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Large-Scale Dynamic Tests

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ABSTRACT

Large scale dynamic testing techniques and their applications are presented for three different structures. The experimental procedures used in the measurement of the dynamic response of the Beauharnois suspension bridge (177 m span length), Outardes 3 gravity dam (84 m crest height and 298 m crest length) and the inclined tower of the Montreal Olympic Stadium (190 m high) are described. Frequency responses are obtained under forced- or free-vibration loading, and the dynamic properties are evaluated for each structure and used to calibrate and validate state-of-the art numerical models.

INTRODUCTION

Large-scale forced- or free-vibration tests provide reliable and accurate data for the study of the dynamic behaviour of structures. A considerable amount of research has been carried out in the field of seismic analysis and modelling of various structures in the past decade. The performance of these modern techniques can be evaluated and quantified only by using dependable full-scale test results. Experimental findings are also used as a reference database for auscultation programs based on repeated tests of the same structure to monitor variations in its characteristic properties.

An analytical and experimental research program on the dynamic behaviour of bridges, dams and buildings is currently underway at the University of Sherbrooke. Some of the objectives of this study include performing large-scale dynamic tests on various structures and creating a detailed and reliable database. Test results are then used to verify and calibrate state-of-the-art commercial and research oriented finite-element modelling programs. Forced- and free-vibration testing procedures and data reduction techniques have been developed and adapted to obtain dynamic properties including vibration frequencies and mode shapes, structural and modal damping, dynamic amplification factors, and frequency responses for acceleration and hydrodynamic pressures.

Several highway bridges and the Beauharnois suspension and cable-stayed bridge were tested under traffic loading (Paultre *et al.*, 1994a) in collaboration with the Québec Ministry of Transportation and, in each case, a finite element model was developed and calibrated using a commercial finite element application. An eccentric mass shaker was used to excite a gravity dam in collaboration with Hydro-Québec and the test results were used to study the dynamic interaction between the dam, reservoir and foundation, and to evaluate the performance of two- and three-dimensional models of the system including water compressibility. The same testing procedures were also applied to obtain the vibration frequencies and mode shapes of the inclined tower of the Montreal Olympic Stadium. This paper presents the dynamic testing techniques used at the University of Sherbrooke and some of the results obtained on these three structures.

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DYNAMIC BRIDGE TESTING UNDER TRAFFIC LOADS

The development of reliable testing equipment and high-frequency analog-digital data recording devices has lead to an increase in structural testing. This tendency is evident in a recent literature review on analytical and experimental studies of highway bridges (Paultre *et al.*, 1992), as large-scale tests are recognized as a reliable means of obtaining the dynamic amplification factor (*DAF*) for a given bridge. Although most tests are carried out under traffic loads and are designed to measure the *DAF*, defined as the ratio of the maximum dynamic response and the corresponding static response, the dynamic properties are evaluated with a high degree of accuracy using a technique derived from modal testing procedures (Paultre *et al.*, 1994a). This information is then used to calibrate finite element models developed for bridge evaluation.

Testing can be carried out with controlled traffic, using test vehicles (trucks and trailers) with known axle loads, or under ambient vibrations generated by the wind and normal flow of traffic. The bridge responses are measured with low-frequency accelerometers, strain gauges and displacement transducers. Typically, deformation and displacement data are used to obtain *DAF* values and acceleration data are used to obtain dynamic properties, although acceleration responses can be integrated to obtain displacement responses (Paultre *et al.*, 1994a). The instruments are distributed on the main span (or multiple spans) and connected to a Hewlett-Packard HP3852a data acquisition system. This recording unit has a 100 kHz aggregate sampling rate and is microcomputer controlled through an IEEE-488 interface.

Customized programs provide a real-time display of all recorded signals and offer considerable flexibility as most commercial fully-automated data acquisition packages are not designed for the testing of large scale structures like bridges, dams and multistorey buildings, and do not offer control over some important parameters (total number of samples, total time of sampling, etc.). Moreover, some packages do not provide anti-aliasing hardware filtering and only include some type of numerical filter.

