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Slope Stability Evaluation and Monitoring of a Sandy Bluff on the Shoreline of Lake Erie

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ABSTRACT
In 2019, a geotechnical investigation and slope stability evaluation for an existing wind turbine site on the northern shoreline of Lake Erie recognized the potential for instability under adverse environmental factors over time. The site features a 24-m high sandy bluff and evidence of past shoreline retrogression is apparent in satellite imagery and field observations. The investigation was therefore followed by real-time geotechnical instrumentation and monitoring with an automated alarm system to provide on-going monitoring of the slope and to provide early warning for ground movements that could potentially affect the nearby wind turbine. Changes in water levels, seepage, rainfall events and soil suction are all expected to influence the stability of the existing slope. Monitoring data from the installed instrumentation combined with periodic field evaluations is anticipated to permit further model refinement and potentially aid in identifying precursory environmental factors leading to further erosion and instability.

RÉSUMÉ
En 2019, une investigation géotechnique et une évaluation de stabilité de pente ont identifié le potentiel pour instabilité en réponse aux facteurs environnementaux à un site d'éolienne, située au littoral nord du lac Érié. Le site fait figure d'une falaise sablonneuse de 24 m en hauteur et preuves de rétrogression littorale sont apparentes en imagerie par satellite et observations fait au site. L'investigation était suivie donc par un programme de surveillance avec des instruments géotechniques et un système d'alarme automatique pour surveiller la falaise et obtenir des alertes de mouvements de sol qui pourraient affecter l'éolienne. Changements au niveau d'eau, suintement, précipitations et succion de sol sont tous anticipés à influencer la stabilité de la falaise. Les données de surveillance obtenues par les instruments installés au site et des évaluations visuelles périodiques sont anticipés à permettre le raffinement du model et à potentiellement aider avec l'identification des facteurs environnementaux préliminaires menant à plus d'érosion et instabilité.

1 INTRODUCTION

Signs of ground instability can quickly be identified on satellite imagery for the north shoreline of Lake Erie in the Long Point region of Southern Ontario. Also visible is suspended sediment in the nearshore waters and vegetation debris along the shore.

This shoreline erosion has had a notable impact on existing infrastructure in the general area. Land loss and erosion have resulted in road closures to ensure the safety of the public. Houses constructed on shoreline properties are increasingly threatened as the shoreline and the corresponding erosion hazard zone retrogress. The region also boasts several wind farms, established along the coast to take advantage of the windy conditions off Lake Erie. However, the shoreline retrogression affecting other infrastructure in the region is also threatening to have potential adverse impacts on these wind farms.

In 2019, a geotechnical investigation and slope stability evaluation were conducted for a shoreline property featuring a wind turbine and a steep 24-m high bluff. The wind turbine had been constructed more than a decade ago and earlier shoreline erosion studies were originally used to determine the offset from the historical shoreline. By May 2019, the 80-m tall turbine was only 60 m from the edge of the bluff (see Figure 1), leading to concerns regarding its continued safe operation.

The recent investigation included the advancement of geotechnical boreholes and completion of a laboratory testing program to characterize the site subsoils and stratigraphy. Slope stability modelling was performed to estimate the site-specific erosion hazard zone to inform when intervening actions might have to be taken to protect the wind turbine. Geotechnical instrumentation was then installed in the boreholes and a monitoring program was commenced to provide automated alerts in the event of established threshold exceedances. The monitoring program was commenced in July 2019 and is contemplated to continue until October 2021.

Figure 1. Wind turbines can be seen along the coast of Lake Erie, with the top of the bluff visible nearby.

2 SITE INVESTIGATION

A site investigation was launched to gather the necessary subsurface information to evaluate the stability of the bluff and identify the likely mechanism(s) of the observed instabilities. Objectives included proposing an erosion allowance from the top of the existing slope to the base of the turbine, and to recommend practical and economical actions that could be taken when the proposed erosion allowance was eventually exhausted. The investigation included a site reconnaissance visit and a desktop study, advancing two geotechnical boreholes, completing a laboratory program, and installing geotechnical instrumentation on site.

