SEISMIC ANALYSIS AND DESIGN CONSIDERATIONS FOR AN AQUEDUCT

by

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ABSTRACT

The paper presents the results of dynamic investigations of a multispan aqueduct structure carrying 357 m^3/sec discharge across a wide alluvial river. The spans are simply supported at the ends and the sub-structure consists of reinforced concrete pier and well foundation. The soil on the sides of wells consists of sand or clay and the base rests on clay layer. The mathematical modelling and dynamic analysis of the aqueduct in two horizontal directions are described here in which a range of properties of side and base soils are considered in order to determine the influence of stiffness of foundation on the response. Modal analysis using site dependent response spectra is employed and force and displacement responses computed. Based on the results, appropriate design requirements of the aqueduct are assessed wherein the design of bearing shoes and water seals to cater for the relative displacements turns out as the most important consideration.

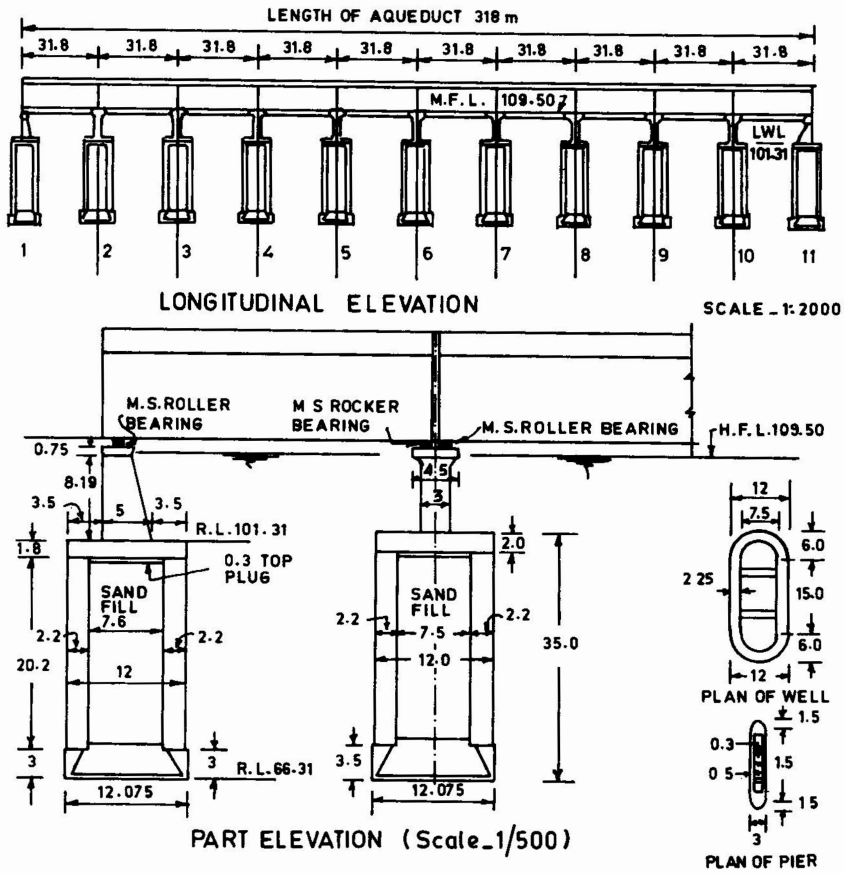
INTRODUCTION

The design of an aqueduct structure across wide alluvial rivers for safe performance during earthquakes is of utmost importance because of its post earthquake importance as well as economic value to the region. Not only the failure of superstructure bearings, or the substructure and foundations but also the leakage of water at the joints has to be completely avoided during the earthquake. The aqueduct structures have much similarity with the bridges with regard to structural system. But there are distinct differences, the loading carried by aqueducts is much heavier due to the weight of flowing water in addition to normal live loads of bridges, and very effective water sealing arrangement is required between the spans which is not the problem in bridges.

The paper describes the mathematical modelling and dynamic analysis of an aqueduct for earthquake motions in two horizontal directions. The foundation soil stiffness and scour levels are varied over a practical range in order to determine their influence on displacements and forces in the structure. The design requirements arrived at through the dynamic analysis are listed to focus attention on the same as important for aqueducts in moderate to severe seismic areas.

