Geotechnical Challenges in the Construction of the Niagara Wind Farm, Niagara Region, Ontario, Canada

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ABSTRACT
The Niagara Region Wind Energy Project consists of 77 wind energy turbines with a total capacity of 230 MWs, located in the Niagara Region of Ontario, Canada. The project also included the construction of 50 kilometres of overhead transmission lines stretching across the Niagara Region. This project was one of the largest wind farms constructed in Ontario. The Niagara Region wind farm was constructed within the Niagara Escarpment- a large bedrock escarpment, that is protected for its environmental significance, and natural beauty. The geology in the area of the project ranged from shallow bedrock associated with the escarpment feature, to deep soft lacustrine clays associated with Lake Erie clay plains. The wind turbines use 3 MW nacelles, supported on 124 m high towers. This wind farm was constructed in a geotechnically challenging, and environmentally significant area of southern Ontario. This paper provides a brief summary of the project, and describes the geotechnical issues associated with the challenging geology and a demanding construction schedule.

RÉSUMÉ
Le projet du parc éolien de la région de Niagara comporte 77 éoliennes d'une capacité totale de 230 MW et est situé dans la région de Niagara, en Ontario (Canada). Le projet a également inclus la construction de 50 km de lignes aériennes de transport d'électricité traversant la région de Niagara. Il s'agit de l'un des plus grands projets de parcs éoliens construits en Ontario. Le parc éolien a été aménagé dans l'escarpement du Niagara, une longue paroi rocheuse escarpée qui bénéficie du statut de zone protégée en raison de son importance environnementale et de sa beauté naturelle. La géologie dans la zone du projet variait entre un socle rocheux à faible profondeur dans la zone de l'escarpement et une argile lacustre molle associée aux plaines argileuses du lac Érié. Les éoliennes utilisent des nacelles de 3 MW reposant sur des tours de 124 m de hauteur. Le parc éolien a été construit dans une zone du sud de l'Ontario caractérisée par son importance écologique et par de nombreux défis sur le plan géotechnique. Le présent article contient un résumé du projet et une description des enjeux géotechniques relatifs à la géologie complexe et à l'échéancier de construction serré.

1 INTRODUCTION

The Niagara Wind Farm consists of 77 wind turbines, 124 m in tower height, and 50 m long turbine blades. The wind farm is currently operational, and generates 230 MW of electricity to the surrounding Niagara community in Southern Ontario. The turbines utilize the largest wind generators in Ontario, at 3 MW each. The project had a relatively short construction period of one year, and was completed in 2016. The wind farm is located about 50 km west of Niagara Falls, in rural agricultural lands.

1.1 Regional Geology

The Niagara Region is known for its natural beauty and excellent wine-growing climate, in part due to the presence of a large bedrock formation known as the Niagara Escarpment. This bedrock escarpment is associated with the Lockport Formation, and consists of dolomitic limestone, with large outcrops in Niagara, and extends some 1000 km, circling around Lake Michigan and Lake Huron.

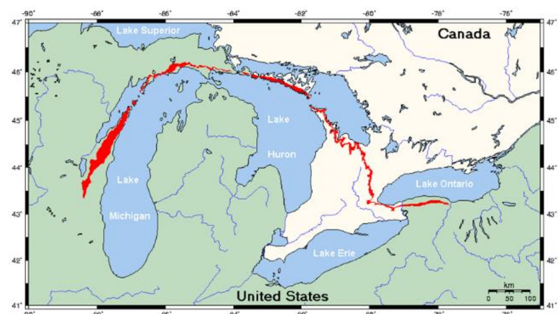

Figure 1- Geographic extent of Niagara Escarpment

The Formation extends across Lake Ontario and creates the world famous Niagara Falls. Figure 1 shows the geographic extent of the escarpment. Figure 2 shows the typical features of the Niagara Escarpment dolomitic limestone outcrops.

Figure 2- Typical image of Niagara Escarpment, showing dolomitic limestone outcrop.

2 NIAGARA WIND FARM DESCRIPTION

2.1 Niagara Wind Farm Description

The project area covered approximately 700 square kilometers stretching from Lake Ontario to Lake Erie. The wind turbines were located in rural agricultural fields, and a 50 km transmission line was constructed from the project across the Niagara Escarpment to the northern reach of the project in Grimsby, Ontario. The project consisted of 77 wind turbines, generating 230 MW of electricity.

2.2 Geotechnical Investigations

Preliminary geotechnical investigations commenced in 2014. The initial geotechnical investigation consisted of 89 boreholes, 25 monitoring wells, multichannel analysis of surface waves (MASW) testing, and bedrock coring at 21 locations.

A second geotechnical investigation was completed in 2015, and consisted of 14 boreholes, 9 CPTs, auger probes, and additional bedrock coring.

GHD Limited (GHD) completed an extensive geotechnical investigation in 2015, focusing on the 50 km of transmission lines. These boreholes were installed to investigate founding conditions for the overhead transmission line poles, and the total geotechnical investigation for this work consisted of 90 boreholes, 15 bedrock cores, soil sampling for thermal resistivity, and boreholes for localized underground transmission line portions.

