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SENSITIVITY OF TRANSMISSION LINE TOWERS TO SEISMIC EFFECTS

De Macedo, Rodrigo[1,3], Tirca, Lucia[2]

[1] PhD student, Department of Building, Civil and Environment Engineering, Concordia University, Montreal, Canada

[2] Associate Prof., Department of Building, Civil and Environment Engineering, Concordia University, Montreal, Canada

[3] r_demace@encs.concordia.ca

Abstract: Steel lattice transmission line towers (TL) are generally designed to carry conductor's weight and environmental loads. Due to an overall perception that these structures have a relatively low vulnerability to earthquake loads, usually, the earthquake effects are not considered in design. Current design standards used in Canada do not require a design check for earthquake loads, although a significant percentage of transmission line infrastructure is located in Western and Eastern Canada, where the seismic risk is considered high and moderate-to-high, respectively. The purpose of this study is to evaluate the sensitivity of TL towers to seismic ground motions. Two guyed towers and two self-supporting towers, designed and built according to current standard provisions, are selected. Then, detailed three-dimensional finite element models of these towers are subjected to nonlinear time-history analysis. Historical crustal ground motions are selected to match the earthquake magnitude and geological profile representative for selected locations in Western Canada. The seismic responses of tower members are compared with those resulted from standard load cases. From this comparison, it is found that guyed towers are more sensitive to seismic ground motions than self-supporting towers. Furthermore, the seismic load case governs the design of primary members of guyed towers. Meanwhile, the dynamic interaction between the overhead powerlines and their supporting guyed towers is evaluated. This is done by carrying out detailed nonlinear transient simulations of the coupled tower-conductor system for a set of earthquake ground motion records of different frequency contents and by comparing the results of these simulations with the ones from free-standing towers.

1 Introduction

Guyed lattice towers sized to carry high-voltage (HV) transmission lines (TL) represent an evolution in conceptual design in comparison to conventional self-supporting towers. They are a cost-effective option among suspension towers and are used in relatively straight segments of a transmission line. As guyed-towers are a relatively new concept of TL towers, recently, researchers started to verify if design standards and methods of analysis developed for self-supporting towers are also applicable to guyed-towers. The TL lattice towers are usually designed for environmental loads, such as wind, and exceptional loads, as cable rupture. Due to an overall perception that these structures have a relatively low vulnerability to earthquake loads, earthquake effects are usually not considered in design. This perception is mostly based on reports focused on post-earthquake damage assessment. However, these reports refer mostly to TLs supported by conventional self-supporting towers. Guyed towers, which rely solely on its pretensioned guy cables for its stability, have dynamic behaviour different from that of self-supporting towers. This feature makes guyed towers more sensitive to seismic ground motions. A large portion of the Canadian high-voltage transmission lines infrastructure is located in Western and Eastern Canada, characterised by high and moderate-to-high seismic risk. Thus, in these regions, the seismic load combination could be the controlling design load case for these structures.

The objectives of the present study are twofold: i) to assess the sensitivity of typical TL towers to earthquake loads and ii) to verify if the dynamic behavior of the couple tower-conductor system should be considered in the design of supporting guyed towers in cases where seismic inertia loads control the design.

2 Transmission Lines Infrastructure and Seismic Hazard in Canada

A significant percentage of the high-voltage transmission lines infrastructure in Canada is located in British Columbia (BC) and Quebec (QC), two of the provinces with the larger number of significant earthquakes recorded in the country. According to GIS format data collected from Natural Resources Canada (NRC) representing the high-voltage transmission lines infrastructure in Canada, it is estimated that about 12% and 26% (totalling 38%) of powerlines are in BC and QC, respectively. According to Adams and Atkinson (2003), about 25% and 14% of earthquakes recorded in Canada are in the Western and Eastern regions of the country, respectively. Lamontagne et al. (2008) showed that 60% of earthquakes with magnitude 6 or greater have been recorded in Western Canada (BC) and 25% in Eastern Canada.

The Canadian high-voltage powerlines and the earthquake epicentres used in the fifth-generation seismic hazard maps of Canada (Halchuk et al., 2015) are illustrated in Fig. 1. As shown in this figure, a significant portion of the powerlines in BC is in seismic region characterized by relatively high magnitude earthquakes. In Quebec, a significant portion of powerlines is along the St. Lawrence River. It is noted that regions of Western Quebec, Charlevoix and Lower St. Lawrence experienced moderate earthquakes (Filiatrault et. al, 2013). Thus, in the case that a potential moderate to large earthquake occurs in Eastern or Western Canada, respectively, it may affect the performance of high-voltage transmission lines infrastructure. In light of this, there is a need to consider seismic loading in the design of TL towers, as well as in the assessment of existing TL towers.

