A case study of frost action on lightly loaded piles at Ontario solar farms

Pierre-Philippe Levasseur
Golder Associates Ltd., Mississauga, Ontario, Canada
Michael L J Maher
Golder Associates Ltd., Whitby, Ontario, Canada
J. Paul Dittrich
Golder Associates Ltd., Mississauga, Ontario, Canada

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
The Ontario Feed-in Tariff (FIT) program was launched in 2009 to encourage the development of renewable energy technology in Ontario and quickly initiated the development of many solar farms across the province. Many developers applied foundation designs that were more suited to the southern United States or Europe than to Ontario conditions. This often resulted in constructability issues as well as poor foundation performance related to frost action of the solar panel supports. This paper considers several key findings and remedial measures associated with poor foundation performance at a number of solar farm developments in Ontario. Minimum adfreeze values back-calculated from the observed pile heave at one of the sites is also presented, for comparison purposes with values published in literature and local design guidelines. A discussion on retrofit measures utilized to remediate heaved piles is also provided.

RÉSUMÉ
Le programme de tarifs de rachat garantis (TRG) de l'Ontario a été lancé en 2009 afin d'encourager le développement des énergies renouvelables. Le programme a entrainé une vague de construction de centrales solaires à travers la province. Plusieurs promoteurs ont appliqué des concepts de fondations visant généralement des sites du sud des États-Unis ou de l'Europe aux sites ontariens. Plusieurs cas de problèmes durant la construction ont été rapportés en plus de problèmes reliés à la mauvaise performance des systèmes de fondations de panneaux solaires en raison du gel. Cet article présente plusieurs observations et mesures de réhabilitation en lien avec la mauvaise performance de fondations de panneaux solaires à quelques centrales solaires en Ontario. Des valeurs minimales d'adhérence due au gel ont été calculées à rebours à l'aide des données d'un site, afin de les comparer aux valeurs publiées dans la littérature et les manuels locaux d'ingénierie des fondations. Une discussion sur les mesures de réhabilitation de pieux soulevés par le gel est aussi présentée dans cet article.

1 INTRODUCTION

The Ontario Feed-in Tariff (FIT) program was launched in 2009 to encourage the development of renewable energy technology in Ontario. The program quickly initiated the development of many solar farms across Ontario over a short period of time. These developments were generally carried out by the private sector as investment vehicles, frequently by foreign developers having no prior experience in Ontario and/or Canada. Many of the projects were constructed by way of design-build contracts with very tight completion schedules and highly competitive pricing. Thus, there was significant pressure to minimize the foundation costs and installation times, for the thousands of panel supports for the developments.

In many instances the local ground and cold climate conditions were inadequately considered, resulting in constructability issues as well as poor foundation performance related to frost action of the solar panel supports.

2 LOCAL DESIGN CONSIDERATIONS

With minimal dead loads, uplift conditions (e.g. wind, frost) typically govern solar panel foundation design. Although lateral resistance must also be considered since frequently small diameter piles are utilized. Typical foundation schemes for solar energy developments often consist of a large number of small diameter, lightly loaded piles installed to support the solar panel arrays. Because the panels in each row are connected, the systems are not very tolerant to differential movement between adjacent supports.

Typical local conditions in Ontario that need to be considered in the design and construction of lightly loaded piles include:

- cold climate and depth of frost penetration;
- potential presence of frost susceptible (silty) soils near the ground surface;
- poor site drainage; and,
- hard glacial tills containing cobbles and boulders which can cause difficulties during pile installation.

Under these conditions, the design of lightly loaded piles can often be governed by frost action forces. Developments of these kinds, which involve thousands of lightly loaded piles, were new to Ontario. Therefore the experience relied on was based on successful projects in other countries, typically the southern United States and Europe. Given that these were private sector developments and their performance did not jeopardize public safety, there were no governing regulations with respect to minimum foundation design standards. Nor was there any sharing of best practice or lessons learned.