GHD also completed additional geotechnical investigations for the turbine foundations to be supported on deep foundations, consisting of 9 deep boreholes and bedrock cores.

Based on these investigations, the geology was found to vary significantly across the project site. The deposits in some areas consisted of competent glacial till soils, and shallow bedrock. Closer to Lake Erie, the soils changed to deep soft clay deposits, with deep bedrock, in excess of 50 m below ground in some areas.

2.3 Wind Turbine Foundations

To accommodate the varied geologic conditions encountered at the site, two types of foundations were designed for the wind turbine foundations. Forty-four of the foundations consisted of conventional shallow mass-concrete foundations. Due to the size of the towers, and the low bearing capacity determined for the shallow soils, the mass-concrete foundations consisted of 1000 cubic metres of concrete, constructed approximately 3 m below grade.

The remaining 33 foundations were supported on steel pipe pile foundations that extended some 40 to 50 m down to the bedrock.

GHD was retained to verify the bearing capacity of the wind turbine foundations subgrades. In some cases, the design of the foundations had to be changed based on our subgrade inspections. Assumptions made based on the boreholes were found to be incorrect once the actual foundation excavations were exposed. Figures 3 and 4 show the visual difference between a competent foundation subgrade, and a soft clay subgrade. Where these soft clay subgrade soils were encountered, the design was changed to allow for the construction of an engineered fill pad, or a deep pile foundation.

Figure 3- Competent Foundation Subgrade.

Figure 4- Soft Clay subgrade, showing desiccation cracking.

3 OVERHEAD TRANSMISSION LINE

The transmission line extended along a 50 km length to the north of the wind turbine locations, crossing the Niagara

Escarpment, and ending to the north in the town of Grimsby, Ontario. The transmission line consisted of approximately 100 poles, approximately 30 to 35 m high. The transmission line extended across extremely variable geologic terrain, again ranging from competent till soils, to deep deposits of soft clay, and bedrock depths ranging from at the ground surface (outcrops) to 30 to 40 m deep.

The geotechnical investigation was completed just before construction, and consisted of 90 boreholes and auger probes, 15 bedrock cores, and geotechnical evaluation of soil thermal resistivity, and limited underground trenching and underpasses.

3.1 Passive Bedrock Anchor Design

The transmission pole foundations generally consisted of conventional augered concrete footings, roughly 2.4 m in diameter, and 6 m deep. Due to the variable soil conditions, some of the lighter pole foundations were designed utilizing skin friction in the clay soils. Where bedrock was available within reasonable depths, the poles were designed using passive rock anchors for additional uplift and overturning resistance. Figure 5 shows the typical rock-anchored pole design.

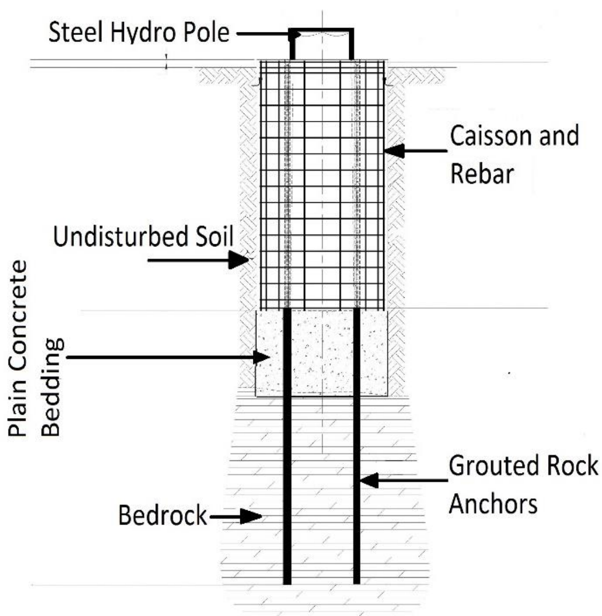

Figure 5- Typical Passive Rock-Anchored Transmission Line Pole Foundation

Based on the results of the geotechnical investigation, 72 of the pole foundations required rock anchoring. These footings ranged in diameter from 2.4 to 4.0 m, and utilized from 6 to 12 anchors per foundation, for a total of 474 rock anchors. These anchors were not designed to be post-tensioned, and strictly relied on the frictional resistance between the grout to rock bond.

3.2 Passive Rock Anchor Testing Program

A major challenge in this design was to develop a testing program to verify the grout to rock bond strength to use in the design. A typical value of $1/30^{th}$ of the design grout strength (30 MPa) was used as per standard practice, and a design grout to rock bond strength of 1 MPa was considered reasonable. This was further reduced with a factor of safety of 2.0 for limit states design.

GHD was challenged to develop a field testing program to verify this bond strength, and to ensure that the installed anchors were going to function as designed. The difficulty with the design as shown on Figure 5, was that the rock anchors were grouted into the concrete foundation, and there was no way to test a finished production anchor to verify the bond strength. The solution to this problem was to install sacrificial anchors at selected locations over the area where the 72 rock-anchored foundations were planned to be constructed. This testing program was carried out on the heels of a contractor who wanted to keep installing production anchors without results, and felt the testing program was holding up his construction.