2.1 Site Reconnaissance and Desktop Study

A site reconnaissance visit was conducted in May 2019, when slide scarps along the face of the bluff and destroyed trees were observed at the base. Sloughing of material was also observed during the site visit, suggesting continued, progressive and on-going failure of the bluffs over time. Wave erosion was evidenced by the considerable amount of disturbed sediment visibly suspended in the near-shore waters.

The cliff-side was examined from a safe distance during this site reconnaissance visit. A surficial layer of sand was observed overlying an apparent siltier unit, visually estimated at approximately 6-8 m below ground surface (mbgs). Seepage was visible at the interface between the two units, likely from groundwater perched on top of the less permeable (assumed) silty unit. A conical slide scarp was observed at the bluff face, as shown in Figure 2.

The ground surface across the site was measured at an approximate elevation of 198 masl during semi-annual topographic surveys completed by the Owner. Fisheries and Oceans Canada data indicates Lake Erie's long-term average water level is about 174 masl. The height of the existing bluff was thus calculated approximately as 24 m.

A review of publicly available satellite imagery taken between September 2005 and July 2018 revealed the occurrence of several landslides at or near the site. The landslide debris were not present in subsequent images, possibly having been removed by a combination of wave action and possible long-shore drift.

Additional sources that were consulted included the Ontario Geological Survey (OGS) datasets for surficial geology and physiography, and the Ontario Ministry of Northern Development and Mines geotechnical borehole database. The OGS identified the site as belonging to the Norfolk Sand Plain physiographic region. Historic borehole records from the area suggest the sand plain deposits overlie clay to silt-textured till deposits. The Norfolk Sand Plain is described as comprising deltaic sand deposits and silts that were deposited by glacial Lake Whittlesey and Warren, and other glaciolacustrine events. The sand plain deposits are described as generally being fine- to medium-grained and are reported to span up to 27 m in thickness in some areas, generally overlying moraine deposits. The sand has been found to be massive within the top metre, below which laminations of fine sand, silt, heavy minerals or clay can be observed. It has been noted that wind in the area has resulted in the formation of transverse sand dunes greater than 6 m high (Barnett, 1982).

Figure 2. View of the bluff face from which seepage can be seen discharging. Limited vegetation is visible at the toe, along with downed trees.

Other historical information that was consulted included a geotechnical borehole record and subgrade inspection report for the turbine itself. The historical borehole identified a loose layer of fine sand with trace to some silt at surface, becoming compact below 3.0 mbgs. At 5.2 mbgs, a 0.3-m thick layer of dense silty sand with some clay was identified. The silty sand layer was underlain by dense to very dense silty sand, absent of clay, extending to the borehole termination depth of 12.6 mbgs.

2.2 Site Stratigraphy and Soil Characterization

Two geotechnical boreholes, designated BH19-01 and BH19-02, were advanced at the Site in July 2019. The boreholes were located approximately 42 m and 20 m from the top edge of the bluff, respectively, and roughly in line with the turbine and the bluff (see Figure 3). Split spoon soil samples were obtained and logged as the boreholes were advanced. BH19-01 and BH19-02 were terminated at depths of 31.1 (el. 167.5 masl) and 35.7 mbgs (el. 162.5 masl), respectively.

A sand deposit was identified at surface and extending to 12.5 mbgs and 14.0 mbgs in BH19-01 and BH19-02, respectively. The sand was encountered in a very loose to loose conditions above 3 to 4 mbgs, below which it became compact. The sand was subsequently encountered in a dense to very dense condition below 7.6 to 9.1 mbgs. A varved textured was noted occasionally within this deposit.

Underlying the upper sand deposit, a sandy silt to silty sand horizon was identified at 12.5 to 14.7 mbgs. The sandy silt to silty sand deposit was distinguished from the overlying sand deposit by a relative increase in silt. This deposit was generally encountered in a compact to very dense condition except for a loose interval at 21.3 mbgs. Below 25.9 mbgs and 22.9 mbgs in BH19-01 and BH19-02, respectively, the deposit returned to a compact to very dense condition. A varved texture was consistently noted throughout this deposit.

