Journal of Structural Engineering
Vol.26 No.4 January 2000 pp.223-234

No.26–19

# A proposed draft for Indian code provisions on seismic design of bridges - Part I : Code

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**Based on an extensive review of the seismic design provisions of the present Indian codes on bridges,[1,2] additions and modifications required in the codal provisions are proposed in this paper. Many of the short-comings in the present code have been addressed. Areas requiring further work and improvement are also proposed.**

Performance of bridges in India during past earthquakes have been summarised recently[3]. The existing provisions of Indian codes applicable to bridge structures have been reviewed in detail[4-5] in the light of those in the codes of other countries. Incorporating most of the suggestions made in these papers, a draft proposal for Indian code is presented. A detailed commentary of these provisions with the intent behind some of these clauses is presented, in a companion paper[6]. Some explanations of a few terms have been borrowed from an earlier proposal on codal provisions for buildings[7]. In line with current discussions in seismic code committee (CED:39) of the Bureau of Indian Standards (BIS), it is assumed that in the revised zone map, the current seismic zones I and II are merged into a single zone which is equivalent to the current zone II. In arriving at these draft provisions, reference has been made to seismic codes of other countries[8-10].

Some major modifications proposed in this paper include upward revision of the design force level, the philosophy of different response reduction factors for different components of a bridge, the concept of capacity design, and design for controlling the consequences of displacements at the structural connections between adjacent sections.

## DEFINITIONS AND SYMBOLS

### Definitions (0.1)

For the purpose of this standard, the following terms are defined:

**Base:** The level at which inertia forces generated in the substructure and superstructure are transferred to the foundation.

**Bridge Flexibility Factor *C*:** A factor to obtain the elastic acceleration spectrum depending on flexibility of the structure, which depends on natural period of vibration of the bridge.

**Center of Mass:** The point through which the resultant of the masses of a system acts. This point corresponds to the center of gravity of the system.

**Critical Damping:** The minimum damping above which free vibration motion is not oscillatory.

**Damping**: The effect of internal friction, imperfect elasticity of material, slipping, sliding, etc., in reducing the amplitude of vibration and is expressed as a percentage of critical damping.

**Design Seismic Force:** The seismic force prescribed by this standard for each bridge component that shall be used in its design. It is obtained as the maximum elastic sesismic force divided by the appropriate response reduction factor specified for each component.

**Ductility:** Ductility of a structure or its members, is the capacity to undergo large inelastic deformation without significant loss of strength or stiffness.

**Ductile Detailing:** The preferred choice of location and amount of reinforcement in reinforced concrete structures to

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provide adequate ductility. In steel structures, it is the design of members and their connections to make them adequately ductile.

**Elastic Seismic Acceleration Coefficient** $A$: Horizontal acceleration value, as a fraction of acceleration due to gravity, versus natural period of vibration $T$, that shall be used in the design of structures.

**Importance Factor** $I$ : A factor used to obtain the design spectrum depending on the importance of the structure.

**Liquefaction :** Liquefaction is the state in saturated cohesionless soil wherein its effective shear strength is reduced to negligible value, due to pore pressures caused by vibrations during an earthquake when they approach the total confining pressure. In this condition the soil tends to behave like a fluid mass.

**Maximum Elastic Seismic Force:** The maximum force in the bridge component due to the expected seismic shaking in the considered seismic zone.

**Natural Period** $T$**:** Natural period of a structure is its time period of undamped vibration.

(a) Fundamental Natural Period $T_1$ : It is the highest modal time period of vibration along the considered direction of earthquake motion.

(b) Modal Natural Period $T_k$ : Modal natural period of mode $k$ is the time period of vibration in mode $k$.

**Normal Mode :** Mode of vibration at which all the masses in a structure attain maximum values of displacements and rotations, and also pass through equilibrium positions simultaneously.

**Overstrength:** Strength considering all factors that may cause its increase e.g., steel strength being higher than the specified characteristic strength, effect of strain hardening in steel with large strains, and concrete strength being higher than specified characteristic value.

**Principal Axes :** Two mutually perpendicular horizontal directions in the plan of a structure along which the geometry of the structure is oriented.

**Response Reduction Factor** $R$**:** The factor by which the the actual lateral force, that would be generated, if the structure were to remain elastic during the most severe shaking that is likely at that site, shall be reduced to obtain the design lateral force.

**Response Spectrum :** The representation of the maximum response of idealized single degree freedom system having certain period and damping, during that earthquake. The maximum response is plotted against the undamped natural period and for various damping values, and can be expressed in terms of maximum absolute acceleration, maximum relative velocity or maximum relative displacement.

**Seismic Mass:** Seismic weight divided by acceleration due to gravity.

**Seismic Weight** $W$**:** Total dead load plus part of live load.

**Soil Profile Factor** $S$**:** A factor used to obtain the elastic acceleration spectrum depending on the soil profile below the foundation of structure.

**Strength:** The usable capacity of a structure or its members to resist the applied loads.

**Zone Factor** $Z$: A factor to obtain the design spectrum depending on the perceived seismic risk of the zone in which the structure is located.

**Symbols (0.2)**

The symbols and notations given at the end of the paper apply to the provisions of this draft. The units used for the items covered by these symbols shall be consistent throughout, unless specifically noted otherwise.

## GENERAL PRINCIPLES (1.0)

**Scope (1.1)**

This standard is applicable for the seismic design of new bridges and for evaluation of safety/adequacy of design for the seismic forces on existing bridges. Bridges and portions thereof shall be designed and constructed, to resist the effects of design seismic force specified in this standard.

**(1.2)** The intention of this standard is to ensure that bridges possess at least a minimum strength to withstand earthquakes. The intention is not to prevent any damage to components or part of the bridge due to the most severe shaking that they may be subjected to, during their lifetime. Actual forces that appear on portions of bridges during earthquakes may be greater than the design seismic forces specified in this standard. However, *ductility* arising from material behaviour and detailing, and *overstrength* arising from the reserve strength in them over and above the design forces, are relied upon to account for this difference between actual and design lateral loads.

