Considerations in the Development of a Lattice Tower Structure Family

Jondy Britton, P.E.[1]; and Travis Bouslog, P.E.[2]

[1]Burns & McDonnell Engineering Company Inc., 9400 Ward Parkway, Kansas City, MO 64114. E-mail: jbritton@burnsmcd.com
[2]Burns & McDonnell Engineering Company Inc., 9400 Ward Parkway, Kansas City, MO 64114. E-mail: tbouslog@burnsmcd.com

Abstract

The process of creating a new lattice tower structure family is complex and requires the involvement of multiple engineering disciplines. Based on the design and construction of the BC Hydro 287-kV AC 344-km (213-mile) Northwest Transmission Line, this paper discusses lattice tower structure family development from initial concept through delivery, construction and energization, and how configuration changes affect tower erection, structure placement and the construction schedule. Topics to be covered include tower types, both self-supported and guyed towers, load development, and tower geometry. Special attention will be given to load development, including statutory, security, and reliability-based loads. To address loading conditions, we provided structure-type alternatives and the benefits of each alternative. Lastly, we addressed the key role of electrical engineers, structural engineers and tower erection firms in the process. The goal of this paper is to help you gain a better understanding of lattice tower family development. More specifically, you will learn more about the benefits of different structure types, special load cases to consider and overall constructability of lattice towers in the context of a design-build project in British Columbia, Canada.

INTRODUCTION

In 2011, the British Columbian government directed provincial Crown Corporation BC Hydro to provide high-voltage transmission service to the northwestern area of the province initiating the Northwest Transmission Line (NTL) project. This interconnection point to the BC Hydro grid will help jump-start potential mining ventures in an area rich with gold, silver, nickel, zinc and other high-value metals and minerals. Additionally, the NTL will provide a secure interconnection point for several renewable run-of-river hydro facilities in the area, connecting isolated communities to the green electricity provided by the BC Hydro grid.

The NTL project called for a 344-km (213-mile) 287-kV AC power line from the town of Terrace, a 1355-km (840-mile) drive north of Vancouver, on the south to a new substation in the north near Bob Quinn Lake, in the heart of mining country. From Terrace to Bob Quinn Lake, most of the NTL route follows a river valley flanked by mountains, and runs parallel to Highway 37, the only major roadway serving northwest British Columbia.

This remote region offered its share of design and construction challenges. "The system had to be designed to span major river crossings at the Skeena and Bell rivers as well as a narrow section of Nisga's Memorial Lava Bed Provincial park. The spans between transmission towers ranged from 95 m to 1090 m (312 to 3576 ft) in areas that required waterway and wetland crossings. The project was planned to accommodate unexpected challenges from weather, geologically unstable areas prone to rockslides, and seismically active areas with liquefiable soils. Other areas were vulnerable to avalanches caused by winter snowfall accumulations that sometimes reach more than 20 m (66 ft)" (Shepherd, Jarvis, and Hunt 2014).

To execute the NTL project, BC Hydro selected the team of Valard-Burns & McDonnell (VBM) in August 2011. To assist in the design and testing of the lattice tower structure family, VBM selected Gammon India Limited (T&D Business) of Nagpur, India. Gammon's lattice tower experience and state-of-the-art testing facility aided VBM in providing an optimized and effective lattice tower structure family.

Early in the project development, VBM identified lattice towers as the optimal structure type for this region. To optimize structure and construction costs, VBM developed a project-specific structure family. The process of developing structure families is common for overhead transmission projects. The steps involved include determining adequate phase spacing for the appropriate voltage, determining proper structure materials and optimizing loading for each structure type. There is a number of important parameters in the design of a lattice tower structure family. These parameters include, but are not limited to, line routing, electrical requirements, maintenance requirements, structure loading, cost, project schedule and construction methods. When properly developed, a well-engineered structure family is a valuable tool for successfully executing the most challenging projects.

Whether developing a lattice tower structure family for a specific project or as a standard family for a transmission system, engineers should consider all design parameters listed above. The influence of each parameter depends on the intended use of the structure family. The lattice tower structure family discussed in this paper was developed as a specific project application. On the NTL project, project cost, schedule and construction methods were the most significant factors in the structure family design.