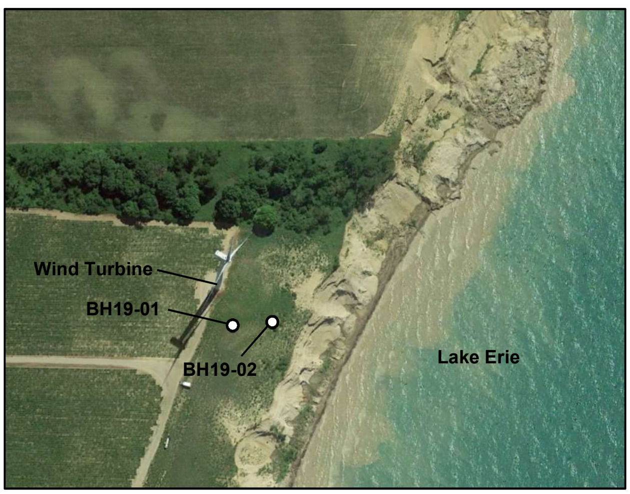

Figure 3. The wind turbine and the boreholes are shown at the study site near the coast of Lake Erie, with recent instabilities visible along the shoreline bluff.

Within the lower sandy silt to silty sand deposit, thin seams of silty clay to clay were observed intermittently. These seams generally ranged from about 0.3 to 0.7 m in thickness, except for one which was approximately 1.8 m thick. Although SPT ‘N’ values recorded in these sublayers corresponded to a stiff to hard consistency, pocket penetrometer readings for this material corresponded to undrained shear strengths of about 25 kPa (soft to firm). Atterberg Limits tests were performed on two samples of this material and indicated it could be classified as a low plasticity clay (CL). The results of the Atterberg Limits tests are summarized in Table 1 and depicted graphically in Figure 4. Unfortunately, field vane tests and Shelby Tube samples were not obtained for this material.

Table 1. Atterberg Limits results from clay seam samples.

Sample ID	MC	PL	LL	PI
BH19-02, SS17 (18.3 – 18.9 mbgs)	25.1	12	20	8
BH19-02, SS25 (30.5 – 31.1 mbgs)	29.0	16	30	14

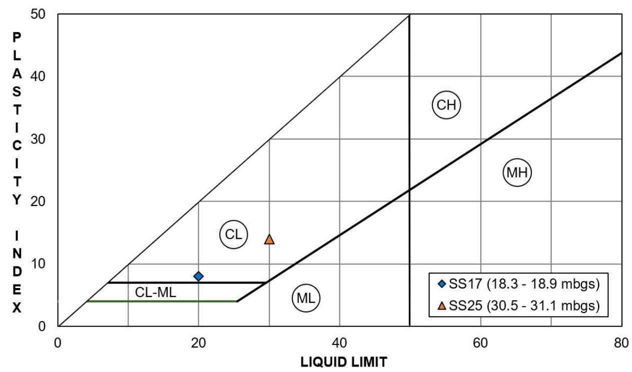

Figure 4. Atterberg Limits results for selected soil specimens obtained during the drilling investigation.

Gradation analyses by sieve and hydrometer were completed to confirm soil descriptions and further characterize the observed subsoils. The gradation results are summarized in Table 2 and depicted graphically in Figure 5.

Table 2. Gradation results from selected samples.

Sample ID	Gravel	Sand	Silt	Clay
BH19-01, SS4 (2.3 – 2.9 mbgs)	0	77	(23)	
BH19-02, SS9 (6.1 – 6.7 mbgs)	0	90	(10)	
BH19-02, SS11 (9.1 – 9.8 mbgs)	0	70	(30)	
BH19-01, SS15 (15.2 – 15.8 mbgs)	0	1	35	64
BH19-01, SS22A (25.9 – 26.2 mbgs)	0	20	63	17

Short-term groundwater conditions were observed during advancement and after completion of the boreholes. Groundwater was first observed at a depth of 17.1 and 17.4 mbgs (el. 181.5 and 180.8 masl) in BH19-01 and BH19-02, respectively. This water level corresponded well to the moisture content profile that was constructed for the obtained soil samples.

