Design Considerations and Seismic Response of High-Voltage Transmission Lines Supported by Guyed-Towers

Rodrigo De Macêdo[1], Lucia Tirca[2]

[1] PhD student, Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, QC, Canada.
[2] Associate Prof., Department of Building, Civil and Environmental Engineering, Concordia University, Montreal

ABSTRACT

A significant percentage of transmission lines infrastructure in Canada is located in regions of moderate and high seismic risk. Guyed latticed towers represent evolutionary structural systems. Both guyed-towers and self-supported towers are used to sustain the transmission lines. Although researchers devoted efforts to assess the impact of environmental loads such as wind, snow and ice, they accorded little attention to seismic effects. The purpose of this study is to evaluate the sensitivity of guyed-towers to seismic ground motions and to identify the conditions in which seismic loads should be considered in design. For locations in British Columbia (B.C.), transmission lines supported by guyed and self-supporting towers are designed according to the current standard provisions which does not include requirements for seismic design. Then, detailed three-dimensional finite element models are developed and subjected to nonlinear dynamic analyses. Seismic ground motions compatible with the intensity-based and geological profile of B.C. were selected and scaled according to NBCC 2015 requirements. To conclude, forces resulted from the seismic combination in guyed-tower members are compared with those resulted from the standard load cases. It is found that guyed-towers are more sensitive to seismic loading than self-supporting towers and the seismic load combination could govern the design of primary members of guyed-towers.

Keywords: transmission lines, guyed-towers, nonlinear dynamic analysis, earthquake ground motions.

INTRODUCTION

The high-voltage transmission line network in Canada is a vital component of the country's infrastructure as it delivers power produced by the hydro power plants usually located far away from the power consumption centers. A significant percentage of this infrastructure is located in the provinces of British Columbia (B.C.) and Quebec (QC) where a large number of significant earthquakes are recorded. According to data collected from Natural Resources Canada (NRC), it is estimated that about 12% and 26% (totaling 38%) of transmission lines are in B.C. and QC, respectively. Adams and Atkinson [1] indicated that about 25% and 14% of earthquakes recorded in Canada are respectively in the western and eastern regions of the country; and Lamontagne et al. [2] specified that 60% of earthquakes with magnitude 6 or greater have been recorded in Western Canada (B.C.) and 25% in Eastern Canada. The Canadian high-voltage powerlines infrastructure and the earthquake epicenters used in the fifth-generation seismic hazard maps of Canada [3,4] are illustrated in Fig. 1. As shown in this figure, a significant percentage of the powerlines in B.C. is in regions of seismotectonic sources with relatively high magnitude earthquakes. In Quebec, a significant percentage of the powerlines is present along the St. Lawrence River. This figure suggests that potentially moderate to large earthquakes expected to occur in Eastern and Western Canada may affect the performance of the high-voltage transmission line infrastructure, indicating that seismic load combination could be the controlling design load case for these structures.

In comparison with conventional self-supporting towers, the latticed guyed-towers represent an evolution in conceptual design of Transmission Lines (TL). Among them, the suspension Delta and Mast guyed-towers have been recently employed in TL projects in Canada. In general, latticed guyed-towers are usually designed for environmental loads (e.g. wind, snow, ice) and exceptional loads (e.g. cable rupture). Due to an overall perception that TL towers have a relatively low vulnerability to earthquakes, seismic loads are usually not considered in design. This perception is mostly based on reports covering post-earthquake damage assessment and remarks related to the behaviour of conventional self-supporting towers. Latticed guyed-towers rely solely on their pretensioned guy cables for stability and have a dynamic behavior different from that of self-supporting towers. As a consequence, guyed-towers are more sensitive to seismic ground motion than the self-supporting towers.