The design of the testing program eventually utilized installation of grouted anchors (rebar) to the same depth for the production anchors. Difficulties were found during the grouting process, due to the fractures and solution cavities in the dolomitic limestone bedrock within the Lockport formation, and the presence of groundwater in the bedrock, leading to the complete loss of conventional cementitious grout at some of the test locations. In some locations, groundwater flow was significant, and artesian conditions were also present.

The solution to these grout loss situations was to utilize a specialized thixotropic grout. Once it could be verified that the grout stayed within the anchored zone, the rock anchor testing program was conducted.

Following a period of hardening of the grout, usually 7 days (a long time for the contractor to wait), the test anchor program was started.

3.3 Rock Anchor Test Program Results

The load testing configuration consisted of a conventional jack pulling on the anchors uses a reaction beam, as shown on Figure 6.

Figure 6- Sacrificial Rock Anchor Pull Test Configuration

There were several issues and limitations that required confirmation prior to the commencement of testing. Due to the presence of solution cavities and difficult groundwater conditions, the initial inspection consisted of verifying the grout level in the test anchor several days after installation. If there was a loss of grout, the grout could be topped up, but in some cases, the test anchor had to be abandoned, and a new anchor installed using thixotropic grout. The rock anchor could not be grouted in the soil overburden, as the purpose of the test was to test the grout to rock bond strength only. The test anchors were sleeved off in the overburden, to prevent hole collapse, and to allow verification of grout levels after installation. The sleeve also eliminated frictional contributions from the soil, so that we could isolate the bond strength in the bedrock zone. The exact length of the grouted zone of the anchor, and the unbonded length, was also needed, to verify the grout to rock bond strength was determined over the correct length.

The pull-testing was performed following using the guidelines provided in the Post-Tensioning Institute's document "Recommendations for Pre-stressed Rock and Soil Anchors". As these anchors were not pre-stressed, or post-tensioned, modifications to the procedures for calculating the results and evaluation of the measured grout to rock bond strength were required to properly assess the results of the tests. A typical result for a successful rock anchor test is shown in Figure 7.

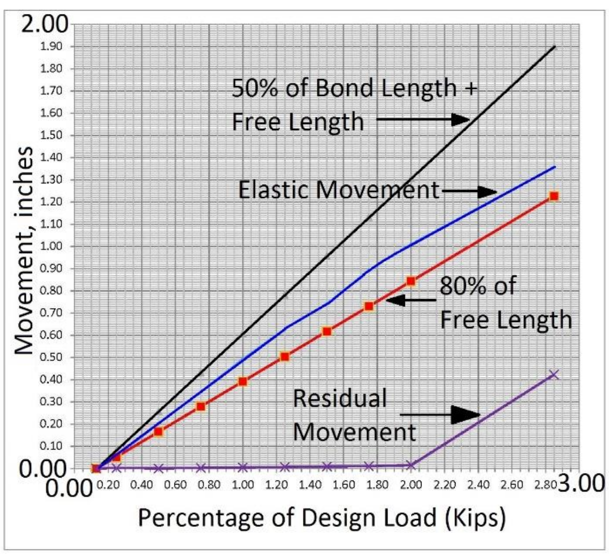

Figure 7- Plot of Successful Rock Anchor Test Result

3.4 Test Program Conclusions

Twenty four anchors were tested, in two rounds of testing. Based on the working loads supplied by the structural engineer, the test anchors were typically tested to at least two times their working load. Nine load cycles were used to load and unload the anchor, and a creep test was performed for 30 minutes at two times the production load. For the performance criteria, the following criteria was considered acceptable:

- Total displacement of less than 13 mm at 2.5 times the working load
- Creep of less than 1.0 mm after 10 minutes, at 2 times the working load

After some complete test anchor failures, typically due to loss of grout, GHD managed to perform a series of successful sacrificial anchor tests, which satisfied all parties and the above design criteria, and allowed us to approve the installation of the production anchors.

Due to the passive nature of the foundation rock anchor design, none of the production anchor capacities could be verified by proof testing. For this reason, GHD had to be satisfied with the sacrificial anchor tests, and our quality control inspections during production anchor installation.

4 CONCLUSION

The Niagara Wind Farm project was a challenging wind farm construction project due to extremely varied geological conditions present across the Niagara Region and Niagara Escarpment. The fractured and porous nature of the Dolomitic limestone deposits of the Lockport Formation made for difficult installation of rock anchors for the overhead transmission line. The pace of the construction project dictated completion of this large project in essentially one year, and this required innovative solutions for the design and construction issues associated with the wind turbine foundations, and overhead transmission line rock-anchored foundations.

At the completion of the project, the wind farm was installed on time and is currently operational, generating 230 MW of clean renewable energy for the surrounding Niagara Region.

5 REFERENCES

Post-Tensioning Institute, 2016. *Recommendations for Prestressed Rock and Soil Anchors*, 5th ed., Post-Tensioning Institute, Phoenix, Arizona, USA.