Geotechnical and geophysical investigation for a complex foundation project

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ABSTRACT
A new smelter utility building (SUB) has been designed to replace the existing building within a facility situated in Ontario, Canada. The existing building is over 100 years old, and the owner reported that the building's foundations, amongst other elements, are in a severely deteriorated state. The new building has a footprint of 28x79 m and is to be constructed in close vicinity to the existing building.
Because of the complex subsurface conditions, the owner originally requested one borehole at every column of the new building (over 40 boreholes). However, following discussion between Advisian and the owner, it was finally agreed to drill 16 boreholes down to the bedrock and core four (4) of them to three (3) m maximum depth into bedrock. However, only 13 of the boreholes were drilled due to site conditions and weather restrictions.
To help resolve uncertainties and better understand the complex subsurface conditions, a geophysical investigation was undertaken after the conclusion of the drilling program. The geophysical survey provided valuable insight on the site lithology and facilitated the development geotechnical recommendations.
Geotechnical recommendations for the SUB included, among others, shallow foundations and a cast-in-situ (bored) piling.
This paper discusses the geotechnical and geophysical investigation findings and sheds light on the lessons learnt.

RÉSUMÉ
Un nouveau bâtiment de fonderie (SUB) doit être conçu et remplacer l'ancien bâtiment en Ontario, au Canada. Le bâtiment existant a plus de 100 ans et le propriétaire a signalé que les fondations du bâtiment, entre autres éléments, sont dans un état gravement détérioré. Le nouveau bâtiment a une superficie de 28x79 m et doit être construit à proximité du bâtiment existant.
En raison de l'état complexe du sous-sol, le propriétaire a initialement demandé un trou de forage à chaque colonne du nouveau bâtiment (plus de 40 forages). Cependant, à la suite de discussions entre Advisian et le propriétaire, il a finalement été convenu de forer 16 forages dans le substrat rocheux et d'en carotter quatre (4) à trois (3) m de profondeur maximale dans le substrat rocheux. Cependant, seulement 13 des forages ont été forés en raison des conditions du site et des restrictions météorologiques.
Pour aider à résoudre les incertitudes et à mieux comprendre les conditions complexes du sous-sol, une étude géophysique a été entreprise après la fin du programme de forage. Le levé géophysique a fourni des informations précieuses sur la lithologie du site et a amélioré les recommandations géotechniques.
Les recommandations géotechniques pour le SUB comprenaient, entre autres, des fondations peu profondes et un empilement coulé in situ (foré) (qui ont ensuite été remplacés par des micro-pieux).
Cet article traite des résultats des études géotechniques et géophysiques et met en lumière les leçons apprises.

1 INTRODUCTION

A new smelter utility building (SUB) has been designed to replace the existing building within a facility situated in Ontario, Canada. The existing building is over 100 years old, and the owner reported that the building's foundations, amongst other elements, are in a severely deteriorated state. The new building has a footprint of 28x79 m and is to be constructed in close vicinity to the existing building.

Considering the subsurface conditions, the owner originally requested one borehole at every column of the new building (over 40 boreholes) because of the complex subsurface conditions; a combination of heavily undulated bedrock and slag material of unconfirmed status and depth. However, following a review of existing information and discussion between Advisian and the owner, it was finally agreed to drill 11 boreholes to the bedrock and core four (4) of them to three (3) m depth into bedrock. During the field geotechnical investigation program, the client requested expanding the project scope to include drilling of five (5) additional boreholes and coring all boreholes to the depth of approximately one (1) m into the bedrock. However, only two (2) of the five (5) boreholes were completed due to adverse site conditions and weather restrictions.

To help resolve uncertainties resulting from the reduced drilling program and better understand the complex subsurface conditions, the client agreed that Advisian undertake a geophysical investigation after the conclusion of the drilling program. The geophysical survey used electromagnetic (EM) terrain conductivity mapping, electrical resistivity tomography (ERT), multichannel analysis of surface waves (MASW) and seismic refraction methods, which provided valuable insight on the site lithology and facilitated the development of geotechnical recommendations.

This paper discusses the geotechnical and geophysical investigations findings and sheds light on the lessons learnt from the investigations and the recommendations given.

2 GEOTECHNICAL INVESTIGATION

2.1 Geological Setting

The site lies near the southern edge of the Precambrian Shield and the Sudbury Basin. The Sudbury Basin is widely thought to be the result of a meteorite collision 2 billion years ago, which deposited nickel and copper ore around the rim of the 150-km elliptical basin. These ore deposits have been mined for over a century from more than 90 mines in the area (Pearson & Pitblado 1995).