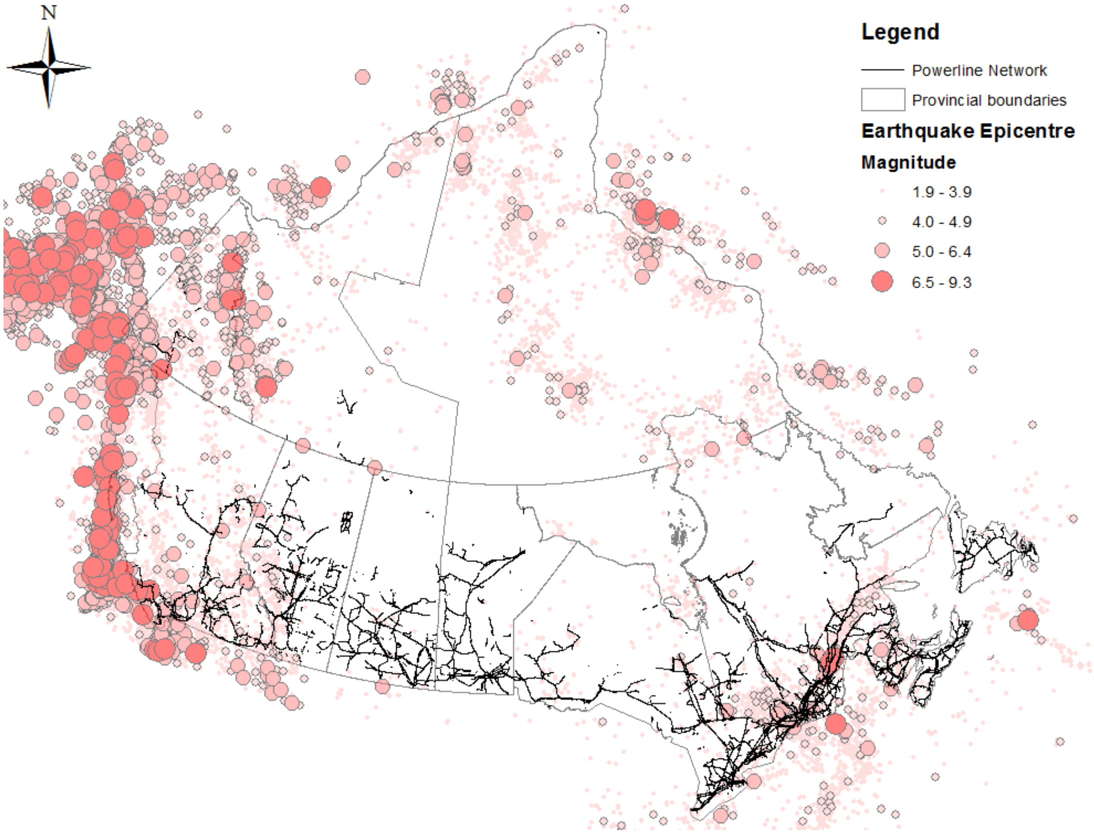

Figure 1: Seismicity of Canada and high-voltage transmission lines infrastructure.

3 Description of the Study

In this study, two guyed towers and two self-supporting towers, designed and built according to current standard provisions used in Canada, are selected for investigation. Detailed three-dimensional finite element models of the towers developed in ANSYS-APDL software are subjected to nonlinear time-history analyses using historical ground-motions. Twenty crustal ground motions considered as representative for Western Canada were selected from the PEER-NGA database (http://peer.berkeley.edu/nga/index.html). It is important to note that the frequency content of these selected records is close to the natural frequency of the studied towers. Details about these ground-motions can be found in De Macedo, R. (2016).

Seismic responses in terms of axial forces triggered in tower members are compared with those resulted from standard load cases used in design. Finally, the dynamic interaction between the overhead powerlines and their supporting guyed towers is evaluated. This is done by carrying out detailed nonlinear transient simulations of the coupled tower-conductor system for a set of three earthquake ground motion records of different frequency contents and by comparing the results of these simulations with the ones carried out for the free-standing towers.

