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Seismic analysis and design consideration of an aqueduct on alluvial soil

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ABSTRACT: Aqueducts founded on alluvial soils are vulnerable to earthquake damage because of several reasons, such as excessive displacement in bearings, cracking of substructure and super-structure and settlement of foundation. In the present study, detailed dynamic analysis of an aqueduct considering soil-structure interaction has been carried out to determine the seismic forces and displacements in the longitudinal as well as transverse directions. Resultant hydrodynamic pressure on the walls of the trough has been calculated. Seismic design considerations for safe performance of the aqueduct in an earthquake have also been discussed.

1 THE STRUCTURE

The aqueduct, which is 372.88 m long with transitions at its two ends, lies in the seismic zone IV of India and forms the life line of the canal. The aqueduct consists of 8 simply supported spans of length 36.6 m each and two end spans of 14.7 m each. The spans are supported on well foundations resting on alluvial soil. The water is carried in two independent troughs of inner size 10m x 5.25m. The total discharge of the canal is 310/372 cumec. The bearings on each pier are of roller/rocker type. The aqueduct has been analyzed for a postulated ground motion in longitudinal and transverse directions, i.e., along and perpendicular to the flow of canal respectively.

2 DYNAMIC ANALYSIS

The dynamic analysis consists of determining forces and displacements developed in the structure subjected to the postulated earthquake motion. The natural frequencies and mode shapes of the structure are first determined from the lumped mass mathematical model. Using the earthquake response spectrum, modal analysis is then carried out to determine earthquake response.

2.1 Assumptions

Following are the assumptions made in the dynamic analysis :

i) Live load : No live load is considered on the bridge for analysis in the longitudinal direction but in the transverse direction, 25% of the design live load is considered on the bridge for dynamic analysis.

ii) Added mass of water : The mass of water in the enveloping cylinder for the submerged part of the pier is added with the mass of the pier for the dynamic analysis. The enveloping cylinder is made as per the guidelines of Indian Standard Code IS:1893-1984, 'Criteria for Earthquake Resistant Design of Structures'.

iii) Inertia of water in trough : The inertia of flowing water in the trough is not considered in the longitudinal direction, i.e., in the direction of flow of canal but it is considered in the transverse direction. The hydrodynamic pressure of water on the walls of trough is also considered in the transverse direction.

iv) Foundation Springs : The embedded part of aqueduct substructure in the foundation strata is replaced by linear and rotational springs.

3 DESIGN EARTHQUAKE AND SEISMIC CONSIDERATIONS

Two types of design earthquakes have been considered, (i) Design Basis Earthquake (DBE), and (ii) Maximum Credible Earthquake (MCE) as shown in Figure 1. The aqueduct has been analyzed under DBE and MCE conditions for various components depending upon their relative importance. For example, the piers have been analyzed and designed for DBE, while the bearings are analysed and designed for MCE and so also the water seals as these are more critical for seismic safety of the aqueduct. The foundation should be checked for MCE. The internal walls of water carrying trough should be checked for hydrodynamic pressure including sloshing effect of water in transverse direction.

4 METHODOLOGY

The aqueduct structure is idealized into a lumped mass mathematical model. The foundation structure interaction is considered by Berdugo and Novak (1972) springs at the centre of gravity of the embedded portion and at the base of well replacing the surrounding soil by translational and rotational springs. Two mathematical models are used, one for analysis in longitudinal direction and other for transverse direction. These models are shown in Figure 2. The soil springs are calculated for the two models separately.

The natural frequencies and mode shapes are determined by transfer function method. The response spectrum method has been used to find the forces and displacements. The damping values used in the analysis for DBE and MCE conditions are 7% and 10% of critical respectively. A range of soil properties, as listed in Table 1 below, has been considered to determine its influence on dynamic response.

Table 1. Description of various cases of dynamic analysis with material properties of founcation.

Pier No.	Direction	GB(t/m^2)	GS(t/m^2)
P1	Long./Tran.	11420.0	4511.0
P2	Long./Tran.	8559.0	5258.0
P4	Long./Tran.	8876.0	4724.0
P6	Long./Tran.	9516.0	7503.0
P7	Long./Tran.	12680.0	6632.0
P8	Long./Tran.	9510.0	6426.0
P9	Long./Tran.	11420.0	6063.0

GB denotes Shear Modulus of the base soil and GS denotes Shear Modulus of the side soil.

5 RESULTS AND DISCUSSIONS

Based on the dynamic analysis carried out for seven piers of the aqueduct, the following results are presented herein.

5.1 Time periods

Table 2 and 3 show the time periods in the first three modes for the seven piers in longitudinal and transverse directions. The minimum fundamental periods in longitudinal and transverse directions are 0.704 sec and 0.624 sec respectively, while the corresponding values of maximum fundamental periods are 0.851 sec and 0.736 sec respectively. Because of the long period of the structure, which is falling beyond hump of the spectra, the seismic forces induced are relatively smaller.

Table 2. Time periods for longitudinal direction.

Pier No.	Time periods (sec)		
	Mode 1	Mode 2	Mode 3
P1	0.851	0.190	0.067
P2	0.817	0.204	0.068
P4	0.851	0.205	0.068
P6	0.704	0.185	0.067
P7	0.727	0.174	0.067
P8	0.749	0.191	0.067
P9	0.758	0.182	0.067

Table 3. Time periods for transverse direction.