A review of Ontario Geological Survey Map 2544, “Bedrock Geology of Ontario, Southern Sheet”, scale 1:1,000,000, identifies that the site is located within an area of bedrock referred to as the Quirke Lake/Hugh Lake/Elliot Lake Group, consisting of sedimentary bedrock, with mafic and related intrusive rocks cutting through the area including diabase sills, dikes, and granophyre (Ontario Geological Survey 1991).

Until approximately 12,000 years ago, the Laurentide ice sheet covered most of Canada with 1-2 km of ice during the last Ice Age. The southwestwardly advance of the ice sheet across the Sudbury area stripped overburden material from the surface, deepened existing rock basins and created others. As the ice retreated over the next 2,000 years, massive glacial lakes were formed in which large quantities of silt and clay were deposited (Pearson & Pitblado 1995).

Today, the Sudbury area’s landscape is dominated by ridges and rocky hills of moderate elevation, scoured and worn by glaciers. Scattered low relief deposits of sandy glacial sediment, silt, silty clay, and organic material cover the bedrock throughout the region in varying thicknesses from tens of metres to no overburden where the bedrock outcrops (Pearson & Pitblado 1995; Ontario Division of Mines 1972).

2.2 Geotechnical Investigation

A track mounted ‘CME 850’ rotary rig was utilized for drilling through overburden material as well as coring through bedrock and in some instances concrete and/or slag. Hollow stem augers were utilized until refusal in the overburden material and subsequent overburden was either wash bored or diamond cored; bedrock was cored. Diamond impregnated bits were utilized for both the core barrel and casing. Water was used as the drilling fluid during diamond coring and wash boring.

The geotechnical investigation included drilling 11 boreholes to bedrock and coring four (4) of them to three (3) m depth into bedrock. During the field geotechnical investigation program, the client requested expanding the project scope to include drilling of five (5) additional boreholes and coring all boreholes to approximately one (1) m into the bedrock. However, only two (2) of the five (5) were completed due to adverse encountered site conditions and weather restrictions.

The 13 boreholes drilled at the site included:

- Four (4) boreholes (Boreholes BH9102, BH9103, BH9105 and BH9108) advanced to the surface of the bedrock, which was encountered at depths between 14.7 m below ground surface (mbgs) and 30.5 mbgs, followed by advancing coring approximately 3.0 m;
- Seven (7) boreholes (designated as Boreholes BH9100, BH9101, BH9104, BH9106, BH9107, and BH9109 and BH9112) advanced to the surface of the bedrock, which was encountered at depths between 14.9 mbgs and 32.6 mbgs, followed by advancing coring approximately 1.0 m into bedrock; and
- Two (2) boreholes (designated as Boreholes BH9110-2 and BH9111-2) were relocated due to refusal of the diamond core barrel or casing at depth. Borehole BH9110-1 was terminated at 0.3 mbgs where a possible metal plate was encountered in the fill or top of concrete. Similarly, BH9111-1 was terminated at 4.0 mbgs when the drillers noted casing refusal on 25 mm diameter rebar at approximately 1.5 mbgs. The subsequently relocated boreholes were designated Boreholes BH9110-2 and BH9111-2, respectively.

Standard Penetration Tests (SPTs) were performed during drilling to interpret the general consistency or density of the soil units encountered. The he SPT N-values are provided in Figure 1.