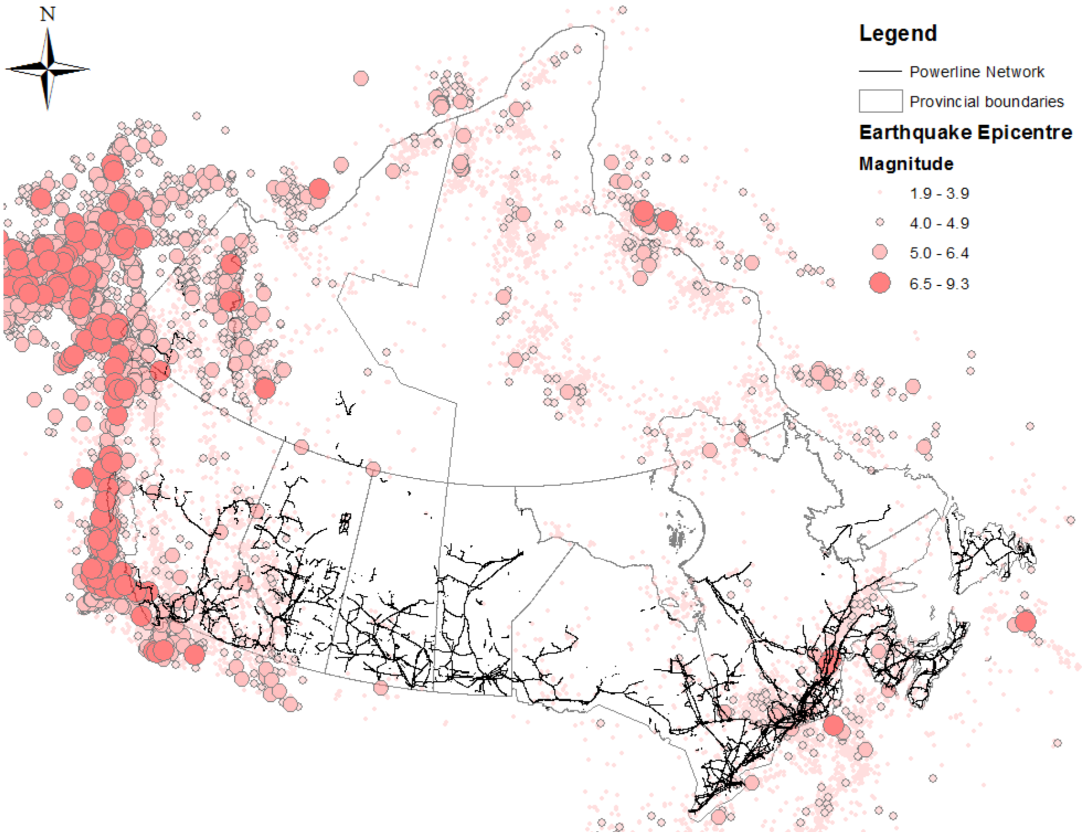


Figure 1. Seismicity of Canada and high-voltage transmission lines infrastructure

In this paper, four (4) different types of TL laticed tower are investigated: Delta self-supporting tower, Mast self-supporting tower, Delta guyed-tower and Mast guyed-tower. These towers were designed and built according to the current provisions and are located in moderate to height seismic areas of B.C. These four towers were first modelled as free-standing structures using finite elements and were subjected to ground motions by means of nonlinear dynamic simulations. Results from these simulations indicated that some members do not have sufficient strength to withstand forces induced by seismic ground-motions. Subsequently, to investigate the cable-tower dynamic interaction, a straight line segment of a 315 kV HVAC (high voltage alternative current) transmission system was modelled and subjected to ground motions using nonlinear dynamic analyis. The segment consists of 3 Delta guyed-towers. Results from these simulations were used to assess the effects of the overhead cables on the response of the supporting towers.