3.1 General Description of the Structures

The guyed towers used in this study are suspension towers of the delta and mast types with heights of 37.7 m and 53.1 m, respectively. The self-supporting towers are strain or dead-end towers of the delta and mast types with heights of 36.6 m and 57.1 m, respectively. Both delta towers used in this study are part of the same transmission line and are illustrated in Fig. 2 below. These delta towers have about the same geometric configuration of their upper sections. The tower's geometry selection was made in order to compare the responses of two towers alike with different supporting configurations (guyed and self-supporting). It is noted that strain towers are usually stiffer and heavier than suspension towers since the former type is required to resist higher loads than the later. Some important characteristics of these towers are listed in Table 1. The geometric layouts of these towers are illustrated in Fig. 2. Parameters presented in Table 1 lead to the following observations: i) guyed towers have lower natural frequency values than self-supporting towers and ii) fundamental flexural frequency of guyed towers are closer to the typical frequency content of ground motion records. These observations are expected since guyed towers are inherently more flexible than self-supporting towers of similar height and upper sections geometry.

The coupled guyed-tower conductor system studied herein is based on a straight segment of 315 kV HVAC TL which is supported by suspension delta guyed towers described above. These towers carry three conductor cables and two ground-wire cables spanning 440 meters between supports. The conductors are twin bundled and have a cross-sectional area of 470 mm^2. Ground-wires have cross-section areas of 96 mm^2 (OHSW) and 158 mm^2 (OPGW). The layout of the studied coupled system is shown in Fig. 3.

3.2 Numerical Modeling

The PLS-Tower and PLS-CADD programs were used to create the numerical models of towers and overhead cables. Because the PLS program does not have dynamic capabilities, the finite element (FE) program Mechanical-APDL (ANSYS, 2013) was used for numerical dynamic simulations. To facilitate the transfer of PLS-Tower model echo files into the input files for the Mechanical-APDL software, a program was developed using the FORTRAN programming language. It is noted that the above echo files contain data and information about the towers structure`s geometric configuration, member dimensions and cross-section properties, as well as member connectivity and material properties.

All towers were modeled as linear elastic three-dimensional structures with frame elements for the main legs and truss elements for all other members. The supports are idealized as pinned on rigid foundations. In Mechanical-APDL, the frame-members are represented by BEAM188 elements and the truss-members are represented by LINK 180 elements. The mass of the tower structures were scaled up by a factor of 1.1 to represent the addition of other non-structural elements attached to the tower and not directly represented in the model. The cables were modeled as a chain of two-node tension-only truss-elements using the LINK180 element. Prestress forces in the guy cables are integrated in the LINK180 elements by using the INISTATE command available in Mechanical-APDL (ANSYS, 2013). For modelling the overhead cables, a trial-and-error procedure involving the number of elements and coordinates of their nodes was carried out in order to approximate the resulting deflected profile and the magnitude of tension forces along the modelled overhead cables.

Table 1: Characteristics of transmission towers studied.

Tower type	Height (m)	Base width Leg-to-leg (m)	Top width Beam/ cross-arm (m)	Total weight (kN)	First mode of vibration Frequency (Hz)	
					Transversal direction	Longitudinal direction
Delta (guyed)	37.7	-	19.8	54.3	1.93	2.51
Mast (guyed)	53.1	-	15.6	77.8	1.82	2.20
Delta (self-supporting)	36.6	13.6	21.8	232.2	3.88	4.94
Mast (self-supporting)	57.1	18.4	24.0	473.6	4.09	4.07

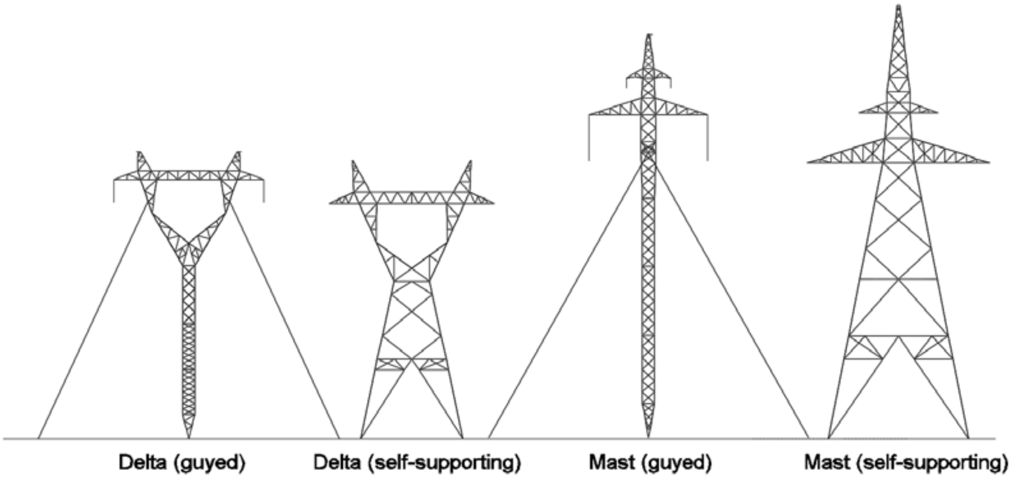

Figure 2: Geometric layout of towers studied.