PROJECT DESIGN CRITERIA

The preliminary scoping of any transmission project is important as it lays the framework for the line design, including structure design. Safety codes provide minimum safety requirements which are then combined with reliability, maintenance, and security expectations to develop the final loading requirements. For the NTL, BC Hydro documented the results of its project design criteria in the Final Functional Specifications (FFS). The FFS provided minimum design parameters, from the system and performance requirements of the line to the design criteria and loading requirements for the structures.

Load Development

BC Hydro developed the structure loading requirements for the NTL project and the requirements included deterministic, reliability, security and construction loads. Load development, with the exception of deterministic and constructability loading, was project-specific and included several atypical load cases.

To develop project-specific loading, BC Hydro used data from meteorological studies along the anticipated NTL route. The statistical data was used as the basis for developing the reliability and security loads. Additionally, BC Hydro performed a terrain assessment to evaluate potential terrain hazards along the proposed NTL route. The terrain hazard assessment was the basis for developing additional security loads and requirements.

Deterministic

The objective of deterministic methods is to comply, as a minimum, with the safety or design-load factors required for each loading case specified. Deterministic design loads for the NTL were governed by CSA C22.3 No. 1 (2010). These deterministic loads are statutory loads and are similar to statutory loading requirements in the United States. These loads must be considered in the design of transmission structures as a means to meet minimum safety requirements.

Reliability

A reliability-based approach can achieve two additional key elements to line design, as outlined in the ASCE Manual of Practice No. 74 (ASCE 2010). The first is the ability to adjust the reliability level of a line design, and the second is to establish appropriate strength correlation between line components and supports.

Table 1. NTL Load Zones

Load Zone	1-100 Year Combined Ice (mm)	1-100 Year Combined Wind (Pa)	1-50 Year Ice (mm)	1-100 Year Ice (mm)	1-100 Year Wind (Pa)	Temp. (°C)
C1	12.5	300	20	25	400	-20
C2	12.5	300	20	25	450	-20
C3	12.5	400	20	25	750	-20
D1	12.5	400	25	30	400	-20

The reliability-based design loads were determined from statistical data of the region collected from a variety of sources, including the meteorological study, various weather maps and the historical performance of neighboring lines. These values, which were based on a 50-year return period, were adjusted to 100-year return period levels, resulting in unique maximum ice glazes, combined ice and wind loads, and maximum wind loads. The factors used for the conversion from 50-year returns to 100-year returns varied between ice and wind loads, and were determined by consultation of the ASCE Manual of Practice No. 74, and the CSA C22.3 No. 60826-10 standard. The ice glazes, combined ice and wind loads, and maximum wind loads were grouped into load zones that occurred throughout the line route (Table 1). In addition, each loading zone had unique loads for evaluating insulator swing. The distinct loading zones created by BC Hydro were not sequential, meaning each loading zone was located multiple times throughout the line route.

Rather than developing structure families for each load zone or a single structure family encompassing all load zones, VBM grouped the four loading zones into two categories: light and heavy. Light consisted of load zones C1 and C2; heavy consisted of load zones C3 and D1. The light and heavy grouping was determined while designing the tangent structure of the family, when VBM observed significant weight savings could be realized by designing separate structures for the C1 and D1 load zones. Additionally, the C1 and D1 load zones constituted the majority of the line route (approximately 50% and 30% respectively). The combination of the weight savings and quantity of each structure resulted in significant material and construction savings, thus the light and heavy categories were born. Based on the results from the tangent towers, VBM elected to design the remaining members of the tower family for the light and heavy categories. Grouping the loading zones and designing structures specific for the light and heavy categories allowed the VBM team to provide an optimized line design.

Security

Security design considerations for the NTL route included flood events, snow creep, snow avalanches, rock falls, debris flows, slides, seismic activities and differential ice loads. VBM considered each of these in the transmission line design, whether specifically by added capacity in the structure design or by some other means. Flood events, rock falls, debris flows, slides and seismic activities were accounted for in the line design by the use of berms, rip-rap or by structure spotting. Snow creep, snow avalanches and differential ice loads were addressed in the structure design. Each offered unique design challenges.