DESCRIPTION OF AQUEDUCT

A general view of the aqueduct is shown in Fig. 1. The aqueduct consists of 10 numbers of simply supported span, each span being 31.8 m long centre to centre of piers. The water carrying trough is of reinforced concrete and is contained between prestressed concrete girders, as shown in Fig. 2. The aqueduct carries a discharge of 357 cumecs (m^3/s) with an average velocity of water in the trough as 2.7 m/s. The substructure consists of reinforced concrete piers and well foundations. The foundation soil surrounding the wells consists of sand and clay in parts and the base consists of clayey soil. The weight of water in a single span is 29.C t. The live load on roadways on both sides of trough is



(ALL DIMENSION IN M)

FIG. 1_ GENERAL VIEW OF AQUEDUCT

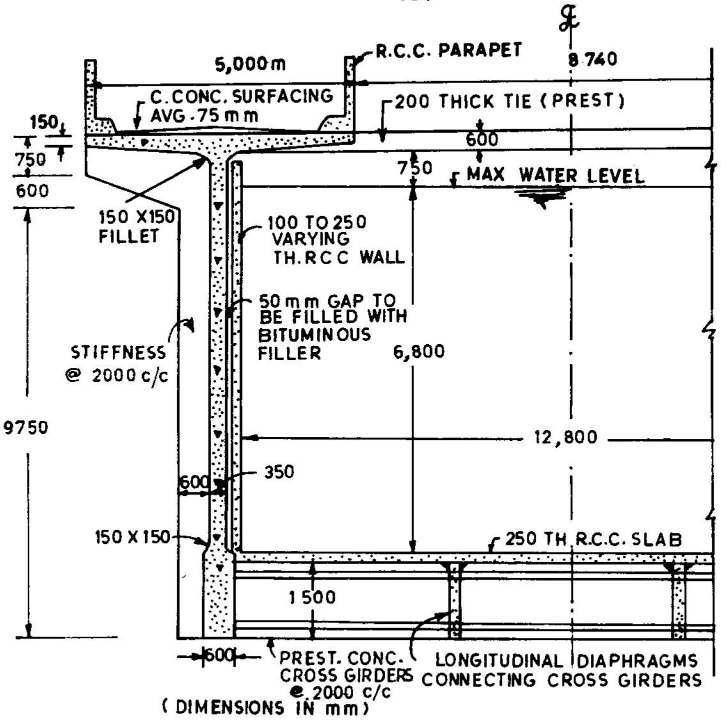


FIG. 2_CROSS SECTION OF TROUGH

class A type of Indian Roads Congress (IRC) (5) consisting of a truck and two trailors, the axle loads being 2.7, 2.7, 11.4, 11.4, 6.8, 6.8 and 6.8 t.

DESIGN CONDITIONS FOR AQUEDUCT

The following combination of loads and the conditions are considered in design at the time of maximum earthquake:

Earthquake and Flood : The maximum specified earthquake and the highest flood in the river crossed by the aqueduct are assumed to occur simultaneously. Consequently the depth of scour corresponding to maximum flood is taken in calculations. A second case in which the scour depth is 90% of scour depth calculated for maximum flood condition is also considered as per IRC recommendation.

Earthquake and Live Load : As per IRC specifications (5), 100 percent of class A loading is assumed to be on roadway at the time of earthquake. Its inertia effect is taken into consideration in the analysis for transverse direction only and it is ignored in the longitudinal direction because of rolling tendency of wheels.

Earthquake and Buoyancy : The full weight of submerged substructure is considered for computing inertia of the mass in the seismic analysis, and the reduction in weight due to buoyancy is considered in computing stresses in the well steining and bearing pressures on foundation soil.

Inertia of Flowing Water in Trough: Seismic force on mass of flowing water is considered in transverse direction only and ignored in the direction of flow of water. The trough walls are required to carry a hydrodynamic pressure and the inertia force on mass of water is transmitted to the prestressed girders and the piers and foundations.