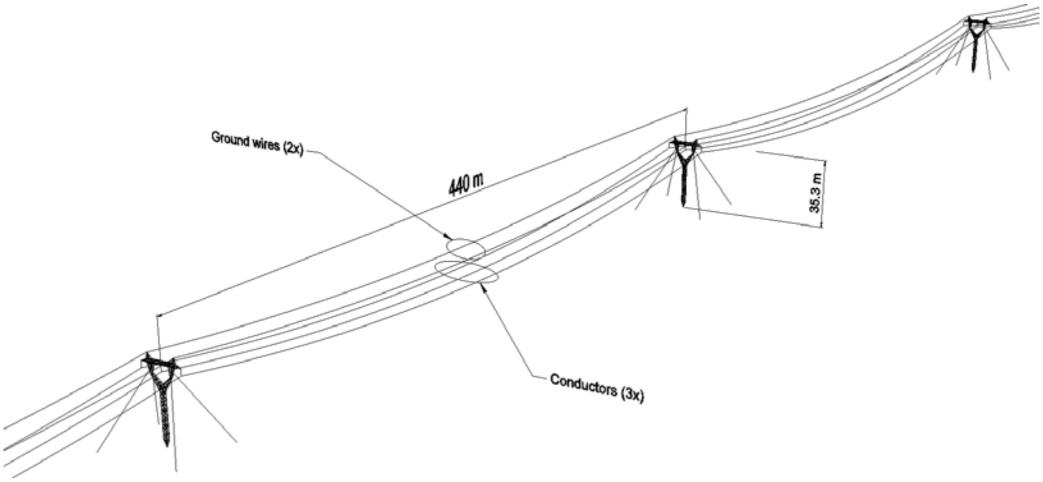

Figure 3: Perspective view of finite element model. Three guyed towers and four span lines forming a coupled system.

For simulating free-standing towers, the mass of the overhead cables were calculated, divided equally, and lumped at their respective end nodes. The Newmark time integration method was used to solve the equations of motion at discrete time-steps for the transient dynamic simulations. The dynamic equation was solved using the Newmark-β constant-average-acceleration method with coefficients $\beta = 0.25$ and $\gamma = 0.5$. A detailed description of the Newmark method can be found in the literature (Chopra, A. K., 1995, Filiatrault et al., 2013). In this study, the critical damping ratio was considered constant and equal to 2.0% for the tower structure and 0.1% for the guy cables.

3.3 Selection and Scaling Earthquake Ground-Motions

The governing design load case for the structures studied herein is related to wind loads acting on the latticed tower structure and on conductors and ground wires. The design wind loads were calculated as per the CSA C22.3 nº 60826-10 standard (CSA, 2015), and these loads are a function of the 10-minutes reference wind speed with a return period of 50 years. Since wind pressures listed in Table C-2 of the NBCC (2010) are calculated from reference wind speeds with a return period of 50 years as well, it is possible, from this table, to establish a set of potential locations where these structures could be displaced. It is noted that these potential locations should have the same ice loading conditions in addition to wind loading. After similar potential locations were identified in seismic areas, the design spectrum is built for each location and the selected ground motions were scaled to match the design spectrum over the periods of interest. Among them, one location in the South-West region of BC was retained for analysis and the spectral acceleration values are provided in Table 2. It is mentioned that all ground motion records considered in analyses were scaled to match the design spectrum (DS) at the fundamental period of the studied tower structures. In addition, the ASCE/SEI 7-10 (2013) provisions require that the mean of the 5% damped response spectra of at least 7 ground motion records should match or be above the target spectra over the interval of $0.2T_1$ to $1.5T_1$. This provision was also adopted in the present study and the scaling factor considered initially was verified. The set of 20 ground motion records, obtained from the PEER-NGA database, were scaled such that the frequency content of their accelerograms was preserved. From this set of scaled ground motion records, three were retained for the seismic analysis of the coupled guyed-tower conductor system. These three seismic ground motions have different levels of frequency content (low, intermediate and high) which is defined by their A/V ratio, where A is the peak ground acceleration and V is the peak ground velocity. Based on the classification of Tso et. al. (1991), records having A/V < 0.8 are classified in the low A/V range whereas those having A/V > 1.2 are categorized into the high A/V range. In the present study, only the time-series of the vertical component and the time-series of the horizontal component with the highest peak ground acceleration value were considered. Parameters for these three ground motion records are listed in Table 3 where V_s is the shear wave velocity, T_p and T_m are the principal period and the main ground motion period, respectively.