**(1.3)** The reinforced and prestressed concrete bridge components shall be under-reinforced so as to cause a tensile failue. Further, they should be designed suitably, to ensure that premature failure due to shear or bond does not occur. Stresses induced in the superstructure due to earthquake induced ground motion are usually nominal. Therefore, ductility demand under seismic shaking has not been a major concern in bridge superstructures as seen from their response during past earthquakes. However, the seismic response of bridges is critically dependent on the ductile characteristics of the substructures, foundations and connections. Provisions for appropriate ductile detailing of reinforced concrete members given in IS: 13920-1993[11] shall be applicable to substructures, foundations and connections.

(1.4) Masonry and plain concrete arch bridges with spans more than 10m shall not be built in severe seismic zones IV and V.

**Ground Motion (1.5)**

The characteristics (intensity, duration, etc.,) of seismic ground motion expected at any location depends upon the magnitude of earthquake, the depth of focus, distance from the epicenter, characteristics of the path through which the seismic waves travel, and the soil strata on which the structure stands. The random earthquake ground motions, which cause the structures to vibrate, can be resolved into any three mutually perpendicular directions. Situations arise where earthquake-generated vertical inertia forces need to be specifically considered in design. These situations include design of vertical hold-down devices at supports or the overall stability analysis of bridges with large spans, wherein stability is a design criterion. Reduction in gravity force due to vertical component of ground motions can be particularly detrimental in prestressed concrete horizontal girders and cantilevered components. Hence, special attention should be paid to the effect of vertical component of the ground motion.

(1.6) The response of a structure to earthquake is a function of the nature of foundation soil, materials, form, size and mode of construction, and characteristics and duration of ground motion. This standard specifies design forces for structures standing on soils or rocks which do not settle or slide due to loss of strength during shaking.

**Assumptions (1.7)**

The following assumptions are made in the earthquake-resistant design of bridges:

(a) Earthquake causes impulsive ground motions, which are complex and random in character, and changes the period and amplitude of vibration, each lasting for a small duration. Therefore, resonance of the type as visualized under steady-state sinusoidal excitations, will not occur due to lack of adequate time to build up such amplitudes.

(b) Earthquake is not likely to occur simultaneously with wind or maximum flood or maximum wave forces.

(c) The value of elastic modulus of materials, wherever required, may be taken as for static analysis unless a more definite value is available for use in seismic conditions.

## DESIGN CRITERIA (2.0)

**Seismic Zone Map (2.1)**

For the purpose of determining design seismic forces, the country is classified into four seismic zones.

**Methods of Calculating Design Seismic Force (2.2)**

The seismic forces for bridges may be estimated by either of the following two methods, namely (a) Seismic Coefficient Method described in section 3.0, or (b) Response Spectrum Method described in section 4.0. For all bridges in seismic zones IV and V, and also for irregular bridges as defined in section 2.2.1 in seismic zones III, the Response Spectrum Method shall be adopted.

Linear static analysis of the bridges shall be performed for the applied inertial forces to obtain the force resultants (Bending moment, Shear and Axial forces) at different locations in the bridge. For this purpose, the analytical model of the bridge must appropriately model the stiffnesses of superstructure, bearings, piers or columns (i.e. substructure), foundations and bridge ends.

Special seismic analysis and design studies shall be performed for regular bridges with span more than 100 m and for all irregular bridges in seismic zones IV and V.

**Regular and Irregular Bridge (2.2.1)**

**Regular Bridge (2.2.1.1)**

A regular bridge has no abrupt or unusual changes in mass, stiffness or geometry along its span and has no large differences in these parameters between adjacent supports (abutments excluded). A bridge shall be considered regular for the purposes of this standard, if

(a) It is straight or describes a sector of an arc which subtends an angle greater than $90^o$ at the center of the arc, and

(b) The adjacent columns or piers do not differ in stiffness by more than 25% (calculated based on the smaller value of the stiffness).

**Irregular Bridge (2.2.1.2)**

All bridges not conforming to clause 2.2.1.1 shall be considered irregular.

**Vertical Motions (2.3)**

The seismic zone factor for vertical motions, when required, may be taken as two-thirds of that for horizontal motions given in Table 2.

**Live Load (2.4)**

The design live loads shall be as specified in the relevant Indian standards.

**Calculation of Magnitude of Seismic Forces (2.4.1)**

The live load shall be ignored while estimating the horizontal seismic forces along the direction of traffic.

The horizontal seismic force in the direction perpendicular to traffic shall be calculated using 50% of design live load (excluding impact) for railway bridges, and 25% of design live load (excluding impact) for road bridges.

The vertical seismic force shall be calculated using 100% of design live load (excluding impact) for railway bridges, and 50% of design live load (excluding impact) for road bridges.

The above percentages are applicable only for calculating magnitude of seismic force.

**Stresses Due to Live Load, but to be Combined with Stresses due to Seismic Forces (2.4.2)**

For calcualting the stresses due to live load, to be combined with those due to seismic forces, 100% of design live load (including impact) for railway bridges, and 50% of the design live load (including impact) for road bridges, shall be considered to be acting at the time of the earthquake.

**Seismic Load Combinations (2.5)**

**(2.5.1)** The seismic forces shall be assumed to come from any horizontal direction. For this purpose, two separate analyses shall be performed for design seismic forces acting along two orthogonal horizontal directions. The design seismic force resultants (Axial force, Bending moments, Shear forces, and Torsion) at any cross-section of a bridge component resulting from the analyses in the two orthogonal horizontal directions shall be combined as below:

$$\begin{aligned}&(a)\ \pm\ r_1\ \pm\ 0.3r_2\\&(b)\ \pm\ 0.3\ r_1\ \pm\ r_2\end{aligned}\qquad(1)$$

**(2.5.2)** When vertical seismic forces are also considered, the design seismic force resultants at any cross-section of a bridge component shall be combined as below:

$$\begin{aligned}&(a)\ \pm\ r_1\ \pm\ 0.3r_2\ \pm 0.3r_3\\&(b)\ \pm\ 0.3r_1\ \pm\ r_2\ \pm 0.3r_3\\&(c)\ \pm\ 0.3r_1\ \pm\ 0.3r_2\ \pm r_3\end{aligned}\qquad(2)$$

**Increase in Permissible Stresses (2.6)**

**Increase in Permissible Stresses in Materials (2.6.1)**

When earthquake forces are considered along with other normal design forces in the elastic method of design, the permissible stresses in material, may be increased by one-half. However, for steels having a definite yield stress, the permissible stress shall be limited to the yield stress; for steels without a definite yield point, the permissible stress shall be limited to 80 per cent of the ultimate strength or 0.2 per cent proof stress, whichever is smaller. In prestressed concrete members, the tensile stress in the extreme fiber of the concrete shall be limited to two-thirds of the modulus of rupture of concrete.

