Ninth Canadian Conference on Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

EARTHQUAKE RESPONSE OF SHORT TO MEDIUM SPAN CABLE-STAYED BRIDGES

B. Crestel[1] and N. Bouaanani[2]

ABSTRACT

The paper presents an investigation of the three-dimensional seismic response of three short to medium cable-stayed bridges subjected to multicomponent ground motions typical of Eastern Canada. 2D and 3D finite element models of three typical cable-stayed bridges with spans varying from 104.50 m to 245.00 m are built and used to perform transient dynamic analyses. In this paper, only the response of the stay cables expressed in terms of peak additional tensions is presented. The effects of the size of the bridge, the angle of incidence and the principal directions of ground accelerations are investigated. Ground motions yielding the most critical peak tensions in the stay cables are identified. General trends in the response of the stay cables are discussed.

Introduction

Cable-stayed bridges are increasingly becoming attractive solutions especially when lightness, flexibility and aesthetics are key design factors. Although considerable work has been devoted to the design and analysis of such structures when subjected to wind, rain and traffic induced vibrations (Virlogeux 1999), research is still needed to assess their dynamic behaviour under complex earthquake loading within the short to medium span range. Furthermore, most research related to bridge earthquake behaviour was validated using Western North America (WNA) ground motions. The main objective of this paper is to assess the dynamic response of short to medium span cable-stayed bridges to multicomponent ground motions typical of Eastern Canada. A special attention is devoted to identifying the structural response of the stay cables under the influence of: (i) the size of the bridge, (ii) the angle of incidence, and (iii) the principal directions of the ground accelerations.

Description of the Cable-Stayed Bridges Studied

A multitude of cable-stayed bridge designs have been used worldwide. The main objective of this research is not to propose a new cable-stayed bridge design, nor to compare various designs based on seismic performance. The focus is rather on investigating the structural response of cable-stayed bridges with the same design but with different sizes, subjected to earthquakes typical of Eastern Canada. A special attention is devoted to assessing the response of the stay cables, and bridges with a thin concrete deck

[1]Graduate Student, Dept. of Civil, Geological and Mining Engineering, École Polytechnique, Montréal, QC H3C 3A7
[2]Assistant Professor, Dept. of Civil, Geological and Mining Engineering, École Polytechnique, Montréal, QC H3C 3A7

are selected for this purpose. Each of the three bridge models considered has three symmetric spans. The main span varies from 104.50 m to 245.00 m, and the side spans from 49.50 m to 119.00 m. These overall dimensions stem from an extensive literature review on cable-stayed bridges built or studied worldwide. Examples of such bridges are the Evripos cable-stayed bridge in Greece (main span of 215 m and a 0.45 m thick concrete deck), and the Tarascon-Beaucaire bridge in France (main span of 192.8 m and a 0.77 m thick concrete deck). The width of each bridge deck corresponds to a realistic number of traffic lanes. The hollow pylons are H-shaped, and their height varies from 39 m to 98 m, providing a clear navigation of 14 m to 37 m. The ratios of the pylon height (from above the deck level) to the main span are within 0.23 to 0.25. The design of the pylons is achieved by ensuring that they provide adequate stiffness to the whole bridge model. Two-plane semi-fan type multiple stay cable arrangement is adopted. The number of stay cables is determined as a function of the design span. The spacing of the cables at deck level is kept relatively small for structural and economic efficiency. It varies from 5.5 m to 7.0 m for the three bridges. Table 1 summarizes the main geometrical properties of the three bridge models studied and Fig. 1 illustrates their elevations.

Table 1. Main geometrical properties of the three bridge models studied.

	Bridge 1	Bridge 2	Bridge 3
Dimensions			
Mainspan	104.500 m	174.000 m	245.000 m
Sidespan	49.500 m	80.000 m	119.000 m
Stay cables			
Number per half total span	9	14	17
Cable spacing at deck level	5.500 m	6.000 m	7.000 m
Concrete deck			
Thickness	0.550 m	0.600 m	0.700 m
Width	8.000 m	12.000 m	16.000 m
Pylon legs			
Overall cross-section	2.500 m x 1.500 m	3.750 m x 2.500 m	5.000 m x 3.500 m
Wall thickness	0.375 m	0.750 m	1.000 m

Fig. 2 shows the elevations of the pylons and the numbering of the stay cables for the three bridge models studied. The bridge deck and pylons are made of concrete with E_c= 40000 MPa, and the stay cables of steel with E_s= 200000 MPa. The finite element software ADINA (2004) is used for 2D and 3D modeling of the three bridges. In the 3D models, the deck and pylon are modeled using shell and solid elements, respectively, while they are modeled using beam elements in the 2D models. Both 2D and 3D models use beam elements to model the stay cables. Similar boundary conditions are adopted for the three bridge models: the pylons are restrained at their bases, and the deck is hinged at the two extreme ends and is connected to the pylons with rollers (Tuladhar 1995). Special care was exercised in calibrating the static profile of the bridges and verifying the convergence of the finite element models.

Seismic Loading

The earthquake loading used in the present work is selected to correspond to the seismic hazard expected in Eastern Canada. To focus on the effects of multidirectional uncorrelated seismic input, ground motions recorded at six different sites during the Saguenay Earthquake of 1988 are considered. The locations of these sites as well as the earthquake epicenter are shown in Fig. 3. The nomenclature of the sites is that used by the Geological Survey of Canada (GSC). The main characteristics of the records are summarized in Table 2. Data files containing the three waveform orthogonal components (longitudinal, transverse, and vertical) at each site are taken from the GSC website. These components correspond to the orientation of the seismograph, aligned such that the longitudinal direction points roughly north and the transverse (+270^o away) points roughly west, according to GSC convention.

