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DISASTER MITIGATION IN BRIDGES BY RESTRICTING MOVEMENT AT BEARINGS

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INTRODUCTION

The behaviour of bridges during severe earthquakes in India, Japan and other countries has clearly shown that no damage to bridges occurred in MM VII or smaller intensity areas and that the extent of damage increased with the increasing intensity (1). The most severe damage like falling of girders is seen to have occurred in MM intensity IX plus. Thus all bridge superstructues in seismic zone V of zoning map of India (2) and those of important bridges lying in zone IV would need special care to avoid this type of severe damage or collapse. It is also observed that the bearings at the ends of spans or articulation sections at the ends of cantilevers play the critical role in this behaviour and most of the complete collapses could have been avoided if the necessary care had been taken in their design from the dynamic response view point. The aim of this paper is to highlight the factors affecting the damage behaviour and show by means of an illustrative example how a safe behaviour could be achieved even under the probable maximum earthquake ground motion.

MODES OF SUPERSTRUCTURE COLLAPSE

The falling of superstuctures has occurred in the past in three ways as follows:

(i) Overturning of high trussed girders on the side (3). This involves lifting of the girder off the bearing shoe indicating the need to hold down the girder so that lifting may not take place at any level through the bearing.

(ii) Shifting of the deck sideways (4). This indicates sliding of the superstructure on the bearing surface in the transverse direction of the bridge. Hence restraint will be needed in the form of shear keys or otherwise to check the transverse sliding movement.

(iii) Excessive rolling or sliding in longitudinal direction and falling off the seat (4). This indicates that the movement occurred far in excess of that calculated and provided for in design.

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Most of the above actions can not be explained by means of the forces computed by the code based design seismic coefficients or even much larger static forces. These could only be seen to occur by a rational dynamic analysis of the bridge as a whole taking ground accelerogram into account (5).

PARAMETERS AFFECTING DYNAMIC RESPONSE

Besides the usual parameters like mass and stiffness distribution of the structural elements, in bridges across rivers with erodible beds, there is a major contributing factor in the form of scour around piers. This level determines the soil stiffness on the sides as as well the base of the foundation and that in turn mainly decides the fundamental period of vibration of the bridge. As a consequence in a multi-span bridge the fundamental periods of adjacent spans could be substantially different from each other inspite of equal span and substructures. During an earthquake, therefore out of phase motions of adjacent spans will form a distinct probability and must be catered for in the design of their supporting elements and the articulations between them.

An example of striking difference in the behaviour of various piers of a bridge due to river bed condition at the time of a moderate earthquake is provided by the shearing of bearing shoes on a few piers of the railway bridge across Narmada River at Broach in the March 23, 1970 Broach Earthquake (6).

Another important effect to be considered is the vertical vibration of the deck due to horizontal vibrations of the piers. This would occur even in simply supported spans due to the frictional force at bearings being eccentric to the centre of the deck (5). This effect will be even more pronounced at the tips of cantilevers in a hammer head system due to bending of the piers in the longitudinal direction (Fig.1).

Fig. 1. Vertical accelerations due to bending of piers in longitudinal direction

CONSIDERATIONS FOR ARTICULATION DESIGN

From the discussions, it is obvious that, whether a dynamic analysis of the bridge is carried out or not, suitable restraints must be incorporated in the bearing supports so as not to permit vertical separation of the superstructure nor its transverse sliding, and in the longitudinal direction either the movement should be stopped after a certain desired amount or a long rolling surface must be provided to avoid the falling away of the girders.

A number of ideas have been developed in Japan for meeting these objectives (9).

RESULTS OF DYNAMIC ANALYSIS

The bridge analysed for this study consists of twenty main spans of 120 m each and two end spans of 67.5 m each. Each main span is of double cantilever type with small suspended span of 15 m length and the cantilever spans are of 52.5 m each as shown in Fig. 2. The substructure consists of reinforced concrete circular piers and wells. The superstructure is of prestressed concrete box girder of varying depth in cantilever portion.