Table 2: Seismic spectral values as per NBCC (2010) (Site class C).

Hourly Wind Pressure (kPa) (1)	Sa(0.2) (2)	Sa(0.5) (2)	Sa(1.0) (2)	Sa(2.0) (2)	PGA (3)
0.50	1.10	0.89	0.45	0.20	0.49

1) hourly wind pressure with a return period of 1:50-year. Table C-2, Appendix C of NBCC (2010); 2) spectral acceleration values in units of g (m/s2); 3) peak ground acceleration.

Table 3: Earthquake records. Horizontal and vertical components characteristics.

Ground Motion	Component	M_w	V_s - (m/s)	T_p (s)	T_m (s)	PGA (g)	A/V Ratio
Jan. 17, 1994	Horizontal	6.7	356	0.52	0.74	0.84	0.75
Northridge	Vertical		356	0.22	0.34	0.62	1.60
Oct. 18, 1989	Horizontal	6.9	489	0.20	0.47	0.57	1.13
Loma Prieta	Vertical		489	0.06	0.37	0.36	1.50
Feb. 9, 1971	Horizontal	6.6	450	0.20	0.51	0.63	0.96
San Fernando	Vertical		450	0.20	0.26	0.38	2.08

4 Seismic Sensitivity of Free-Standing Towers

The relevance of considering seismic loads in the design of typical lattice high-voltage TL towers is evaluated by comparing the seismic response of towers studied herein with the response resulted under standard design load cases. The sensitivity of these towers to earthquake ground motions is assessed by determining the percentage of members with capacity exceeded and the number of cases where structural instability due to member failure occurred when the structure was subjected to earthquake loads. To attain this objective, the maximum axial forces developed in all members of towers when subject to earthquake ground motions by means of nonlinear time-history analysis were compared with the maximum axial forces resulted from the set of standard design load cases that were considered in the design of these towers.

The percentage of TL tower's members in which seismic axial forces exceed the maximum axial forces resulted from standard design load cases is depicted in Fig. 4 against different scaled peak ground accelerations of the selected 20 ground motions, applied in the transversal direction (i.e. direction normal to the direction of the transmission line). Table 4 presents the statistics of percentage of members with seismic axial forces exceeding maximum axial forces from design load cases for all directions analyzed such as: longitudinal, transversal (normal to tower) and vertical. These results were centralized after analysing the tower responses to 20 scaled ground motions. Overall, the results presented in this table indicate that although the weight of self-supporting towers is five to six times greater than the weight of similar guyed towers, there is a greater number of guyed tower members that trigger larger seismic axial forces than those resulted from typical design load cases. This observation leads to the conclusion that guyed towers are more sensitive to seismic demand than self-supporting towers. In addition, members of guyed towers are more sensitive to earthquake loads because the frequency content of the seismic input is more likely to match the tower frequency and their mast exhibits significant bending. The results presented in Table 4 also show that the effect of vertical component of seismic ground motion is more important in the response of heavier self-supporting towers than in flexible guyed towers.

It should be mentioned that previous studies carried out on the seismic analyses of lattice transmission towers also emphasized the relevance of seismic loads on the design of these structures. However, these studied were mostly performed for self-supporting towers and telecommunication guyed towers.

