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SEISMIC STUDIES OF THE ARADE RIVER CABLE-STAYED BRIDGE

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SUMMARY

The studies performed to assess the earthquake behaviour of a cable-stayed bridge to be built over the Arade River are presented. The influence of the site conditions in the frequency content and the spatial variability of the design earthquake action was considered with the help of a finite element model of the soil layers. Linear dynamic analysis were performed to compute the response of the structure and assess the influence of the different models used for the earthquake action.

DESCRIPTION OF THE BRIDGE

The Arade river bridge has a total length of 842 m, and consists of a cable-stayed portion with a central span of 256 m and two equal side spans with 104 m each, and two access viaducts, with lengths of 144 m (right bank) and 234 m (left bank). The reinforced concrete pylons are 60 m high and of an inverted Y-shape. The deck is a continuous two-cell box girder 17 m wide, supported in the cable-stayed zone by cables 8 m apart, and in the access viaducts by short piers 30 m apart; those piers and the deck are also in reinforced concrete. The piers under the transition between the access viaducts and the suspended spans are of a special design since they are used to anchor the extreme cable stays; they will be referred to as the "transition piers". In the transition pier of the right bank there is a mechanical fuse system restraining the longitudinal motion of the deck for small horizontal forces (braking-forces). This system will break for moderate intensity earthquakes and the deck then becomes almost isolated from the earthquake vibration in the longitudinal direction. Preliminary studies have indicated that the behaviour of the bridge before and imediatelly after the breaking of the fuse system could be disregarded for the assessment of its earthquake safety; analysis of mechanical fuse systems is presented in Ref. 1. In the transversal direction the deck is elastically restrained only at the abutments and the transition piers. It should bo noted that the cable-stayed portion is of the "total suspension" type since the only connection to the pylons is through the cable stays. Pile foundations will be used everywhere.

ANALYTICAL MODEL

For the analysis of the bridge structure a finite element global analytical model was elaborated. A general aspect of the model is presented in Fig. 1. This model has 758 nodes (4548 degrees of freedom) and is constituted by 998 beam elements and 502 plate elements.

The pylons were idealized by beam elements in the legs and beam and plate elements in the upper part; in this part the position of the nodes was selected in order to reproduce accurately the geometry of the cable stays.

The deck was idealized with plate elements to reproduce the structural contribution of the upper slabs and with beam elements to reproduce the stiffning effect of the box girders. The extreme nodes of the deck were located to define exactly the geometry of the cable stays. The connection between deck (in the acess viaduct zone) and piers is made by beams with spherical swivels at both ends.

The boundary conditions were introduced as two different types. The translational degrees of freedom of the boundaries were fixed so that the earthquake displacements could be imposed. To the rotational degrees of freedom was attributed a stiffness value equal to the stiffness of the corresponding groups of piles.

The idealization of the pylons and deck was improved by the study of parcial models. The partial model idealizing the pylons has 474 nodes (1422 degrees of freedom) and is constituted by 237 three dimensional elasticity elements; advantage was taken from the two planes of simmetry of the pylon. Horizontal forces were applied at several levels of the models and the displacements were compared, allowing the improvement of the idealization of the pylons in the global model. The partial model of the deck represents a 24 m long section and has 334 nodes (2004 degrees of freedom) and is constituted by 361 shell elements. This section was supposed built-in in one end and, at the other end, horizontal and vertical forces and torsional moments were applied. The comparison of displacements in the partial model and in the model of the 24 m section idealized as in the global model allowed the improvement of the deck idealization in the global model.

IDEALIZATION OF EARTHQUAKE VIBRATIONS

Soil layers model. The geological soil conditions are characterized by alluvionar deposits of loamy sand and clay about 30 m deep, over a bedrock constituted by a shale formation with basaltic intercalations. The soft soil layers were idealized by a plane strain finite element model with 601 nodes (1202 degrees of freedom) ; 1072 triangular elements were used. This model represents a transversal section of the valley along the longitudinal axis of the bridge.

For the dynamic characterization and analysis, 100 natural modes of vibration were computed. The fundamental frequency was found out to be 0,7 Hz and highest frequency obtained was 7.4 Hz. The three first mode shapes are shown in Fig. 2. It should be noted that higher modes present, sometimes, significative vertical displacements in zones subject to horizontal tensions or compressions (Poisson effect); those values of vertical displacements may be partially ascribed to the use of a plane strain model. Nevertheless, a careful analysis of the results has shown that each zone behaved almost as an uni-dimensional shear beam; hence, it was not deemed necessary to perform an analysis in longitudinal valley direction, for which there was no available geotechnical data.