**Increase in Allowable Pressure in Soils (2.6.2)**

When earthquake forces are included in the design of Foundations, the allowable bearing pressure in soils shall be increased as per Table 1 of IS:1893-1984[2], depending upon type of foundation and the type of soil.

## SEISMIC COEFFICIENT METHOD (3.0)

**Elastic Seismic Acceleration Coefficient A (3.1)**

The Elastic Seismic Acceleration Coefficient $A$ due to design earthquake along a considered direction shall be obtained as:

$$A = ZICS \qquad (3)$$

where

$$C = \text{Bridge Flexibility Factor along the considered direction} \begin{cases} \dfrac{1.25}{T_1^{2/3}} & T_1 \leq 4.0sec \\ \dfrac{3.15}{T_1^{4/3}} & T_1 > 4.0sec \end{cases}, \qquad (4)$$

However, the bridge flexibility factor $C$ need not exceed 2.5 irrespective of the soil type. A plot of $CS$ versus $T_1$ is given in Figure 1.

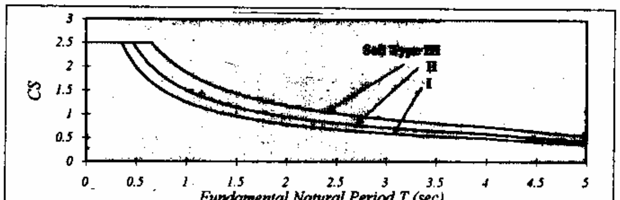


FIG.1 PLOT OF $CS$ VERSUS FUNDAMENTAL NATURAL PERIOD $T_1$ TO BE USED IN THE SEISMIC COEFFICIENT METHOD

TABLE 2
ZONE FACTOR Z FOR HORIZONTAL MOTION

| Seismic Zone | I, II | III | IV | V |
|---|---|---|---|---|
| Z | 0.10 | 0.16 | 0.24 | 0.36 |

TABLE 3
IMPORTANCE FACTOR $I$ FOR DIFFERENT BRIDGES

| Type of Bridge | $I$ |
|---|---|
| Important Bridges (e.g., Bridges on National and State Highways) | 1.5 |
| Other Bridges | 1.0 |

TABLE 4
SOIL PROFILE FACTOR S FOR DIFFERENT SOIL PROFILE TYPES AT THE SITE

| Soil Type | $S$ |
|---|---|
| Type I :: Rock or Hard Soils | 1.0 |
| Type II :: Medium Soils | 1.2 |
| Type III :: Soft Soils | 1.5 |

Note :: The soil types same as in Table 1 of IS: 1893-1984[2].

(3.1.1) The fundamental natural period $T_1$ of the bridge along a horizontal direction, may be estimated by:

$$T_1 = 2.0\sqrt{\frac{D}{1000F}} \qquad (5)$$

in which

$D$ = Total dead load of the bridge in $kN$, and

$F$ = Horizontal force in kN required to be applied at the center of mass of the superstructure for one *mm* horizontal deflection of the bridge along the direction of horizontal force.

**Maximum Elastic Forces and Deformations (3.2)**

The inertia forces due to mass of each component or portion of the bridge as obtained from clause 3.2.1 shall be applied at the center of mass of the corresponding component or portion of the bridge. A linear static analysis of the bridge shall be performed for these applied inertia forces to obtain the force resultants (Bending moment, Shear and Axial forces) and deformations (Displacements and Rotations) at different locations in the bridge. The stress resultants $V^e$ and deformations so obtained are the maximum elastic force resultants (at the chosen cross-section of the bridge component) and the maximum elastic deformations (at the chosen locations in the bridge), respectively.

**Inertia Force due to Mass of Each Bridge Component (3.2.1)**

The inertia force due to the mass of each bridge component (superstructure, substructure and foundation) under earthquake ground shaking along any direction shall be obtained from:

$$F^e = A \cdot W \tag{6}$$

**Elastic Seismic Acceleration Coefficient for Portions of Foundations below Scour Depth(3.2.2)**

For portions of foundations at depths of 30m or below from the scour depth (as defined in clause 6.2), the inertia force as defined in clause 3.2.1 due to that portion of the foundation mass may be computed using the elastic seismic acceleration coefficient taken as $0.5A$, where $A$ is as obtained from clause 3.1.

For portions of foundations placed between the scour depth and 30m below the scour depth, the inertia force as defined in clause 3.2.1 due to that portion of the foundation mass may be computed using the elastic seismic acceleration coefficient obtained by linearly interpolating between the value as $A$ at scour depth and $0.5A$ at a depth 30m below the scour depth, where $A$ is as specified in clause 3.1.

**Seismic Weight (3.2.3)**

The seismic weight of the superstructure shall be taken as its full dead load plus appropriate amount of live load specified in clause 2.4.1. The seismic weight of the substructure and of the foundation shall be their respective full dead load. Buoyancy and uplift shall be ignored in the calculation of seismic weight.