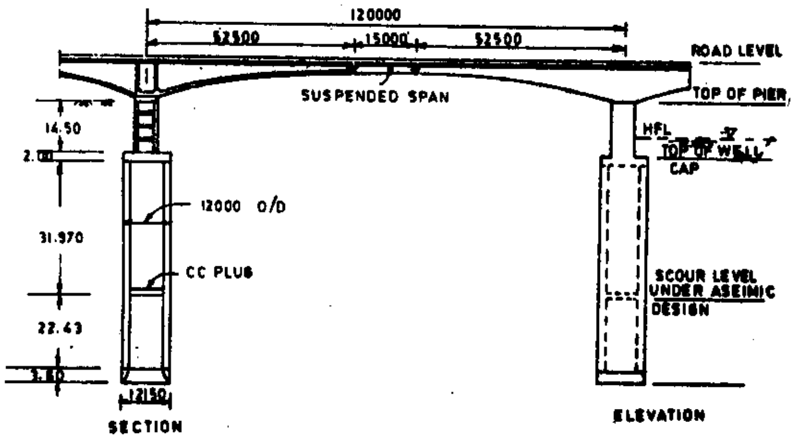

Fig. 2. Details of Bridge

The dynamic analysis of the bridge was carried out with general assumptions of IS:1893-1975 regarding live load and flood combination. Specific seismotectonic studies were carried out to determine probable maximum earthquake spectra for design at ultimate load condition (Fig. 3). It was to be divided by a factor 1.85 to arrive at spectra for working stress design (7). The embedded part of the well in the soil was replaced by linear and rotational springs at the centre of the embedded length. Two lumped mass models were made one for dynamic analysis in longitudinal and/or vertical direction and the other in the transverse direction as shown in Figures 4 and 5. It may be noted that in view of the symmetry in the mathematical model, antisymmetric modes were excited under horizontal ground motions and symmetric modes under vertical vibrations.

A number of founding levels of the well base and a range of scour levels from minimum to maximum probable were considered as to arrive

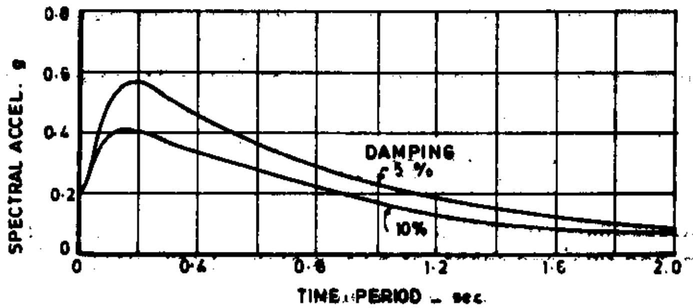

Fig. 3. Recommended acceleration response spectra for design of structures at project site. A multiplying factor of 1/1.85 is to be used when working stress method of design is adopted

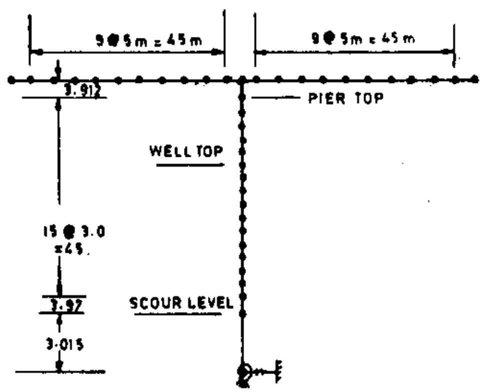

Fig. 4. Mathematical model of Bridge in longitudinal direction

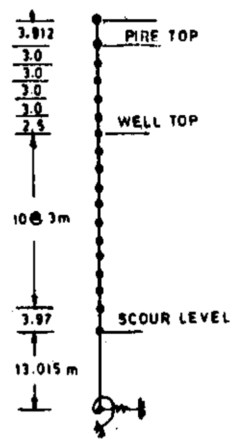

Fig. 5. Mathematical model of Bridge in transverse direction

at the maximum force and displacement responses under highest and lowest stiffness conditions.

The vibration analysis was carried out by the method of transfer functions (8). The dynamic response for the maximum probable earthquake was found out in first four modes. The total response was obtained by taking square root of sum of squares (S. R. S. S.) of individual modal responses. Table 1 shows the maximum dynamic displacements for ultimate condition taking each double cantilever structure as one unit. It will be interesting to state that under the action of longitudinal earthquake, the maximum probable horizontal and vertical acceleration at the tip of cantilever were 0.3 g and 0.795 g respectively indicating a very large vertical acceleration in the cantilever even under the horizontal earthquake.