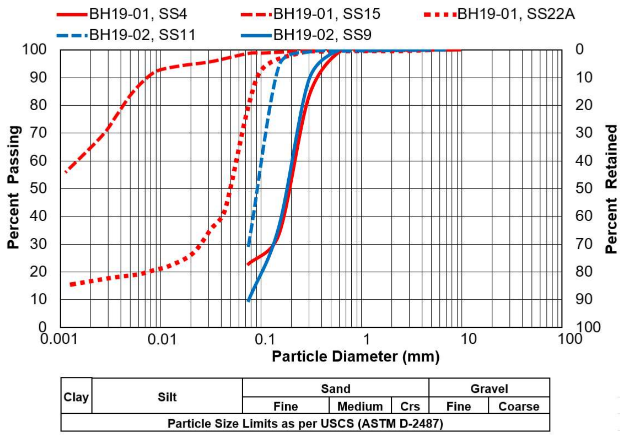

Figure 5. Grain size distribution curves for selected soil specimens obtained during the drilling investigation.

2.3 Geotechnical Instrumentation

Within the geotechnical boreholes advanced on Site in July 2019, geotechnical instrumentation was installed to allow for longer-term monitoring.

Two vibrating wire piezometers (VWP) were installed in BH19-01 at depths of 18.12 mbgs and 28.79 mbgs, respectively. The VWP were installed using the fully grouted method. These installation depths were selected to be below the observed water level at the time of drilling (assumed to be at a temporal low based on the season), and to explore the possibility of a porewater pressure differential with depth. The existence of clay seams introduced the possibility that different depth intervals could be hydraulically isolated from one another. The intent was to gain a better understanding of these possible pressure variations and explore their possible impact on the site model.

A 70-mm OD inclinometer casing was installed in BH19-02 to a depth of 34.96 mbgs. The casing was grouted in place then allowed to set. A string of seventeen in-place inclinometer (IPI) sensors were then installed at 2-m depth intervals from 1.0 mbgs to 33.0 mbgs. The inclinometer was installed to permit monitoring of lateral ground displacements. It was assumed the slope would not exhibit any substantial movement below the toe, based on the assumed slope failure mechanism (discussed in Section 3).

After installation, the IPI and VWP were both routed to a datalogger at surface. The datalogger was installed on a fencepole with a solar panel and antenna for remote uplink. A program was written to obtain hourly readings from the installed instruments and provide e-mailed alerts if the data exceeded certain thresholds. While construction control applications often involve thresholds established to ensure the safety of workers, the thresholds for this project were established to provide early warning of sudden changes in the site conditions that might warrant closer inspection. For the VWP, a variation of more than 0.5 m in the computed water level was adopted as the initial alert threshold. For the inclinometer, a cumulative displacement of more than 10 mm was adopted as the initial alert threshold.

3 PRELIMINARY STABILITY MODELLING

The objectives of the slope stability component of this investigation were to identify the probable trigger(s) and mechanism(s) of the observed instability, to provide an estimate of the top of stable slope for the existing slope geometry, and to provide broad recommendations for possible slope rehabilitation measures.

3.1 Constructing the Preliminary Site Model

A preliminary model of the site was constructed in the Slope/W module of GeoStudio (by GeoSlope). The existing ground surface was reproduced using the most recent bi-annual survey of the site topography by the owner. Unfortunately, the topographic survey did not include the bluff face, so the geometry of the bluff was approximated using Google Earth's Digital Elevation Model (DEM) for the site.

The subsurface stratigraphy was drawn using the borehole data from the recent investigation, as well as the historic borehole log from when the turbine was constructed. The stratigraphy between borehole locations was interpolated in consideration of the depositional environment discussed previously in Section 2.2. The soils were differentiated into sublayers broadly defined by the relative density / consistency of the soil, as indicated by the SPT 'N' values obtained during drilling. A piezometric surface was drawn below ground using the VWP data. The water level of Lake Erie was drawn based on the average annual water level for 2018, as reported by Fisheries and Oceans Canada (2019). The lakebed was assumed to be about 2 m below the water surface based on Google Earth's DEM for the area near shore.

The modelled stratigraphy is shown in Figure 6. Borehole locations are identified by thick black lines, including a historic borehole where the turbine was constructed.