This soil layers model was subjected to the earthquake actions prescribed in the Portuguese code for rock sites, applied at the bedrock level. Maximum strains were computed for the different layers; the values obtained indicated that nonlinear behaviour would not be important, according to generally accepted criteria (Ref. 2).

Correlation functions. In the Portuguese code the fundamental definition of the earthquake action is a stationary gaussian stochastic process with an appropriate power spectrum (Ref. 3). For the idealization of the spatial variability the spectrum is divided in frequency bands (Ref. 4). In this study, as in other previous studies (Ref. 5, 6,7) five frequency bands were considered, separated by the following limit frequencies: 0, 0.333, 1, 3, 9 and 20 Hz. The correlation functions between the different nodes at the soil surface were computed, for each frequency band, according to general principles of stochastic analysis (Ref. 5,8). A selection of those correlation functions are presented in Fig. 4. Those functions were computed for one of the actions prescribed in the Portuguese code modeled with a spatial variability corresponding to independent motions at minimum distances verying from 3000 m to 111 m according to the frequency band under consideration, which corresponds to an high spatial variability of the motions. The variances of the absolute aceeleration at the soil surface were also computed for each frequency band, as well as the maximum values of the absolute accelerations (for the total spectrum).

Earthquake vibration model. The earthquake vibration model was elaborated in two phases (Ref. 8). In the first phase, for each frequency band, "weighting functions" were contructed taking into account the characteristics of the correlation functions; those weighting functions idealize the degree of correlation between different points. In the second phase, the power spectra associated to each weighting function were calibrated on the basis of the appropriate variance values for absolute acceleration. The goodness of this model was checked, comparing the maximum absolute accelerations imposed at the base of the bridge (which are obtained from the elaborated earthquake vibration model) with those given by the soil layers model; although in a few points some differences could be observed, there was a good fit for engineering purposes. Obviously if a larger number of frequency bands were considered those differences would be smaller.

EARTHQUAKE ACTION EFFECTS

Dynamic characteristics. 80 natural modes of vibration were computed, with frequencies ranging between 0.14 and 5.5 Hz. The design situation considered is the bridge after the breaking of the mechanical fuse system. The mode shapes of modes nº.1, 2, 6 and 13 are presented in Fig. 3; those modes are the "fundamental" modes for transversal, longitudinal, vertical and torsional vibrations. It should be noted that the first natural frequencies of the bridge are lower than the fundamental frequencies of the soil layers.

Structural response. The response of the bridge was computed for 2 pairs of earthquake actions. According to the Portuguese code a pair of actions should be considered: Type 1 and Type 2, corresponding to a moderate magnitude earthquake at moderate focal distance and a larger magnitude earthquake at a larger focal distance, respectively. A rigid base vibration with the power spectra of the Portuguese code is one pair of actions. The other pair is constituted by the elaborated spatial variability model (for the two types of actions).

The response variables that were computed are the maximum values of relative displacements, absolute accelerations, internal forces in the beam elements, stresses in the plate elements and support reactions. Since a stochastic model was used for the earthquake actions, those values are in effect the mean values of the probabilistic distribution of the maxima of the responses. In Fig. 5 are presented the distributions of transversal and vertical displacements and vertical accelerations in the deck; the following values are considered representative of the earthquake action effects in the bridge:

- Displacements at the top of the pylons:
  Longitudinal direction: 15.9 cm
  Transversal direction : 0.5 cm
- Displacements at mid central span:
  Longitudinal direction: 13.9 cm
  Transversal direction : 43.3 cm
  Vertical direction : 10.9 cm
- Maximum vertical deck displacement: 18.9 cm
- Maximum global horizontal reaction:
  Longitudinal direction: 6763 kN
  Transversal direction: 13877 kN

The total weight of the structure (excluding foundations) is about 300 000 kN.

FINAL REMARKS

The first natural frequencies of the bridge are lower than the fundamental frequencies of the soil layers; hence, the important amplification of the earthquake vibrations near those frequencies did not cause a commensurate increase in the values of the response. The differences between the responses due to the rigid base models and the spatially variable models can be imputed to the higher spectral content of the last model and not to the spatial variability. The small influence of the spatial variability have already been observed in previous studies (Ref. 6,7).

