as per **6.2(c)**. Weight of piping, cable trays, any other such utility that runs across the floors shall be included in the seismic weight of upper and lower supporting floors using law of statics.

8.4.2 *Seismic Weight of Structure*

Seismic weight of structure is the sum of seismic weight of each floor.

8.5 Importance Factor (*I*)

Relative importance assigned to a structure to take into account the consequences of its damage. Importance factors for structures in different categories are given in Table 3. Higher importance factor may be assigned to different structures at the discretion of the project authorities.

8.6 Response Reduction Factor (*R*)

Response reduction factor *R*, takes into account the margins of strength, safety, redundancy and ductility of the structure. For industrial structures including stack-like structures, response reduction factors are given in Table 4. These factors shall be used only for steel and RCC structures/support structures and not for design of equipment. For equipment, $\left(\frac{I}{R}\right) = 1$ shall be used.

Table 3 Importance Factor *I* for Various Categories of Industrial Structures and Stack-Like Structures

(*Clauses* 7.3.1, 8.5, 7.3.2, 12.4.2.1 *and* 12.4.2.2)

Sl No. (1)	*Categories of Structures (*see* **8.1**) (2)	Importance Factor *I* (3)
i)	Structures in Category 1	2.00
ii)	Structures in Category 2	1.50
iii)	Structures in Category 3	1.20
iv)	Structures in Category 4	1.00

*Categorization of individual structure and components applicable to typical industries are given in Tables 6, 7 and 8.

Table 4 Response Reduction Factor, *R* for Industrial Structures and Stack Like Structures (*Clauses* 7.3.1, 7.3.2 *and* 8.6)

Sl No. (1)	Lateral Force Resisting System (2)	*R* (3)
i)	Moment frame systems:	
	a) RC structures with ordinary moment resisting frame (OMRF) (*see* Note 1a)	3.0
	b) RC structures with special moment resisting frame (SMRF)	5.0
	c) Steel structures with ordinary moment resisting frame (OMRF) (*see* Note 1a)	3.0
	d) Steel structures with special moment resisting frame (SMRF)	5.0
ii)	Braced frame systems (*see* Note 2):	
	a) Structures with ordinary braced frame (OBF) having concentric braces	4.0
	b) Structures with special braced frame (SBF) having concentric braces	4.5
	c) Structures with special braced frame (SBF) having eccentric braces	5.0
iii)	Structural wall systems (*see* Note 3):	
	a) Structures with load bearing masonry walls	
	1 Unreinforced masonry without horizontal RC seismic bands (*see* Note 1a)	1.5
	2 Unreinforced masonry with horizontal RC seismic bands	2.0
	3 Unreinforced masonry with horizontal RC seismic bands and vertical reinforcing bars at corners of rooms and jambs of openings (with reinforcement as per IS 4326)	2.5
	4 Reinforced masonry [*see* SP 7 (Part 6/Sec 4)]	3.0
	5 Confined masonry [*see* SP 7 (Part 6/Sec 4)]	3.0
	b) Structures with ordinary RC structural walls (*see* Note 1a)	3.0
	c) Structures with RC special structural walls (SSW)	4.0
iv)	Dual systems (*see* Notes 3 and 4)	
	a) Structures with ordinary RC structural walls and RC OMRFs (*see* Note 1a)	3.0
	b) Structures with ordinary RC structural walls and RC SMRF*s* (*see* Note 1a)	4.0
	c) Structures with RC special structural walls with RC OMRFs (*see* Note 1a)	4.0
	d) Structures with RC special structural walls with RC SMRFs	5.0
v)	Flat slabs (Two-way slabs without beams) (*see* Note 1b)	2.5
vi)	Structures designed to remain elastic	1.0
vii)	Stack like Structures:	
	a) Reinforced concrete ventilation stacks	1.5
	b) Reinforced concrete chimneys	1.5
	c) Reinforced brick masonry chimney	1.25
	d) Unreinforced brick masonry chimney	1.0

Table 4 (*Concluded*)

Sl No. (1)	Lateral Force Resisting System (2)	*R* (3)
	e) Reinforced concrete TV towers	1.5
	f) Reinforced electric and traffic poles	2.0
	g) Steel chimneys and HRSG steel stack	2.0
	h) Slender and thin-walled silos (*see* Note 6)	2.0
	j) Squat and thin-walled silos (*see* Note 6)	2.0
	k) Squat and thick-walled silos (*see* Note 6)	3.0
	m) Steel refinery vessels	2.0
	n) Steel tubular support structures for onshore wind turbine generator systems	1.5
	p) Natural draught cooling tower	1.5

NOTES

1 Limitations on use of lateral force resisting systems:

a) RC and steel structures in Seismic Zones III, IV and V shall be designed to be ductile. Hence, this system is not allowed in these seismic zones.
b) Flat slabs (two-way slab without beams) as a part of lateral force resisting system are permitted in Seismic Zones II and III only for buildings with height less than 20 m.

2 Eccentric braces shall be used only with SBFs.

3 Structures with structural walls shall also include structures having structural walls and moment frames, but where:

a) Frames are not designed to carry lateral loads; or
b) Frames are designed to carry lateral loads but do not fulfill the requirements of 'dual systems'.

4 In case of dual system, the moment resisting frames shall be designed to independently resist at least 25 percent of the design base shear.

5 Structures or equipment not defined in the table above, shall have the *R* value based on the strength, safety, redundancy and ductility requirement keeping its usage/earthquake damage level in consideration.

6 Classification of silos are as follow:

Slender silo:	Height/inner diameter ≥ 1.0
Squat silo:	0.4 < height/inner diameter < 1.0
Thick-walled silo:	Inner diameter/wall thickness ≤ 200
Thin-walled silo:	Inner diameter/wall thickness > 200

For silos supported on moment resisting frames or on frames with bracings, and for cast-in-place concrete silos supported on concrete walls continuous to the foundation, *R* values defined in the above table for the corresponding structural system times a factor equal to 0.7 shall be considered.

9 MATHEMATICAL MODELLING

9.1 Modelling Requirements

The mathematical model of the physical structure shall include all elements of the lateral force-resisting system. Also, the model shall include the stiffness and strength of elements, which are required for the distribution of forces. The model shall represent properly the spatial distribution of the mass and stiffness of the structures, especially the mass of equipment, cable trays and piping systems and the associated accessories. Further, fifty percent (50 percent) of the imposed load shall be included, besides SIDL and MSIL, as distributed mass on the structure.

9.1.1 *Effective Moment of Inertia*

For structural analysis of RC structures, the effective moment of inertia shall be considered as per **6.4.3.1** of IS 1893 (Part 1).

9.1.2 *Soil-Pile Structure Interaction*

The soil-structure interaction refers to the effects of the supporting foundation medium on the motion of structure. Specialist literature may be referred to include this effect. But, maximum reduction in the base shear on account of soil-structure interaction shall not be more than 20 percent of base shear of fixed base structure.

The soil-structure interaction shall not be considered in the seismic analysis of structures supported on rock or hard soil or rock-like material (with $N > 50$ or $V_s \geq 760$ m/s).

9.2 Interaction Effects between Primary and Secondary Systems

The design seismic forces on the structure (primary system) and equipment (secondary system) falling under Categories 2, 3 and 4 shall be considered as per **9.2.1** and **9.2.2**. For primary and secondary systems falling under Category 1, the design seismic forces shall be estimated as per **9.2.3**.

9.2.1 For estimation of design seismic forces in primary systems, interaction effects between structure and equipment shall be considered as given below:

9.2.1.1 Wherever secondary system is rigidly supported or fastened to the floor of the primary system, the secondary system mass M_R, shall be considered as lumped mass at its support location appropriately. No interaction between the primary and secondary systems need to be considered.

9.2.1.2 For flexibly mounted secondary system with mass, M_F, that is, equipment mounted on *isolators*, one of the following two procedures shall be adopted:

a) If $\frac{M_F}{M_{ps} + M_F} < 0.20$, no interaction needs to be considered between the primary and secondary systems. In such a case, M_F should be considered as lumped mass at appropriate locations.

b) If $\frac{M_F}{M_{ps} + M_F} \geq 0.20$, the interaction between the primary and secondary systems shall be considered by suitably modelling the flexibly mounted support system while considering the equipment as lumped mass (coupled analysis).

9.2.2 For estimation of design seismic forces in secondary systems falling under Categories 2, 3 and 4, one of the following two procedures shall be adopted:

a) Decoupling criteria as given in Annex D shall be used for the interaction effects.

b) Specialist literature on design on secondary system shall be referred.