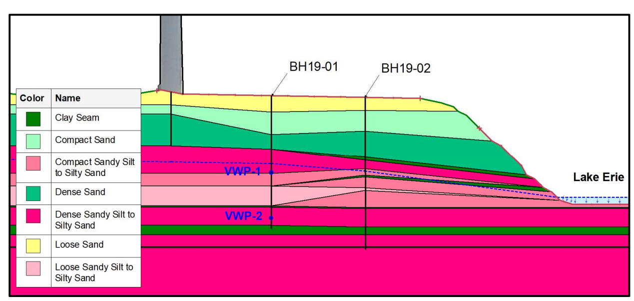

Figure 6. Modelled stratigraphy for the site.

Analytical modelling of the existing slope was undertaken using the results of the field and laboratory investigation to reproduce the observed slope instabilities. In the interest of establishing a simple base model appropriately matched to the relatively low-complexity soil data that had been obtained to date, the slope was modelled to replicate its existing state using the limit equilibrium method (LEM). Soil parameters were initially defined using reasonable values for the observed soil types, with shear strength modelled using the Mohr-Coulomb (MC) yield criterion. The assumptions central to the MC yield criterion include the material being considered isotropic and the intermediate principal stress having a negligible effect on failure (Labuz and Zang, 2012). Having observed predominantly granular, non-cohesive subsoils at the site, an isotropic condition was not considered unreasonable, albeit unlikely in a strict sense. Given the geometry of the site; a relatively long and consistent shoreline bluff; a plane strain condition was considered an appropriate fit for the site. Hence, the MC yield criterion was accepted as a satisfactory constitutive model for the site subsoils, at least for preliminary modelling. The modelled soil parameters are summarized in Table 3, below.

Table 3. Soil parameters adopted for preliminary modelling.

Soil Type	Relative Density	γ (kN/m^3)	c' (kPa)	Φ' (°)
Upper Sand	Very Loose to Loose	19.0	0	31
Lower Sand	Compact	20.0	0	33
	Dense to Very Dense	21.0	0	35
Sandy Silt to Silty Sand	Loose	20.5	0	29
	Compact	21.0	0	31
	Dense to Very Dense	21.5	0	33
Silty Clay	Soft to Firm	18.0	5	18

3.2 Mechanism(s) and Trigger(s) for Instability

Prior to running the model, several theories were put forward to possibly explain the observed instabilities at the turbine site. Possible triggers included toe erosion from wave action, rainfall events leading to temporary loss of soil suction, seepage forces at the bluff face leading to piping or loss of suction, and the introduction of the wind turbine itself leading to increased static and dynamic surcharge stresses acting on the slope. Possible mechanisms of instability included sliding along the observed clay seams, unravelling or flowing of the non-cohesive soils at the bluff face, and soil slope deformation. Modelling was used to gain a better understanding of the failure mechanism and explore the relative impacts of the above-noted factors on global stability.

The observed site processes and instabilities affecting the bluff were also compared with the descriptions of known landslide types proposed by Hungr et al. (2014). By matching the site to a well-documented landslide type, it was believed that additional information might be inferred about the slope's possible future behaviour. At this preliminary stage, it was understood that the working model would likely evolve as assumptions were confirmed or uncertainties were reduced by the introduction of monitoring data. Based on the presence of predominantly loose, dry sandy to silty soils of deltaic origin at the site, the landsliding affecting the bluff was tentatively classified as either a dry sand/silt flow or a sand/silt flowslide.

Hungr et al. (2014) describe "talus slides and sand slides on the lee slopes of sand dunes" as examples of dry flows. Movement is described as slow to rapid and flow-like, absent of excess pore-pressure. Conversely, Hungr et al. describe flowslides as very rapid to extremely rapid flows. Flowslides involve the movement of saturated granular material experiencing excess pore-pressure. Multiple retrogressive failures are also included as a typical feature of flowslides. Loess is noted by Hungr et al. as being particularly susceptible to flowslides as a result of it being unsaturated and weakly cemented. Similarities are apparent between the soil descriptions provided by Hungr et al. and the geological setting described in Section 2.1.

3.3 Modelling and Sensitivity Analyses

The stability (Factor of Safety, FOS, against shear failure) and location of the critical slip surface was computed using the preliminary model described in Section 3.1. A summary of the computed FOS for a few modelled scenarios is provided in Table 4.

Table 4. Computed FOS for the critical slip surface obtained for various modelled scenarios.