The improvements in the characterization of the influence of site conditions in earthquake vibrations is presently conditioned by the scarcity of geotechnical data usually available. A better knowledge of the spatial disposition of soil layers and of the soils behaviour under repeated and alternate loading with typical earthquake frequency and amplitude characteristics is considered to have an high priority among the open problems in this field.

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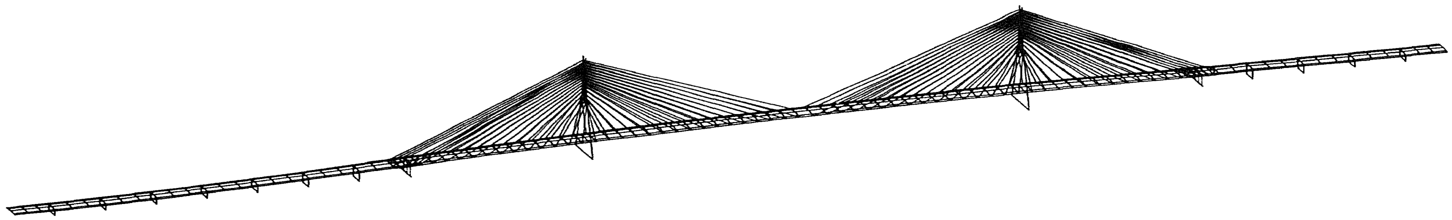

Fig. 1 - General aspect of the global model.

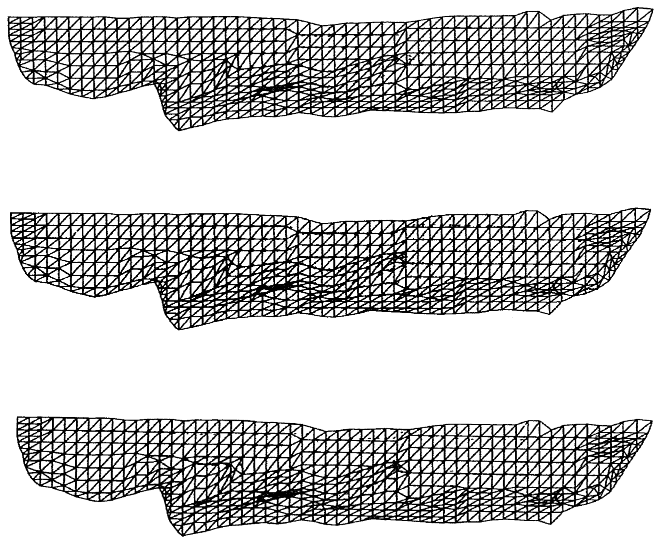

Fig. 2 - Shapes of the 3 first natural modes of the soft soil layers (0.71Hz, 0.80Hz, 0.93 Hz).

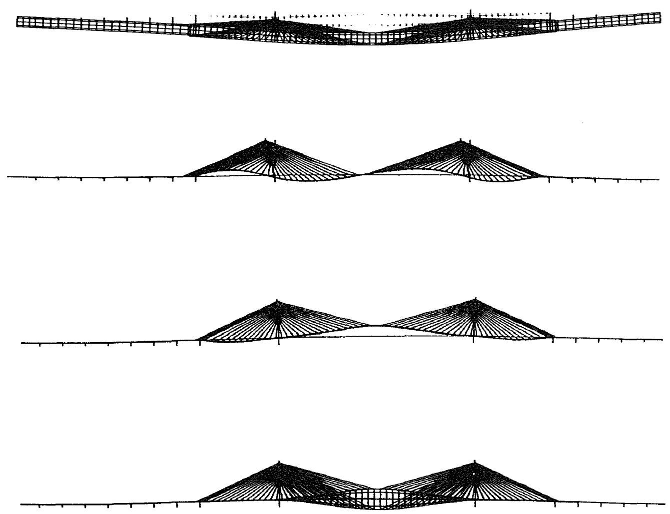

Fig. 3 - Shapes of the fundamental modes of the bridge
Transversal: 0.14 Hz; Longitudinal: 0.16 Hz
Vertical: 0.37 Hz ; Torsional: 1.03 Hz