**Design Seismic Force Resultants for Bridge Components (3.3)**

The design seismic force resultant $V$ at a cross-section of a bridge component due to earthquake shaking along a considered direction shall be given by:

$$V = \frac{V^e}{R} \tag{7}$$

TABLE 5
RESPONSE REDUCTION FACTOR $R$ FOR BRIDGE COMPONENTS AND CONNECTIONS

| Bridge Components | $R$ |
|---|---|
| Superstructure | 6 |
| Substructure | |
| (a) Reinforced Concrete | |
| with special ductile detailing | 4 |
| with ordinary detailing | 3 |
| (b) Masonry | 2 |
| Foundation | 2 |
| Connections | |
| Adjacent sections of Superstructure | 0.8 |
| Superstructure and Substructure :: Hinge | 0.8 |
| Superstructure and Substructure :: In-situ | 1.0 |
| Substructure and Foundation | 1.0 |

**Multi-directional Shaking (3.4)**

When earthquake ground shaking is considered along more than one direction, the design seismic force resultants obtained from clause 3.3 at a cross-section of a bridge component due to earthquake shaking in each considered direction, shall be combined as per clause 2.5.

**Combination of Seismic Design Forces with Design Forces due to Other Effects (3.5)**

The design seismic force resultant at a cross-section of a bridge component given by this draft code, shall be appropriately combined with those due to other forces.

## RESPONSE SPECTRUM METHOD (4.0)

The Response Spectrum Method requires the evaluation of natural periods and mode shapes of several modes of vibration of the structure. This method will usually require a suitable dynamic analysis.

**Elastic Seismic Acceleration Coefficient $A_k$ in Mode $k$ (4.1)**

The elastic seismic acceleration coefficient $A_k$ for mode $k$ shall be determined by:

$$A_k = ZIC_kS \tag{8}$$

where $Z$, $I$ and $S$ are as defined in clause 3.1, and $C_k$ is the bridge flexibility factor for mode $k$ given by the following expression:

$$C_k = \begin{cases} \dfrac{1.25}{T_k^{2/3}} & T_k \leq 4.0sec \\ \dfrac{3.15}{T_k^{4/3}} & T_k > 4.0sec \end{cases} \tag{9}$$

where $T_k$ is the natural period of vibration of mode $k$ of the bridge. However, the bridge flexibility factor $C_k$ for mode $k$ need not exceed 2.5 irrespective of soil type. For modes other than the fundamental mode, the bridge flexibility factor $C_k$ in mode $k$ for $T_k \leq 0.1$ sec may be taken as:

$$C_k = 1 + 15\, T_k \tag{10}$$

A plot of $C_k S$ versus $T_k$ is given in Fig. 2.

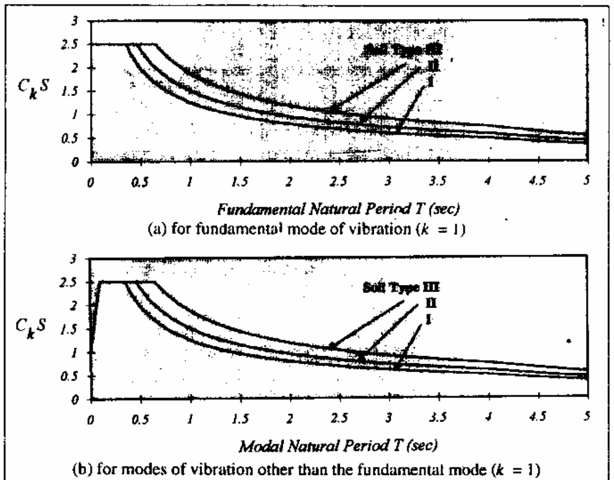


FIG.2 PLOT OF $C_k S$ VESUS NATURAL PERIOD $T_k$ IN MODE $k$ OF THE BRIDGE TO BE USED IN THE RESPONSE SPECTRUM METHOD

**Inertia Force due to Mass of Bridge at Node *i* in Mode *k* (4.2)**

The vector $\left\{F_k^e\right\}$ of inertia forces to be applied at different nodes in mode k of vibration due to earthquake shaking along a considered direction shall be obtained as:

$$\left\{F_k^e\right\} = [m]\,\left\{\varphi_k\right\}\, P_k\, A_k\, g \tag{11}$$

**Seismic Mass Matrix (4.2.1)**

The seismic mass matrix of the bridge structure shall be constructed by considering its seismic weight lumped at the nodes. The seismic weight of each bridge component shall be estimated as per clause 3.2.3, and shall be proportionally distributed to the nodes of discretisation of that bridge component.

**Number of Modes to be considered (4.2.2)**

The number of modes to be considered in the analysis shall be such that at least 90% of the seismic mass of the structure is included in the calculations of response for earthquake shaking along each principal direction.

**Maximum Elastic Forces and Deformations (4.3)**

The maximum elastic seismic forces in mode $k$ obtained from clause 4.2 shall be applied on the bridge and a linear static analysis of the bridge shall be performed to evaluate the maximum elastic force resultants $F_k^e$ (Bending moment, Shear and Axial Forces) and the maximum elastic deformations (Displacements and Rotations) in mode $k$ at different locations in the bridge for a considered direction of earthquake shaking.

The maximum elastic force resultants $F_{net}^e$ and the maximum elastic deformations, due to all modes considered, for the considered direction of earthquake shaking, shall be obtained by combining those due to the individual modes, by either: (a) the Complete Quadratic Coefficient (CQC) method, or (b) the Square Root of Sum of Squares (SRSS) method described in clauses 4.3.1 and 4.3.2, respectively. Let the modal response quantity due to $i$th and $j$th modes of vibration be $\lambda_i$ and $\lambda_j$, respectively; let $\omega_i$ and $\omega_j$ be the corresponding natural frequencies. Also, let $m$ be the number of modes considered.

**CQC Method (4.3.1)**

The net response quantity $\lambda$ due to all modes considered may be estimated as:

$$\lambda = \sqrt{\sum_{i=1}^{m} \sum_{j=1}^{m} \lambda_i\, \rho_{ij}\, \lambda_j} \tag{12}$$

where

$$\rho_{ij} = \frac{8\zeta^2\,(1+\beta)\beta^{1.5}}{(1-\beta^2)^2 + 4\zeta^2\,\beta(1+\beta)^2} \tag{13}$$

Here, it is assumed that the modal damping ratio is same for all modes considered; else, the above expression shall be replaced by appropriate equations.