STUDY DESCRIPTION AND METHODOLOGY

Structural Modelling

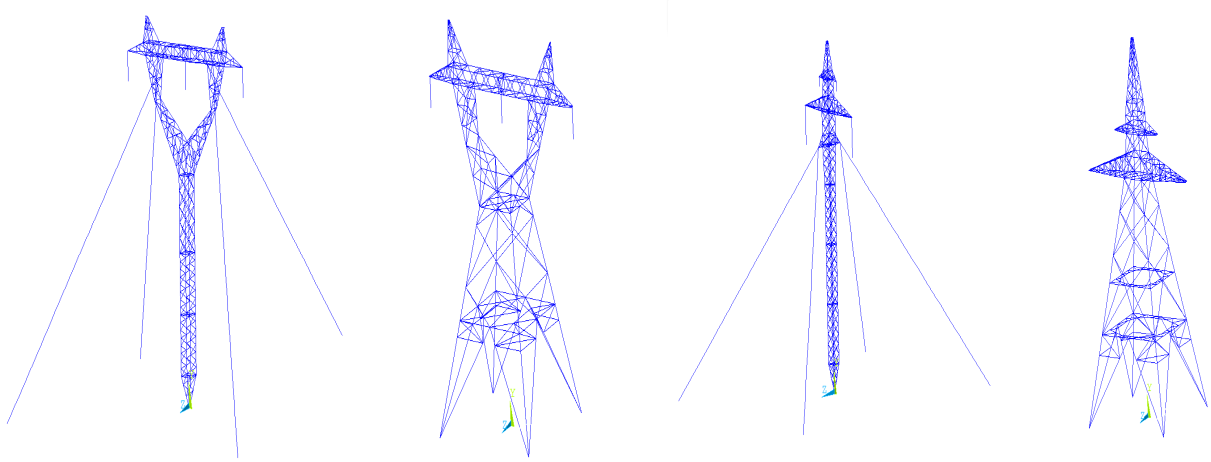
Two guyed-towers and two self-supporting towers designed and built according to the current standard provisions of Canada were considered in this study. Detailed three-dimensional finite element models of these towers were developed with the PLS-TOWER software [5] and were exported to ANSYS-APDL software [6,7]. Then, these models were subjected to nonlinear time-history analysis using twenty historical crustal ground motions considered as representative for Western Canada. These ground motions were selected from the PEER-NGA database (http://peer.berkeley.edu/nga/index.html). The selected ground-motions [8] have a frequency content close to the natural frequency of the studied towers. The axial forces triggered in tower members are then compared with those resulted from standard load cases used in design. The dynamic interaction between the overhead cables (conductors and ground-wires) and their supporting guyed towers is also evaluated by carrying out detailed nonlinear transient simulations of the coupled tower-conductor system. A set of three ground motion records of different frequency contents were selected for simulations and the results were compared with the ones obtained for the free-standing towers.

The four latticed towers used in the present study are depicted in Figure 2 and their main characteristics are listed in Table 1. The two guyed-towers are suspension towers of Delta and Mast type with heights of 37.7 m and 53.1 m, respectively. The self-supporting towers are strain or dead-end towers of Delta and Mast type 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 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 should be noted that strain towers are stiffer and heavier than suspension towers since the former type is required to resist higher loads than the later at the end of a transmission line segment. Parameters presented in Table 1 indicates that guyed-towers have lower natural frequency values than self-supporting towers and the fundamental frequency of guyed-towers is closer to the typical frequency content of ground motions. These observations are expected as guyed-towers are more flexible than self-supporting towers of similar height and upper sections geometry.

The 315 kV HVAC straight transmission line segment considered in the present study is supported by three suspension Delta guyed-towers described above. These towers support conductor cables and two ground-wire cables spanning 440 meters between supports. A perspective view of the studied transmission line segment is shown in Figure 3.

Table 1: Characteristics of studied transmission towers.

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



(a) (b) (c) (d)

Figure 2. The 3-D view of Finite Element Models developed in ANSYS-APDL environment. (a) Delta Guyed tower, (b) Delta Self-supporting tower, (c) Mast Guyed tower, and (d) Mast Self-supporting tower.