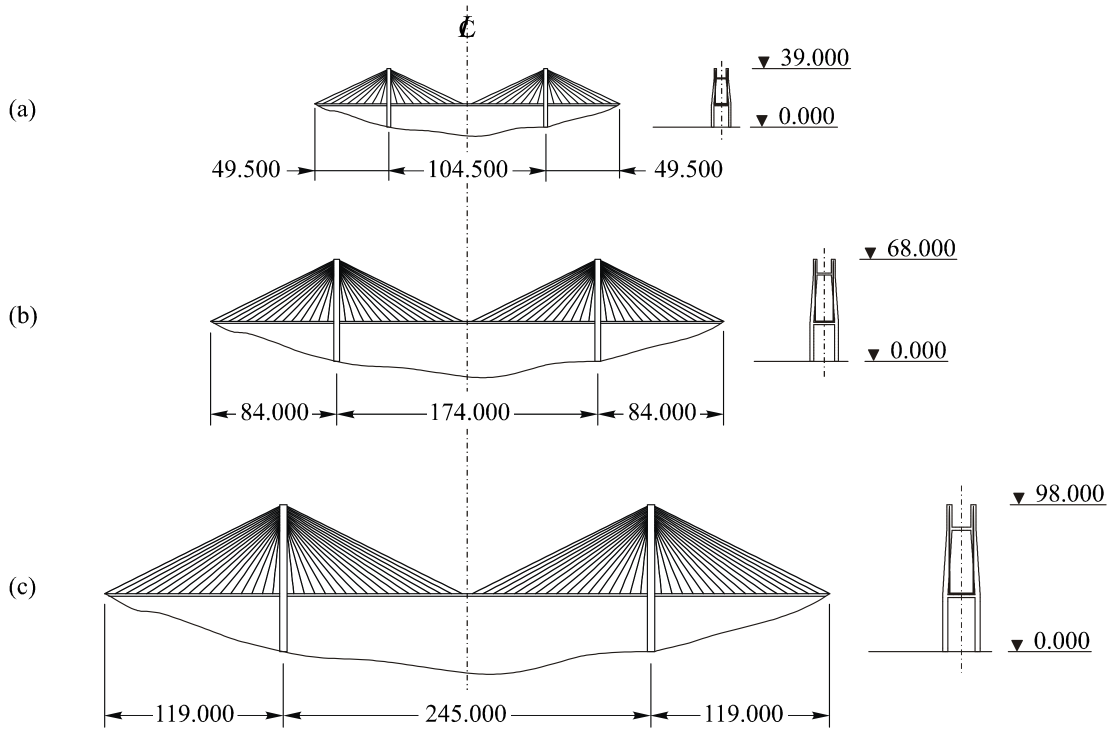

Figure 1. Elevations of the three bridge models studied (dimensions in meters).

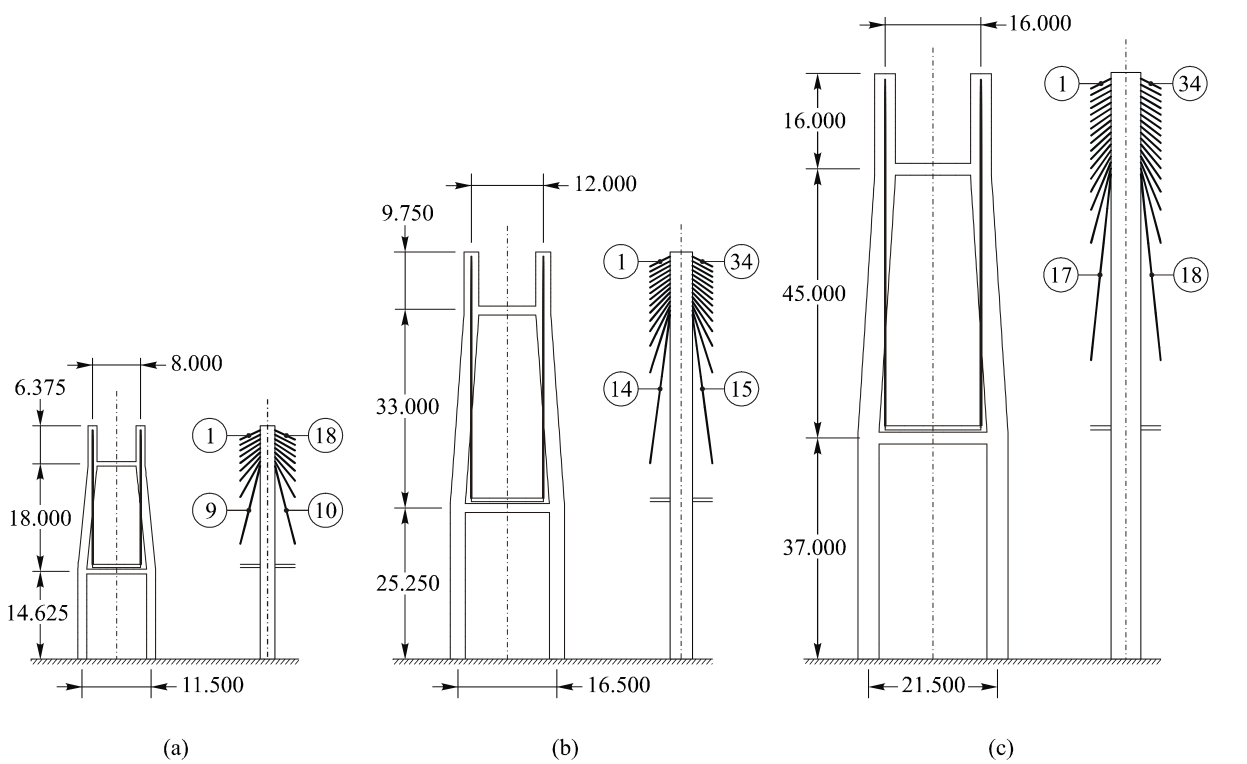

Figure 2. Elevations of the pylons and numbering of the stay cables for the three bride models studied: (a) Bridge 1, (b) Bridge 2, and (c) Bridge 3 (dimensions in meters).