9.2.3 For Category 1 structures**,** the design seismic forces shall be estimated considering the decoupling criteria as given in Annex D for the interaction effects between primary system (structure) and secondary system (equipment).

9.3 Design Base Shear

The fundamental natural period of different industrial structures varies considerably depending upon structural configuration, height of the structure, soil conditions and appropriate percent of SIDL, IL and MSIL, as per applicable clauses. A single generalized formula for the natural period may not cover all such structures and may lead to erroneous results in certain cases. Hence, no simple guidelines can be given for estimation of natural period of industrial structures.

Whenever masonry infill walls contribute to the in-plane stiffness of the structure, two different mathematical models are required to be considered during design. In the first mathematical model, the stiffness of infill wall panel shall be accounted and modeled as diagonal struts. IS 1893 (Part 1) shall be referred for modeling of equivalent diagonal strut and for estimation of in-plane stiffness of the masonry infill walls. This model shall be used for estimation of natural periods and storey drifts. The base shear of the model V_{BI} shall be estimated from this model.

The second mathematical model shall be a model of the bare frame structure without considering the stiffness of the infills. The mass of the infill shall be duly considered in the model. The second model shall be used for the estimation of forces in the structural members. The base shear of this model, V_{BB}, shall be enhanced by the ratio of V_{BI}/V_{BB} to obtain the design base shear. Similar amplification by this ratio shall be carried out for all member seismic forces. But, this amplification shall not be applied to storey drifts.

The formulae given in IS 1893 (Part 1), for estimation of natural period for buildings (*see* **7.6**) are not applicable for industrial structures. Therefore, there is no need to increase base shear, $\overline{V_B}/V_B$ for industrial structures, as recommended for buildings in IS 1893 (Part 1).

The natural period shall be estimated by Eigen value analysis of the structural mathematical model developed in accordance with **9.1**, **9.2** and **9.3**.

9.3.1 For preliminary design, the fundamental natural period can be established based on its static deflection under mass proportional loading in each of the three principal directions. The structure is analyzed by applying a force equal to the weight of the structure or equipment at each corresponding node in X, Y or Z direction (one at a time) and corresponding deflection δ is evaluated in X, Y and Z direction.

The fundamental natural period T (in s), would then be:

$$T = 2\pi\sqrt{\frac{\delta}{g}},$$

where δ is the maximum value of deflection of the structure (maxima out of δ_x, δ_y and δ_z) and g is acceleration due to gravity, both of which are taken in consistent units.

9.3.1.1 Where the founding soil is soft soil, the effect of the same shall also be considered in the model for estimation of static deflection.

9.4 Damping

The damping ratio to be used in determining spectral acceleration coefficient $\left(\frac{S_a}{g}\right)$ depends on the material. The recommended damping ratios are given in Table 5.

9.4.1 For combined structures with more than one material, damping ratio shall be determined based on well established procedures.

9.4.2 If such a composite damping ratio is not evaluated, it shall be taken as that corresponding to material having lower damping.

9.4.3 When soil-structure interaction effects are considered, the composite modal damping values shall be estimated. The estimated composite modal damping values shall be limited to 20 percent of critical damping.

9.4.4 The damping ratio of water and other liquids contained in tanks shall be considered as 0.5 percent unless otherwise determined. For other liquids in sloshing mode, specialist literature shall be referred for damping ratio.

9.4.5 The damping ratio of granular materials contained in tanks and silos shall be considered as 10 percent.

Table 5 Damping Ratio for Different Construction Materials

(*Clauses* 9.4 *and* 15)

Sl No.	Material	Damping Ratio
(1)	(2)	(3)
i)	Aluminum	0.02
ii)	Steel	0.02
iii)	Reinforced concrete	0.05
iv)	Brick masonry and plain concrete	0.07
v)	Pre-stressed concrete	0.03

NOTE — For equipment, storage tanks, onshore wind turbine generator system and piping system, reference may be made to specialist literature for damping ratio.

10 DYNAMIC ANALYSIS

10.1 Dynamic analysis shall be performed for the three orthogonal (two horizontal and one vertical) components of earthquake motion resulting in evaluation of earthquake loads EL_X, EL_Y, EL_Z on the structure. The influence of $P - \Delta$ effect (*see* **10.5**) as well as torsion (*see* **10.6**) shall be included in the dynamic analysis.

Detailed dynamic analysis (*see* **10.3**) shall be carried out for:

a) Structures of Category 1 in all seismic zones;
b) Structures of Category 2 in Seismic Zones III, IV and V; and
c) Structures of Category 3 in Seismic Zones IV and V.

Simplified dynamic analysis (*see* **10.4**) may be carried out for:

a) Structures of Category 2 in Seismic Zone II;
b) Structures of Category 3 in Seismic Zones II and III; and
c) Structures of Category 4 in all seismic zones.

10.2 Those Category 4 structures which are identified as buildings and whose failure does not affect plant performance, may be analyzed and designed in accordance with the provisions of IS 1893 (Part 1).

10.3 Detailed Analysis

Detailed dynamic analysis shall be performed by either the response history method or the response spectrum method.

10.3.1 *Response History Method*

a) Specialist literature shall be referred while carrying out nonlinear response history analysis of Category 1 structures subjected to seismic loads for study of safety against collapse (*see* Table 2).

b) All industrial structures shall be designed using linear analysis and all deflection and drifts are also limited as per linear analysis approach.

c) The floor response spectra for use in design of secondary systems (like piping and equipment supports) shall be generated by linear response history analysis from linear structural analysis or by a direct spectra-to-spectra method within their established range of applicability.

10.3.2 *Response Spectrum Method*

Analysis using Response Spectrum Method shall be performed using the spectra specified in **7.3.2** or by a site-specific spectra mentioned in **7.3.1**.

10.3.2.1 Sufficiently large number of modes shall be used for response spectrum method to include the influence of at least 90 percent of the total seismic mass. The modal seismic mass shall be evaluated as per **10.3.2.2**.

10.3.2.2 *Modal Mass*

The modal mass M_k in mode 'k' is given as:

$$M_k = \frac{\sum_{i=1}^{n} [W_i \varphi_{ik}]^2}{g \sum_{i=1}^{n} W_i (\varphi_{ik})^2}$$

where

g = acceleration due to gravity;
φ_{ik} = mode shape coefficient at floor i in mode k;
W_i = seismic weight of floor i of the structure; and
n = number of floors of the structure.

10.3.2.3 *Modal Combination*

The peak response quantities (for example, member forces, displacements, storey forces, storey shears, and base reactions) shall be combined as per complete quadratic combination (CQC) method as follows:

$$\lambda = \sqrt{\sum_{i=1}^{r} \sum_{j=1}^{r} \lambda_i \rho_{ij} \lambda_j}$$

where

λ = estimate of peak response quantity;
λ_i = response quantity of mode i (with sign);
λ_j = response quantity of mode j (with sign);
ρ_{ij} = cross-modal correlation coefficient, expressed as

$$\rho_{ij} = \frac{8\zeta^2 (1+\beta)\beta^{1.5}}{(1-\beta^2)^2 + 4\zeta^2 \beta (1+\beta^2)}$$

r = number of modes being considered;
ζ = modal damping ratio as specified in **9.4**;
β = frequency ratio = $\frac{\omega_j}{\omega_i}$
ω_i = circular natural frequency in mode i; and
ω_j = circular natural frequency in mode j.

Alternately, the peak response quantities may be combined as follows:

a) If the structure does not have closely-spaced modes, then the peak response quantity λ due to all modes considered shall be obtained as:

$$\lambda = \sqrt{\sum_{k=1}^{r} (\lambda_k)^2}$$

where

λ_k = peak response quantity in mode k; and
r = number of modes being considered.

b) If the structure has a few closely-spaced modes, then the peak response quantity λ^* due to these closely-spaced modes alone shall be obtained as:

$$\lambda^* = \sum_{c} |\lambda_c|$$

where

λ_c = Peak response quantity in closely spaced mode c. The summation is for the closely spaced modes only. Then this peak response quantity λ* due to the closely spaced modes is combined with those of the remaining well-separated modes by the method described above.

10.4 Simplified Dynamic Analysis

Simplified dynamic analysis shall be carried out by applying equivalent static seismic forces along each of the three principal directions. The horizontal seismic coefficient A_h shall be determined in accordance with 7.3.1 for site-specific spectra or 7.3.2 for design spectrum given in this standard, as the case may be, using fundamental natural period T as per 9.3.1.

Design vertical seismic coefficient A_v shall be in accordance with **6.4.6** of IS 1893 (Part 1).