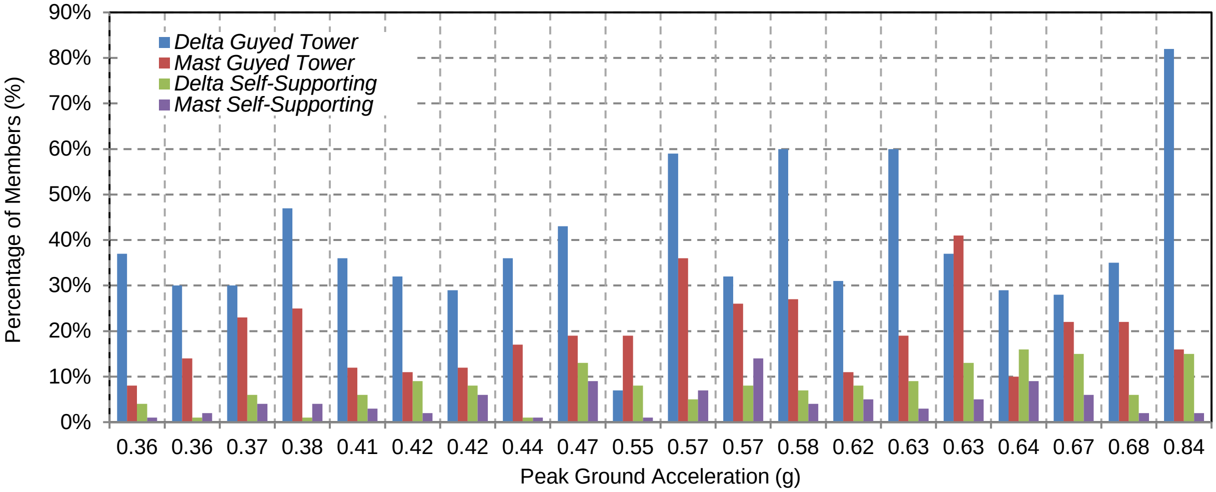

Figure 4: Percentage of members with seismic axial forces greater than those resulted from standard design load cases when TL towers are subjected to ground motions acting in the transversal direction.

Table 4: Percentage of members with seismic axial forces greater than those resulted from standard design load cases. Statistics per direction of ground motions application.

Earthquake incidence direction	Statistics	Guyed towers		Self-supporting	
		Delta	Mast	Delta	Mast
Transversal	Min.	7%	8%	1%	1%
	Max.	82%	41%	16%	14%
	Mean	39%	20%	8%	5%
Longitudinal	Min.	7%	4%	1%	1%
	Max.	62%	22%	23%	22%
	Mean	25%	12%	10%	7%
Vertical	Min.	1%	1%	8%	1%
	Max.	31%	4%	16%	8%
	Mean	2%	3%	11%	3%

5 Seismic Response of the Coupled Guyed Tower-Conductor System

Ground motions listed in Table 3 were used in the seismic analyses of the coupled guyed tower- conductor system. All supporting towers were subjected to synchronous ground motions at their base. These ground motions were applied separately in the three main orthogonal directions (longitudinal, transversal and vertical). The effect of the overhead cables' mass to the response of the supporting towers is studied by comparing the responses of the free-standing towers with the responses of the supporting towers when the coupled-system is considered. In Table 5 is showed a comparison of both responses. The results presented in Table 5 shows that earthquake ground motions with low frequency content applied in the longitudinal direction lead to increase force responses of supporting towers due to the inertia effects of the overhead cables, whereas under the effect of intermediate and high frequency content ground motions, the overhead cables attenuate the responses developed in the supporting towers. Figure 5 presents a comparison between the time-history series of horizontal base shear reactions of the free-standing tower and the tower in the coupled-system when subject to NGA 953 seismic ground-motion applied in the longitudinal direction. By comparing the time-history results of all simulations, it was observed that the motion of the overhead cables introduced a phase shift in the response of the supporting delta guyed towers for records of intermediate and high frequency content, resulting in a damped oscillation of the system. Conversely, for the low frequency content record, the oscillatory inertia effects of the overhead cables enhanced the base shear reaction on the supporting towers. The effects of A/V ratio in the response of the coupled tower-line system has also been discussed in previous studies (e.g El-Attar, 1997). Figure 6 presents the persistence curves of the base shear time-history series resulted under NGA 953 (low frequency content) and NGA 739 (high frequency content). These persistence curves give a measure of how much the base shear reaction in the supporting delta guyed tower is enhanced or attenuated by the inertia action of the overhead cables. The greater is the difference between the persistence curves of the free-standing delta guyed tower and the supporting delta guyed tower of the coupled-system, the greater is the influence of the mass of the overhead cables in the response of the supporting delta guyed tower.

These comparisons suggest that the higher is the frequency content of an earthquake ground motions (as defined by its A/V ratio) the greater is the damped oscillation effect introduced by the overhead cables. The results presented in Table 5 also show that the inertia effects of the overhead cables tend to attenuate the maximum responses in the supporting tower when the earthquake ground motions act in the transversal direction. Figure 7 presents a map of Canadian seismic zones classified according to their frequency content. This map was developed using GIS format grids of Peak Ground Motion (PGA) and Peak Ground Velocities (PGV) at 2% probability of exceedance in 50 years that were both developed to produce the 2015 NBCC Seismic Hazard Maps (Halchuk et al., 2015). This map suggests that seismic ground-motions in BC would be in the low frequency range, while in the Eastern seismic active regions of Canada, ground-motions would be in the intermediate and high frequency ranges. Based on indications that the low frequency content of ground-motion may enhance the responses of the supporting towers, transmission lines in BC would be more at higher seismic risk then those in Eastern Canada.