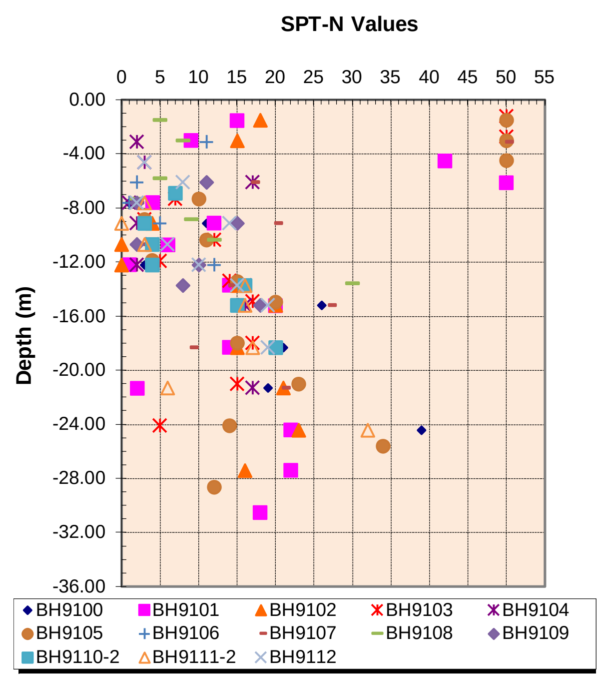

Figure 1 SPT N versus Elevation

The soil sampling program included collection of grab samples directly from the auger and collection of split spoon samples immediately after the SPT testing. The samples were collected at regular intervals, or as directed by the Advisian Site Supervisor. All soil samples were placed in sealed containers. The sampling program also included retrieval of Shelby tube samples. These samples were relatively undisturbed and were collected from cohesive soils using a thin-walled, open Shelby tube sampling device. The Shelby tube samples were sealed from both ends to maintain its field moisture content.

Where encountered, boulders and bedrock were cored using an NQ diamond core barrel and rock samples were placed in NQ core boxes. Select samples were sent to the laboratory for geotechnical testing.
All boreholes were backfilled with drill cuttings and sealed with bentonite chips near to the surface of the borehole.

Results of the natural moisture content and Atterberg limits are provided in Figure 2.

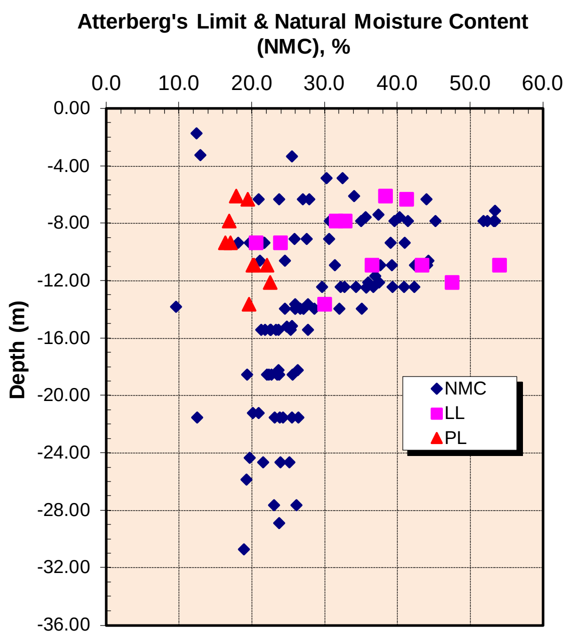

Figure 2 Natural moisture content and Atterberg limits versus depth

2.3 Subsurface Profile

The subsurface profile of the SUB footprint generally consisted of Sand and Gravel Fill material, followed by Slag, interbedded Clay and Silt, Sandy Silt/Silty Sand/Silt and Sand, occasionally Silt/Clayey Silt and/or Boulders, and finally bedrock. Concrete, likely footings of pre-existing structures, were also encountered at several boreholes. Refer to Figure 3 for the soil layers encountered at different borehole locations.

Fill material and/or buried concrete was encountered in all boreholes completed during the geotechnical investigation except for BH9100 and BH9111-2.

Relict concrete foundations were detected in Boreholes BH9103, BH9109, BH9110-2, BH9111-1, and BH9112. Concrete encountered at the Site required rotary coring in order to advance the borehole within igneous clasts and slag fragments as large as 50 mm diameter, except for BH9109 in which the top layer of concrete was augered through. The concrete in Borehole BH9109 and BH9110-2 was encountered at two (2) separate levels.

Slag was encountered at varying thicknesses in all boreholes completed during the geotechnical investigation except for Borehole BH9110-1, which was terminated in the fill material and relocated as stated in Section 2.2.

Three (3) types of slag were encountered at the Site, Granular Slag, Poured Slag and Fragmented Slag. The Granular Slag could be augered through, whereas the Poured Slag required rotary coring to advance the borehole. The fragmented slag could be augered through at shallow depths but predominantly required rotary coring. SPT 'N' values in the slag ranged from 9 to over 50 (refusal) emphasizing the wide range of its condition within the Site.

Brown to grey clay was encountered immediately beneath the Fill and/or Slag across the Site. The top of this layer was encountered approximately between 3.1 m and 8.5 mbgs with a thickness ranging from 1.5 m to 6.7 m. Consistency of this material was generally soft to very soft with occasionally firm to stiff lenses. SPT 'N' values within the soft clay layer ranged from zero (0) (weight of the hammer) to 11, but generally were between 1 to 4. The clay can be characterized, generally, as CL in accordance with the Unified Soil Classification System (USCS).