The seismic force at each node in each of the three directions shall be equal to the product of its seismic weight and corresponding seismic coefficient.

10.5 $P - \Delta$ Effect

Structures in all categories and in all seismic zones shall be analyzed to account for the $P - \Delta$ effect.

10.6 Torsion

The torsional effect of accidental eccentricity shall be considered for structures of Category 4 in all seismic zones.

This effect shall be considered for structures with rigid floors or diaphragms. This effect shall be applied as an additional torsional moment equal to product of the seismic force at floor level and 5 percent of the structure dimension perpendicular to the earthquake direction at the centre of mass of the floor.

10.6.1 The design eccentricity e_{di} to be used at floor i shall be taken as:

$$e_{di} = \begin{cases} (a)\ 1.5\, e_{si} + 0.05\, b_i \\ (b)\ e_{si} - 0.05\, b_i \end{cases}$$

Analysis shall be performed for both cases, and at the member force level, the more severe effect of the two cases shall be considered.

e_{si} = static eccentricity at floor i; and

b_i = floor plan dimension of floor i, perpendicular to direction of force

The factor 1.5 represents dynamic amplification factor, and $0.05b_i$ the extent of accidental eccentricity. The above amplification of 1.5 need not be used when performing structural analysis by the dynamic analysis method.

NOTES

1 For the purposes of this clause, all Steel or Aluminum flooring system shall be considered as flexible unless properly designed floor bracings have been provided.

2 Reinforced concrete flooring systems in steel structures shall be considered flexible, unless formally designed floor bracings are provided.

3 Reinforced concrete flooring system at a level shall be considered rigid only if the total area of all the cut-outs at that level is less than 25 percent of the floor plan area at that level.

11 DEFORMATION

11.1 Storey Drift Limitation

The storey drift in any storey of a structure shall not exceed 0.004 times the storey height, under the action of base shear V_{BI} with partial safety factor for all loads taken as 1.0.

11.2 Separation Between Adjacent Units

To avoid damage due to pounding between two adjacent structures, or due to two adjacent units of the same structure, they shall be separated by a distance equal to the square root of sum of squares of inelastic storey displacements, R_1 times Δ_1 and R_2 times Δ_2 evaluated as per 11.1, given by

$$\Delta_{sep} = \sqrt{(R_1\Delta_1)^2 + (R_2\Delta_2)^2},$$

where R_1 and Δ_1 correspond to structure 1, and R_2 and Δ_2 correspond to structure 2.

12 MISCELLANEOUS

12.1 Foundations

Isolated RC footings without tie beams or unreinforced strip foundations, shall not be permitted in soft soils (with corrected $N < 10$) in any seismic zone. Use of foundations that are vulnerable to significant differential settlement due to ground shaking, shall not be used for structures in Seismic Zones III, IV and V. In Seismic Zones IV and V, individual spread footings or pile caps shall be interconnected with ties (*see* **5.3.4.1** of IS 4326), except when individual spread footings are directly supported on rock. All ties shall be capable of carrying, in tension and in compression, an axial force equal to $A_h/4$ times the larger of the column or pile cap load, in addition to the otherwise computed forces, subjected to a minimum of 5 percent of the larger of the column or pile cap loads. Here, A_h is as per 7.3.1 or 7.3.2.

In case the interconnection between individual spread footings or pile caps is not feasible due to interference between foundations (such as dynamic equipment foundations, large span equipment foundations etc), it shall be demonstrated that equivalent restraint is provided by RC beams within slabs on grade or RC slabs on grade or confinement by competent rock, hard cohesive soils, very dense granular soils or other approved means.

Wherever piles are provided, these shall be designed and constructed to withstand the effects of maximum response induced in the part of the structure above the foundation under earthquake ground shaking. Design of anchorage of piles into pile cap shall consider combined effects, including that of axial forces due to uplift and bending moments due to fixity to pile cap.

Pile foundations shall have the capacity to resist the effect due to inertia forces induced by earthquake ground shaking from the superstructure and the foundation.

12.2 Cantilever Projections

12.2.1 *Vertical Projections*

Towers, tanks, parapets and other vertical cantilever projections attached to structures and projecting above the roof, but not a part of structural system, shall be designed for five times the design horizontal seismic coefficient A_h specified in 7.3.1 and 7.3.2. In the analysis of the structure, weights of these projecting elements shall be lumped with the roof weight.

12.2.2 *Horizontal Projections*

All cantilever structural members of structure or all horizontal projections attached to structures (like brackets, cornices and balconies) shall be designed for five times the design vertical acceleration coefficient A_v specified in 7.4.

12.2.3 The increased design forces specified in 12.2.1 and 12.2.2 are only for designing the projecting parts and their connections with the main structures, and not for the design of the main structure.

12.3 Non-Structural Elements in Industrial Structures

Specialist literature shall be referred for earthquake resistant design of non-structural elements (NSE) of industrial systems (such as cable trays, bus ducts, HVAC ducting, piping, etc). The provisions given in IS 16700 may be used.

12.4 Additional Provisions

12.4.1 *Structure Supporting Cranes*

While evaluating earthquake ground shaking effects on the structure supporting cranes in horizontal direction, the seismic mass of cranes moving and trolleys without payloads shall be considered. Payloads shall only be considered for the effects due to vertical shaking. In case of more than one crane in a bay or in parallel bays, the design shall consider a load combination with all the cranes unloaded and parked at the most unfavourable position.

12.4.2 *Liquid Storage Tanks*

12.4.2.1 For seismic design of liquid storage tanks in an industrial structure, its category shall be as per Table 7, the Importance Factor shall be as per Table 3 and the design shall be carried out as per IS 1893 (Part 2).

12.4.2.2 For the seismic design of ground supported flat bottom liquid storage tanks, that are not covered by IS 1893 (Part 2), specialist literature shall be referred. For such tanks, the Category shall be as per Table 7 and the Importance Factor shall be as per Table 3.

12.4.2.3 Foundations and footings for mechanically-anchored flat-bottom tanks shall be proportioned to resist peak anchor uplift and overturning bearing pressure. Overturning stability shall be evaluated for uplift due to seismic moment. The factor of safety against overturning stability shall be at least 2.0.

12.4.2.4 Content weight and soil load directly over the ring-wall and footing may be used to resist the maximum anchor uplift on the foundation, provided the ring-wall and footing are designed to carry the eccentric loading.

12.4.3 *Anchorages*

12.4.3.1 Anchorage design shall be based on ductile design philosophy. Common types of concrete and steel failure modes for anchors are due to:

a) Brittle failure:

1 Failure of the concrete part considering concrete breakout strength of anchor in tension;
2 Pullout strength of anchor in tension;
3 Side-face blowout of concrete due to tensile force in anchor bolts with headed or hooked ends;
4 Bond strength of adhesive anchor in tension;
5 Concrete breakout strength of anchor in shear; and
6 Concrete pry-out strength of anchor in shear as applicable.

b) Ductile Failure: Failure of the anchors based on steel strength of anchor in tension, and steel strength of anchor in shear.

12.4.3.2 The following shall be ensured in design of ductile anchorage systems:

a) Anchoring capacity of the concrete shall be greater than 1.2 times that of the nominal tensile capacity of the anchor bolt;
b) Anchor bolt shall be designed for tension, shear and combination of shear & tension. Out of these, the design shall be made to govern by tension criterion; and
c) Friction between the base plate and the foundation shall not be considered in the design of anchorage elements while transferring shear forces to the foundation system.

Specialist literature shall be consulted for calculating the concrete anchor capacity.

12.4.4 *Structural Considerations During Maintenance*

In industrial structures, key structural elements that are part of seismic-force resisting system may be required to be temporarily removed, as dictated during the erection, replacement and maintenance of large size equipment and machinery. Such removal of structural elements may result in change in centre of resistance leading to alternate load path for resisting seismic forces than originally designed. For such structures, seismic analysis shall be carried out for both the conditions, that is, with and without removal of these key structural elements. Further, structural stability shall be assessed under both of these conditions.

12.4.5 *Bunkers and Silos*

The requirements shall be as given hereunder:

a) Categories indicated in Tables 7 and 8 for Bunkers and Silos are applicable to all RCC and steel bunkers and silos as well as RCC Silos supported on RCC frame and RCC shafts;
b) For design of Silos and Bunkers, seismic forces shall be estimated considering full range of material loading, that is, from empty condition to full condition. The most critical condition shall be adopted for design;
c) The effects of earthquake ground shaking in the supporting structure shall be estimated assuming that the particulate contents move together with the silo shell and modelling them with their effective mass at their centre of gravity; and
d) The unit weight of stored material used for computing seismic forces shall be same as that used for all load calculations.