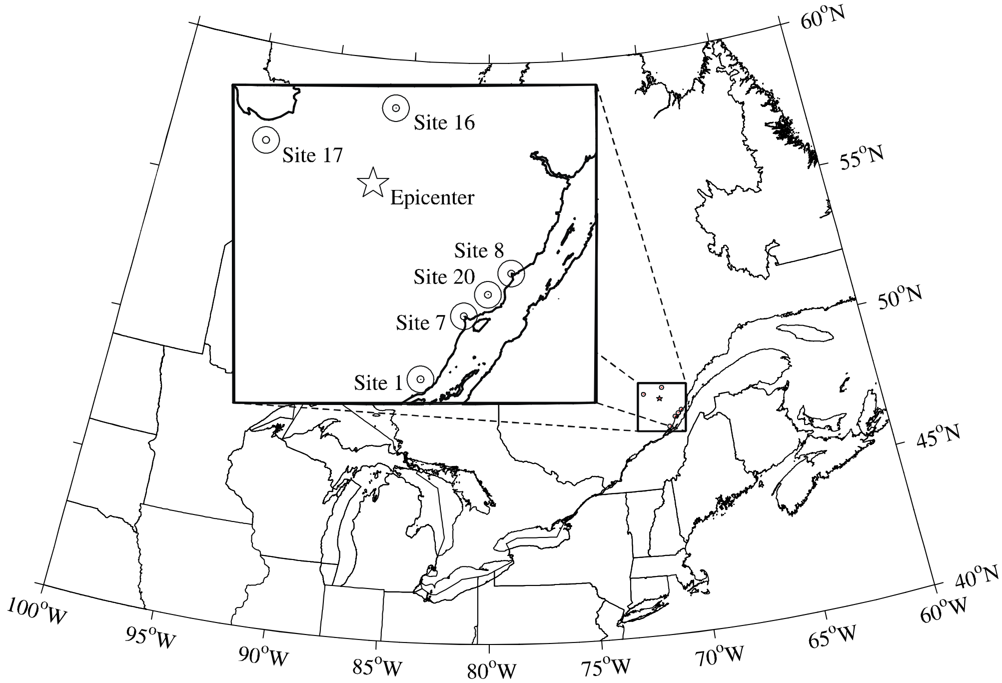

Figure 3. Map of the Saguenay event seismic sites used for the dynamic analysis.

Table 2. Properties of the Saguenay event recording sites.

Site	Latitude / Longitude	Distance to epicenter	Component	PGA	Ratio *a*/*v*
Site 1	47.126 N /	113 km	0°	0.121g	4.5
St-Ferreol, QC	70.828 W		270°	0.097g	4.0
			Vertical	0.062g	3.7
Site 7	47.442 N /	90 km	175°	0.125g	3.3
Baie-St-Paul, QC	70.507 W		85°	0.174g	3.3
			Vertical	0.124g	5.1
Site 8	47.655 N /	92 km	175°	0.124g	2.7
La Malbaie, QC	70.153 W		85°	0.060g	4.5
			Vertical	0.068g	3.9
Site 16	48.490 N /	43 km	175°	0.107g	7.0
Chicoutimi-Nord, QC	71.012 W		85°	0.131g	5.2
			Vertical	0.102g	5.5
Site 17	48.325 N /	64 km	175°	0.156g	8.5
St-Andre-du-Lac-St-	71.992 W		85°	0.091g	9.7
Jean, QC			Vertical	0.045g	5.1
Site 20	47.550 N /	90 km	175°	0.125g	2.8
Les Éboulements, QC	70.327 W		85°	0.102g	3.9
			Vertical	0.234g	4.7

In this paper, the longitudinal, transverse, and vertical components are denoted X, Y, and Z, respectively. These waveforms are generally statistically correlated, and can be uncorrelated using the technique proposed by Penzien and Watabe (1975). This method assumes that the ground motion is a nonstationary stochastic process defined as the product of a deterministic function by a stationary stochastic function. A matrix transformation is then applied to each set of three earthquake components to determine three orthogonal principal directions, according to which the transformed signals are statically uncorrelated. Under the assumption of ergodicity, the principal directions are independent of the original axes *X*, *Y* and *Z* of the seismograph used for recording. Fig. 4a illustrates the principal and original axes of a given 3D translational ground motion. The effects of various earthquakes can be compared and assessed more rigorously once they are transformed into principal directions. The 3D bridge models are subjected to the simultaneous action of two orthogonal horizontal ground accelerations corresponding to the X and Y components of the earthquake, and a vertical acceleration corresponding to the Z component. Four incidence angles are considered to determine the maximum peak tensions (0°, 30°, 60°, 90°) as shown in Fig. 4b. For each site and each bridge, Fig. 4c illustrates three 2D transient dynamic analyses carried out using the same vertical recorded acceleration, but three different horizontal accelerations: the *X* and the *Y* components of the recorded ground motion, and the major principal uncorrelated horizontal ground motion, denoted herein as the Principal component.