Table 5: Percentage of members with seismic axial forces greater than those resulted from standard design load cases.

Seismic Case	Configuration	Direction		
		Longitudinal	Transversal	Vertical
NGA 953 (1)	Free-Standing	60%	82%	-
	Coupled	91%	70%	2%
NGA 57 (2)	Free-Standing	62%	37%	-
	Coupled	30%	31%	-
NGA 739 (3)	Free-Standing	34%	59%	-
	Coupled	21%	39%	1%

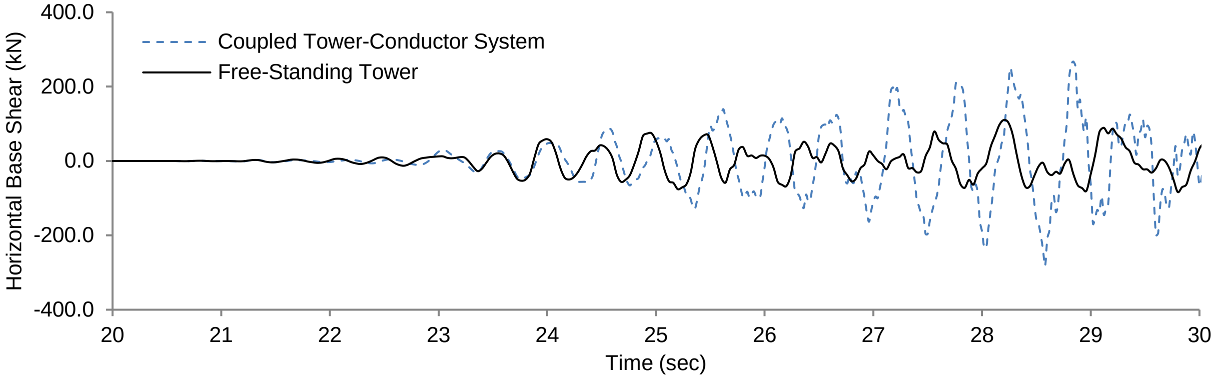

Figure 5: Time-history of horizontal base shear of Free-Standing Delta Guyed Tower and Coupled Delta Guyed Tower-Conductor System under NGA 953 record (low frequency content) applied in the longitudinal direction.

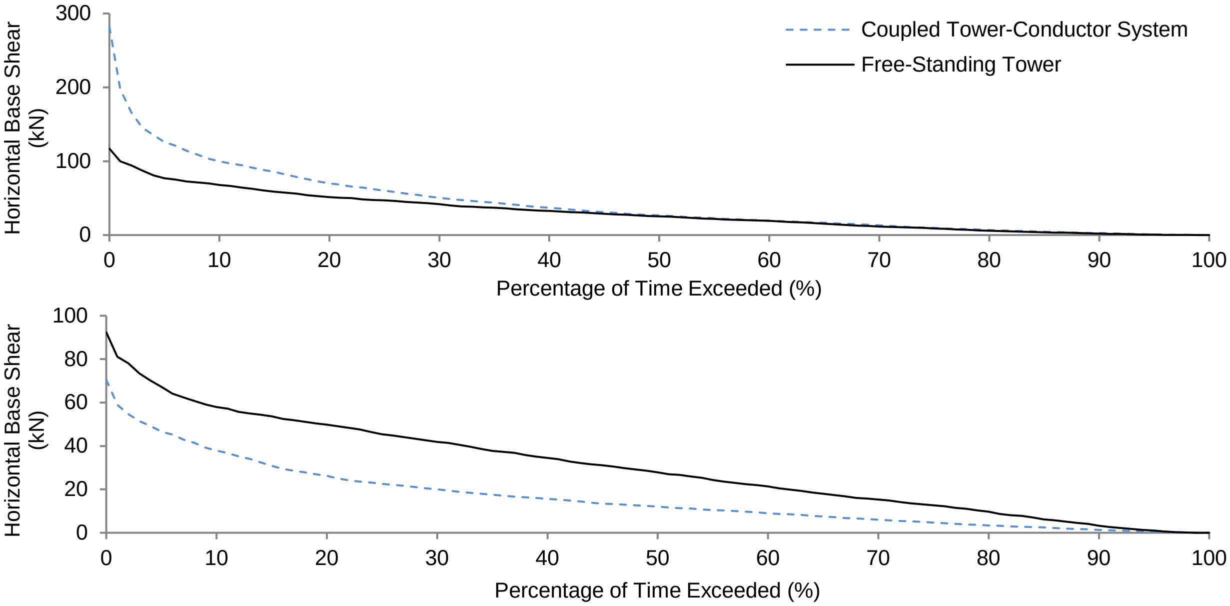

Figure 6: Time-history of persistence curve of horizontal base shear of Free-Standing Delta Guyed Tower and Coupled Delta Guyed Tower-Conductor System under NGA 953 record (low frequency content) (top) and NGA 739 record (high frequency content) (bottom) applied in longitudinal direction.