12.4.6 *Pre-Engineered Steel Structures*

Pre-Engineered steel industrial structures (for example, Pre-engineered Buildings) shall be checked for adequacy against earthquake effects as per the provisions of this standard. Steel design and detailing, member sizing, check for deflections and minimum member thickness shall also conform to IS 800 and IS 18168. Loads and load combinations shall be as per IS 800 and IS 1893 (Part 1).

Table 6 Categorization of Industrial Structures

(*Foreword*, *Clause* 8.1.3)

Sl No.	Structures	Category
	A. Main Plants and Process Plants	
	(Power plants, Hydrocarbon plant, Chemical, Fertilizer and Metallurgy plants etc)	
i)	Bagging and palletizing building	2

Table 6 (*Continued*)

Sl No.	Structures	Category
ii)	Boiler house	2
iii)	Coke drum structure	2
iv)	Compressor or expander foundation	2
v)	Compressor house	2
vi)	Control building (Power plant)	2
vii)	Control building or Satellite rack room	2
viii)	Generator building and house	2
ix)	Main plant building (TG bay and Electrical bay)	2
x)	Mill and bunker bay structure	2
xi)	Machine foundations of main plant (Turbo generator, Turbo compressor, Pumps, Fans, Mills, etc)	2
xii)	Pipe rack with or without Deaerator, Air fin coolers, Two phase flow lines	2
xiii)	Polymerization and extrusion building	2
xiv)	Process building closed or open conforming to Note 1	1
xv)	Process building closed or open conforming to Note 2	2
xvi)	Reactor – regenerator supporting structure conforming to Note 1	1
xvii)	Reactor – regenerator supporting structure conforming to Note 2	2
xviii)	Sheds (tall and large span, high-capacity cranes, like pot room and cast house)	2
xix)	Substation buildings	2
xx)	Substation of power plant	2
xxi)	Switch-gear building (Power plant)	2
xxii)	Switchyard structures	2
xxiii)	Technological structures in RCC or steel supporting process columns and equipment conforming to Note 1	1
xxiv)	Technological structures in RCC or Steel supporting process columns and equipment conforming to Note 2	2
	B. Utilities	
	[Water system (Intake, Conveying, Treatment, Storage and Pumping), ETP/ STP/Waste water treatment plant, DM water, Condensate polishing, RO plant, Cooling water system, Fire protection/Extinguishing, Fighting system, Air separation unit, Nitrogen/Oxygen plant, Fume and Gas treatment plant, Captive power plant, Service buildings]	
i)	Air washer pump house	4
ii)	Air or nitrogen compressor foundation	2
iii)	Ash dyke	3
iv)	Ash water pump house	4
v)	Ash water re-circulation building	4
vi)	Ash or slurry pump house	4
vii)	Boiler house	2
viii)	Bottom ash hopper and conveying system	2
ix)	Chiller plant	3
x)	Coal handling plant	3
xi)	Coal slurry settling pond	4
xii)	Compressor house and turbine house	2

Table 6 (*Continued*)

Sl No.	Structures	Category
xiii)	Control and instrumentation building	3
xiv)	Conveyor galleries	3
xv)	Crusher house	3
xvi)	Cryogenic hydrocarbon handling and dozing building	1
xvii)	DCP and desludge building	2
xviii)	Digester	2
xix)	DG building & DG foundation	2
xx)	Dirty and clean oil building	2
xxi)	DM plant	2
xxii)	Effluent treatment plant	3
xxiii)	Electrostatic precipitator structure	2
xxiv)	Fire station	2
xxv)	Fire water pump house	2
xxvi)	Fire water reservoir	2
xxvii)	Flare stack supporting structure	*2*
xxviii)	Flare trestle	2
xxix)	Fuel oil pump house	2
xxx)	H_2 plant building	1
xxxi)	Machine foundations for utilities (motors, compressor, pumps, fans, etc)	3
xxxii)	Mechanical draught cooling tower (induced or forced)	2
xxxiii)	Microwave towers	2
xxxiv)	Overhead water tank	3
xxxv)	Pipe rack (hydrogen, DM, power plant)	2
xxxvi)	Pipe rack offsite	3
xxxvii)	Pump house (water and effluents, etc)	3
xxxviii)	Road and rail loading gantry handling non-inflammable, non hazardous material	3
xxxix)	Road and rail loading gantry handling LPG or hydrocarbons	2
xl)	Switchgear building and substations	3
xli)	Switchyard structures	3
xlii)	Technological structures in RCC or steel or both	2
xliii)	Water intake structure	3
xliv)	Water treatment plant	3
	C. Storage and Handling	
	(Raw material, Intermediate product, Final product, Bulk storage of chemicals)	
i)	Catalyst storage building	2
ii)	Chemical house	3
iii)	Hazardous chemical house	1
iv)	LPG storage shed	1
v)	Pipe rack	2

Table 6 (*Concluded*)

Sl No.	Structures	Category
vi)	Product storage sheds or buildings	3
vii)	Road and rail loading gantry handling non-inflammable, non hazardous material	3
viii)	Road and rail loading gantry handling LPG or hydrocarbons	2
	D. Infrastructure	
	(Administrative block, Laboratory building, Service buildings, Road crossings etc)	
i)	Administration building	4
ii)	Bridges over rivers or canals or drains	2
iii)	Canteen building	4
iv)	Communication building or repeater station or telephone exchange	2
v)	Gate and gate house	4
vi)	Hospital	2
vii)	Laboratory building or MCC room	3
viii)	Maintenance stores	4
ix)	Maintenance workshop	4
x)	Medical center or first aid center	2
xi)	Other non-plant buildings and utility structures	4
xii)	Service building	4
xiii)	Warehouse	4

Table 7 Categorization of Industrial Stack-Like Structures and Ground Supported Vertical Cylindrical Structures

(*Foreword*, *Clauses* 8.1.3, 12.4.2.1, 12.4.2.2 *and* 12.4.5)

SI No.	Structure or Components	Category
	A. Main Plants and Process Plants	
	(Power plants, Hydrocarbon plant, Chemical, Fertilizer and Metallurgy plants etc)	
i)	Coke drum	2
ii)	Electric or traffic light poles	4
iii)	HRSG stack	2
iv)	Process column or vessel or reactors or any other equipment on low rcc pedestal conforming to Note 1	1
v)	Process column or vessel or reactors or any other equipment on low rcc pedestal conforming to Note 2	2
vi)	Reinforced brick masonry chimney	2
vii)	Reinforced concrete chimneys	2
viii)	Reinforced concrete T V towers	2
ix)	Reinforced concrete ventilation stacks	2
x)	Settling and digestion tanks	2

Table 7 (*Concluded*)

Sl No.	Structure or Components	Category
xi)	Steel stack	2
xii)	Steel tubular support structures for onshore wind turbine generator systems	2
xiii)	Storage silos and bunkers	2
xiv)	Unreinforced brick masonry chimney	4
	B. Utilities	
	[Water system (Intake, Conveying, Treatment, Storage and Pumping), ETP/STP/Waste water treatment plant, DM water, Condensate polishing, RO plant, Cooling water system, Fire protection/Extinguishing Fighting system, Air separation unit, Nitrogen/Oxygen plant, Fume and Gas treatment plant, Captive power plant, Service buildings]	
i)	Acid or alkali storage tank	2
ii)	Cryogenic hydrocarbon storage (bulk storage)	1
iii)	Cryogenic hydrocarbon storage (day consumption)	1
iv)	Cryogenic storage tanks or vessel with hazardous or toxic refrigerated liquefied gases conforming to Note 1	1
v)	Cryogenic storage tanks or vessel with refrigerated liquefied gases (day tanks) conforming to Note 2	1
vi)	Fire water storage tank	2
vii)	Fuel oil storage tank and day tank	2
viii)	Gas holder conforming to Note 1	1
ix)	Gas holder conforming to Note 2	2
x)	Main condensate storage tank	3
xi)	Nitrogen storage vessel, air receiver, chemical dosing vessel	2
xii)	Water or effluent storage tank (dome/cone roof)	3
	C. Storage and Handling	
	(Raw material, Intermediate product, Final product, Bulk storage of chemicals)	
i)	Cryogenic bulk storage tank (double walled) with refrigerated liquefied gases (for example, Ethylene, LNG, NH_3 etc)	1
ii)	Hydrocarbon storage tanks (Cone or floating roof)	2
iii)	Hydrocarbon storage tanks (Dome roof)	2
iv)	Process water storage tank	3