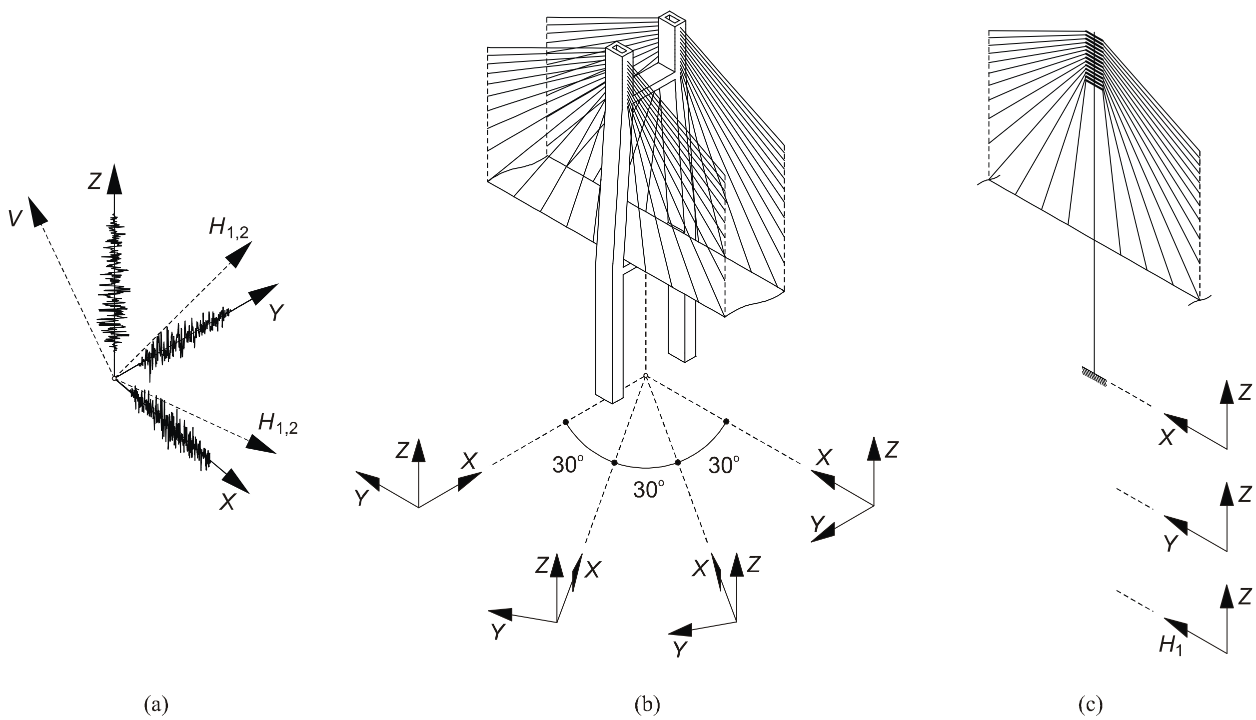

Figure 4. Presentation of the seismic input: a) Principal direction; b) 3D seismic input; c) 2D seismic input.

Transient Dynamic Analyses and Results

Transient dynamic analyses are performed using the 2D and 3D finite element models described before. Only geometrical nonlinearity is considered in the analysis. To get an overall appreciation of bridge size effects, Fig. 5 shows maximum peak tension increases in the 3D models subjected to ground motions from all the sites. Based on this figure, the effects of seismic inputs from the six sites can be compared. It can be seen that site 7 yields the most critical peak tensions in the stay cables. Although a general trend can be observed indicating lower peak tensions with larger bridge dimensions, ground accelerations at sites 8 and 17 are relatively severe when applied to Bridge 3. Since only four incidence angles are considered to determine maximum peak tensions, more critical loading cases may have been missed for these two sites. To get a closer look at the influence of bridge size, Figs. 6 to 8 show the variations of peak tensions for all the stay cables of the three bridges. These figures confirm that input from site 7 results in the highest peak tension increases. The three bridges behave differently when subjected to accelerations from the other sites: Bridge 1 is more affected by sites 1 and 20, Bridge 2 by site 20 and Bridge 3 by site 8. It is again observed that maximum peak tensions decrease with increasing bridge size.

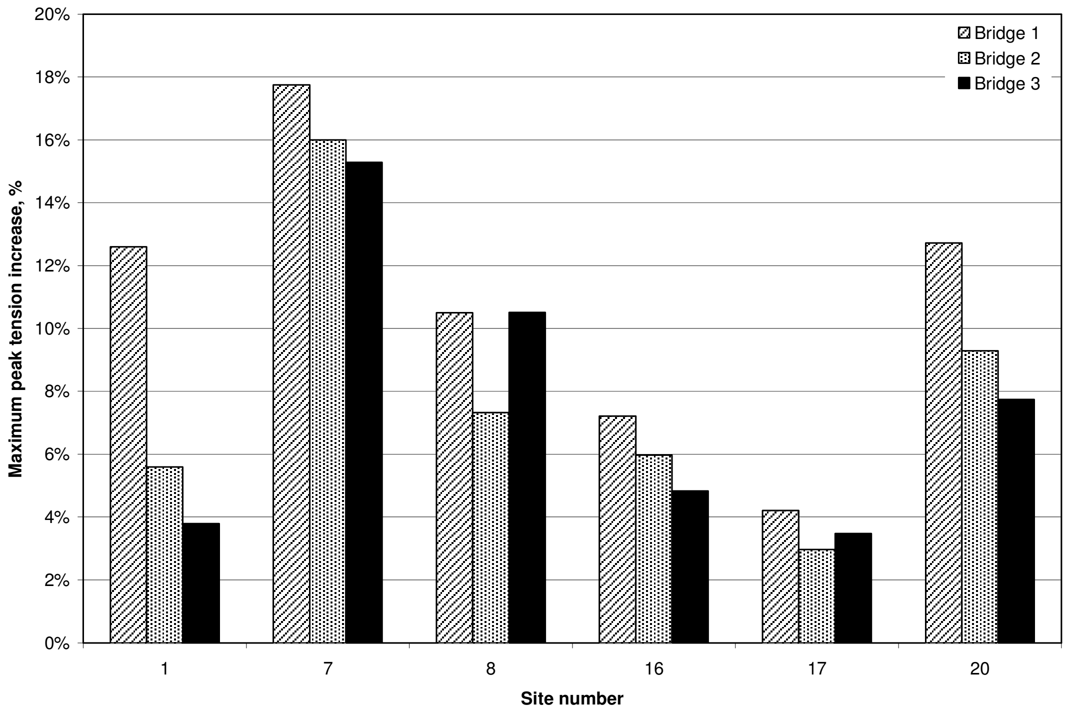

Figure 5. Seismic scale effect for the six Saguenay events.