Added Mass of Water in Substructure : The added mass of water surrounding piers and wells below high flood level is calculated on the basis of cylinder analogy as per IS:1893-1975(2). This added mass is assumed to be associated with submerged parts of piers and wells and is considered in dynamic calculations.

Inertia on Buried Portion of Well : The buried portion of the well foundation is considered to be elastic and inertia force acting on this portion is also considered in the calculation. The effect of deformation of surrounding soil is considered by idealising it in the form of elastic translational and rotational springs.

MATHEMATICAL MODELLING

The Structure : As each pier carries a rocker and roller bearing, it is assumed that inertia force of one span is fully transmitted to the top of a pier in longitudinal as well as transverse direction. The pier is replaced by lumped multi-mass system in both directions as shown in Fig. 3. In the longitudinal direction, the entire mass of superstructure is lumped at the top of pier, the mass of water in the trough and the live load on the bridge decks are ignored. In the transverse direction, the mass of roadway and live load taken together is lumped at the mass point A, the mass of water in the trough and that of side walls is lumped at mass point B, and the mass of bottom of trough is lumped at the point C (Fig. 3). The masses at A, B and C are assumed to be connected to each other by rigid links. The lumped masses of the portion of well below scour level include the structural portion of well and the sand filling inside.

The Foundation : The elastic resistance of soil on the sides of well below scour level is replaced by side springs and the base resistance is replaced by rotational spring at the base. This portion of the well itself is considered as a rigid body subjected to tilting about the point of rotation at base.

In case of sand, the stiffness of soil varies linearly with depth, while in preconsolidated clay it may be assumed to remain constant with the depth (4). The stiffness of discrete springs is obtained by lumping triangular stiffness distribution in the case of sand and uniform stiffness distribution in the case of clay at discrete points. The spring at the base is rotational and its stiffness is determined by writing the equation of restoring moment of the clay resistance.

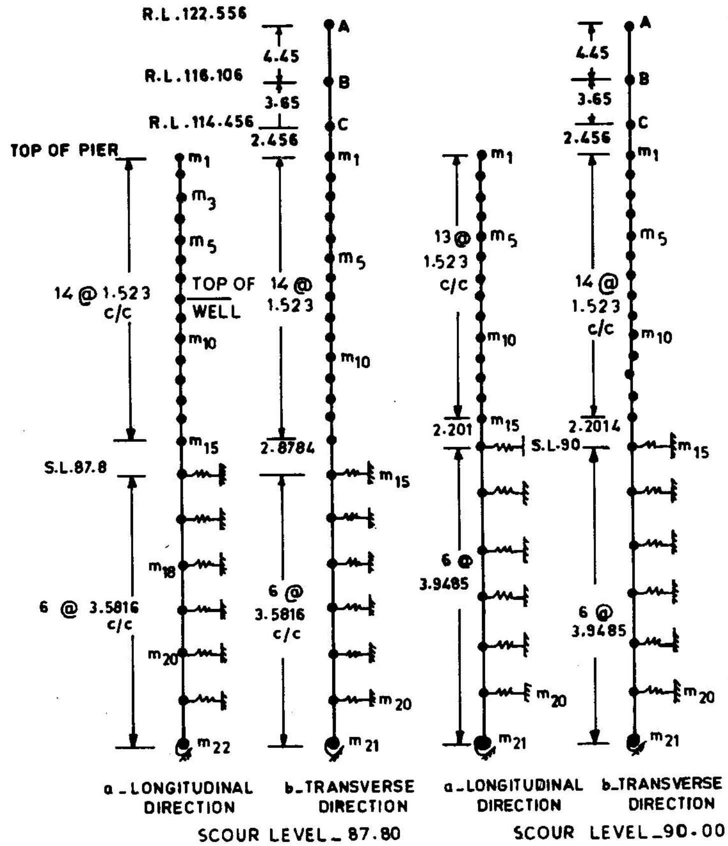


FIG. 3 - MATHEMATICAL MODEL OF AQUEDUCT

METHOD OF DYNAMIC ANALYSIS

The dynamic analysis of the structure consists of the following steps,

Natural Frequency and Mode Shapes of Structure : The pier well system is treated as beam type of structure which is restrained by elastic springs below scour level. The natural frequencies and mode shapes are computed using the method of transfer functions (1,3).