Table 8 Categorization of Vessels, Equipment and Piping

(*Foreword*, *Clauses* 8.1.3 *and* 12.4.5)

Sl No.	Vessels, Equipment and Piping	Category
	A. Main Plants and Process Plants	
	(Power plants, Hydrocarbon plant, Chemical, Fertilizer and Metallurgy plants etc)	
i)	Bagging and palletizing equipment	2
ii)	Boiler	2
iii)	Converters	2
iv)	Heater or furnace	2
v)	Heat recovery steam generator	2
vi)	Heaters with steel stack	2
vii)	Horizontal vessel, heat exchanger or filter, coalescer, desalter, air fin cooler or flash drum	2
viii)	Pharma chemical reactors	2
ix)	Piping	2
x)	Process column on elevated structures conforming to Note 1	1
xi)	Process column on elevated structures conforming to Note 2	2
xii)	Scrubber or FGD system	2
xiii)	Smelters on RCC or steel structures	2
xiv)	Storage silos (RCC, steel or aluminium) on elevated structures	2
xv)	Track hopper	2
xvi)	Transformers and radiator bank	2
xvii)	Turbo generator, turbo compressor, boiler feed pump	2
	B. Utilities	
	[Water system (Intake, Conveying, Treatment, Storage and Pumping), ETP/STP/Waste water treatment plant, DM water, Condensate polishing, RO plant, Cooling water system, Fire protection/Extinguishing Fighting system, Air separation unit, Nitrogen/Oxygen plant, Fume and Gas treatment plant, Captive power plant, Service buildings, Pharmaceutical Industry]	
i)	Air pre-heaters, tempered water cooler or drum, pre or inter or after condenser, coalescer	3
ii)	Boiler	2
iii)	Chiller plant	3
iv)	Centrifuges and nutsche filters	3
v)	Coal or limestone ball mill and bowl mill	2
vi)	Coal bunker or silo	2
vii)	Condenser polishing unit	3
viii)	Corex gas station (for cogeneration plant)	2
ix)	Cooling towers (wet and dry)	3
x)	Critical piping and pipelines	2
xi)	Crushers	3

Table 8 (*Concluded*)

Sl No.	Vessels, Equipment and Piping	Category
xii)	Digester	2
xiii)	DM plant	2
xiv)	Dryers: Vacuum tray, hot air oven and cone dryers	3
xv)	Electrostatic precipitator- ESP	2
xvi)	Fans – PA, FD, GR, SA, ID and booster fans	2
xvii)	Filtration and chlorination plant	3
xviii)	Flare knock out drum and water seal drum	2
xix)	Heat exchangers (pharma industry)	3
xx)	Miller	3
xxi)	Piping	3
xxii)	Process gas compressor	2
xxiii)	Receivers and storage vessels	3
xxiv)	Silos (ash silos, cement silos, any powdery material storage silos, grain storage silos etc)	3
xxv)	Stability humidity chamber	3
xxvi)	Transformers and radiator bank	3
xxvii)	Wagon tippler	4
	C. Storage and Handling	
	(Raw material, Intermediate product, Final product, Bulk storage of chemicals)	
i)	Bagging and palletizing equipment	3
ii)	Hydrogen bullet	1
iii)	Mounded LPG bullet	1
iv)	Sphere or bullets storing hydrocarbon or with liquefied gases	1

NOTES

1 For the structures and equipment not included herein, the category shall be selected by the designer considering the classification defined in **8.1**.

2 For design of supporting structures and foundations which have not been listed in the above table, the category shall be selected same as that of the supported equipment or vessel or piping.

SECTION 2 STACK-LIKE STRUCTURES

13 DESIGN CRITERIA

Stack-like structures are those in which the mass and stiffness is more or less uniformly distributed along the height. Cantilever structures like reinforced or pre-stressed cement concrete electric poles; reinforced concrete and steel chimneys (including multi-flue chimneys), ventilation stacks and refinery vessels are examples of such structures. Guyed structures are not covered here.

14 NATURAL PERIOD OF VIBRATION

Natural period of vibration, T of such structures when fixed at base, shall be estimated using either of the following two formulae given (*see* **14.1** and **14.2**). The formulae given at **14.1**, is more accurate. Only one of these two formulae should be used for design. Natural period of structure, if available, through vibration measurement on similar structure and foundation soil condition can also be adopted.

14.1 The fundamental natural period T for stack-like structures is given by:

$$T = C_{\mathrm{T}} \sqrt{\frac{W_{\mathrm{t}} h}{E_{\mathrm{s}} A g}}$$

where

C_{T} = coefficient based on the slenderness ratio of the structure given in Table 9;

W_{t} = total weight of the structure including weight of lining and contents above the base;

h = height of structure above the base;

E_{s} = modulus of elasticity of material of the structural shell;

A = area of cross-section at the base of the structural shell, for circular sections, $A = 2\pi r_s t$, where r_{s} is the mean radius of structural shell and t is thickness; and

g = acceleration due to gravity.

NOTE — This formula is only applicable to stack-like structures in which both mass and stiffness are more or less uniformly distributed along the height.

14.2 The fundamental natural period, T of a stack like structure can be determined by Rayleigh's approximation for fundamental mode of vibration as follows:

$$T = 2\pi \sqrt{\frac{\sum_{i=1}^{n} W_{\mathrm{i}} \delta_{\mathrm{i}}^2}{g \sum_{i=1}^{n} F_{\mathrm{i}} \delta_{\mathrm{i}}}}$$

where

W_{i} = weight at level i;
F_{i} = lateral force at level i;
δ_{i} = lateral displacement at level i;
n = number of levels of lumped weight; and
g = acceleration due to gravity.

NOTES

1 Any elastic analysis procedure like moment area theorem or matrix method may be used for determining the lateral static deflection δ value.

2 For determining the fundamental natural period of vibration of structures resting on frames or skirts like bins, silos, hyperbolic cooling towers, refinery columns, only the formula given at **14.2** shall be used. Approximate methods may be adopted to estimate the lateral stiffness of the frame or skirt in order to determine the lateral static deflection. Response spectrum analysis will be necessary in such cases.

15 DAMPING

The damping ratio for different materials, to be used in determining $\left(\frac{S_{\mathrm{a}}}{g}\right)$, are given in the Table 5.

16 HORIZONTAL SEISMIC FORCE

Horizontal seismic coefficient A_{h} shall be obtained corresponding to natural period T, as per **14**.

For site-specific spectra: $A_{\mathrm{h}} = \left(\frac{S_{\mathrm{a}}}{g}\right)_{\mathrm{SS}} \frac{I}{R}$

For design spectrum given in this standard:

$$A_{\mathrm{h}} = \frac{Z}{2}\left(\frac{S_{\mathrm{a}}}{g}\right)\frac{I}{R}$$

(For nomenclature, refer **7.3.1** and **7.3.2**)

Based on the design horizontal seismic coefficient A_{h}, the design lateral force shall be computed. The horizontal earthquake force shall be considered acting in one lateral direction at a time.

For estimation of seismic forces on stack-like structures mounted on building or structure, the following provisions shall apply:

The stack-like structure shall be analyzed based on a model considering the flexibility of the supporting structure and connecting component between the stack and the supporting structure.

When the decoupled dynamic analysis of the structure mounted stack-like structure is carried out, it shall be performed by either the response history method or the response spectrum method using the floor acceleration time series or floor response spectra as input for subsystem analysis.

17 DESIGN SHEAR FORCE AND MOMENT

Either simplified method (equivalent static lateral force method) or response spectrum analysis method may be used to estimate the seismic forces developed in such structures. Site-specific spectrum compatible response history analysis may be carried out instead of response spectrum analysis.

The expressions given in simplified method for evaluating the shear force and bending moment above the base are to be used when the first mode contributes maximum towards base shear. When higher modes influence the response, dynamic analysis shall be performed.

17.1 Simplified Method (Equivalent Static Lateral Force Method)

When the first mode contributes to over 80 percent of the base shear, the design shear force V and design bending moment M at a distance x from the top, shall be estimated using the following formulae:

$$V = C_v A_h W_t D_v, \text{ and}$$

$$M = A_h W_t \bar{h} D_m$$

where

C_v = coefficient of shear force depending on slenderness ratio, k, given in Table 9;

A_h = design horizontal seismic coefficient determined in accordance with **16**;

W_t = total weight of structure including weight of lining and contents above the base;

$\bar{h}$ = height of centre of gravity of structure above base; and

D_v, l = distribution factors for shear and moment respectively at a distance X from the top as given in Table 10. The expressions for these distribution factors for moment and shear along the height is given in Table 11 for use in computer program.