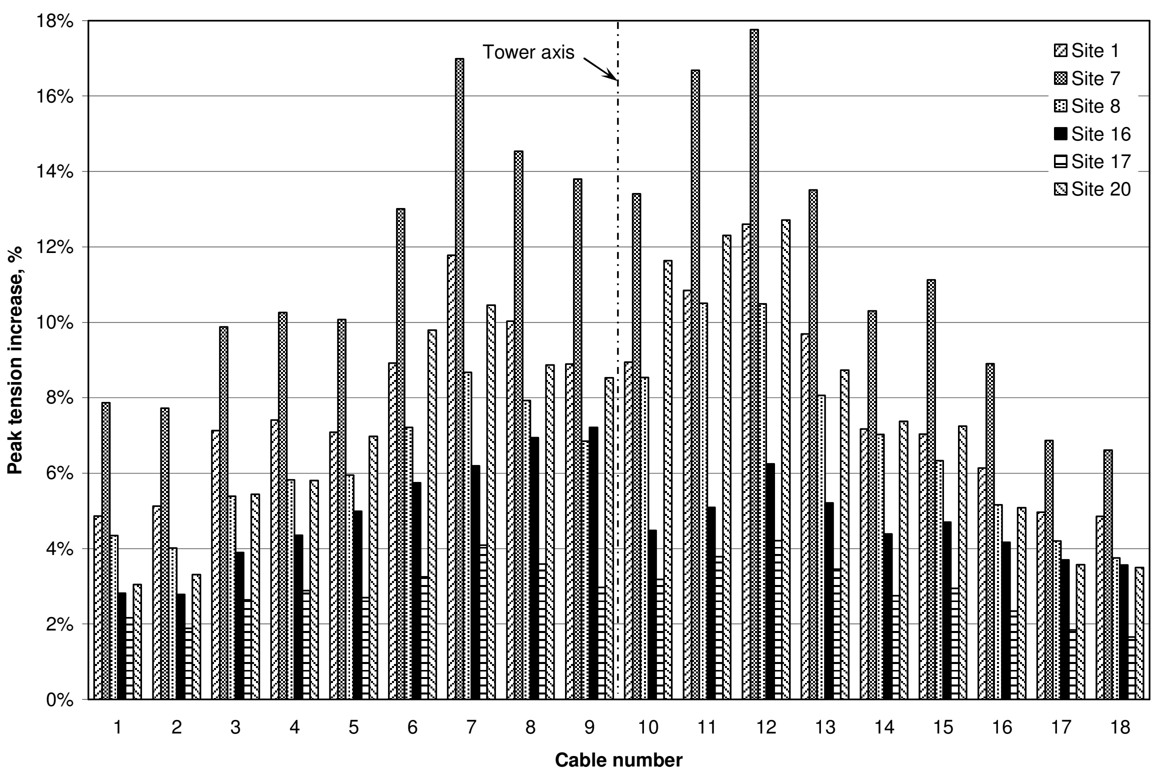

Figure 6. 3D Seismic response of bridge 1 for the six Saguenay sites used.

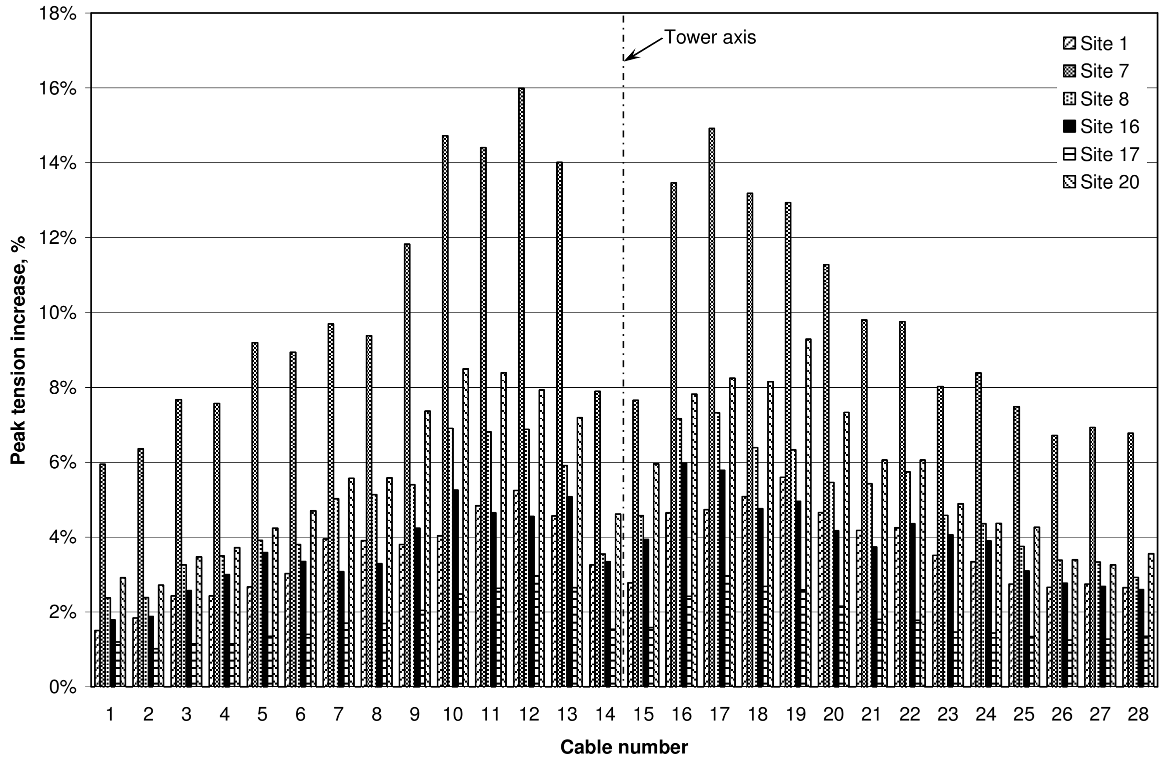

Figure 7. 3D Seismic response of bridge 2 for the six Saguenay sites used.