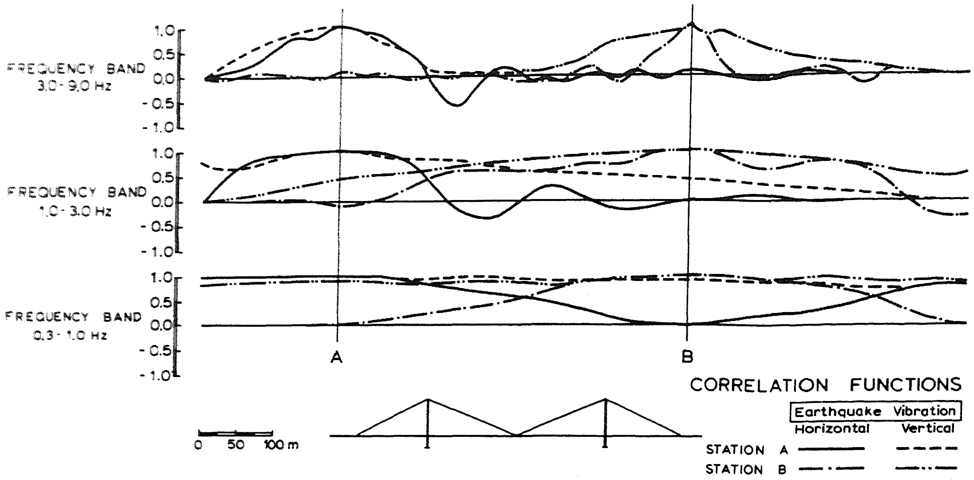

Fig. 4 - Typical correlation functions for stations near the transition piers.

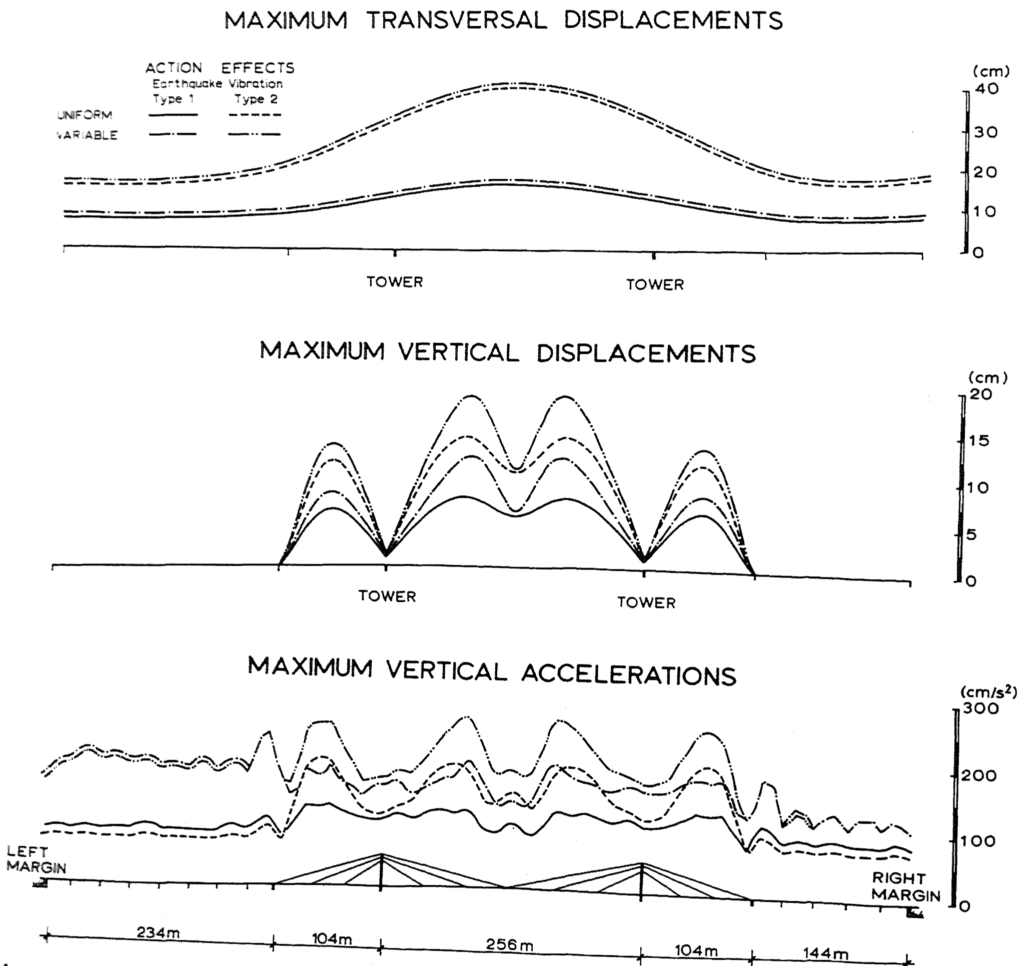

Fig. 5 - Maximum displacements and accelerations in the deck.