Beauharnois suspension bridge

Built in 1947 the 177-m Beauharnois suspension bridge crosses one of the spillway channels of a hydroelectric power plant south-west of Montreal (Fig. 1a). Considerable structural modifications were carried out in 1989 with the installation of an orthotropic steel deck and a mixed suspension and cable-stayed system (Paultre *et al.*, 1994b). The eastern part of the symmetric deck was instrumented as shown in Fig. 1b. Low-frequency accelerometers were successively placed at each cable location to measure the vertical, transverse and longitudinal responses of the deck and east tower under controlled and ambient traffic loads. A total of 70 measurements of ambient vibration responses were recorded for 120 s with a sampling rate of 100 Hz. Two trucks and a trailer (Fig. 1b) were used to carry out 75 test runs at various speeds and positions on the bridge.

The frequency content of the ambiant acceleration responses is computed and, using the response obtained with a reference accelerometer (position 0 on Fig. 1b) as an input signal, cross spectrums are evaluated for each measurement point. The coherence or degree of linearity between the reference point and a given location is computed. A high value indicates the occurrence of a mode shape of the structure. The frequency contents and coherence functions are shown in Fig. 1c for vertical acceleration at stations 0 and 10 and averaged over four different recordings. Frequencies are identified from the amplitude curves with a resolution of ± 0.01 Hz. Experimental mode shapes are obtained from the amplitude and phase of the frequency responses. Responses obtained on both sides of the deck are added and subtracted to separate closely-spaced flexural and torsional modes.

Initial tensions in the main cables and stays were computed with a program designed for nonlinear analysis of suspension bridges and used for the rehabilitation of this structure. A three dimensional finite element model was developed for the bridge with a commercial program including nonlinear cable behaviour. An eigen value analysis was then carried out and analytical mode shapes were obtained. Calibration of the model was achieved with experimental data, by comparison of both vibration frequencies and mode shapes. With this method, the 23 experimental deck modes (10 flexural, 8 torsional, 4 lateral and 1 longitudinal) and 8 tower modes were predicted with an average of 5% accuracy. Figure 1d shows the first and second experimental and analytical flexural and torsional modes with corresponding frequency values.

DYNAMIC TESTING OF DAMS AND BUILDINGS

Forced vibration tests on structures can be carried out with various types of force generating mechanisms. The use of an eccentric mass shaker generating a sinusoidal force is particularly useful for the study of the dynamic interaction phenomena present in dam-reservoir-foundation systems. This testing technique leads to well-defined frequency response functions for the structure and surrounding media, such as hydrodynamic pressures in the reservoir. Acceleration and pressure responses are measured under a horizontal harmonic load of up to 90 kN at frequencies ranging from 0 to 20 Hz. The dynamic load is provided by two sets of weights rotating about parallel vertical shafts. Their eccentricity can be varied to modifiy the magnitude of the resulting force. The exact frequency of operation is computed from a pulse signal generated by the rotation of the weigths.

For a given excitation frequency, the harmonic responses are recorded for a few seconds and the amplitude of the motion is normalized by the magnitude of the exciting force. The phase difference between the measured response and the shaker force is also computed. A frequency increment is chosen and a complete sweep is performed in the operating range of the shaker. In this way, the frequency response curves for both amplitude and phase are directly obtained for each measurement station. The instrument characteristics are taken into account by correcting for amplitude reduction and phase shift related to the excitation frequency. This correction is carried out for the accelerometers, hydrophones and the filters of the data acquisistion system.

Experimental vibration frequencies are derived from the peaks in the various response curves and the corresponding modal damping is computed by the half-bandwidth method. Resonance shapes are obtained by computing the steady-state displacement for a specific resonance, using amplitude and phase information. These dynamic properties are then used to calibrate numerical models of the system. Complete frequency responses for the structure and surrounding media are calculated with finite element programs operating in the frequency domain and compared with experimental findings.

Outardes 3 gravity dam

Figure 2a shows an upstream view of Outardes 3 gravity dam which consists of 19 monoliths with a maximum crest height of 84 m and a total length of 298 m. Forced vibration tests were carried out with the shaker located on the crest at the centre and two quarter points, and the recording unit described above was used to measure all data (Proulx *et al.*, 1992).