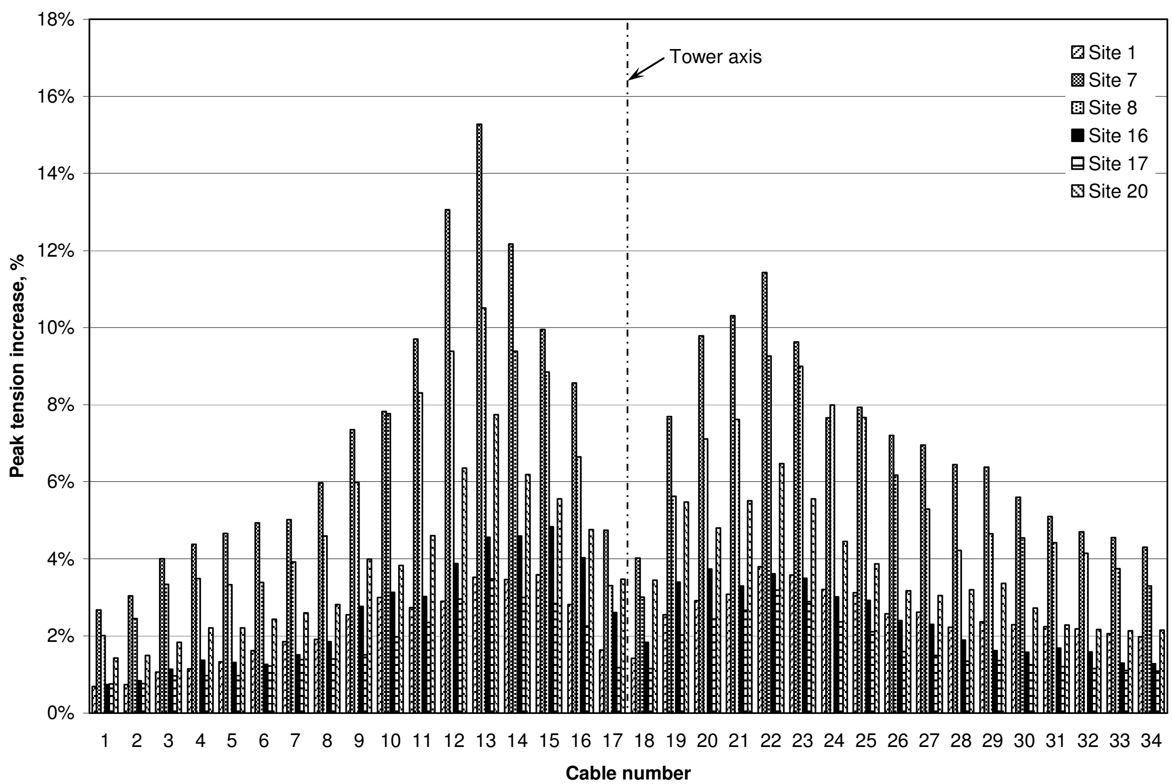

Figure 8. 3D Seismic response of bridge 3 for the six Saguenay sites used.

In order to assess the influence of the earthquake principal axes, 2D calculations are conducted for every site and correlations are drawn between 3D results and the orientation of the principal directions. Fig. 9 shows peak tension increases in the stay cables of Bridge 1 when subjected to 3D and 2D seismic input at site 7. It can be seen that the tension increases obtained using the 2D principal component and the *Y* component are close. This is expected in this case since the *Y* and the principal directions are 4^{o} away according to the seismological analysis. The figure also illustrates the tension reduction in 3D results because of the lateral seismic component, leading to a conservative 2D modeling in this case.

To assess the influence of the waveform source site, Fig. 10 portrays 2D and 3D tension increases when ground motions from site 20 are used. Overall, the 2D and 3D results compare well. Important differences are however observed for stay cables no. 8, 9 and 12. It is apparent from the figure that 3D results are generally more conservative in this case. To better understand the effect of bridge size on the 2D *vs* 3D results, Figs. 11 and 12 show the tension increases obtained for Bridges 2 and 3 subjected to input from site 7. Again, it can be seen that the 2D and 3D results compare well, with the latter being generally more conservative. Finally, the response of the three bridges to ground motions from the six sites exhibited a general trend for a critical incidence angle around 75° clockwise from the longitudinal direction of each bridge.

Conclusions

The study of the seismic behaviour of cable-stayed bridges subjected to Eastern Canada seismic hazard has rarely been reported in the literature. In the present work, the effect of high frequency content hazard typical of Eastern North America (ENA) is addressed. The response of three small to medium span cable-stayed bridges is investigated under the effect of ground motions recorded at six different sites during the Saguenay Earthquake of 1988. Only the response of the stay cables was addressed in this paper. Ground motions yielding the most critical peak tensions in the stay cables are identified. General trends indicating lower peak tensions with larger bridge dimensions are observed, but some exceptions are pointed out and discussed. Correlations between the results from 2D and 3D transient dynamic analyses are identified. It is shown that 2D models using the major principal longitudinal component as seismic input can be used effectively to assess the seismic response in a preliminary design.

Acknowledgments

The authors would like to acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada.