All tower structures were modeled as three-dimensional linear elastic with frame elements for the main legs and truss elements for all other members. The supports are idealized as pinned on rigid foundations. The mass of some of the tower members were scaled up to include the mass of other non-structural elements attached to the tower that were not simulated in the model. Cables were modeled as a chain of two-node tension-only truss-elements and prestress forces in the guy cables are integrated in these elements at the beginning of the simulations. A trial-and-error procedure involving the number of elements and coordinates of their nodes was carried out in order to approximate the resulting profile and tension guy cables along the modeled overhead cables to the design catenary profile and tension force values.

In simulating free-standing towers subjected to ground motions, the mass of the overhead cables was 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 and the Newmark-β constant-average-acceleration method with coefficients $\beta = 0.25$ and $\gamma = 0.5$ was used to solve the dynamic equations. The critical damping ratio was considered constant and equal to 2.0% for the tower structure and 0.1% for the guy cables.

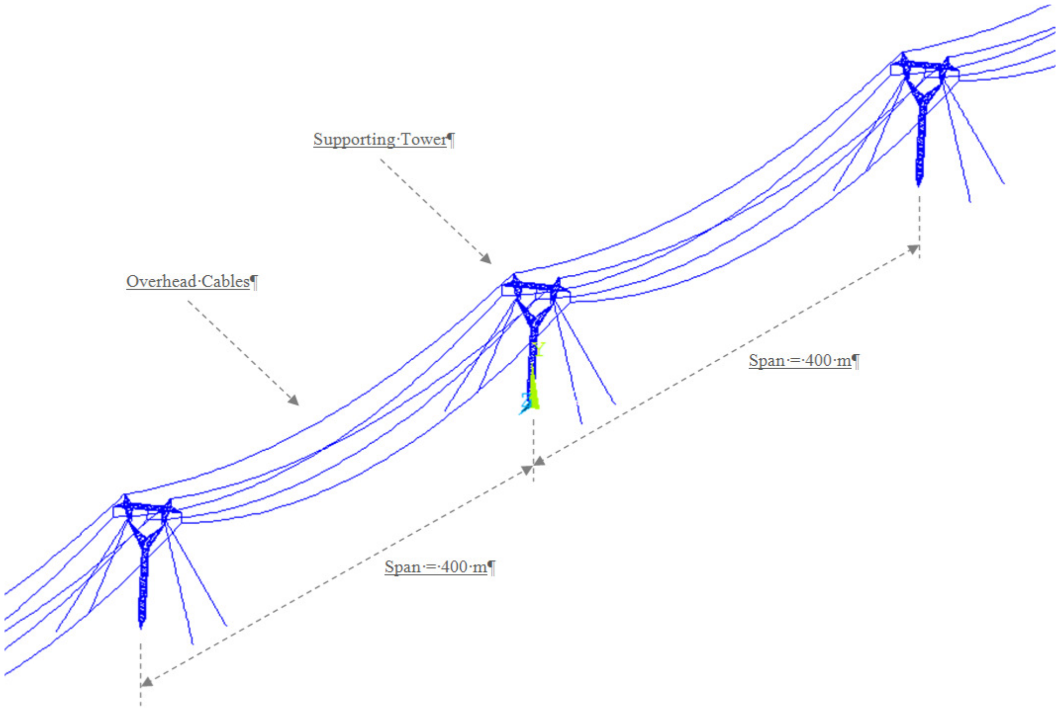


Figure 3. Perspective view of 315 kV HVAC straight transmission line segment

Selection and Scaling of Seismic Ground Motion Records

Wind load acting on tower structure and overhead cables is typically the governing design load case. For the above structures, the design wind loads were calculated as per the CSA C22.3 nº 60826-10 standard [9]. These wind loads were generated in 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 (2015) [10] have been also calculated from the reference wind speeds with a return period of 50 years, it is possible to establish potential locations where the wind pressures are the same. As aforementioned, these towers were designed to withstand the wind loads. Among the potential locations, it was selected one in the southwest region of B.C. corresponding to Site Class C. For this location, the design spectrum was built and compatible ground motions were selected and scaled to match the design spectrum over the periods of interest. Therefore, the goal is to identify the earthquake effects on tower structures proportioned to wind loads.