Snow creep and glide is a phenomenon that produces slow, viscous deformation of snow cover on a slope. Creep and glide act simultaneously at rates of millimeters to meters a day and results in pressure on rigid transmission structures. If not considered in the design, snow creep has the ability to damage transmission tower legs by first buckling the redundant members and subsequently buckling the main brace and leg members. For snow creep and glide to occur, the snow depths needed to be greater than three meters (≈ 10 feet) and the terrain slope at the particular structure must be greater than 15 degrees. Snow creep was assessed to occur along particular sections of the line route, but not its entirety; approximately 25% of the line could be subject to snow creep loadings.

Snow depth and snow creep loads associated with 1-in-100 year return period were used in the design. The maximum snow depth along the NTL route was four meters (≈ 13 feet). This maximum snow depth was of particular importance as snow depths in most areas of British Columbia can reach upward of 7 to 8 meters (23 to 26 feet). Because the snow depth was limited to 4 meters and could be limited to the region of the tower below the body and body extensions, the VBM team designed "snow legs." A snow leg was an alternate steel leg for each tower that was designed to resist the snow creep loads. The snow legs were designed to be interchangeable with the standard legs. Using snow legs in locations susceptible to snow creep and glide rather than alternate tower designs limited the number of tower designs, providing an efficient way to account for snow creep.

Along with snow creep, VBM accounted for snow avalanches in the structure design. Snow avalanches consist of a volume of snow that moves downslope under the effect of gravity. In addition to snow, avalanches may contain rock, broken trees, soil or ice. Considerations for the NTL route were limited to very specific locations along the route and varied from small powder avalanches to large flowing avalanches containing debris. The 1-in-100 year pressures from the avalanches ranged from 2,000 pascals to 120,000 pascals (42 to 2,500 psf). Because of the terrain and route, avoiding all avalanche paths was not possible. To the extent possible, VBM spotted structures outside the paths of avalanche flows. In instances where structures were in direct paths of potential large, flowing avalanches, VBM designed large, protective berms (Figure 1) at least 5 meters tall as it was not economical to design location-specific structures to withstand the potential avalanche loads. In areas where structures were not in direct paths of flowing avalanches, but still exposed to avalanches, structures designs took the avalanche loads into consideration.

As with snow creep, the VBM team sought a solution that did not require the design of location-specific structures. First, in areas of snow avalanches, strain or dead-end towers were installed for their large, transverse load capacities able to withstand residual avalanche loading. Second, a break-away hardware assembly system was designed to accommodate the avalanche loads. This break-away hardware system was designed with a weak point that would fail under specific loadings. When a load caused by an avalanche becomes excessive, the assembly will fail, dropping the conductor from the tower, thus removing the wire load. Further propagation of the released conductor load would be contained by the adjacent strain or dead-end towers. This break-away hardware system allowed the VBM team to

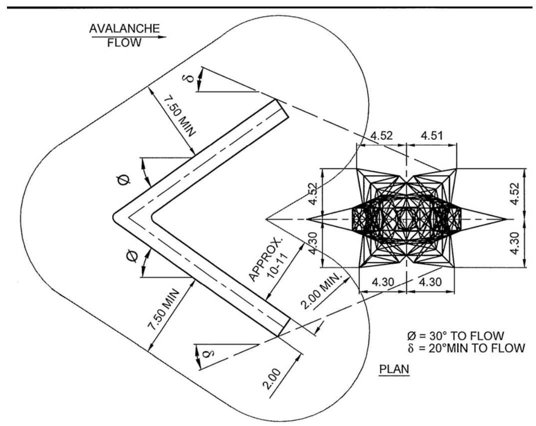

Figure 1. Earth-splitting Berm

forego special structure designs and provided a cost-effective means to address snow avalanche load cases.

Lastly, differential ice loads were considered in the design of all suspension towers. BC Hydro deemed a 50-year return period sufficient for this condition based on the type of structures for which it would be applied. These differential ice thicknesses were based on statistical data from the meteorological study. As with the reliability loads, the differential ice thicknesses were specific to the four load zones. The unequal glaze ice for zones C1, C2 and C3 was 6 mm and D1 was 12.5 mm. The differential ice loads were applied to any number of wires at a time, with the ahead spans subject to a radial ice glaze and the back spans bare.