Improper consideration of the local conditions in the design of foundations for solar energy projects, and decisions to rely on lower factors of safety, have resulted in inappropriate foundation designs. Together with insufficient oversight during construction, this often resulted in poor foundation performance. The poor performance has generally manifested itself in the form of differential frost heave necessitating expensive and disruptive retrofitting.

An evaluation of poor foundation performance at a solar farm development in southern Ontario is presented below.

3 CASE STUDY

This section presents a study of two solar power development sites which were constructed by a private developer in a southwestern Ontario rural municipality. The two sites, referred to as Site A and Site B, were formerly used for agricultural (farming) purposes. The project required the installation of more than 25,000 steel H-piles to support the solar panels. During the first winter following construction, the solar panels at both sites experienced distortion due to frost heave of the support piles.

3.1 Site Description

More than 13,000 piles and 12,000 piles were installed to support the solar panel arrays at Site A and Site B, respectively. The piles consist of 150 mm (6 inch) driven steel H-piles. The piles are approximately 4.6 m (15 ft) long and are embedded to a depth of 3.4 m (11 ft) below ground surface, with a stick-up of 1.2 m (4 ft) above ground surface. The solar panels are attached at a fixed angle to the pile stick-ups (Figure 1). The ground clearance is to avoid snow accumulation over the base of the panel.

Pre- and post-construction subsurface investigations established that Site A is generally underlain by silt (ML) and silty sand (SM), with some areas of fine sand (SP). Site B is underlain by a range of soils including silt (ML) to silty clay (CL), also with some areas of fine sand (SP). The groundwater table at both sites is variable and was measured to be near the ground surface at many locations across the two sites. A summary of the subsurface conditions at the two sites is provided in Table 1.

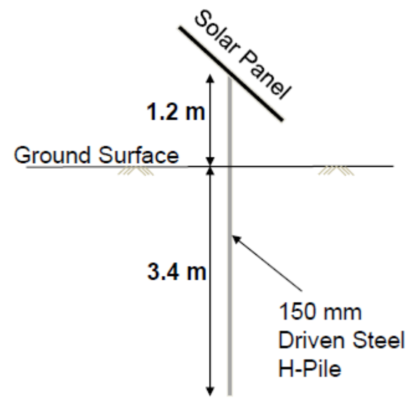


Figure 1. Typical solar panel support pile (Sites A and B).

Table 1. Summary of subsurface conditions.

Site	Within frost penetration depth[1]		Below frost penetration depth[1,2]		Average groundwater level depth (m)
	Soil type[3]	Average SPT 'N' value	Soil type[3]	Average SPT 'N' value	
Site A:					
Array 1	ML	7	ML	15	0.8
Array 2	ML	14	ML	17	0.8
Array 3	ML	11	ML	8	1.6
Array 4	SM	5	ML	9	2.1
Array 5	SM	9	CL	4	2.8
Array 6	ML	4	ML	7	2.3
Array 7	ML	6	ML	7	1.8
Array 8	SP	6	ML	5	3.2
Array 9	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
Site B:					
Array 1	SP	5	CL / SP	11	1.7
Array 2	ML	12	ML	21	1.6
Array 3	ML	12	ML	21	1.6
Array 4	ML	10	ML	39	2.5
Array 5	CL	4	ML	38	0.7
Array 6	CL	8	CL	28	0.2
Array 7	CL	13	ML	41	0.9
Array 8	ML	8	ML	20	*n/a*

[1] Estimated frost penetration depth of 1.2 m

[2] Between depths of 1.2 m and 3.4 m, corresponding to the portion of the piles embedded below the frost depth

[3] Predominant soil type (Unified Soil Classification System)

3.2 Estimated Depth of Frost Penetration

The mean freezing index, I_m, at the site based on the closest available weather station is about 530 °C-days (Environment Canada Climate Data). A frost penetration depth of about 1.1 m (with snow cover) to 1.4 m (without snow cover) is estimated based on frost penetration predication equations provided in CFEM (2006). The prediction is based on a design freezing index, I_d, equal to 784 °C-days, as derived from the mean freezing index, I_m, and the equations provided in CFEM (2006). Frost penetration contour maps from the Ministry of Transportation of Ontario, which are commonly used for foundation design in Ontario, indicate a similar estimated frost penetration depth of about 1.2 m for the case study site (OPSD, 2010).