**SRSS Method (4.3.2)**

The maximum response $\lambda$ due to all modes considered may be estimated as:

$$\lambda = \sqrt{\sum_{k=1}^{m} \left(\lambda_k\right)^2} \tag{14}$$

**Design Seismic Force Resultants in Bridge Components (4.4)**

The design seismic force resultant $V_{net}$ at any cross-section in a bridge component for a considered direction of earthquake shaking shall be determined as:

$$V_{net} = \frac{F_{net}^e}{R} \tag{15}$$

where the maximum elastic force resultant $F_{net}^e$ due to all modes considered as recommended in clause 4.3, and Response Reduction Factor $R$ of that component of bridge is as per Table 5.

### Multi-directional Shaking (4.5)

When earthquake ground shaking is considered along more than one direction, the design seismic force resultants obtained from clause 4.4 at a cross-section of a bridge component in each considered direction, shall be combined as per clause 2.5.

### Combination of Seismic Design Forces with Design Forces Due to Other Effects (4.6)

The design seismic force resultant at a cross-section of a bridge component given by this draft code, shall then be appropriately combined with those due to other forces.

### Site-Specific Spectrum (4.7)

In case design spectrum is specifically prepared for a structure at a particular site, the same may be used for design. However, the bridge structure shall still comply with all the minimum requirements specified in this standard.

## SUPERSTRUCTURE (5.0)

**(5.1)** The superstructure shall be designed for the design seismic forces specified in clauses 3. or 4., along with all other possible loadings, such as dead, live, wind and wave loads.

**(5.2)** Under simultaneous action of horizontal and vertical accelerations, the superstructure shall have a factor of safety of at least 1.5 against overturning.

**(5.3)** The superstructure shall be secured to the substructure, particularly in seismic zones IV and V, through vertical hold-down devices and/or horizontal linkage elements as specified in clauses 5.4 and 5.5. These vertical hold-down devices and/or horizontal linkage elements shall also be used to secure the suspended spans, if any, with the restrained portions of the superstructure. Frictional forces shall not be relied upon in the design of these hold-down devices or linkage elements.

### Vertical Hold-Down Devices (5.4)

Vertical hold-down devices shall be provided at all supports (for hinges in continuous structures), where resulting vertical force *U* due to the maximum elastic horizontal and vertical seismic forces calculated as per clause 2.5, opposes and exceeds 50% of the dead load reaction *D*.

**(5.4.1)** Where vertical force *U*, due to the combined effect of maximum elastic horizontal and vertical seismic forces, opposes and exceeds 50%, but is less than 100% of the dead load reaction *D*, the vertical hold-down device shall be designed for a minimum net upward force of 10% of the downward dead load reaction that would be exerted if the span were simply supported.

**(5.4.2)** If the vertical force *U*, due to the combined effect of maximum horizontal and vertical seismic forces, opposes and exceeds 100% of the dead load reaction *D*, then the device shall be designed for a net upward force of 1.2 (*U*-*D*); however, it shall not be less than 10% of the downward dead load reaction that would be exerted, if the span were to be simply supported.

### Horizontal Linkage Elements (5.5)

Positive horizontal linkage elements (high tensile wire strand ties, cables and dampers) shall be provided between adjacent sections of the superstructure at supports and at expansion joints within a span.

**(5.5.1)** The linkages shall be designed for, at least the elastic seismic acceleration coefficient *A* times the weight of the lighter of the two connected spans or parts of the structure.

**(5.5.2)** If the linkages is at locations where relative deformations are permitted in the design then, sufficient slack must be allowed in the linkage so that linkages start functioning only when the relative design displacement at the linkage is exceeded.

**(5.5.3)** When linkages are provided at columns or piers, the linkage of each span may be connected to the column or pier instead of the adjacent span.

## SUBSTRUCTURE (6.0)

**(6.1)** Design earthquake forces, and forces due to maximum flood shall not be considered to occur simultaneously. The designer shall also provide for other loads where they might be critical, *e.g.*, vehicle or ship impact on substructure.

### Scour Depth (6.2)

Earthquake forces on the substructure shall be calculated based on the depth of scour caused by the discharge corresponding to the mean design flood. In the absence of measured site data, this depth shall be taken as 90% of the maximum scour depth.

### Design Seismic Force (6.3)

The design seismic forces for the substructure shall be obtained as the maximum elastic force (as defined in clause 6.3.1) divided by the appropriate response reduction factor given in Table 5.

### Maximum Elastic Seismic Forces (6.3.1)

The maximum elastic seismic force resultants at any cross-section of the substructure shall be calculated considering all the following forces:

(a) Maximum elastic seismic force transferred from the superstructure to the top of the substructure through bearings (Fig.3).

(b) Maximum elastic seismic forces applied at its center of mass due to the substructure's own inertia forces.

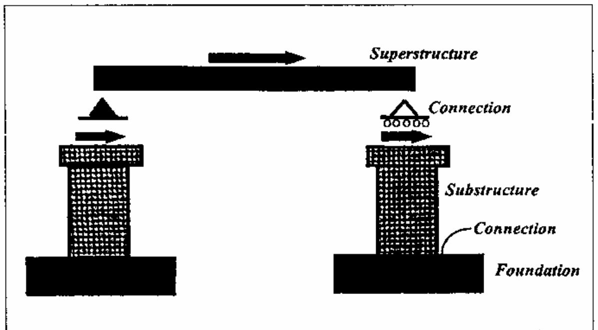


FIG.3 TRANSFER OF FORCES FROM SUPERSTRUCTURE TO SUBSTRUCTURE, AND TO FOUNDATION

Reduction due to buoyancy and uplift shall be ignored in the calculation of seismic weight.

(c) Hydrodynamic forces acting on piers as per clause 6.4, and modification in earth-pressure due to earthquake acting on abutments.

**(6.3.1.1)** When the substructures are oriented normal to the direction of the traffic and along the direction of stream flow, two separate load cases, namely seismic forces acting parallel to (a) the current direction, and (b) the traffic directions, shall be considered. When the substructures are oriented skew either to the direction of traffic or to the direction of current, the load combination as given in 2.5, shall be considered.