Construction & Maintenance

The VBM team also addressed construction and maintenance loads in the development of the tower load cases. Due to the challenging terrain and limited access along the line route, all tower types were designed for conductor installation (snub) loads. This included designing for one, two or three phases snubbed at one time to provide flexibility during construction. Designing strain or dead-end towers for snub loads was easily attainable due to their other loading conditions such as one-side only loading or broken wire loading; however designing suspension towers for this level of flexibility can result in construction loads controlling the tower design. However, because of the loading on the suspension towers from the 1-in-100 year reliability and security loads, designing suspension towers for snub loads was easily accomplished without increasing the tower weight.

BC Hydro maintenance load requirements included consideration of touch-and-go helicopter loading on all towers of the tower family. To account for the loading on the tower due to the helicopter, point loads were applied at the contact points under anticipated weather conditions for maintenance activities. Additionally, the top of the bridge required extra bracing to minimize the chance of a lineman from falling through the bridge when exiting the helicopter. The extra bracing was installed in the designated helicopter landing zone only and dense enough so that no single opening on the top of the bridge was larger than 500mm in diameter.

TOWER FAMILY DEVELOPMENT

The NTL is a single-circuit, 287-kV AC transmission line consisting of approximately 1,100 structures. Developing a structure family for this scope of project encompasses a variety of design parameters including, but not limited to, line routing, right-of-way, electrical requirements, maintenance requirements, foundations, construction methods, cost and project schedule. The influence of these parameters varies when developing a project-specific structure family versus a standard family for an entire transmission system.

The following sections address each key factor in project-specific tower family development for the NTL.

General

BC Hydro's FFS had very specific requirements to determine whether the structures would be lattice steel towers, tubular steel poles or wood. The requirements were for all facets of structure design: design, testing and manufacturing parameters. For lattice towers specifically, the project FFS specified a horizontal configuration on either self-supporting or guyed structures. NTL did not require conductor shielding (except outside the substations), but a single, compact peak was used to support an optical ground wire cable for communication. While BC Hydro had explicit requirements for the design of the structures, it allowed enough flexibility for VBM to deliver an optimal structure family.

Strength Factors

Load development for the NTL was consistent with the system design approach described by CAN/CSA-C22.3 No. 60826 (2010). Rather than using load factors and computing ultimate loads as done with deterministic design, VBM applied working loads to the structure and a strength reduction factor to the particular component's rated strength. This design methodology provides reliable structure designs, but a reliable transmission line design. The NTL strength reduction factors for various components are listed in Table 2.

Table 2. Strength Reduction Factors

Component	Reliability	Construction & Maintenance
Structure – Tangent	0.90	0.50
Structure – Angle	0.80	0.50
Structure – Dead-End	0.75	0.50
Structure – Strain	0.75	0.50
Insulator Assemblies	0.50	0.50
Conductor	0.75	0.50
Guy Insulators	0.50	0.50
Foundations and Anchors	0.60	0.50

As shown in Table 2, the strength reduction factor applied to tangent towers is less conservative than that applied to angle, strain or dead-end towers. This creates a desired sequence of failure in which tangent towers would theoretically fail before the other tower types. This same philosophy was applied to each component of the transmission line creating a design sequence of failure among transmission components.

Conductor

For the NTL, the conductor was 2-bundle 1,590 kcmil 45/7 ACSR Lapwing, which was selected based on a conductor analysis study that showed the 1,590 kcmil provided the best long-term cost and operation benefits to the project. As the conductor size was fixed for the project, no optimization was necessary. However, if a conductor size has not been specified, iterations can be performed to pinpoint the conductor to optimize the entire construction of the project.

Electrical

Electrical considerations for structure designs are critical because they govern the dimensions of the structure. Phase-to-phase, phase-to-ground, and climbing and working clearances are all considered. The evaluation of the electrical clearances is closely tied to the structure configuration and hardware assembly selection. When evaluating the structure phase spacing, it is imperative that the phase spacing of all structures in the family be evaluated, not just the individual structure.

BC Hydro's FFS provided the minimum requirements for phase-to-phase, structure-to-phase, and climbing and working clearances. The tower configuration and phase spacing was largely driven by the climbing and working clearances required for live-line work resulting in a window larger than what would have been necessary to meet the structure-to-phase or phase-to-phase clearance requirements. Phase-to-phase spacing at the structure was consistent across all the tower types and of sufficient spacing to ensure the phase-to-phase clearance requirements were met along the line. As previously noted, each load zone had specific ice and wind and wind conditions for evaluating structure-to-phase clearances. With the exception of load zone C3, the conditions were nearly identical and the difference in insulator was negligible, thus the light and heavy towers were designed for the same insulator swing conditions. Load zone C3 was specific to a particular river crossing on the project and only affected a few structures. Rather than design the heavy towers for the swing conditions of the C3 load zone and unnecessarily increase the structure width, VBM used location-specific tubular steel poles.