Low-frequency accelerometers were placed on the dam crest, inside the inspection galleries and on the downstream face of the dam to record horizontal acceleration perpendicular to the axis of the dam. Relative joint motions were also investigated by placing accelerometers on both sides of selected construction joints and by switching the position of the instruments to eliminate calibration errors. Frequency responses were obtained for each station by varying the operation frequency of the shaker. As shown on Fig. 2a, nylon cables anchored to the shores and the dam crest were used to suspend arrays of 4 to 5 hydrophones at depths of 15, 30, 45, 60 and 75 m. Hydrodynamic pressure responses were obtained along the upstream face in the centre of blocks F, H and M, and at distances of 30, 60 and 90 m from the dam face.

A complete set of frequency response curves for the dam and reservoir was obtained for each shaker position, and four modes were identified in the 4 to 10 Hz range. Placing the shaker at the quarter points yielded a clearer definition of the first antisymmetric mode. The experimental frequencies and resonance shapes for the dam and reservoir were used to calibrate specialized finite element programs and to investigate the effects of dam-reservoir interaction.

Figure 2b shows the three-dimensional finite element model developed for the system with a modified version of the EACD program used for 3D seismic analysis of concrete dams (Fok *et al.*, 1986). A substructure approach is used with finite element meshes for the dam, reservoir and foundation. The foundation model is massless and its stiffness matrix is condensed at the dam-foundation interface. A finite region of the reservoir is modelled, including reservoir bottom absorption, and a constant-depth semi-infinite portion of the reservoir extending upstream is included. The model accounts for water compressibility and radiation damping in the upstream direction. Complex frequency-dependent hydrodynamic forces are computed and added to the system equations, which are solved in the frequency domain. Some modifications were implemented in the program in order to compute frequency response functions for acceleration and hydrodynamic pressure under a concentrated harmonic force applied on the crest.

The accuracy of the complete 3D model can be summarized by comparing experimental and numerical resonance shapes. Figure 2c shows the excellent correspondence observed for horizontal crest displacement as well as for the vertical distributions at the centre block, including the downstream face, for the first symmetric and antisymmetric modes (similar results are obtained for the second symmetric and antisymmetric modes). Measured and computed frequencies are given for each resonance with the corresponding damping ratios. Also shown are the vertical pressure profiles at various distances from the dam face. Good agreement is observed for pressure distribution only with the compressible water model, including reservoir bottom absorption (Proulx and Paultre, 1994).

Inclined tower of the Montreal Olympic Stadium

The experimental method developed for concrete dams was recently applied to the 190-m inclined tower supporting the textile roof of the Montreal Olympic Stadium (Paultre and Proulx, 1994). The main objectives were to obtain the vibration frequencies and mode shapes to be used in the calibration of existing three-dimensional finite element models. Of particular interest was the evaluation of modal damping, as the lower part was first built of concrete (up to 133 m) and the upper part was completed later with steel. Figure 3a shows an elevation view of the tower and plan views of instrumented floors.

A frequency sweep ranging from 0.5 to 9 Hz was carried out with the shaker located on top of the tower floor level 577 (176 m) and on floor level 372 (133 m) at the top of the concrete section. At a frequency of 4 Hz the eccentricity of the masses was changed from 100% to 40% to reduce the level of excitation. Accelerometers were located on these floors and three additional floors, to measure longitudinal, transverse and vertical responses of the tower.

Figure 3b shows the frequency responses for normalized amplitude and phase obtained at station 3 (longitudinal) and station 4 (vertical). The instrumentation scheme used was critical in the evaluation of mode shapes to distinguish torsional and flexural modes. Four torsional modes, including the fundamental mode, and four flexural modes were identified in the testing frequency range, as well as three other coupled modes. Ambient responses were also measured under wind loading and frequency analysis of the data correlated with the dynamic properties obtained under harmonic loading. Vibrations generated by the motion of the exterior scenic elevator were recorded to evaluate the magnitude of the resulting accelerations and to identify specific modes excited by its operation. The experimental results were used to calibrate models including the interaction with the cable-supported roof.