TABLE 1—MAXIMUM ULTIMATE DYNAMIC DISPLACEMENTS

Direction of Earthquake	Position	Max. Disp. cm
Transverse	c. g. of deck	10.55
Longitudinal	cantilever tip–	
	horizontal	8.38
	vertical	15.45

DESIGN OF ARTICULATION FOR RESTRICTFD MOVEMENTS

For safety of the suspended span, the articulation section should be capable to absorb the maximum prabable 'out of phase' displacements in both the longitudinal and transverse directions. Also the suspended span should not be allowed to lift off the bearings due to vertical acceleration. For meeting these aims, a special design of bearings is suggested. This consists of friction bearing (steel on steel) at one end and PTFE bearing at the other end of suspended span. The idea is that the friction in the sliding bearing is sufficient to prevent any movement under normal conditions but could permit sliding under severe earthquake. A fixed bearing is avoided to reduce the twisting effects due to transverse displacements. Restrainers are introduced to check more than the maximum computed displacements and vertical ties are introduced to hold the suspended span to the cantilevers in vertical direction. The details are presented below.

LONGITUDINAL DIRECTION

The maximum longitudinal diplacement at tip of cantilever is 8.38 cm due to probable maximum earthquake and 5 cm could be the relative temperature movement. Taking the probability of outward or inward movements of the two consecutive piers into account with any temperature rise the maximum relative movement between them can be taken as

$$\sqrt{2(8.38)^2 + 5^2} = 12.86, \text{ say } 13 \text{ cm.}$$

The maximum longitudinal force that can exist in the suspended span without sliding at ends is determined by the forces of friction at its end, that is, equal to

$$\tfrac{1}{2}(\text{weight of suspended span})\mu$$

Where μ is the coefficient of friction between steel and steel, say 0.3. This force works out 350 kN.

The arrangement of bearings, stoppers and holding down ties at an articulation is shown in Fig. 6. There are two sliding bearings, one under each longitudinal beam, two box-in-box stoppers of steel and three holding down ties. The longitudinal parrallel sides of the sliding plates are to be shaped to account for the transverse relative displacements as explained later. The arrangement at the other end will be similar except that the sliding bearing will be PTFE permitting movement with little friction.

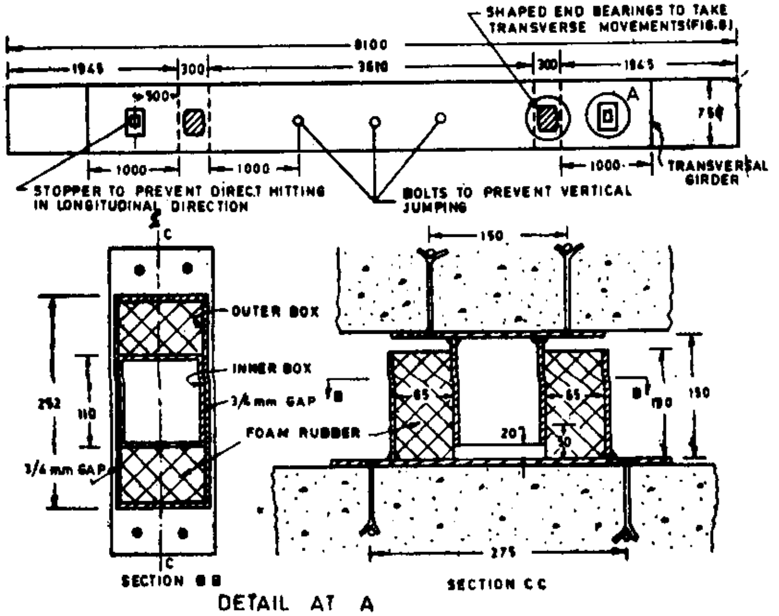

Fig. 6. Plan at articulation showing strengthening arrangements

Under normal loading condition and temperature movement, the frictional force of 350 kN will hold one end in fixed position, PTFE bearing will allow longitudinal movement and because of 65 mm gap being more than 50 mm needed for temperature movement, the movement will be free without any restraint from the stoppers.

When a severe earthquake will hit with temperature movement in any position, and the total mevement exceeds 65 mm, the inner box will strike against the wall of the outer box. If the force exerted by the earthquake between the two spans will be less than 350 kN, no further relative movement will occur. But if the force exceeds 350 kN, sliding will occur at the other end, steel on steel, and the gap between the steel box at that end will absorb the additional movement. Thus a total movement of 130 mm can be absorbed at both the ends put together (See Fig. 7). In case the earthquake happens to be even more severe than the