Alignment

Assessing the terrain, access and route obstacles is one the first steps in developing a structure family. VBM used this assessment to establish the preliminary structure locations along the NTL route. This effort provided a first attempt at determining wind and weight spans achievable in the given terrain as well as the line angles encountered. Preliminary spotting combined or eliminated any unnecessary or sparsely used structures and allowed for optimization of structure use via comparison of structure overuse and the cost of developing and testing a new structure type. For instance, rather than having a long span tangent structure, a symmetrical light angle structure could double as both a light angle and long span tangent structure.

The preliminary spotting of the NTL route yielded a myriad of different structure types. Through front-end optimization, the structure family was reduced to five structure types, each with a light and heavy option for a total of 10 tower designs. During detailed design, VBM further reduced the towers to seven based on an economic assessment of constructability and material costs. The structure types for the NTL project are listed in Table 3.

Table 3. Structure Types

Structure Type	Line Angle
Tangent	0-3 Deg
Running Angle	0-10 Deg
Strain	0-25 Deg
Dead-End	0-25 Deg
Dead-End	25-65 Deg

There were locations along the NTL route that required specific structure designs to accommodate either excessively long spans or an excessively tall structure. Rather than design the typical tangent for these specific locations or even design a long span tangent, the running angle structures were designed symmetrically so it could also be used as a long span tangent. In the locations that required excessively tall structures, VBM designed special tubular steel poles. The strain structure was developed to account for the mountainous terrain and mitigate uplift without utilizing a dead-end structure. Lastly, the preliminary alignment did not have line angles greater than 60 degrees, therefore VBM chose to design for only the necessary line angles.

Construction and Schedule

Developing a structure family requires understanding the proposed construction methods. The remoteness of the project and limited access made it necessary to limit the size of construction equipment on the right-of-way (ROW). In some instances, parts of the line were only accessible via helicopter. Additionally, the NTL project had a very aggressive schedule; project award was in August 2011 and the line was energized in the summer of 2014. The combination of challenging terrain and minimal access, coupled with the aggressive project schedule, lead the VBM team to the use of helicopter construction to erect the lattice towers.

It was critical to limit the number of lifts to erect the tower, otherwise construction costs would increase significantly. The loading requirements were such that self-supporting tangent towers were too heavy for the helicopter to pick in a single lift; however, guyed towers could accommodate a single lift. This resulted in significant cost savings and schedule benefits that drove the structure type toward guyed lattice structures (Figure 2). Using guyed towers offered the additional benefits of faster, easier assembly as they required less construction equipment in comparison to self-supporting structures. This was particularly advantageous because the limited access and rugged terrain was not ideal for large equipment.

Figure 2. The Northwest Transmission Line

Foundations

Because of the remoteness and limited access of the NTL route, the ability to gather sub-surface information was extremely limited. Subsurface data was not available at every structure location and it was not complete during the design and procurement of foundation materials. The ability to use cast-in-place concrete was also very limited. Foundations needed to be designed for the various soil and rock conditions encountered, but also easily interchangeable in instances where rock or soil was encountered and not expected. One of the benefits of lattice towers is the flexibility to connect to a wide variety of foundation types without changes to the foundation connection. The guyed tower used a small pin connection at the center mast. The same pin and connection plates were used for the rock or soil grillage foundations. For drilled shaft foundations, the pin was replaced with a longer threaded bar embedded into the concrete, which was the same threaded bar used for the soil or rock guy anchors. Self-supporting towers used the same stub regardless of the foundation type: soil grillage, rock grillage or drilled shaft foundation. The level of flexibility, regardless of tower type, made it easier to accommodate foundation changes on-site.

Although guyed towers required five foundations instead of four, the foundations were much smaller, making them easier to transport. That allowed for quicker installation and smaller construction equipment which was particularly advantageous from construction, cost and schedule aspects.