CONCLUSIONS

The reliability of the experimental procedures and the quality of the results obtained from well-documented large-scale dynamic tests are the basis of the investigation of the seismic performance of structures. The most sophisticated mathematical and numerical models can only be evaluated when detailed correlation studies are carried out with experimental findings. These results fully characterize the dynamic behaviour of bridges, dams and buildings, and constitute a solid database for further developments in seismic engineering.

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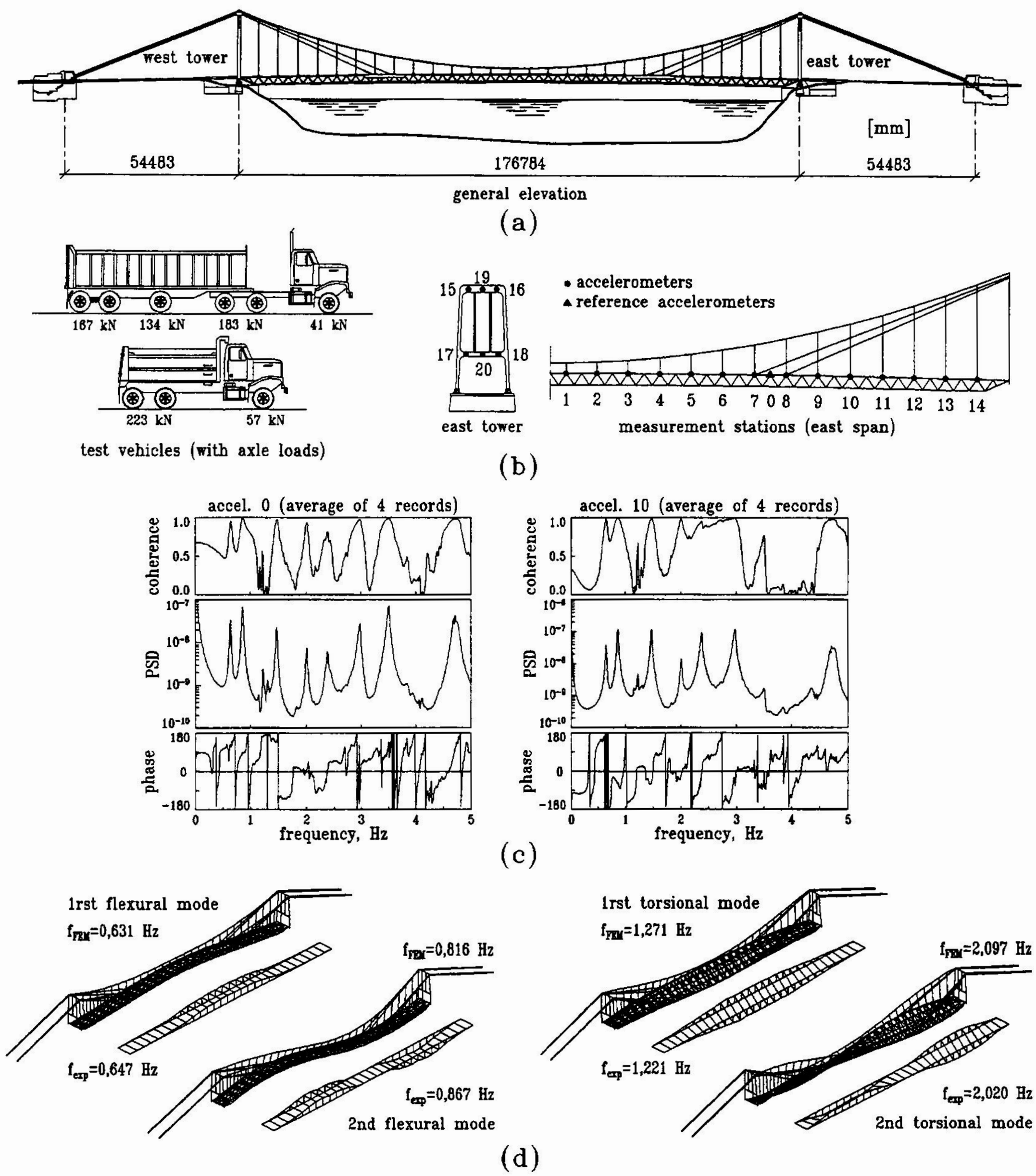

Figure 1. Beauharnois suspension bridge: (a) elevation; (b) experimental setup and test vehicles; (c) frequency analysis of acceleration response; (d) experimental and numerical mode shapes.