Brown to grey interbedded clay, silt and sandy silt / silty sand / sand was encountered beneath the generally soft clay across the Site. The top of this layer was encountered approximately between 6.1 m and 15.2 mbgs, with a thickness ranging from 4.3 m to 23.5 m. Consistency of this material was variable, with the fine-grained fractions generally ranging from firm to stiff with some very soft to very firm lenses, and the coarse-grained fractions generally ranging from compact to dense. SPT 'N' values in this interbedded layer ranged greatly between one (1) in clay-rich layers to 39 in sandy silt layers. The fine-grained materials (silts and clays) were generally of intermediate plasticity, two (2) samples showed low plasticity while only one was of high of plasticity. The clay of this layer can be characterized as CL, locally CH, the silt is interpreted as ML and the sand as SM, in accordance with the USCS.

In eight (8) of the 13 boreholes, i.e., BH9100, BH9103, BH9104, BH9106, BH9108, BH9109, BH9111-2 and BH9112, boulders were encountered beneath the interbedded in-situ soils and underlain by bedrock. This layer ranged in thickness from 0.2 m to 2.8 m and was generally a combination of fine to coarse grained mafic and felsic igneous rock. It is noted that no SPT testing was completed within the boulder layer. Further, the boulder layer was cored through during the geotechnical drilling program.

A minimum of 1 m of meta-gabbro/gneiss bedrock was cored through for nine (9) boreholes, while a minimum of 3 m was cored through four (4) boreholes across the site, at depths between 14.7 m and 32.6 m. The meta-gabbro bedrock was dark greenish grey to black with white flecks throughout, fine to medium grained, generally very strong to extremely strong, massive to moderately foliated at 30 to 65 degrees from horizontal, and fresh to slightly weathered. Thin veins of pyrite and quartz and/or calcite were commonly observed throughout the rock core retrieved. Slightly more pronounced gneissosity was noted in Borehole BH9106 and BH9107, with weak to moderate gneissosity/foliation at 40 to 60 degrees from horizontal and lighter grey banding. This bedrock was classified as “Meta-Gabbro/Gneiss”. Select core samples from boreholes BH9102, BH9103, BH9105 and BH9108 were sent to the laboratory for UCS testing. The UCS of the bedrock at the Site ranged from 90 MPa to 123 MPa, with an average of 103 MPa. Results of the laboratory strength testing indicate that the meta-gabbro/gneiss bedrock present across the Site ranges from Strong (R4) to Very Strong (R5), according to the rock strength classification included in the Canadian Foundation Engineering Manual (CFEM 2006).