According to NBCC 2015, the minimum number of records used in analysis should be not less than 11. However, for a defined scenario-specific target spectrum, using fewer than 11 records per suite is permitted but the number should not be less than 5. In this study, twenty ground motion records obtained from the PEER-NGA database (Site Class C) were scaled such that the frequency content of their accelerograms was preserved. It is noted that the suite of subduction records was not considered. To perform nonlinear time history analysis, these ground motions were scaled with respect to NBCC 2015 procedure such that the mean spectrum of a suite of minimum records discussed above is not less than 90% of the design spectrum in the period range of $0.2T_1$ to $2.0T_1$, where T_1 is the fundamental period of the studied tower structures. To emphasize the response of the coupled guyed-tower conductor system resulted from seismic analysis, from this set of scaled ground motions, three records were retained. 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. [11], 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 vertical time-series 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 main period and the average ground motion period, respectively.

Table 2: Seismic design data (Site Class C) for a location in southwest region of B.C. as per NBCC (2015).

Hourly Wind Pressure (kPa) (1)	Sa(0.2) (2)	Sa(0.5) (2)	Sa(1.0) (2)	Sa(2.0) (2)	Sa(5.0) (2)	PGA (3)
0.48	0.83	0.75	0.43	0.26	0.086	0.36

1) hourly wind pressure with a return period of 1:50-year. Table C-2, Appendix C of NBCC (2015); 2) spectral acceleration values in units of g (m/s2) corresponding to 2% in 50 years; 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 Northridge	Horizontal	6.7	356	0.52	0.74	0.84	0.75
	Vertical		356	0.22	0.34	0.62	1.60
Oct. 18, 1989 Loma Prieta	Horizontal	6.9	489	0.20	0.47	0.57	1.13
	Vertical		489	0.06	0.37	0.36	1.50
Feb. 9, 1971 San Fernando	Horizontal	6.6	450	0.20	0.51	0.63	0.96
	Vertical		450	0.20	0.26	0.38	2.08

FREE-STANDING TOWERS SUBJECTED TO SEISMIC GROUND MOTIONS

To assess the relevance of considering seismic loads in the design of typical latticed TL towers, a comparison of the seismic response of studied towers with the response obtained from the typical design load cases is carried out. This comparison is performed by determining the percentage of members overloaded when the towers are subjected to earthquake loads. The maximum axial forces developed in all members of studied towers subjected to seismic ground motions were compared with the maximum axial forces resulted from the set of governing design load cases. The percentage of TL tower's members in which seismic axial forces exceed the axial forces of governing design load cases is presented in Figure 4 against different scaled peak ground accelerations of 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 greater than those resulted from governing load cases for all simulated directions: longitudinal, transversal (normal to the direction of the transmission line) and vertical. The results presented in this table indicate that even though the weight of self-supporting towers is five to six times greater than the weight of similar guyed-towers and therefore seismic inertia loads in these heavier towers are higher, 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 the self-supporting towers. Also, 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 due to significant bending of their mast. Finally, the results presented in Table 4 indicate that the effect of the vertical component of ground motions 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 in the design of these structures. However, these studies were mostly performed for self-supporting towers and telecommunication guyed-towers.