Choice of Design Spectrum : From the geo-seismological considerations of site, it is concluded that parameters of probable earthquake at the aqueduct site could be as follows: Magnitude = 6.0, epicentral distance= 30 km, depth of focus = 25 km. For these parameters, it is estimated that the ground velocity at this could be taken as 15 cm/sec. For alluvial conditions at the site the Elcentro Earthquake of May 18, 1940 N-S component is considered representative with regard to its frequency characteristics. The design accelerogram is obtained by reducing the acceleration ordinates of this Elcentro earthquake in the ratio of ground velocities, that is, 15/43 = 0.349. The displacement spectrum for a damping factor of 5 percent for this accelerogram is shown in Fig. 4.

Dynamic Response : The maximum dynamic response of the aqueduct structure in any mode at any section due to the chosen earthquake motion is obtained using the usual modal analysis procedure. The analysis shows that the contribution of the higher modes than fundamental is not significant because of heavy mass lumped at top and rather rigid pier well system compared to soil springs. Therefore the response due to first mode alone is computed.

RANGE OF FOUNDATION PARAMETERS

On the basis of standard cone penetration N values and the C and ϕ values available from soil tests, the range of soil modulus values chosen are given in Table 1. The sides of well have sand in some locations while clay at other locations. The base soil of foundation consists of clay in all cases.

RESULTS OF SEISMIC ANALYSIS

Some important results obtained for the various parameter combinations listed in Table 1 are mentioned below:

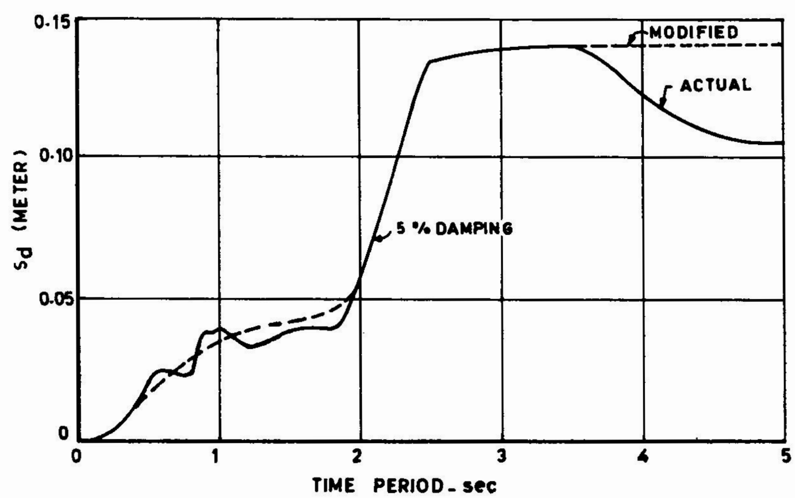


FIG. 4 _ DISPLACEMENT SPECTRA FOR EL CENTRO EARTHQUAKE ACTUAL AND MODIFIED

TABLE 1

PARAMETERS DATA AND RESPONSE VALUES OF SHEARS, MOMENTS AND DEFLECTIONS

Case No.	Direction of Motion	Scour level	Basic Soil Stiffness K_{si}	Side Soil and its stiffness: Sand n_h	Side Soil and its stiffness: Clay K_{si}	Values at Base: Shear	Values at Base: Moment	Maximum Moment: Point above foundation	Maximum Moment: Moment value	Maximum deflection
		m	t/m^2	t/m^3	t/m^2	t	tm	m	tm	mm
1.	Longi.	87.8	732	450	-	1827	475	14.32	21226	211
2.	Longi.	87.8	1100	900	-	2440	474	14.32	28234	144
3.	Longi.	87.8	732	-	732	271	483	17.91	4408	210
4.	Longi.	87.8	1100	-	1100	316	725	17.91	5292	210
5.	Trans.	87.8	732	450	-	1374	4541	14.33	27210	216
6.	Trans.	87.8	1100	900	-	1169	2847	14.33	22097	092
7.	Trans.	87.8	732	-	732	184	4674	17.91	8869	220
8.	Trans.	87.8	1100	-	1100	277	7006	17.91	13302	220
9.	Longi.	90.0	732	450	-	2195	452	15.79	26755	200
10.	Trans.	90.0	732	450	-	2721	413	15.79	30005	190