**(6.3.2)** While considering the stability of the substructure against overturning, the minimum factor of safety shall be 1.3 under simultaneous action of maximum elastic seismic forces in both horizontal and vertical directions during the earthquake.

### Hydrodynamic Force (6.4)

For the submerged portion of the pier, the total horizontal hydrodynamic force along the direction of ground motion is given by:

$$F = C_e A W_e \qquad (16)$$

where $C_e$ is a coefficient given by Table 6, depending on the height of submergence of the pier relative to that of the radius of a hypothetical enveloping cylinder (Fig. 4). The pressure distribution due to hydrodynamic effect on pier is given in Fig. 5; the coefficients $C_1$, $C_2$, $C_3$ and $C_4$ are given in Table 7.

TABLES 6
VALUES OF $C_e$

| Height of Submerged Portion of Pier H/ Radius of Enveloping Cylinder | 1.0 | 2.0 | 3.0 | 4.0 |
|---|---|---|---|---|
| $C_e$ | 0.39 | 0.58 | 0.68 | 0.73 |

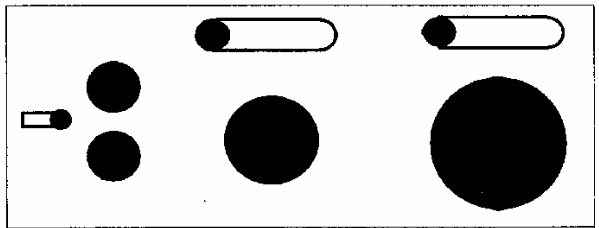

FIG.4 HYPOTHETICAL ENVELOPING CYLINDERS TO ESTIMATE HYDRODYNAMIC FORCES ON SUBSTRUCTURES DUE TO SEISMIC SHAKING

TABLE 7
PRESSURE DISTRIBUTION COEFFICIENTS $C_1$, $C_2$, $C_3$ and $C_4$

| $C_1$ | $C_2$ | C3 | $C_4$ |
|---|---|---|---|
| 0.1 | 0.410 | 0.026 | 0.9345 |
| 0.2 | 0.673 | 0.093 | 0.8712 |
| 0.3 | 0.832 | 0.184 | 0.8013 |
| 0.4 | 0.922 | 0.289 | 0.7515 |
| 0.5 | 0.970 | 0.403 | 0.6945 |
| 0.6 | 0.990 | 0.521 | 0.6390 |
| 0.8 | 0.999 | 0.760 | 0.5320 |
| 1.0 | 1.000 | 1.000 | 0.4286 |

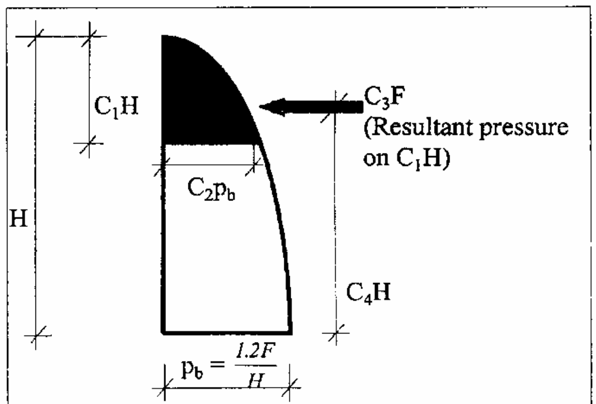


FIG.5 HYDRODYNAMIC PRESSURE DISTRIBUTION ON THE SUBSTRUCTURE DUE TO STEAM FLOW

### FOUNDATIONS (7.0)

**(7.1)** In loose or poorly graded sands with little or no fines, vibrations due to earthquake may cause liquefaction or excessive total and differential settlements. Founding bridges on such sands shall be avoided in seismic zones III, IV and V, unless appropriate methods of compaction of soil stabilisation are adopted and suitable foundations designed.

**(7.2)** When substructure terminate on a footing which rests on rock or on piles, they may be considered rotationally fixed. Foundations on soft soil may be modelled using equivalent linear springs. Also, well foundations may be analysed assuming soil springs to lateral supports.

### Seismic Zones IV and V (7.3)

The foundations of bridges in seismic zones IV and V shall be designed to resist smaller of the following forces:

(a) Design seismic forces obtained from Clauses 3.3 or 4.4.

(b) Forces developed when overstrength plastic moment hinges are formed in the substructure, as described in section 9.

## CONNECTIONS (8.0)

### Design Forces for Connections within Superstructure and between Superstructure and Substructure (8.1)

#### Seismic Zones I, II and III (8.1.1)

The connections between adjacent sections of the superstructure or between the superstructure and the substructures shall be designed to resist atleast horizontal seismic force in the restrained directions equal to 0.20 times the vertical dead load reaction at the bearing, irrespective of the number of spans.

#### Seismic Zones IV and V (8.1.2)

The connections between the superstructure and substructure, and the substructure and foundation shall be designed to resist the smaller of the following forces:

(a) Maximum elastic horizontal seismic force obtained from analysis and transferred through the connection in the restrained directions, divided by the appropriate Response Reduction Factor $R$ are applicable to connections, which are given in Table 5.

(b) Maximum horizontal force, when overstrength plastic moment hinges are formed in the substructure.

### Displacements at Connections where Motions are Permitted (8.2)

#### Separation Between Adjacent Units (8.2.1)

When relative movement between two adjacent units of a bridge are designed to occur at a separation joint, sufficient clearance shall be provided between them, to permit the calculated relative movement under design earthquake conditions to freely occur, without inducing damage. Where the two units are out of phase, the clearance to be provided may be estimated in the squareroot of the sum of squares of the calculated displacements of the two units under maximum elastic seismic forces given by clauses 3.2 or 4.3.