The appropriate foundation soil and pile group stiffness equations are given in Table 12. For $N > 50$, fixed based condition may be assumed. When soil-structure interaction effects are to be considered, shear wave velocities are to be determined by suitable methods. Specialist literature may be referred to include this effect. But, maximum reduction in the base shear on account of soil-structure interaction shall not be more than 20 percent of base shear of fixed base structure. The classification of soil shall be as given in Table 1B.

17.2 Dynamic Analysis (Response Spectrum Method)

When higher modes contribute significantly to the base shear, dynamic analysis shall be carried out by the response spectrum method. The number of modes to be considered in the analysis shall be such that the minimum excited mass is 90 percent. The modes shall be combined by modal combination of corresponding response, like base shear and overturning moment.

17.2.1 *Mathematical Model*

The mathematical model of stack like structures should be able to represent sufficiently the variation in its stiffness (variation in cross-section and thickness of shell), lining mass, intermediate loadings due to various appurtenances and other geometrical changes. The number of elements shall be such as to capture the variation of stiffness and mass of the system.

When a stack is modelled as a stick-model, a minimum of ten elements shall be used for the analysis. It is desirable that the model yields frequencies up to 33 Hz. If this is not achieved, the number of elements shall be increased such that frequencies up to 33 Hz are achieved. The number of elements shall be further increased to include any of above geometrical changes in the model. For stack-like structures with complex geometries and non-uniform mass distribution, finite element analysis shall be conducted.

In chimneys, no stiffness is considered to be provided by the lining but, the mass of lining above any corbel or support is considered to be lumped at the respective corbel or support level.

Table 9 Values of C_T and C_V

(*Clauses* 14.1 *and* 17.1)

Sl No. (1)	$k = h/r_e$ (2)	C_T (3)	C_V (4)
i)	5	14.4	1.02
ii)	10	21.2	1.12
iii)	15	29.6	1.19
iv)	20	38.4	1.25
v)	25	47.2	1.30
vi)	30	56.0	1.35
vii)	35	65.0	1.39
viii)	40	73.8	1.43

Table 9 (*Concluded*)

Sl No.	$k = h/r_e$	C_T	C_V
(1)	(2)	(3)	(4)
ix)	45	82.8	1.47
x)	50 or more	1.8k	1.50

NOTES

1 k = slenderness ratio.

2 r_e= radius of gyration of the structural shell at the base section.

Table 10 Digitized Moment and Shear Distribution Factors D_m and D_v Along the Stack Height

(*Clause* 17.1)

Sl No.	x/h[(1)]	Moment Distribution (D_m)			Shear Distribution (D_v)		
		Fixed	Soil	Pile Foundation	Fixed	Soil	Pile Foundation
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
i)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ii)	0.05	0.09	0.13	0.11	0.28	0.21	0.14
iii)	0.10	0.13	0.19	0.16	0.42	0.27	0.19
iv)	0.20	0.18	0.27	0.22	0.64	0.34	0.26
v)	0.30	0.22	0.33	0.28	0.83	0.38	0.31
vi)	0.40	0.27	0.39	0.33	1.00	0.41	0.35
vii)	0.50	0.32	0.45	0.38	1.00	0.44	0.40
viii)	0.60	0.39	0.52	0.45	1.00	0.49	0.46
ix)	0.70	0.48	0.60	0.54	1.00	0.55	0.54
x)	0.80	0.60	0.70	0.65	1.00	0.65	0.65
xi)	0.90	0.77	0.83	0.80	1.00	0.80	0.80
xii)	0.95	0.88	0.91	0.89	1.00	0.89	0.89
xiii)	1.00	1.00	1.00	1.00	1.00	1.00	1.00

[(1)] 'x' is the distance from top and 'h' is the height of chimney above the base.

Table 11 Values of D_m and D_v

(*Clause* 17.1)

Sl No.	Soil Foundation Condition	D_m	D_v
(1)	(2)	(3)	(4)
i)	Fixed base or raft on hard soil (based on N values)	$0.4\left(\frac{x}{h}\right)^{1/2} + 0.6\left(\frac{x}{h}\right)^{4}$	$1.1\left(\frac{x}{h}\right)^{1/2} + 0.75\left(\frac{x}{h}\right) + 0.9\left(\frac{x}{h}\right)^{4}$ but ≤ 1
ii)	Raft on soil (based on N values)	$0.6\left(\frac{x}{h}\right)^{1/2} + 0.4\left(\frac{x}{h}\right)^{4}$	$1.1\left(\frac{x}{h}\right)^{1/2} - 0.75\left(\frac{x}{h}\right) + 0.65\left(\frac{x}{h}\right)^{4}$
iii)	Pile foundation	$0.5\left(\frac{x}{h}\right)^{1/2} + 0.5\left(\frac{x}{h}\right)^{4}$	$0.66\left(\frac{x}{h}\right)^{1/2} - 0.20\left(\frac{x}{h}\right) + 0.54\left(\frac{x}{h}\right)^{4}$

Table 12 Foundation Soil and Foundation Pile Group Stiffness

(*Clause* 17.1)

Sl No.	Type of Foundation	Stiffness
(1)	(2)	(3)
i)	*Circular raft foundation on soil*:	
	a) Horizontal soil stiffness	$K_h = 32(1-\upsilon)Gr_0/(7-8\upsilon)$
	b) Rocking soil stiffness (full circular raft)	$K_\tau = 8Gr_0^{\;3}/3(1-\upsilon)$
ii)	*Annular raft:*	
	a) Friction pile foundation (under reamed piles not covered)	
	b) Translational stiffness of piles at the base of pile cap	$K_h = n_p E_p I_m/1.2T_l^{\;3} + \eta_h d^2/2$, and $T_l = \left(E_p I_m/\eta_h\right)^{1/5}$

where

G = shear modulus of foundation soil = ρV_s^2;

V_s = shear wave velocity of the medium;

ρ = soil density;

r_0 = radius for circular raft foundation, $\sqrt{ab}$ for a rectangular foundation, where *a* and *b* are the dimensions of the rectangular foundation;

υ = Poisson's ratio of soil;

n_p = number of piles;

E_p = modulus of elasticity of pile material;

I_m = moment of inertia of pile section;

T_l = characteristic length of pile;

d = thickness of pile cap or raft; and

η_h = modulus of subgrade reaction of soil in horizontal direction.

18 SPECIAL DESIGN CONSIDERATIONS FOR REINFORCED CONCRETE STACKS AND CHIMNEYS

18.1 The total vertical reinforcement shall not be less than 0.25 percent of the concrete area of the section under consideration. When two layers of reinforcement are provided, the outside layer of vertical reinforcement shall not be less than 50 percent of the total vertical reinforcement.

18.2 The total circumferential reinforcement shall not be less than 0.20 percent of the concrete area in vertical section under consideration. When two layers of reinforcement are provided, the circumferential reinforcement in each layer shall not be less than 0.1 percent of the concrete area at the section.

18.3 The circumferential reinforcement for a distance of 0.2 times the diameter of the chimney (from top of the chimney) shall be twice that arrived as stated above.

18.4 Extra reinforcement shall have to be provided in addition to the reinforcement determined by design at the sides, top, bottom and corners of the openings. The extra reinforcement shall be placed onNboth faces of the chimney shell as close to the opening as proper spacing of bars shall permit. Unless otherwise specified, all extra reinforcement shall extend past the opening to a minimum of the development length in tension.

18.5 At each side of the opening, the additional vertical reinforcement shall have an area at least equal to the design steel ratio times one-half the cross-sectional area of opening.

The additional vertical reinforcement shall be placed as close as practical to the edge of the opening within a distance not exceeding three times the shell thickness.

18.6 At the top and bottom of each opening, the additional reinforcement shall have an area at least equal to one-half the established design circumferential reinforcement interrupted by the openings.

The additional circumferential reinforcement shall be placed as close as practical to the top or bottom of the opening, within a distance not exceeding three times the shell thickness. One-half of this additional reinforcement shall extend completely around the circumference of the chimney. The other half of the additional reinforcement shall extend beyond the vertical edges of the opening for a minimum of development length in tension.

18.7 Deflection Criterion

The maximum lateral deflection $D_{\max}$ of the top of a stack-like structure with partial safety factor for all loads taken as 1.0, shall not exceed the limits set forth by the following equation:

$$D_{\max} = 0.005\ h$$

where

$D_{\max}$ = maximum lateral deflection; and
h = height of structure above the base.