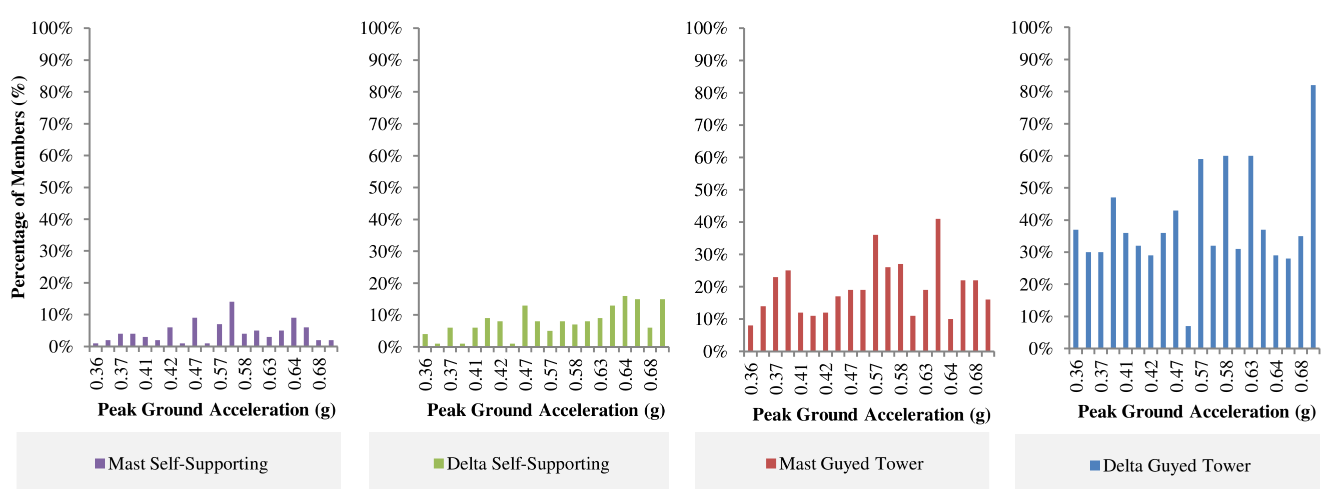


Figure 4. Percentage of members with seismic axial forces greater than those resulted from governing design load cases.

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

Direction of earthquake incidence	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%

TRANSMISSION LINE SEGMENT SUBJECTED TO SEISMIC GROUND MOTIONS

The transmission-line segment model described above (Fig. 3) was subjected to the seismic motions listed in Table 3 and the dynamic interactions of the coupled tower-conductor system was considered in analysis. The towers were subjected to synchronous ground motions at their base and 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 was assessed by comparing the responses of the free-standing towers with the responses of the supporting towers when the coupled-system is considered. Table 5 shows a comparison of both responses. For earthquake ground motions with low frequency content applied in the longitudinal direction, the inertia effects of the overhead cables enhance the responses of supporting towers, whereas under the effect of intermediate and high frequency content ground motions, the overhead cables attenuate the seismic responses of Delta guyed-towers. Figure 5 presents a comparison between the time-history series of horizontal base shear reactions of the free-standing tower and the guyed-tower in the coupled-system under 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 in case of supporting towers. The effects of A/V ratio in the response of the coupled tower-line system has also been raised in previous studies [12]. Figure 6 presents the persistence curves of the base shear time-history series for 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. When the difference between the persistence curves of the free-standing Delta guyed-tower and the supporting Delta guyed-tower of the coupled-system is high, the influence of the mass of the overhead cables on the response of the supporting Delta guyed-tower increases.

Comparisons presented herein suggest that seismic signals with high frequency content (as defined by its A/V ratio) tend to enhance the dampening oscillation effect induced by the overhead cables. For earthquake ground motions acting in the transversal direction, the inertia effects of the overhead cables tend to attenuate the maximum responses in the supporting tower.

Table 5: Delta guyed-towers: percentage of members with seismic axial forces greater than those resulted from typical design load cases.