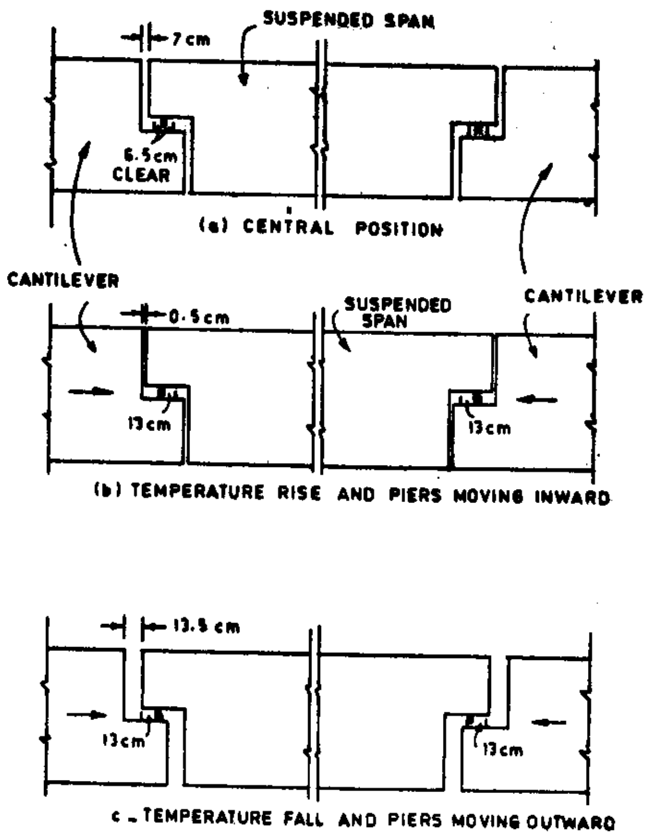

Fig. 7. Movement of inner box inside the outer box

probable maximum value estimated, the stoppers will not allow further relative movement but rather restrain the two consecutive piers to move together. At this stage a certain longitudinal force will be generated which could only be estimated dynamically involving too many variables and non-linear analysis. The authors would recommend an arbitrary force equal to the frictional force of 350 kN for designing the stoppers.

TRANSVERSE DIRECTION

The maximum transverse displacement of a pier at the centre of gravity of the deck is 10.55 cm. Considering the probability of maximum relative displacement between two consecutive piers, it value could be taken as

$$\sqrt{10.55^2 + 10.55^2} = 14.92 \text{ cm, say } 15 \text{ cm.}$$

Assuming that this relative displacement will be taken by the suspended span by its rotation in the horizontal plane, the angle of rotation will be

$$15/1500 = 0.01 \text{ radian}$$

This will require a clearance of 0.005 B on each side of the longitudinal sides of the sliding plates where B is its straight length. The central 150 mm length of the plates may be kept straight and then chambered at an angle of 0.005 radian. This will require a clearance of 0.75 mm on either side (see Fig. 8).

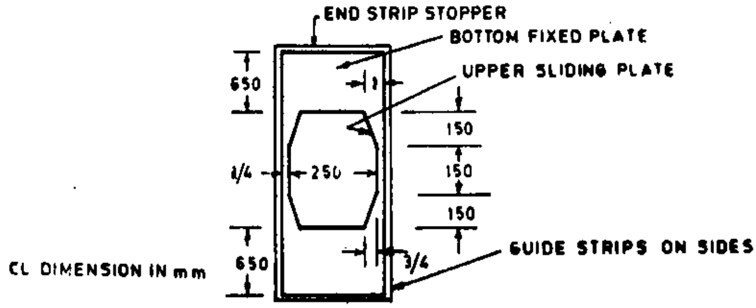

Fig. 8. Shaped end bearing plate

VERTICAL DIRECTION

The maximum vertical acceleration acting on the suspended span is indicated by the dynamic response analysis as 0.795 g. This being less than the gravity acceleration, jumping of the span is not indicated. It will however be safer to provide vertical holding down ties in case the estimated ground accelerations are exceeded. For this purpose an arbitrary separating force equal to 5% of the weight of span is suggested. Thus the design force for ties will be 0.05 × weight of suspended span and at each end it will be 0.025 × weight. Mild steel bars may be located vertically in holes through the cross diaphragm at the articulation. These bars should be anchored at the ends only, through nuts and washers, so that they have a free length and clearance in the holes to accommodate the longitudinal movements as far as possible.

CONCLUSION

The behaviour of bridges observed during earthquakes as well as their dynamic response analysis clearly points out to the need of special design consideration in the design of bearings and articulations at ends of span. These include the provision for probable maximum displacements on the one hand and the stoppers and holding down arrangements on the other hand to restrict further movements. It has been shown by an example of a major bridge to be constructed in severe seismic zone how to cater for the various requirements.

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