Pier No.	Time Periods (sec)		
	Mode 1	Mode 2	Mode 3
P1	0.715	0.200	0.047
P2	0.714	0.214	0.047
P4	0.736	0.216	0.047
P6	0.624	0.194	0.047
P7	0.625	0.182	0.047
P8	0.658	0.200	0.047
P9	0.653	0.191	0.047

5.2 Dynamic displacements

The maximum values of dynamic displacements at critical sections of the aqueduct, both in longitudinal and transverse directions are given below in Table 4 and 5. The maximum displacements at the bearing level under MCE conditions taking into account out of phase movement of piers, are 5.89 cm and 4.86 cm in longitudinal and transverse directions, respectively. The bearing design should be able to accommodate these predicted displacements. The design considerations will be more critical for water seal and bearings.

Table 4. Maximum dynamic displacements in longitudinal direction.

Section	Displacements (cm)	
	DBE Condition	MCE Condition
Top of Pier Cap (R.L. 259.26 m)	1.79	4.16
Top of Well Cap (R.L. 256.00 m)	1.57	3.63
Mean Scour Level (R.L. 248.40 m)	1.06	2.47

Table 5. Maximum dynamic displacements in transverse direction.

Section	Displacements (cm)	
	DBE Condition	MCE Condition
Mass Point 2 (R.I. 263.76 m)	1.49	3.43
Top of Pier Cap (R.L. 259.26 m)	1.30	2.99
Top of Well Cap (R.I. 256.00 m)	1.15	2.65
Mean Scour Level (R.I. 248.40 m)	0.82	1.89

5.3 Equivalent seismic coefficient

Equivalent horizontal seismic coefficient has been worked out to be 0.138 in transverse direction on the basis of dynamic analysis under DBE condition for the design of bearings and super-structure. This value is somewhat larger than code coefficient.

5.4 Shear forces and bending moments

The maximum values of shear forces and bending moments at critical sections, out of the seven piers analysed in longitudinal direction under DBE condition, are listed in Table 6 and 8 respectively, and those for the transverse direction are given in Tables 7 and 9.

Table 6. Maximum shear forces in longitudinal direction.

Section	Shear Force (t)
Bearing Section (R.I. 258.96 m)	564.10
Well Cap (R.I. 255.75)	675.80
Well Steining (R.I. 249.40 m)	1129.70

Table 7. Maximum bending moments in longitudinal direction.

Section	Bending Moment(tm)
Pier Cap (R.I. 258.66 m)	339.20
Base of Pier (R.I. 256.00 m)	1944.40
Well Steining (R.I. 248.40 m)	9254.60

Table 8. Maximum shear forces in transverse direction.

Section	Shear Force (t)
Bearing Section (R.I. 258.96 m)	1114.20
Well Cap (R.I. 255.75)	1175.50
Well Steining (R.L. 249.40 m)	1508.30

Table 9. Maximum bending moments in transverse direction.

Section	Bending Moment (tm)
Pier Top (R.L. 259.26 m)	4997.20
Base of Pier (R.L. 256.00 m)	8927.00
Well Steining (R.L. 248.40 m)	20374.00

5.5 Hydrodynamic pressure on aqueduct walls

Hydrodynamic pressures on the walls of aqueduct have been calculated based on the formulae given in code IS: 1893-1984. Because both the troughs are identical and depth of water is also same, the impulsive and convective pressures as well as their point of application will also be same in the two troughs. The impulsive pressure is 3.743 t/m length of the trough acting at a height of 1.875 m from the base of the trough along the flow of the canal. Because of the magnitude of the convective pressure being very less, it is neglected in the design. The maximum amplitude of sloshing is found to be 2.26 cm.

6 CONCLUSIONS

In this study seismic analysis of an aqueduct on alluvial soil has been carried out. The maximum dispalcements at the bearing level under MCE condition considering out of phase displacements are worked out. The bearing design should be such that it is able to accommodate these displacements. These design displacements also apply to water seals. The effective seismic coefficients worked out on the basis of dynamic analysis are somewhat larger than code coefficients above the bearing level. The seismic forces induced are relatively smaller because of top heavy and long period structure.

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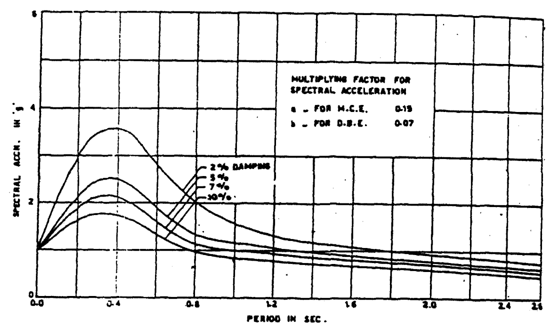

Fig. 1. Acceleration Response Spectrum

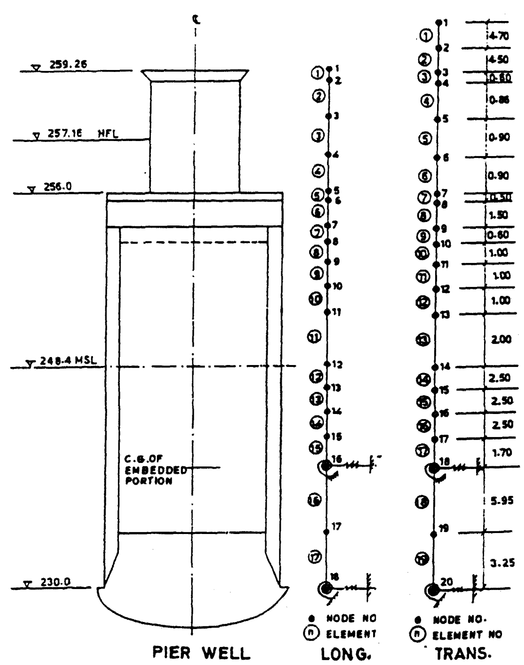

Fig. 2. Mathematical Models