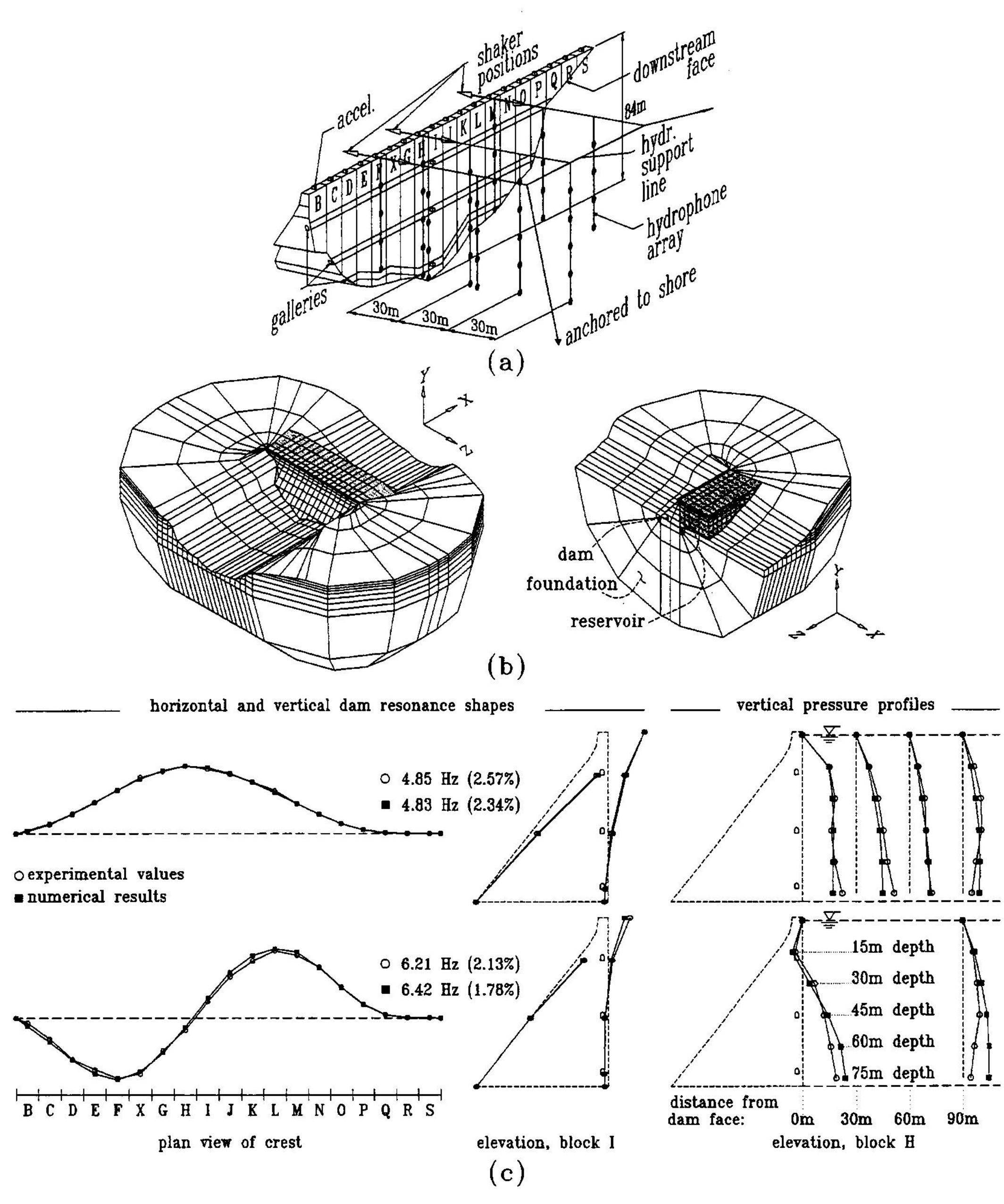

Figure 2. Outardes 3 gravity dam: (a) experimental setup; (b) 3D model of dam-reservoir-foundation system; (c) experimental and numerical resonance shapes and pressure profiles.