Scenario	Computed FOS
Simple Base Scenario	0.8
Soil Suction Added	1.0
Soil Suction + 1 m Rise in GWL	1.0
Soil Suction + Turbine Surcharge	1.0

For the simple base scenario described in Section 3.1, a critical zone (i.e., FOS less than unity) was identified along the bluff face. The modelled slip surface entry and exit locations were constrained to reproduce the observed instability, specifically a concave slide scarp at the bluff face roughly matching the geometry shown in Figure 7. Once satisfied with the match, the slip surface entry and exit locations were relaxed to consider a broader area. Initially, the strength of the subsoils was modelled using average parameters that were deemed reasonable based on experience. However, the initial run yielded a global FOS of 0.8, suggesting the model was conservative. The critical slip surface also extended from the top of slope to the toe. This slide scarp geometry was accepted as representative of the existing condition, although it is expected based on the observed scarp geometry that the actual slope is failing in a piecewise manner involving retrogression of the upper and lower portions semi-independent of one another.

To refine the model, the contribution of soil suction was considered in the next stage of analysis. It was reasoned that some degree of soil suction could be incorporated since the static groundwater level observed during drilling was more than 17 mbgs and moisture data for the sand deposit had ranged between 3.7% and 11.6%. Soil-water characteristic curves (SWCC) for the sand and silt units were estimated using Slope/W's built-in estimator, which considers the available grain-size data and liquid limit for a soil type. A saturated volumetric water content of 30% was assumed based on the maximum moisture content value obtained below the static groundwater level observed during drilling. Residual water content was estimated as 0% and 5% of the saturated water content for the sand and silt, respectively.

Figure 7. The shape of the bluff face can be seen in this side view photo taken during the initial site visit. Another turbine can be seen in the background.

As expected, incorporating potential soil suction into the model had a favorable effect on the computed FOS. The FOS for the critical slip surface increased to 1.0, representing a short-term pseudo-stable condition. The model output is shown below in Figure 8.

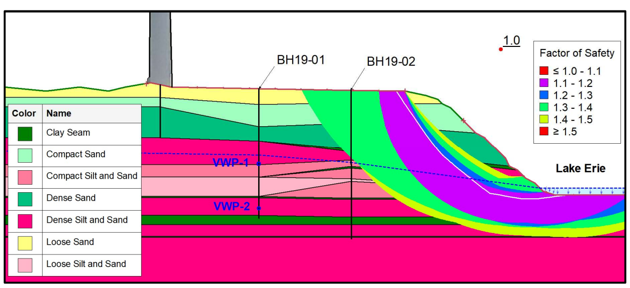

Figure 8. Preliminary slope model incorporating the contribution of soil suction.

Incorporating the contribution of soil suction in the model yielded a positive effect on the apparent global stability of the bluff that cannot be relied on over time. It is expected that a rainfall event during the wet season could temporarily reduce or eliminate potential soil suction by bringing the subsoils closer to a saturated condition. This supported the possibility that the landsliding could be triggered primarily by rainfall events.

Next, the model sensitivity to different groundwater levels was examined. A rise of 1.0 m in the groundwater level was considered first. A rise of 1.0 m in the lake water level was also considered with this rise in the groundwater level. Data for Lake Erie from Fisheries and Oceans Canada indicates the surface water level has varied by up to 1.7 m over the past 100 years, an all-time maximum variation of 1.7 min lake water levels over the past 100 years, and as much as 0.85 m in the span of one year. Hence, the modelled rise of 1.0 m was considered an extreme case. The model was run again but the computed FOS did not change. A rapid-drawdown scenario was not considered since this site setting (a Great Lake) was not expected to experience such conditions, and especially not regularly.

Toe erosion was identified as a possible contributing factor of instability prior to modelling. Since the conditions observed on site suggest the bluff is in a pseudo-stable state, the contribution of toe erosion is expected to be limited to the removal of failed material. This process would prevent the accumulation of buttressing materials, thereby prohibiting the bluff from reaching a long-term stable geometry.

The last factor considered for preliminary modelling was the surcharge load applied by the turbine. The surcharge load was modelled by applying a distributed load of 175 kPa at a depth of 2.9 m, based on information obtained from the subgrade inspection from the tower's construction. The surcharge load was not found to have any effect on the computed critical FOS; however, it did result in the long-term top of stable slope line (FOS of 1.5), moving several metres toward the tower. The top of stable slope is discussed further in Section 3.4.