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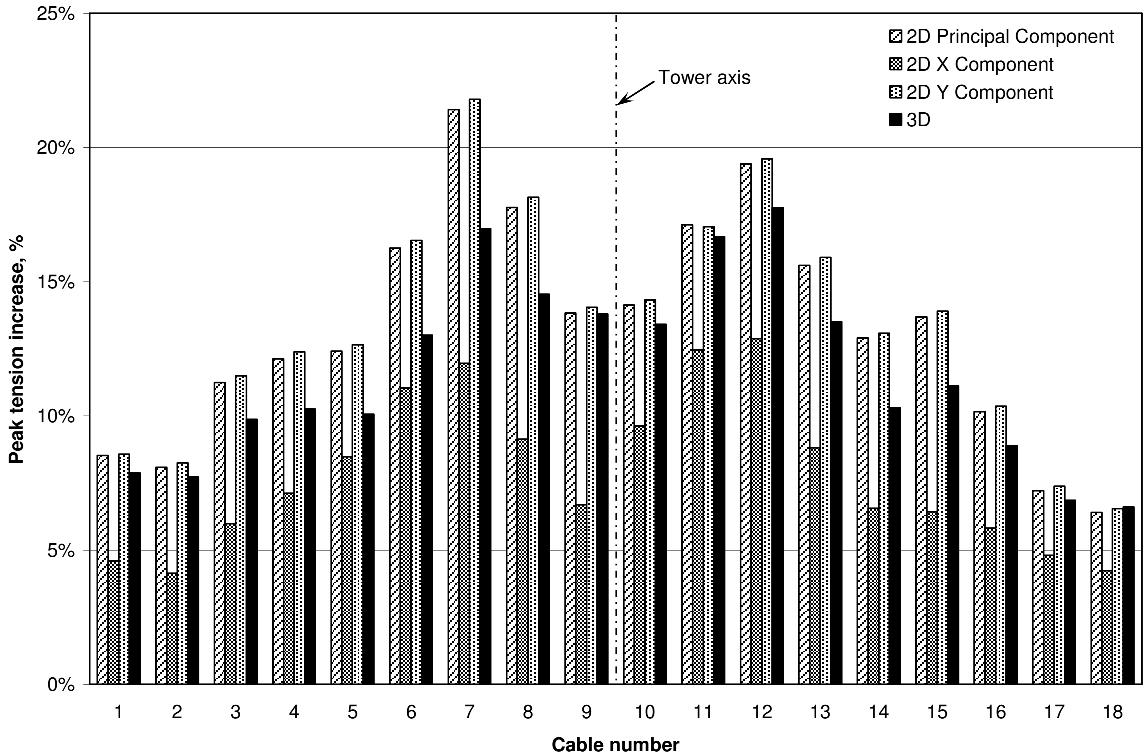

Figure 9. 2D *vs* 3D seismic analysis - Bridge 1 - Site 7.

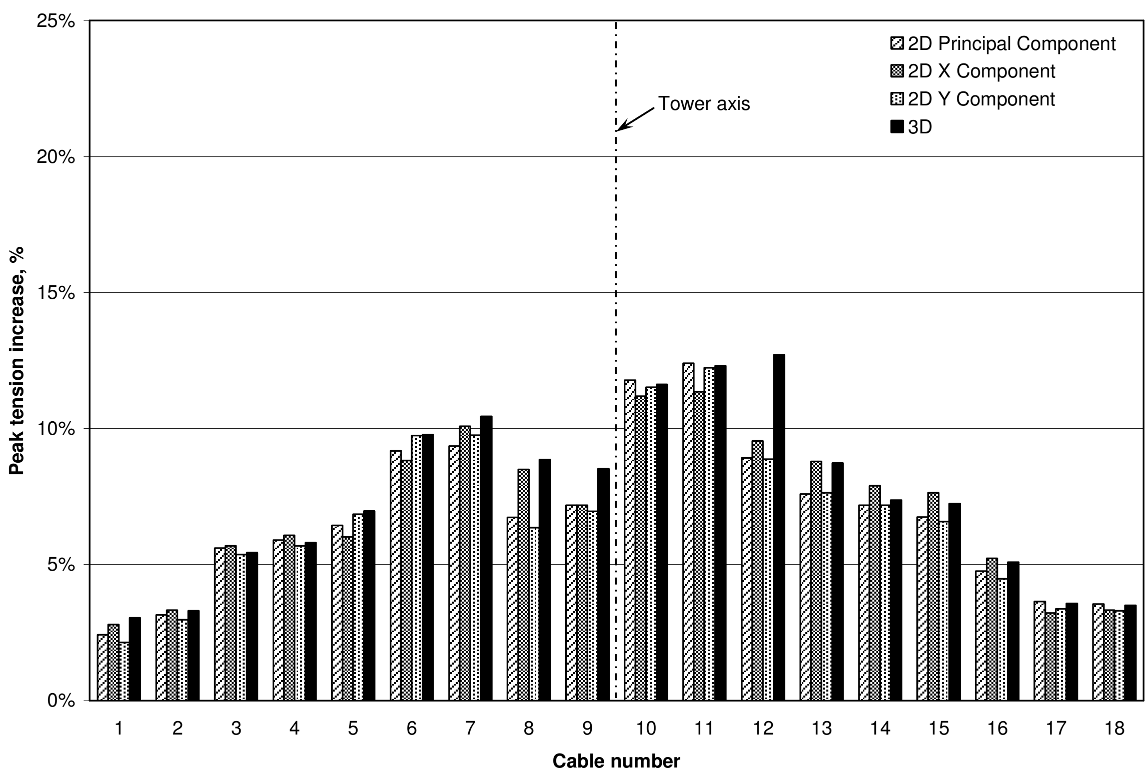

Figure 10. 2D *vs* 3D seismic analysis - Bridge 1 - Site 20.