### Minimum Width of Seating at Supports of Superstructure or of the Suspended Span Portion on the Restrained Portion of the Superstructure (8.3)

The width of seating $W$ (in mm) at supports measured normal to the face of the abutment/pier/restrained portion of superstructure from the closest end of the girder (Fig.6) shall be the larger of the calculated displacement under the estimated maximum elastic seismic forces as per clauses 3.2 or 4.3, and the value specified below:

$$W = \begin{cases} 500 + 1.5L + 6H & \text{for seismic zone I, II and III} \\ 800 + 2.5L + 10H & \text{for seismic zone IV, V} \end{cases} \quad (17)$$

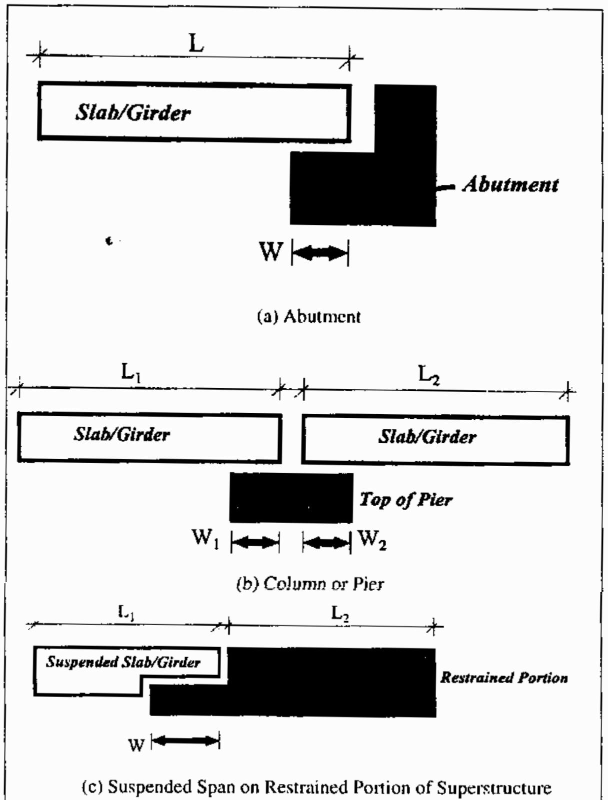


FIG.6 MINIMUM WIDTH OF SEATING ON SUPPORTS

where

$L$ = Length (in metres) of the superstructure to the adjacent expansion joint or to the end of superstructure. In case of bearings under suspended spans, it is the sum of the lengths of the two adjacent portions of the superstructure. In case of single span bridges, it is equal to the length of the superstructure.

$H$ = For bearings at abutments, Average height (in metres) of all columns supporting the superstructure to the next expansion joint. It is equal to zero for single span bridges. For bearings at columns or piers, height (in meters) of column or pier. For bearings under suspended spans, average height (in metres) of the two adjacent columns or piers.

## CAPACITY DESIGN OF BRIDGE COMPONENTS (9.0)

The design seismic force for bridges is lower than the maximum expected seismic force on them. However, to ensure good performance at low cost, the difference in the design and the maximum expected seismic force shall be accounted for, through additional safety provisions. The capacity design provisions given under clause 9, shall be applicable to seismic zones IV and V only. These provisions are meant for bridges having reinforced concrete substructure. However, if steel substructure is used in high seismic zones reference should be made to the relavent codal provisions of other countries.

### Design Force for Substructure (9.1)

Provisions given in IS:13920-1993[11] for the ductile detailing of RC members subjected to seismic forces shall be adopted for all the components of the bridge. Further, the design shear force at the critical section(s) of substructures shall be the higher of the following forces:

(a) Maximum elastic shear force at the critical section of the bridge component divided by the Response reduction factor for that component as per Table 5.

(b) Maximum shear force that develops when the substructure has maximum moment that, it can sustain (overstrength plastic moment capacity as per clause 9.3) in single-column or single-pier type substructure, or maximum shear force that is developed when plastic moment hinges are formed in the substructure so as to form a collapse mechanism in multiple-column frame type or multiple-pier type substructures. The plastic moment capacity shall be the overstrength plastic moment capacity as per clause 9.3.

In a single-column or pier type substructure, the critical section is at the bottom of the column or pier (Fig. 7a). And, in multi-column frame-type or multi-pier substructure, the critical sections are at the bottom and/or top of the columns/piers (Fig.7b).

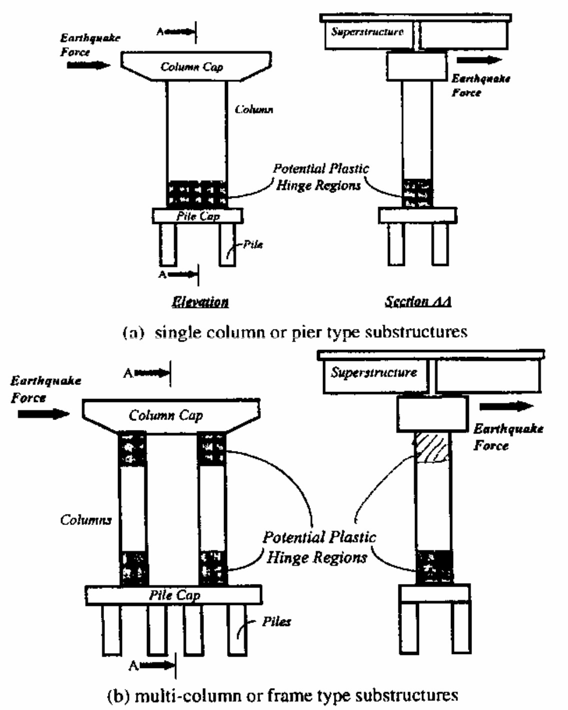


FIG.7 POTENTIAL LOCATION OF PLASTIC HINGES IN SUBSTRUCTURES

### Design Force for Connections (9.2)

Connections at the restrained ends shall be designed for the lower of the following.

(a) Maximum elastic shear force transferred through them at the critical section of the bridge component divided by the Response reduction factor for that component as per Table 5.

(b) Maximum shear force that develops when the substructure is analysed for maximum moment that it can sustain (overstrength plastic moment capacity as per clause 9.3)

### Overstrength Plastic Moment Capacity (9.3)

### Limit State Method of Design (9.3.1)

The overstrength plastic moment capacity at a reinforced concrete section shall be taken as 1.4 times the ultimate moment capacity based on the partial safety factors recommended by the relevant Indian codes of practice for materials and loads, and on the actual dimensions of members and the actual reinforcement detailing adopted.