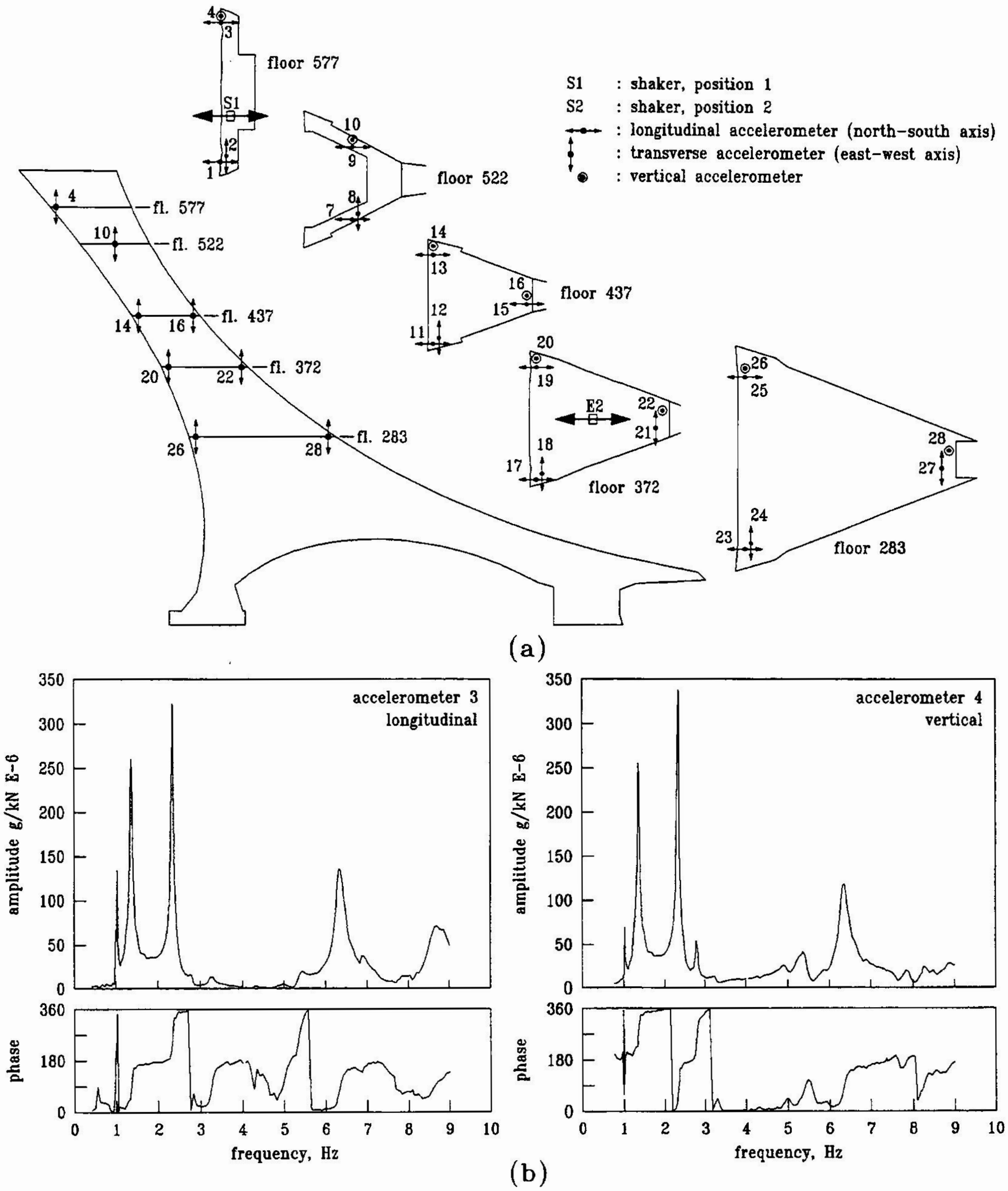

Figure 3. Inclined tower of the Montreal Olympic stadium: (a) experimental setup; (b) longitudinal and vertical frequency responses