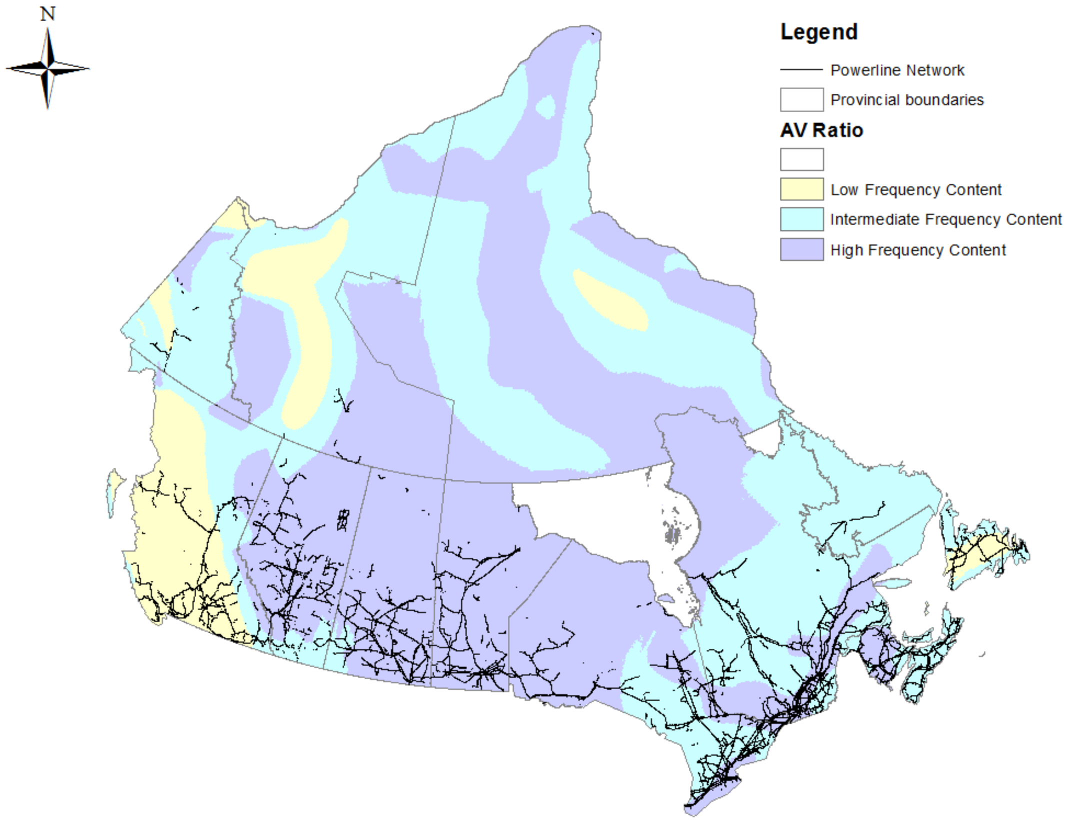

Figure 7: Canadian seismic zones of low, intermediate, and high frequency content and the high-voltage transmission lines infrastructure.

6 Concluding Remarks

Previous studies on the seismic response of TL tower were mainly devoted to self-supporting, while studies involving guyed towers where mainly devoted to telecommunication towers. The TL guyed towers studied herein were found to be more sensitive to seismic excitation than typical self-supporting towers. Since these lattice guyed towers have become popular structures for supporting high-voltage transmission lines, they should receive more attention when employed in areas of high seismic risk.

As it was shown from dynamic analyses carried out for free-standing towers and for the coupled guyed tower-conductor system, the seismic response of the supporting guyed tower structure is significantly modified by its dynamic interactions with the overhead conductor motion. The results of these simulations indicate that the frequency content of earthquake ground motions is relevant in determining the responses of the coupled system. In addition, ground motions with low frequency content ($A/V < 0.8$) tend to increase the shear forces trigger in members of supporting towers. Further investigations are suggested to ascertain from the observations regarding the effect of the frequency content of ground motion on the response of these structures and to develop simplified methods capable to approximate the effects of the overhead cable motion on the response of supporting towers. These findings should be considered in design in order to build a sustainable infrastructure.

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