ANNEX A

(*Clause 2*)

LIST OF REFERRED STANDARDS

IS No.	*Title*
IS 456 : 2000	Plain and reinforced concrete — Code of practice (*fourth revision*)
IS 800 : 2007	General construction in steel — Code of practice (*third revision*)
IS 875	Code of practice for design loads (other than earthquake) for building structures:
Part 1 : 1987	Dead loads — Unit weights of building material and stored materials (*second revision*)
Part 2 : 1987	Imposed loads (*second revision*)
Part 3 : 2015	Wind loads (*third revision*)
Part 4 : 2021	Snow loads (*third revision*)
Part 5 : 1987	Special loads and combinations (*second revision*)
IS 1343 : 2012	Prestressed concrete — Code of practice (*second revision*)
IS 1498 : 1970	Classification and identification of soils for general engineering purposes (*first revision*)
IS 1888 : 1982	Method of load test on soils (*second revision*)
IS 1893	Criteria for earthquake resistant design of structures:
Part 1 : 2016	General provisions and buildings (*sixth revision*)
Part 2 : 2014	Liquid retaining tanks (*fifth revision*)
Part 3 : 2014	Bridges and retaining walls
Part 6 : 2022	Base isolated buildings
IS 1905 : 1987	Code of practice for structural use of unreinforced masonry (*third revision*)
IS 2131 : 1981	Method for standard penetration test for soils (*first revision*)
IS 2809 : 1972	Glossary of terms and symbols relating to soil engineering (*first revision*)
IS 2810 : 1979	Glossary of terms relating to soil dynamics (*first revision*)
IS 2974	Code of practice for design and construction of machine foundations:
Part 1 : 1982	Foundation for reciprocating type machines (*second revision*)
Part 2 : 1980	Foundations for impact type machines (hammer foundations) (*first revision*)
Part 3 : 1992	Foundations for rotary type machines (medium and high frequency) (*second revision*)
Part 4 : 1979	Foundations for rotary type machines of low frequency (*first revision*)
Part 5 : 1987	Foundations for impact machines other than hammer (forging and stamping press, pig breaker, drop crusher and jolter) (*first revision*)
IS 4326 : 2013	Earthquake resistant design and construction of buildings — Code of practice (*third revision*)
IS 4998 : 2015	Design of reinforced concrete chimneys — Criteria (*third revision*)
IS 6403 : 1981	Code of practice for determination of bearing capacity of shallow foundations (*first revision*)
IS 6533	Code of practice for design and construction of steel chimneys
Part 1 : 1989	Mechanical Aspect (*first revision*)
Part 2 : 1989	Structural aspect (*first revision*)

IS No.	*Title*
IS 8009	Code of practice for calculation of settlement of foundations:
Part 1 : 1976	Shallow foundations subjected to symmetrical static vertical loads
Part 2 : 1980	Deep foundations subjected to symmetrical static vertical loading
IS 13827 : 1993	Improving earthquake resistance of earthen buildings — Guidelines
IS 13828 : 1993	Improving earthquake resistance of low strength masonry buildings — Guidelines
IS 13920 : 2016	Ductile design and detailing of reinforced concrete structures subjected to seismic forces — Code of practice (*first revision*)
IS 13935 : 2009	Seismic evaluation, repair and strengthening of masonry buildings — Guidelines (*first revision*)
IS 15988 : 2013	Seismic evaluation and strengthening of existing reinforced concrete buildings — Guidelines
IS 16700 : 2017	Criteria for structural safety of tall concrete buildings
IS 18168 : 2023	Earthquake resistant design and detailing of steel buildings – Code of practice
SP 7 : 2016	National Building Code of India 2016

ANNEX B

(*Clause* 7.3.2)

SEISMIC ZONE FACTORS AND MULTIPLYING FACTORS FOR OBTAINING SPECTRAL VALUES FOR OTHER DAMPING RATIOS

Table 13 Seismic Zone Factor *Z*

(*Clause* 7.3.2)

Seismic Zone	II	III	IV	V
Z	0.10	0.16	0.24	0.36

Table 14 Multiplying Factor for Obtaining $\left(\frac{S_a}{g}\right)$ Values for Other Damping Ratios

(*Clause* 7.3.2)

Damping Percent	0	0.5	1.0	2	4	5	7	10	15	20	25	30
Factors	3.2	1.9	1.6	1.4	1.1	1.0	0.9	0.8	0.7	0.6	0.55	0.5

NOTE — For natural period T = 0, the multiplying factor shall be 1. For 0< T ≤0.1, the factor shall be linearly interpolated between 1 and the factor given in the Table. For T >0.1, the factor shall be same as specified in the Table.

ANNEX C

(*Foreword*, *Clauses* 7.3.2 *and* 16)

DESIGN SPECTRUM

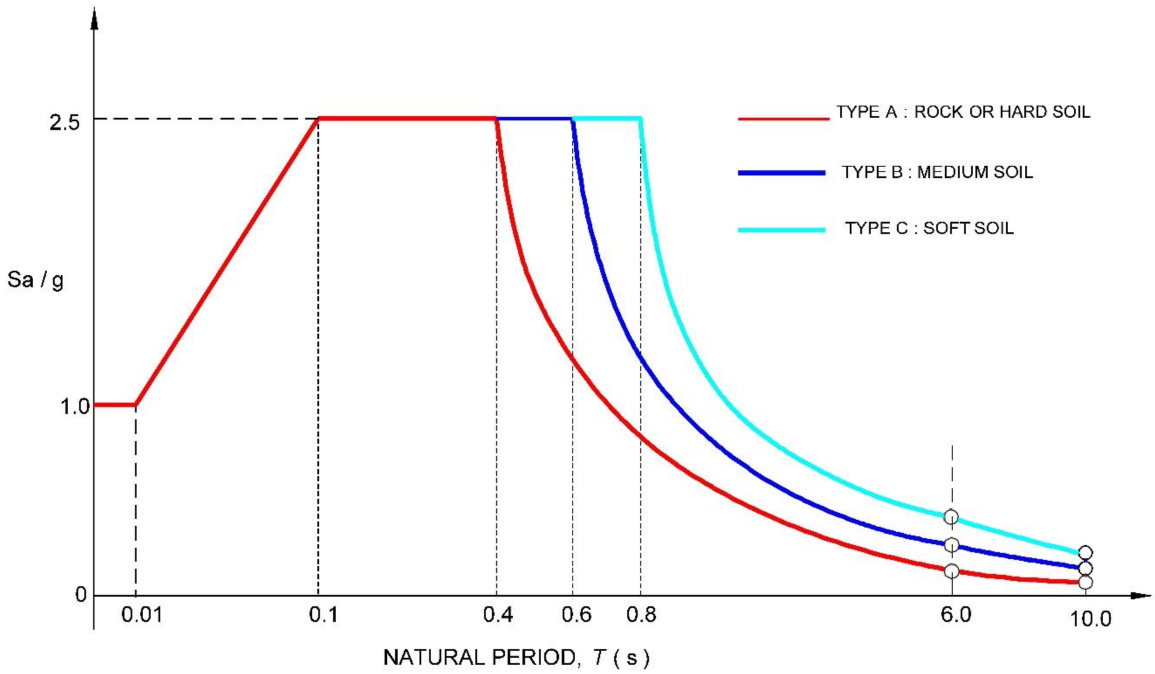

FIG. 1 (NOT TO SCALE) RESPONSE SPECTRA CORRESPONDING TO 5 PERCENT DAMPING RATIO.

(FOR OTHER DAMPING RATIOS, *see* NOTE 3 BELOW)

NOTES

1 The spectra shown above is for 5 percent damping ratio for different soil types.

2 Ratio of $\left(\frac{I}{R}\right)$ in no case shall be more than 1.0.

3 For other damping ratios, necessary interpolations shall be done using multiplying factors as given in Table 14.

4 For determining the spectrum to be used in estimating $\left(\frac{S_a}{g}\right)$, the type of soil on which the structure is placed shall be identified by the classification given in Table 15.