3.3 Frost Action (Pile Heave) Event

The first winter following construction was relatively cold in southern Ontario. A freezing index of 669 °C-days was recorded for the winter at the closest weather station to the case study site (Environment Canada Climate Data), compared to the average (mean) freezing index of 530 °C-days. Extensive differential movement between adjacent piles supporting the solar panels was observed during the winter. This resulted in distortion of the solar panels (Figure 2). It is worth noting that a series of test piles (pipe piles) had been installed on one of the sites prior to the previous winter. These were monitored for movement and minimal heave was recorded.

Figure 2. Example of Solar Panel Distortion.

The distortion of the panels was more extensive at Site A than at Site B. Within the nine (9) solar panel arrays of Site A, between 1% and 9% of the piles had moved in excess of the structural tolerance of 36 mm between adjacent piles, and 7% to 17% of the piles recorded movement within the 20 mm to 36 mm range (Figure 3). At Site B, generally less than 2% of the piles within the eight (8) solar panel arrays had moved in excess of the structural tolerance of 36 mm, and less than 9% of the piles recorded movement within the 20 mm to 36 mm range (Figure 4).

The solar panel distortion was most likely the result of frost heave of the upper soils surrounding the support piles. The subsurface soils located within the frost penetration depth at the sites, particularly the silts (ML) and silty sands (SM), are highly frost susceptible. The frost susceptibility of these soil types (based on USCS soil classification) is classified as F4 in CFEM (2006) on a scale of F1 to F4, with F4 corresponding to the most frost susceptible soils. Frost susceptible soils within the seasonal frost penetration zone are subject to the development of ice lenses, resulting in overall heave.

Figure 3. Percentage of piles with recorded movements (heave) in excess of 20 mm (Site A).

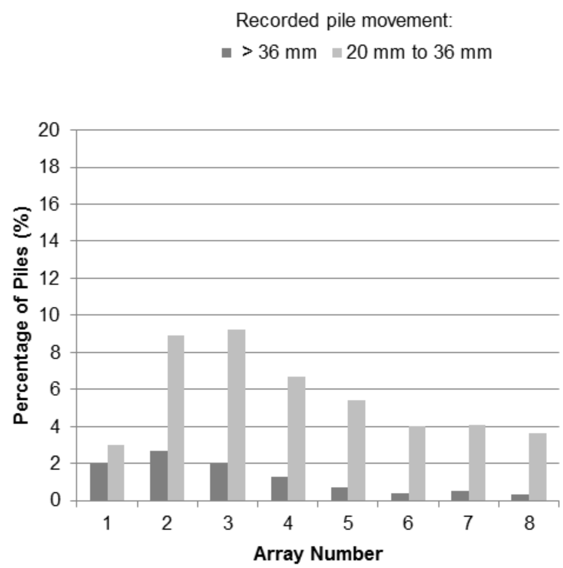


Figure 4. Percentage of piles with recorded movements (heave) in excess of 20 mm (Site B).

More extensive pile movements were observed at Site A. The subsurface conditions summarized in Table 1 indicate that almost all solar panel arrays at Site A are underlain by soils with a F4 frost susceptibility (i.e. ML, SM) within the frost penetration depth. Further, Table 1 indicates that soil conditions below the frost depth (i.e. within the lower portion of the pile) are more competent at Site B than those at Site A, with markedly higher Standard Penetration Test (SPT) 'N' values. The more competent conditions below the frost depth have likely provided more uplift resistance of the piles to resist frost action forces acting on the piles within the frost depth. It is also noted that, within Site A, the largest proportion of piles having moved out of tolerance (>36 mm) was observed within Arrays 1 and 2, where the groundwater levels are highest and have likely favoured more extensive development of ice lenses within the frost penetration depth.