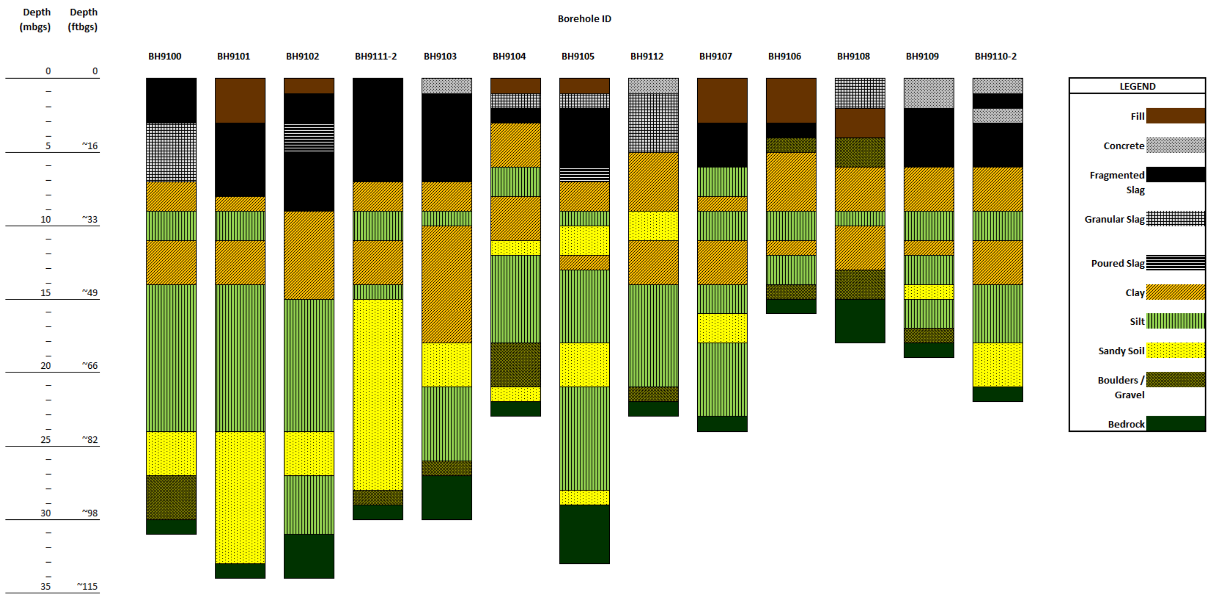

Figure 3 Approximate borehole cross-sections

Figure 3 shows the stratigraphy encountered within each borehole and sheds light on the complexity of the site.

Groundwater was measured at depths ranging from 2.25 mbgs to 3.63 mbgs upon drilling completion.

3 GEOPYSICAL INVESTIGATION

The objectives of the geophysical investigation were to:

- map depth to bedrock under the footprint of the site,
- determine the presence of and map slag or construction materials below the surface, and
- measure the physical properties of the subsurface layers, including seismic velocities, which could be used for dynamic soil analysis.

An EM31 electromagnetic terrain conductivity survey was completed over the site footprint to map out areas of shallow slag or construction materials based on changes in soil electrical conductivity. This survey successfully delineated the buried foundations of a former building (dark blue, low-conductivity area shown in Figure 4.

Electrical resistivity tomography (ERT), seismic refraction, and multichannel analysis of surface wave (MASW) data were collected along six profiles across the site footprint (ERT lines are plotted in yellow in Figure 4, whereas seismic refraction and MASW lines are plotted in red).

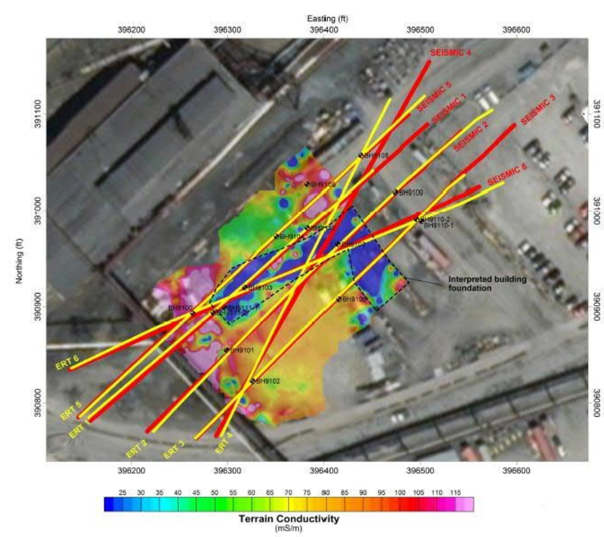

Figure 4. EM31 terrain conductivity map over site footprint and location of geophysical survey lines.

The processed geophysical cross-sections were correlated with the available geotechnical borehole logs and used to ground truth interpretations. Seismic refraction data revealed that bedrock generally sloped downward from northeast to southwest under the proposed SUB footprint, varying in depth between 15 m and 30 m. A combination of slag, concrete and fill was inferred as a relatively stiff, shallow layer that was up to 12 m thick, as interpreted from the MASW shear-wave velocity model (Figure 5), and the ERT resistivity and IP chargeability models. The geophysical data also successfully mapped an intermediate layer of clay, silt, sand, and gravel.