Table 15 Classification of Soil

Sl No. (1)	Soil Type (2)	*N* Value* (3)	Shear Wave Velocity* (m/s) (4)
i)	Type A: Rock or hard soil	> 30	> 760
ii)	Type B: Medium soil	10 to 30	360 to 760
iii)	Type C: Soft soil	< 10	< 360

* Weighted average shall be considered of corrected values of *N* or shear wave velocity up to 30 m, for the layered strata.

$$
\left(\frac{S_a}{g}\right) = \begin{cases}
\begin{cases}
1.0 & 0 < T < 0.01s \\
1 + \left(\frac{50}{3}\right)(T - 0.01) & 0.01 < T < 0.1s \\
2.5 & 0.1s < T < 0.4s \\
\frac{1}{T} & 0.4s < T < 6.0s \\
\frac{6}{T^2} & 6.0s < T < 10s
\end{cases} & \text{Type A} \\
\begin{cases}
1.0 & 0 < T < 0.01s \\
1 + \left(\frac{50}{3}\right)(T - 0.01) & 0.01 < T < 0.1s \\
2.5 & 0.1s < T < 0.6s \\
\frac{1.5}{T} & 0.6s < T < 6.0s \\
\frac{9}{T^2} & 6.0s < T < 10s
\end{cases} & \text{Type B} \\
\begin{cases}
1.0 & 0 < T < 0.01s \\
1 + \left(\frac{50}{3}\right)(T - 0.01) & 0.01 < T < 0.1s \\
2.5 & 0.1s < T < 0.8s \\
\frac{2}{T} & 0.8s < T < 6.0s \\
\frac{12}{T^2} & 6.0s < T < 10s
\end{cases} & \text{Type C}
\end{cases}
$$

ANNEX D

(*Clause* 9.2, 9.2.3)

DE-COUPLING CRITERIA FOR CATEGORY 1 STRUCTURES

D-1 For Category 1 structures, decoupling criteria given below shall be used for the interaction effects between primary system (structure) and secondary system (equipment).

D-1.1 The participation factor for mode j shall be:

$$\Gamma_j = \frac{\{\varphi_j\}^T [M]\{U_b\}}{\{\varphi_j\}^T [M]\{\varphi_j\}}$$

where

$\{M\}$ = mass matrix of the structural system;

$\{\varphi_j\}$ = normalized mode shape of mode j, where $\{\varphi_j\}^T [M]\{\varphi_j\} = 1$; and

$\{U_b\}$ = influence vector (displacement vector) of the structural system when the base is displaced by unity in the direction of earthquake motion.

D-2 All combinations of the dominant secondary system modes and the dominant primary system modes shall be considered, and the most restrictive combination shall govern.

D-3 Coupled analysis of primary structure and secondary system shall be performed when the effects of interaction are significant based on **D-9** and **D-10**.

D-4 Coupling need not be considered, if the total mass of the equipment or secondary system is 1 percent or less of the mass of the supporting primary structure. But, the requirements of **D-10** regarding the multiple supports shall be considered.

D-5 In applying **D-9** and **D-10**, one sub-system at a time may be considered, unless the sub-systems are identical and located together, in which case the sub-system masses shall be lumped together.

D-6 When coupling is required, a detailed model of the equipment or secondary system is not required, provided a simple model adequately represents the major effects of interaction between the two parts. When a simple model is used, the secondary system shall be re-analyzed in appropriate detail using the output motions from the first analysis as input at the points of connectivity.

D-7 For applying the criteria of this section, the dominant frequency shall have a modal mass greater than 20 percent of the total system mass. The total system mass is defined by:

$$[M] = \sum_{j=1}^{n_m} (\Gamma_j)^2$$

where

Γ_j = Participation factor for mode j; and

n_m = Number of modes.

D-8 When detailed analysis is to be carried out for structures with equipment attached at a single point, the coupling criteria shown in Fig. 2 shall be used. The mass ratio in Fig. 2 is the modal mass ratio computed as per **D-9**, and the frequency ratio is the ratio of dominant uncoupled modal frequencies of the secondary and primary systems.

D-9 For a secondary system dominant mode and the primary system mode i, the modal mass ratio can be estimated by:

$$\Lambda_i = \frac{M_s}{M_{pi}}$$

where

M_{pi} = $(1/\varphi_{ci})^2$;

φ_{ci} = mode vector value from the primary system's modal displacement at the location where the secondary system is connected, from the normalized modal vector $\{\varphi_{pi}\}$, in mode i, $\{\varphi_{pi}\}^T [M_p] \{\varphi_{p_i}\} = 1$;

$[M_p]$ = mass matrix of the primary system; and

M_s = total mass of the secondary system.

D-10 Multi-support secondary system shall be reviewed for the possibility of interaction of structure and equipment stiffness between the support points, and for the effect of equipment mass distribution between support points. Specialist literature shall be referred for evaluating the structural response while considering such interaction effects.

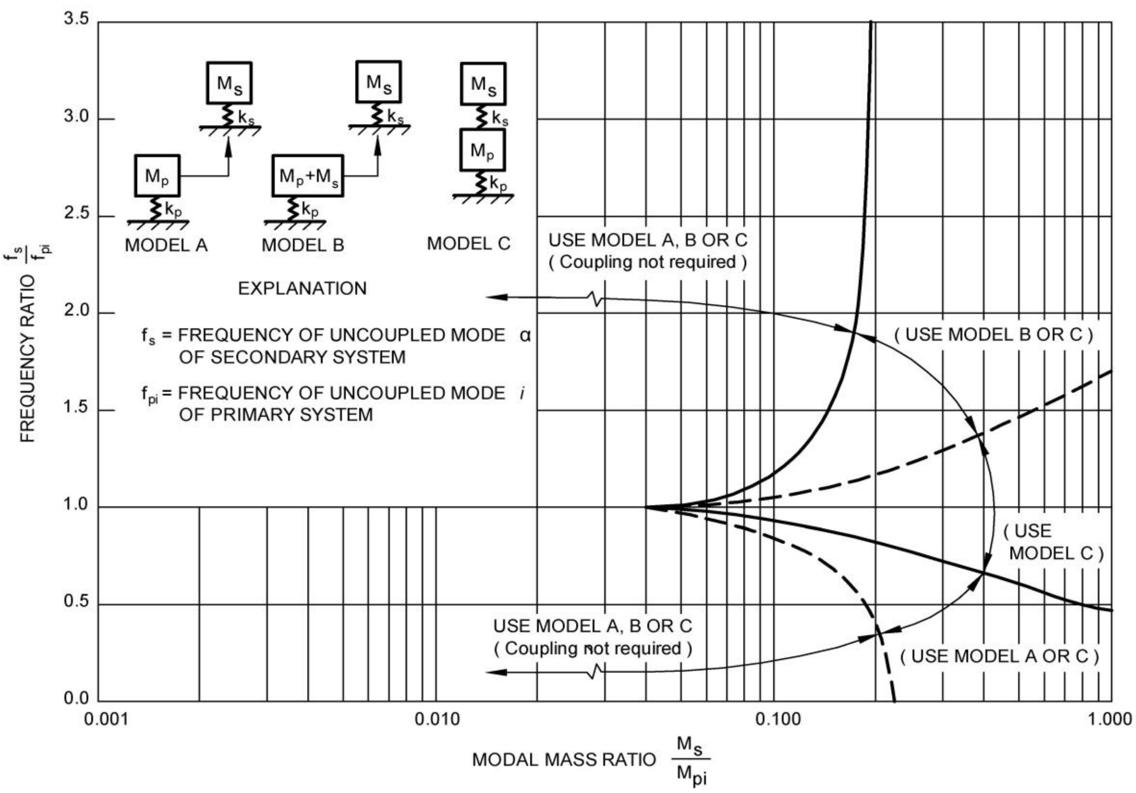

FIG. 2 DECOUPLING CRITERIA FOR EQUIPMENT OR SECONDARY SYSTEM WITH SINGLE-POINT ATTACHMENT TO THE PRIMARY SYSTEM

ANNEX E

(*Foreword*)

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(*Continued from second cover*)

The composition of the Committee responsible for the formulation of this standard is given in Annex E.

This standard contributes to the United Nations Sustainable Development Goal 9: 'Industry, innovation and infrastructure', particularly its target to develop quality, reliable, sustainable and resilient infrastructure, and also promote inclusive and sustainable industrialization.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or estimated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 2022 'Rules for rounding off numerical values (*second revision*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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Headquarters:

Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Delhi 110002
Telephones: 2323 0131, 2323 3375, 2323 9402 *Website*: www.bis.gov.in

Regional Offices:		*Telephones*
Central	: 601/A, Konnectus Tower -1, 6th Floor, DMRC Building, Bhavbhuti Marg, New Delhi 110002	2323 7617
Eastern	: 8th Floor, Plot No 7/7 & 7/8, CP Block, Sector V, Salt Lake, Kolkata, West Bengal 700091	2367 0012 2320 9474
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