3.4 Adfreeze forces

As the soil freezes, it adheres to embedded objects, such as metal piles. In combination with frost heave, this adherence results in an uplift force on the embedded structure. This process is known as “adfreezing”. To prevent upward movement of an embedded pile in this situation, the adfreeze forces need to be counteracted by frictional forces derived from the embedded length of the pile below the frost depth, or suppressed by minimizing the bond between the pile and the frozen soil (e.g. bond breaker) or preventing the soil from freezing (e.g. insulation).

Recommended adfreeze bond stresses for pile design are provided in CFEM (2006) and other sources in the literature. This section of the paper provides a comparison of back-calculated adfreeze bond stresses from the case study to recommended design values in the literature. In order to back-calculate minimum adfreeze values having acted on the piles at the case study site, the following assumptions were made:

- the adfreeze force (driving force), Q_a, acting on the piles within the frost depth is equal to the shaft resistance (resisting force), Q_s, acting over the portion of the piles embedded below the frost depth (i.e. $Q_a \cong Q_s$, or Factor of Safety $\cong$ 1.0, refer to illustration shown on Figure 5);
- the estimated shaft resistance coefficient, β, between the site soils and the driven steel piles (below the frost depth) is on the order of 0.7 to 1.0 (see below);
- the frost penetration depth is equal to 1.2 m (see below);
- the buk unit weight of the site soils is 19 kN/m^3; and,
- the groundwater levels at the site range between depths of 0.2 m below the ground surface to below the pile termination depth of 3.4 m.

Although climate data confirms that the first winter following construction was colder than normal (refer to Section 3.3), the freezing index for that winter did not exceed the design freezing index for the site (refer to Section 3.2). Based on the freezing index of 669 °C-days recorded for that winter and the frost penetration prediction equations provided in CFEM (2006), a frost penetration depth of about 1.0 m to 1.3 m (depending on the snow cover) can be estimated for the site during the first winter following construction. For the purpose of back-calculating the adfreeze forces, an average frost penetration depth of 1.2 m was utilized.

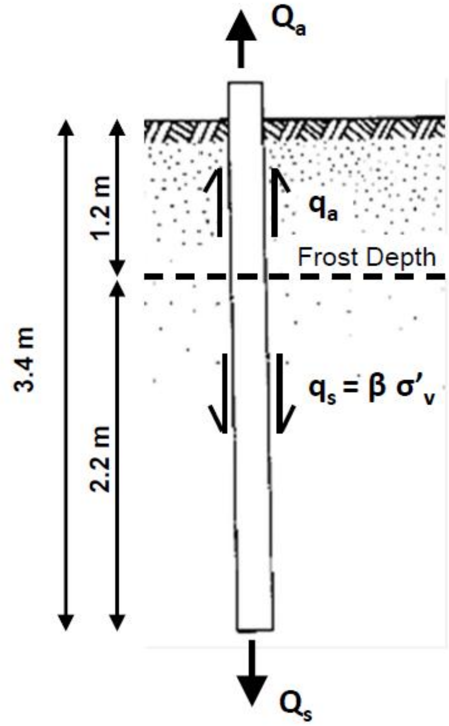


Figure 5. Illustration of (driving) adfreeze forces, Q_a and (resisting) shaft resistance forces, Q_s.

As mentioned above, the shaft resistance coefficient, β, between the site soils and the driven steel piles (below the frost depth) is estimated to be on the order of 0.7 to 1.0. These values were back-calculated using the results of limited uplift load testing carried out prior to construction on 102 mm diameter steel pipe piles installed at Site A, during which time piles with embedments of 1.8 m and 2.4 m were tested to failure.