Seismic Case	Configuration	Direction		
		Longitudinal	Transversal	Vertical
1. NGA #953	Free-Standing	60%	82%	-
	Coupled	91%	70%	2%
2. NGA #57	Free-Standing	62%	37%	-
	Coupled	30%	31%	-
3. NGA E739	Free-Standing	34%	59%	-
	Coupled	21%	39%	1%

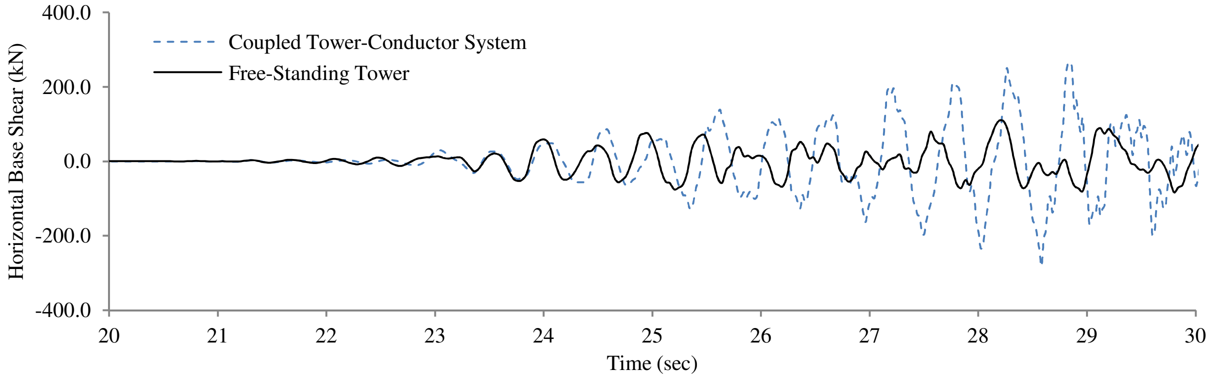


Figure 1: Time-history of horizontal base shear of Free-Standing Delta Guyed Tower and Coupled Delta Guyed Tower-Conductor System under NGA #953 record (low frequency content) applied in the longitudinal direction.