### Working Stress Method of Design (9.3.2)

The overstrength plastic moment capacity at a section may be taken as 2.1 times the design moment capacity obtained using the permissible stresses for materials given in the relevant Indian codes of practice, and on the actual dimensions of the members and the actual reinforcement detailing adopted. The increase in permissible stresses given in clause 2.6.1 need not be considered for calculation of overstrength plastic moment capacity.

## SUMMARY AND CONCLUSIONS

A draft proposal for the seismic design of bridges is presented for the next revision of IRC.6[1] and IS.1893[2]. Many of the issues raised in the earlier reports on the performance of bridges in India during past earthquakes[3] and on the state-of-the-art review of IRC 6-1966 provisions[4,5] have been incorporated.

The following is a brief summary of some major and important modifications in this paper:

1. Relative values of seismic zone factor have been changed, these are the same as the ones included in the draft provisions of IS:1893, which is under revision.

2. Two methods, namely Seismic Coefficient Method and Response Spectrum Method, are given for estimating design seismic forces, this is in line with the draft Indian code for buildings and codes of some other countries for seismic design of bridges.

3. The concept of ductility and overstrength is brought into the code explicitly, by introducing the Response reduction factors in place of the performance factor.

4. Response reduction factors have been proposed for the different components of the bridge, depending on the expected ductility and overstrength in them.

5. The design force level for bridges has been raised and brought in line with the currnt international practices.

6. The concept of *capacity design* is introduced in the design of connections, substructures and foundations.

7. The soil-foundation system factor is dropped. A soil profile factor depending on the soil profile has been introduced for obtaining the design spectrum.

8. Design for displacements in the structure is introduced.

9. Use of vertical hold-down devices and horizontal linkage elements to account for the large displacements generated during seismic shaking, is made mandatory for bridges in high seismic zones.

10. A minimum width of seating of superstructure over substructures, is proposed for all bridges.

The proposed draft includes significant improvements over the IRC:6-1966[1] and the IS:1893-1984[2]. However, there are still a number of areas that need to be further improved. These include detailed clauses on the design and detailing of individual components of foundations and abutments, of all structural steel and reinforced concrete bridge components.


## ACKNOWLEDGEMENT

The authors are thankful to the Ministry of Surface Transport, New Delhi, for the financial support, which made this work possible. The authors sincerely thank the anonymous reviewer for providing a detailed and extremely useful review of the paper.


## NOTATION

| | |
|---|---|
| $A$ | Elastic seismic acceleration coefficient |
| $A_k$ | Elastic seismic acceleration coefficient of mode $k$ |
| $C$ | Bridge flexibility factor |
| $C_e$ | Hydrodynamic force coefficient |
| $C_k$ | Bridge flexibility factor of mode $k$ of vibration |
| $C_1, C_2, C_3, C_4$ | Pressure coefficients to estimate flow load due to stream on the substructure |
| $D$ | Dead load reaction at the support |
| $E$ | Modulus of Elasticity |
| $F$ | Hydrodynamic force on substructure |
| $F_e$ | Inertia force due to mass of a bridge compontent under earthquake shaking along a direction |
| $\{F_k^e\}$ | Inertia force vector due to mass of bridge under earthquake shaking along a direction in mode $k$ |
| $F_{net}^e$ | Maximum elastic force resultants at a cross-section due to all modes considered |
| $H$ | Height of water surface from level of deepest scour; height of substructure as per clause 8.2.2. |
| $I$ | Importance Factor |
| $L$ | Length of bridge deck as per clause 8.2.2. |
| $M_h$ | Moment due to horizontal fluid pressure on submerged superstructure about the center of gravity of its base |
| $P_k$ | Modal participation factor of mode $k$ of vibration |
| $R$ | Response Reduction Factor |
| $S$ | Soil Profile Factor |
| $S_E$ | Seat length of the superstructure on the substructure (or, the suspended portion of the superstructure on the restrained portion) |
| $T$ | Natural Period of Vibration |
| $T_1$ | Fundamental Natural period |
| $T_k$ | Natural Period of Vibration of mode $k$ |
| $U$ | Vertical force at support due to seismic force |
| $V$ | Lateral Shear Force |
| $V^e$ | Maximum elastic force resultant at a cross-section of a bridge component |
| $V_{net}$ | Design seismic force resultant in any component of the bridge due to all modes, considered |
| $W$ | Seismic weight, which includes full dead load and part live load as discussed in clause 3.2.3 |
| $W_b$ | Widths of seating at bearing supports at expansion ends of girders. |
| $W_e$ | Weight of water in a hypothetical enveloping cylinder around a substructure |
| $Z$ | Seismic zone factor |
| $f_c'$ | Characteristic cylinder compressive strength of concrete at 28 days |
| $f_{ck}$ | Characteristic cube compressive strength of concrete at 28 days |
| $f_y$ | Characteristic yield strength of reinforcement steel |
| $g$ | Acceleration due to gravity |
| $m$ | Number of modes of vibration considered |
| $[m]$ | Seismic mass matrix of the bridge structure |
| $p$ | Pressure due to fluid on submerged superstructures |

| | |
|---|---|
| $r_1, r_2\ r_3$ | Force resultants due to full design seismic force along two principal horizontal directions and along the vertical direction, respectively |
| $y$ | Height of water in a hypothetical enveloping cylinder around a substructure |
| | the bridge due to all modes considered |
| $\alpha$ | Horizontal seismic coefficient |
| $\alpha_h$ | Horizontal seismic coefficient |
| $\alpha_o$ | Basic horizontal coefficient |
| $\beta$ | Ratio of natural frequencies of modes i and j |
| $\{\varphi_k\}$ | Mode shape vector of the bridge in mode $k$ of vibration |
| $\lambda$ | Net response due to all modes considered |
| $\lambda_k$ | Response in mode k of vibration |
| $\rho_{ij}$ | Coefficient used in combining modal quantities of modes i and j by CQC Method |
| $\omega_k$ | Natural frequency of mode $k$ of vibration |
| $\zeta$ | Modal damping ratio |

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