3.4 Determination of Top of Stable Slope

After settling on a satisfactory preliminary model of the site, the top of stable slope was estimated by identifying the setback from the bluff crest that yielded a FOS of 1.5. This FOS was selected as an appropriate value to satisfy the top of stable slope criteria defined by the MNR since it is widely accepted as the minimum requirement for long-term stability in public infrastructure works across Ontario. Based on this approach, the top of stable slope was estimated at 18.7 m south of the turbine tower base. If a minimum FOS of 1.3 were considered, which is generally accepted for short-term stability applications such as construction, the top of stable slope could be as much as 37.2 m south of the turbine tower base. These distances do not account for the turbine foundation, understood to be 18 m in diameter, but were nevertheless adopted as the erosion hazard allowances for the purpose of this study.

3.5 Estimating the Erosion Hazard Allowance Life

The owner was advised that corrective or intervening action (i.e., stabilization of the slope or removal of the turbine) should be taken prior to the estimated erosion hazard allowances are exhausted. An estimate for the time until these distances are exhausted should ideally be provided by a coastal engineer and/or a hydrologist. However, the average rate of shoreline regression could be roughly approximated by observing the position of the shoreline over time.

Such an exercise was performed using Google Earth's historic satellite imagery for the site, by tracing the shoreline and the outline of an assumed fixed structure (a warehouse) nearby as a control to verify the geolocated imagery was not drifting. Between September 17, 2005 and July 7, 2018, the shoreline appears to have receded by 66 m. Based on this estimate, the average rate at which the shoreline appears to be receding is approximately 5 m/year. Hence, the estimated erosion hazard allowance would be exhausted in 3 to 7 years assuming the rate at which the shoreline recedes and the slope geometry that results from the continued loss of material both remain constant. Nevertheless, the methodology adopted to produce such an estimate is rudimentary at best and should not be considered a reliable nor accurate replacement for a qualified estimate by the appropriately specialized practitioner.

4 MONITORING RESULTS

The geotechnical instrumentation monitoring program was commenced in August 2019, after the field program and preliminary slope stability analysis was completed. The purpose of the monitoring program was to provide a means by which to obtain early warning of sudden slope movements or porewater pressure changes that could potentially affect the turbine. It was also expected the monitoring data could be used to further refine the preliminary slope model by revealing additional information about the slope behaviour.

The shallow and deep VWP recorded porewater pressures that correspond to a computed water level of about 16 mbgs and 19.5 mbgs, respectively. The discrepancy between the porewater pressures recorded by the two VWP is believed to be a result of hydraulic isolation between layers, caused by the clay seams identified at depth. It was noted that the porewater pressure recorded by the deep VWP corresponds to a lower computed water level than the shallow VWP. The deep VWP was installed at an elevation of about 170 masl, while the water level of Lake Erie is expected to be about 175 masl. Hence, it was concluded that a perched water table condition must be present and affecting the porewater pressure being recorded by the shallow VWP. The existence of a perched water table is not unexpected, considering the presence of clay seams identified during the drilling program and the visual observation of seepage discharging from the midslope level of the bluff face. This conclusion was further supported by an observed divergence between the two computer water levels in the spring months, when increased groundwater volumes might reasonably be expected to result in a greater column of perched water.

The porewater pressure data collected in 2020 are shown below, in Figure 9. The recorded porewater pressure did not vary substantially over time, although several small peaks can be identified throughout the spring. These spikes are more evident in the shallower VWP data (shown in blue) but are still discernible in both.

After nine months of monitoring, almost 15 mm of cumulative displacement at ground surface was recorded by the IPI (see Figure 10). The initial alert threshold of 10 mm was exceeded in March 2020, at which time the slope conditions were visually examined and subsequently the threshold was increased to 20 mm. To date, the cumulative rate of displacement at surface has averaged approximately 21 mm/year. This rate of displacement is considered Very Slow, as per the definitions proposed in the Varnes landslide velocity classes. Up until February 2019, a rate of 17 mm/year had been observed, suggesting the spring thaw has resulted in a slight increase in the rate of movement.