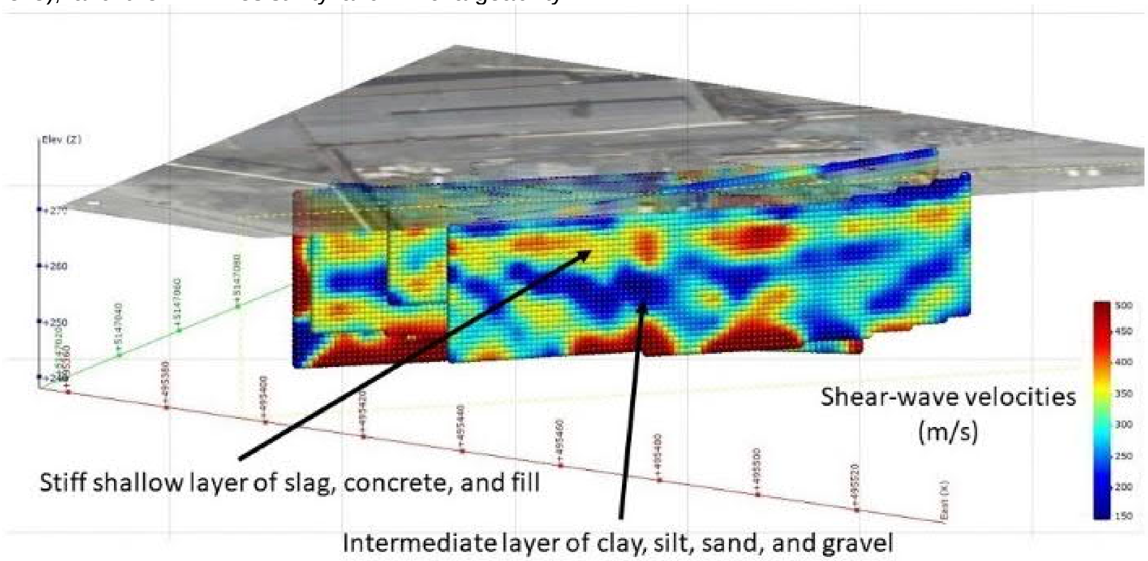

Figure 5. 3-D view of MASW shear-wave velocity contours.

4 FOUNDATION ENGINEERING

Shallow foundations consisting of spread footings and deep pile foundations were considered feasible for the site. The deep foundations consisting of bored cast-in-place concrete piles were initially considered for the site. Driven piles were not considered feasible as they would not be practical to install due to encountering historical concrete foundations (masses) and very dense slag at several borehole locations. Later, during construction, the bore piles were replaced by micropiles. The piles were socketed into the bedrock with the rock socket length varying depending on the required pile load.

The site was raised approximately one (1) m to ensure positive drainage. This introduced settlements that had to accounted for in addition to the settlement caused by the shallow foundation applied pressure.

Later, during the construction, the bored piles, which was the preferred pile type by the structural engineer, were replaced by micropiles These micropiles were designed by the piling contractor's structural engineer and accepted by the owner and Advisian, who acted as the geotechnical engineer-of-record for the rest of the foundations work.

Finally, the Advisian geotechnical team provided valuable recommendations for the raft foundation bearing capacity and associated settlement of multiple structures. During the late detailed design phase of these shallow foundations, the structural team asked the geotechnical team to review the final raft foundation design and confirm the bearing capacity and settlement values originally recommended in the geotechnical report. The foundation sizes were different to what was originally assessed, they ended up larger than originally considered by the geotechnical team and their bearing capacity and expected settlements influenced by the presence of the soft Clay that was encountered underneath the Fill/Slag layers. Although the foundation sizes increased, the bearing capacity was at locations reduced and the settlements increased, as the stress change (stress bulb) impacted now the soft Clay soil encountered below the Fill and Slag layers. The geotechnical team coordinated efficiently with the structural team and reassessed the bearing capacity and settlement of the raft slabs, assisting in that way the structural team to redesign the raft foundations considering properly the impact of the soft Clay layer to the shallow foundation and proposing in the end a design.

Also, it was identified that there was a miscommunication between the geotechnical and structural teams on what is a "slab-on grade" against a uniformly loaded raft (mat) slab. The mat foundation, from a geotechnical point-of-view, is a foundation that supporting more than one line of column. This was clarified during the final design review of the foundation drawings by the geotechnical team.

5 CONCLUSIONS AND LESSONS LEARNT

The combined geotechnical and geophysical investigation helped interpret subsurface soil conditions and provided the data necessary for completing the geotechnical design for the facility. The main findings and lessons learnt are:

- A well-executed geophysical investigation can provide information on continuous subsurface conditions. And, if combined with geotechnical investigation in order to be calibrated, it will provide insight on the information and data required by the geotechnical team to form a better and concise design consideration for the structural team, limiting data gaps. On this project this was particularly important to identify the extend of the Fill and Slag layers and better understand the depth to bedrock and pile lengths.

- It is prudent to engage the geotechnical disciplines at every level of the design process, from the FEED to the detail design phases. The geotechnical engineer can provide valuable data for the design process and ultimately the owner will benefit from an efficient design. This project showed that a final review of the issued for construction foundation drawings by the geotechnical team is of at most importance. The CFEM rightfully states in Section 7.7 that the interaction and effective communication between structural and geotechnical engineers "*is especially important, if not essential, for more complex soil-structure interaction considerations where the design procedures involve or are based on a modulus of subgrade reaction*".
- It is essential for the structural and geotechnical engineers to reach a conclusion about the terminology used by two disciplines.

6 REFERENCES

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