Maximum Forces and Displacement: The maximum shear force, bending moment and deflections in different cases are given in Table 1. The section where the maximum values occur are also presented therein. The distribution of the responses along the height of the structure are shown in Figure 5. It is seen that the maximum moment occurs at a certain level a little below the deepest scour level and then it starts decreasing towards the base. The shear and moment at the base are very much less than the maximum values occurring in the well.

Effect of Range of Soil Properties : It is always difficult to assign one definite value to the soil stiffness characteristics. The effect of the variation of soil stiffnesses on the response quantities can be readily seen from Table 1. Comparing the values for cases 1 and 2, it is seen that for the higher values of Ksi and nh, the maximum moment in the well foundation will increase from 21226 to 28234 tonne, an increase by 33 percent and the top deflection decreases from 211 to 144 mm a decrease by 32 percent. Also those piers whose foundation gets clay on the sides have higher flexibility than those having sand around them. It also shows that the adjacent piers could have different fundamental periods due to difference in scouring action of the flood waters, changes of soil strata elevations and variation of soil types. Thus the displacements of adjoining piers could have quite large phase differences both in the longitudinal and transverse directions, which must be taken into consideration while designing, the bearing shoes and the water seals between the aqueduct spans. For design purposes, it would naturally be safer to consider the larger forces and moments that arise in the stiffer cases and the larger displacements generated in the more flexible cases.

Out of Phase Displacements : The maximum deflections at top of an intermediate pier work out as 212 mm and 221 mm in longitudinal and transverse directions respectively. It may be assumed that there will be a probability of out of phase displacement of consecutive piers of the order of $\sqrt{2}$ times the above displacement, that is, 300 mm in the longitudinal direction and 313 mm in the transverse direction. Special details of construction are necessary between the spans so as to permit these displacements without distress in the connecting elements as well as without leakage of water from the trough.

ASEISMIC DESIGN REQUIREMENTS

On the basis of the dynamic analysis of the aqueduct considering probable ground motion spectra, the following design requirements are projected:

a) Bearing Shoes on Intermediate Piers : A maximum horizontal shear force of 250 t would occur on the fixed bearing in the longitudinal direction whereas in the transverse direction there will be a lateral shear of 600 t and an uplift force of 1250 t due to overturning moment. In order to ensure proper fixity of the shoe plates into the concrete of the pier cap at bottom and the prestressed concrete beams at the top, it will be desirable to have projecting lugs in both directions, that is in a grid form, which should be capable of resisting the shears and transferring the load to concrete in bearing. Bolts will then only be requ-