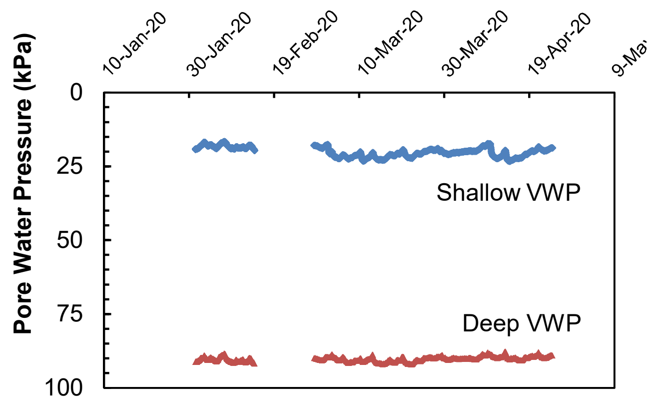

Figure 9. Porewater pressure recorded in 2020.

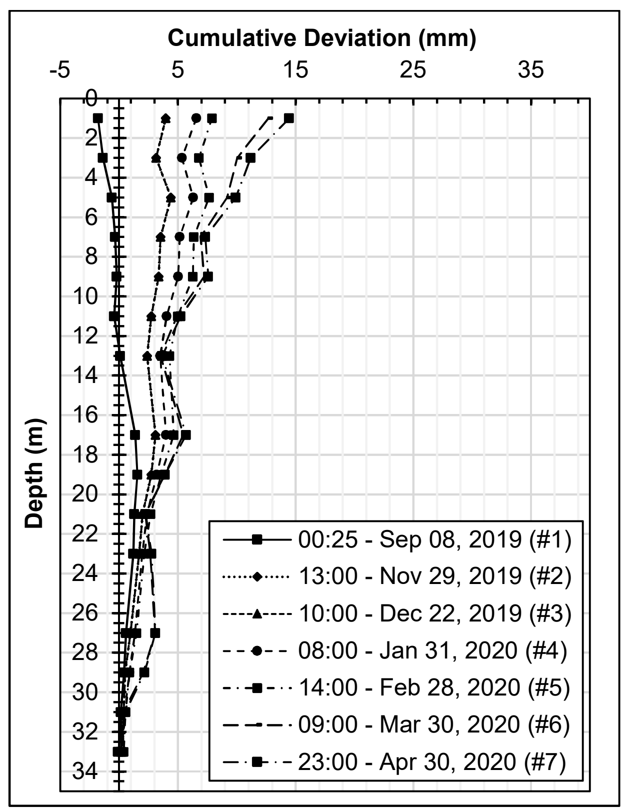

Figure 10. Inclinometer data in A-Axis direction (toward Lake Erie) showing movement recorded to date.

The ground movements recorded to date suggest the slope is exhibiting surficial creep, as evidenced by the slow but consistent increase in cumulative displacement near surface. At depth, a small degree of movement (less than 6 mm) has also been recorded but there is no concrete evidence of discrete slide surfaces at this point in time. Hence, the theory that sliding might be occurring along the clay seams appears to be unlikely based on this data.

The monitoring program is on-going and continues to provide value in several ways. The automated system has proven to be flexible and advantageous for obtaining data, particularly during the global COVID-19 pandemic. The automatic alert functionality has provided ease of mind to the owner and reduced the frequency with which manual instrument checks are required. The data has been used to improve our understanding of the site and the slope behaviour and potential creep. The evaluation of impacts has benefited the owner to ensure safety and created cost savings during the current operations.

Next steps in numerical modelling may include constructing a finite element (FE) model to replace the preliminary LE model. The contemplated FE model would be calibrated to reproduce the observed slope movements recorded by the inclinometer. The porewater pressure data obtained from the nested VWPs has improved our understanding of the distribution of porewater pressure across the site profile and in response to rainfall events. These learnings would be integrated into the revised model as well.

Over the course of this study, it has been noted that other wind turbine sites along the north shore of Lake Erie are also experiencing alarming rates of land loss as a result of shoreline erosion. Based on the successful demonstration of the value provided by this project, a similar study and monitoring program are being contemplated for another wind turbine near the Lake Erie shoreline.

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