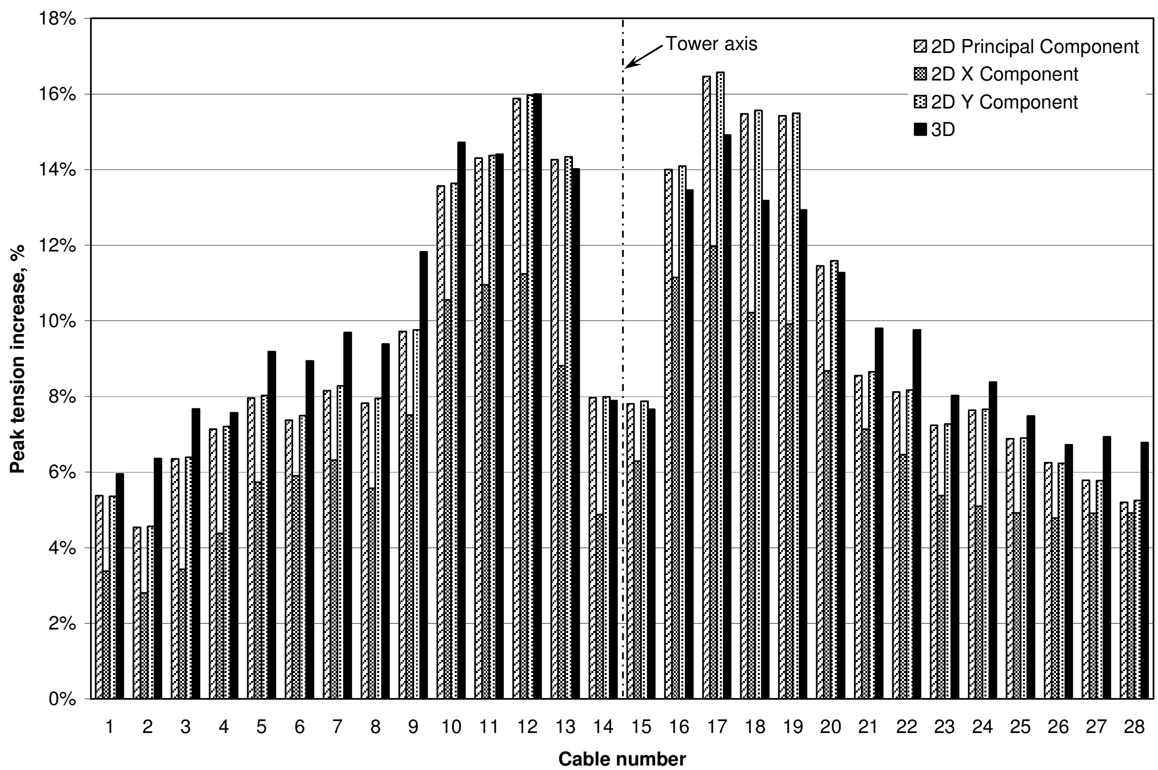

Figure 11. 2D *vs* 3D seismic analysis - Bridge 2 - Site 7.

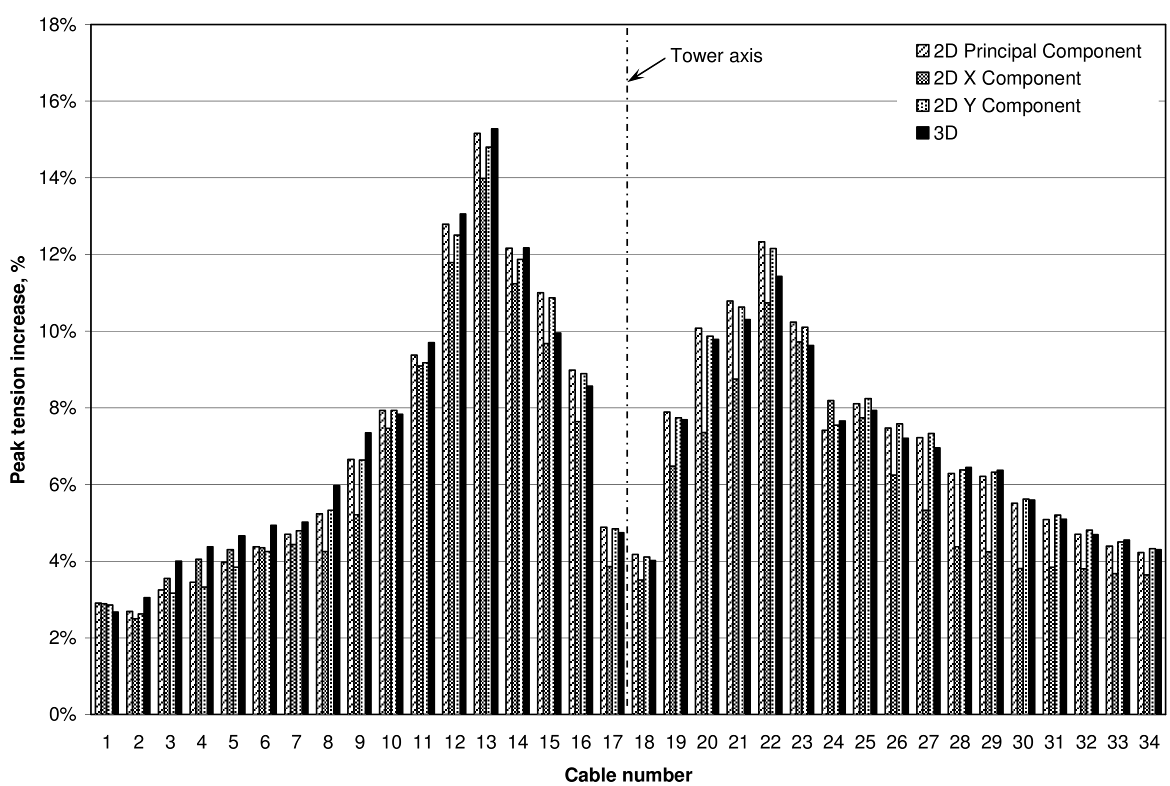

Figure 12. 2D vs 3D seismic analysis - Bridge 3 - Site 7.