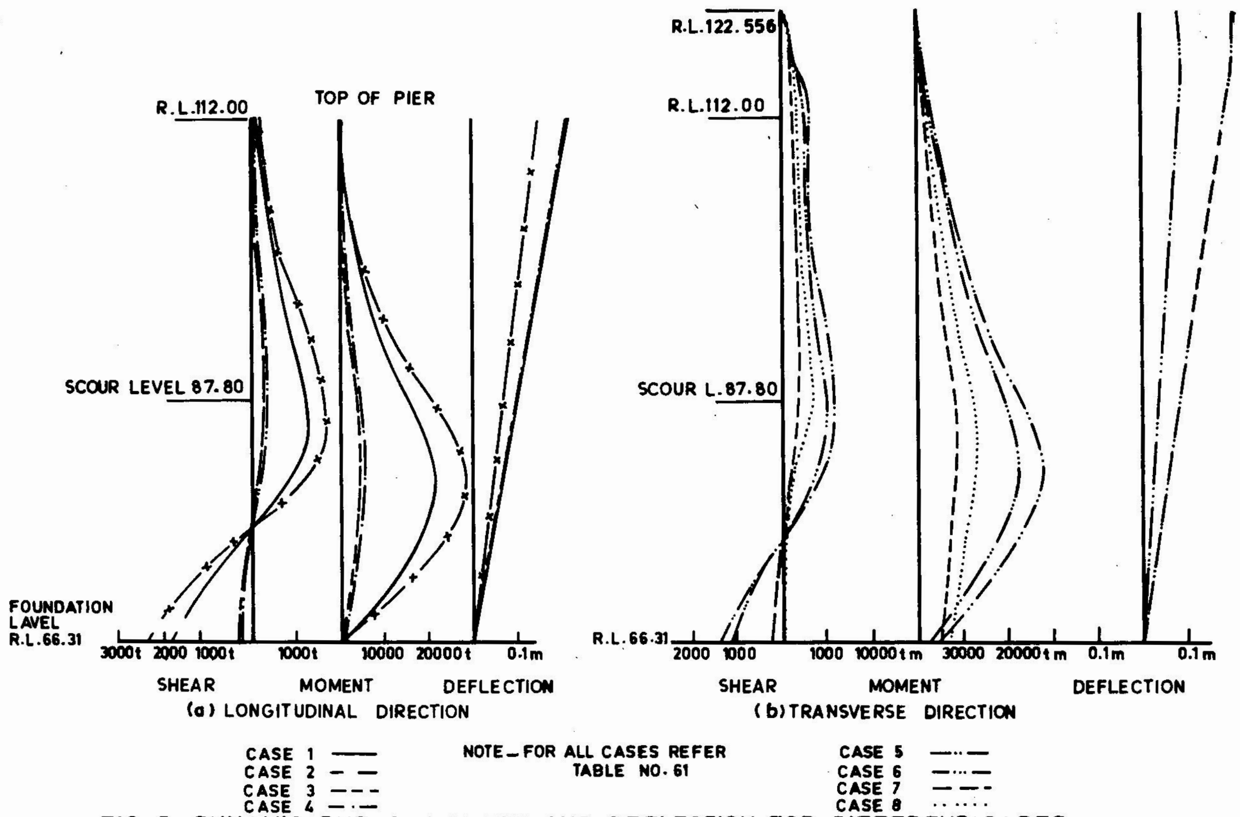


FIG. 5_ DYNAMIC SHEAR MOMENT AND DEFLECTION FOR DIFFERENT CASES

ired for holding down the shoe to the concrete and not for resisting shearing forces.

b) Pier and Well Foundation : The substructure should be designed to withstand the maximum shear forces and bending moments developed as shown in Table 1 and Figure 5. It will be desirable that to meet the requirements of larger energy demands in more severe earthquakes, the reinforced concrete structure should be designed to have adequate ductile deformation capacity. Knowing the maximum forces in the soil springs, the safety of the soil should be checked with reference to its shear and bearing strengths.

CONCLUSION

The dynamic modal analysis of a major aqueduct across an alluvial river as carried out using site dependent displacement response spectra shows the importance of soil structure interaction in regard to the forces and displacements of the structure. It will be advisable to consider an appropriate range of soil stiffnesses for this purpose rather than one fixed value. It is also seen that besides the forces and moments, it will be an important criterion for the aqueduct design to evaluate the probable maximum relative displacements between consecutive piers and cater for them in the design of bearing shoes and the water seals, so that the structure remains safe against failure as well as functional regarding carriage of water.

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REFERENCES

1. Arya, A.S. and Thakkar, S.K., 'Response of the substructure of a Major Bridge to Earthquake Motions', Journal of Indian Roads Congress, Vol. XXXIII-2, September 1970, pp.377-392.

2. Indian Standards Institution, IS:1893-1975, 'Criteria for Earthquake Resistant Design of Structures', ISI, Manak Bhawan, New Delhi.

3. Keightley, W.C., 'Vibration Tests of Structures', Ph.D. Thesis, California Institute of Technology, Pasadena, California, July 1963.

4. Terzaghi, Karl, 'Evaluation of Coefficient of Subgrade Reaction', Geotechnique, Vol. V, No. 4, Dec. 1955, pp. 297-326.

5. The Indian Roads Congress, 'Standard Specification and Code of Practice for Road Bridges', Section II, Loads and Stresses, Jamnagar House, Shahjahan Road, New Delhi.