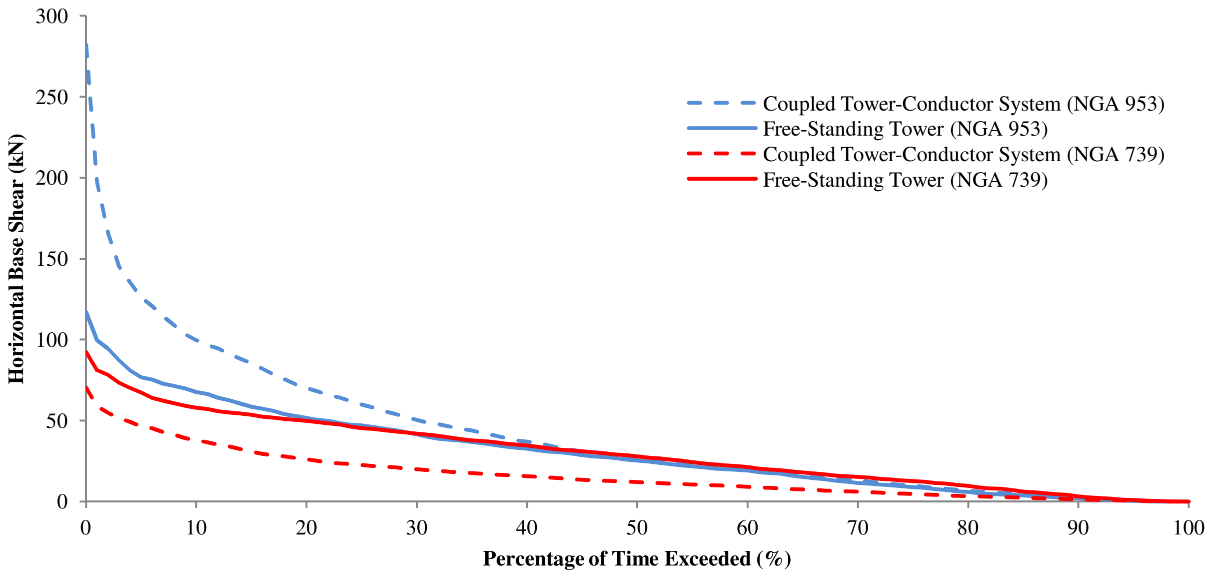


Figure 2: Persistence curve of horizontal base shear of Free-Standing Delta Guyed Tower and Coupled Delta Guyed Tower-Conductor System under NGA #953 record (low frequency content) and NGA #739 record (high frequency content) applied in longitudinal direction.

CONCLUSIONS

Previous studies on the seismic response of latticed TL towers were mostly conducted for self-supporting towers, while studies involving guyed-towers where mainly carried out for telecommunication towers which are free-standing towers and do not support overhead cables. The TL guyed-towers studied herein were found to be more sensitive to seismic ground motions than the typical self-supporting towers. Since these latticed Delta and Mast guyed-towers have been employed in high-voltage transmission lines, they should also be investigated to seismic loads when located in areas of moderate and high seismic risk.

As it was shown from dynamic analyses carried out for the 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 the 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 motions 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 the supporting towers. The effect of subduction ground motions on these TL towers will be reported in other article. Further investigations will be conducted to improve the design practice for safer and more reliable transmission-line structures.

REFERENCES

[1] Adams, J., and Atkinson, G.M. 2003. Development of seismic hazard maps for the proposed2005 edition of the National Building Code of Canada. Can. J. Civ. Eng., 30, 255-271.

[2] Lamontagne, M., Halchuk, S., Cassidy, J.F., and Rogers, G.C. 2008. Significant Canadian earthquakes of the period 1600-2006. Seismological Research Letters, 79(2), 211-223.

[3] Halchuk, S; Allen, T I; Rogers, G C; Adams. 2015. Seismic Hazard Earthquake Epicentre File (SHEEF2010) used in the fifth generation seismic hazard maps of Canada. J. Geological Survey of Canada, Open File 7724, 2015; 21 pages, doi:10.4095/296908.

[4] Halchuk, S C; Adams, J E; Allen, T I. 2015. Fifth generation seismic hazard model for Canada: grid values of mean hazard to be used with the 2015 National Building Code of Canada. Geological Survey of Canada, Open File 7893, 2015, ; 26 pages, doi:10.4095/297378

[5] Power Line Systems Inc. PLS Tower Software. http://www.powline.com/products/tower.html

[6] ANSYS. 2013. Mechanical APDL Command Reference. Release 15.0. November, 2013.

[7] ANSYS. 2013. Mechanical APDL Theory Reference. Release 15.0. November, 2013.

[8] De Macedo, R. 2016. Seismic Response of Transmission Line Guyed Towers with and without the Interaction of Tower Conductor Coupling. Master's thesis. Concordia University. Montreal. Canada.

[9] Canadian Standards Association – CAN/CSA-C22.3 NO. 60826-10 (R2015) - Design criteria of overhead transmission lines (Adopted CEI/IEC 60826:2003, third edition, 2003-10, with Canadian deviations).

[10] National Building Code of Canada – NBCC. 2015. User's Guide. Structural Commentaries. Part 4 of Division B. Issued by the Canadian Commission on Fire Codes. National Research Council of Canada.

[11] Tso, W. K., Zhu, T. J., Heidebrecht, A. C. 1991. Engineering implication of ground motion A/V ratio. Soil Dynamics and Earthquake Engineering. 11. (1992). 133-144. Elsevier Science Publisher Ltd.

[12] El-Attar, M. (1997). Nonlinear Dynamics and Seismic Response of Power Transmission Lines. PhD Thesis. McMaster University.