Based on the assumed parameters presented above, the ultimate shaft resistance, Q_s, acting on the portion of the 150 mm driven steel H-piles located below the frost depth at the case study site is estimated to range between 22 kN and 58 kN. For an equal adfreeze force, Q_a (i.e. corresponding to a Factor of Safety around unity, as evidenced by the pile heave event), the ultimate adfreeze bond stress, q_a, acting on the piles within the frost depth (see illustration on Figure 5) is estimated to range from about 30 kPa to 80 kPa. Table 2 provides a comparison of the back-calculated adfreeze bond stresses against values provided in literature. Table 2 shows that the estimated (back-calculated) adfreeze bond stresses having acted on the piles during the pile heave event are less than values recommended in the literature. This suggests that either a shallower design depth of frost penetration or adfreeze forces on average much less than those recommended in literature (or both) may have been utilized during the pile design for Sites A and B.

Table 2. Ultimate adfreeze bond stress values for steel piles in contact with fine-grained / silty soils.

Source	Ultimate Adreeze Bond Stress (kPa)
Back-calculated values:	
Southw estern Ontario solar fam case study	30 to 80
Recommended values in literature:	
CFEM, 2006	100
Tomlinson, 1994	113
Fang, 1991	140 to 270

4 POOR SOLAR FARM FOUNDATION PERFORMANCE IN ONTARIO

The case study presented in Section 3 is one of many reported cases of poor solar farm foundation performance over recent years in Ontario. The poor foundation performance at these solar farms has generally been the result of a combination of the following main contributors:

- Frost Action. Adfreeze forces have been improperly considered in many instances. Design assumptions may also have resulted in under-estimations of the frost penetration depths at solar farm sites, notably by relying on an undisturbed snow cover (to reduce frost penetration) while observations suggest that snow cover was generally limited due to wind action and the cover protection provided by the solar panels themselves.
- Lack of local experience. Solar energy projects are relatively new in the Ontario energy landscape; most of them were initiated by the FIT program launched in 2009. The majority of the developments were undertaken by developers with no prior experience in Ontario and/or Canada and with unrealistic expectations of what solar panel foundations should cost. Further, frost loads are seldom the governing factor in foundation design for the vast majority of local foundation applications in southern Ontario.
- Lack of geotechnical oversight. Limited geotechnical oversight during construction of solar energy projects (sometimes involving 24-hour/day operations) has resulted in as-constructed foundation conditions that did not meet the intended design.
- Difficult piling conditions. Hard glacial till soils containing cobbles and boulders are prevalent in many regions of southern Ontario. These conditions have often resulted in failure to implement intended foundation designs due to the difficult piling conditions, particularly when using relatively light construction equipment as often utilized for the installation of the small diameter, lightly loaded piles.

An example of difficult piling conditions resulting in failure to implement the intended foundation design was observed at a solar farm site in eastern Ontario. The subject site is underlain by hard silty clay till material containing cobbles and boulders. The foundation design included 114 mm diameter steel “earth screws” which are reportedly used in solar farm applications in Europe. The pile system consists of helical steel piles with small diameter helices. The pile installation for the eastern Ontario solar farm site included pre-drilling (150 mm diameter) within the frost penetration depth, the embedment of the helices within the till below the frost depth, and the backfilling of the pre-drilled annulus with a gravel pack (Figure 6). While the effectiveness of the gravel pack as a bond-breaker to reduce frost loads acting on the piles can be debated, piles constructed as per the design have performed satisfactorily in most cases. However, due to the difficult piling conditions, many pile locations were pre-drilled to the full pile depth and backfilled with gravel prior to the installation of the “earth screws” within the gravel. An excavated pile showing the gravel pack extending to the tip of the pile is shown on Figure 7. The excavated pile also showed notable wear of the helices when compared to the original pile condition. During the first winter following construction, a large proportion of the piles with helices installed within gravel backfill (i.e. within fully pre-drilled holes and not meeting the intent of the original design) have recorded significant heave movements.

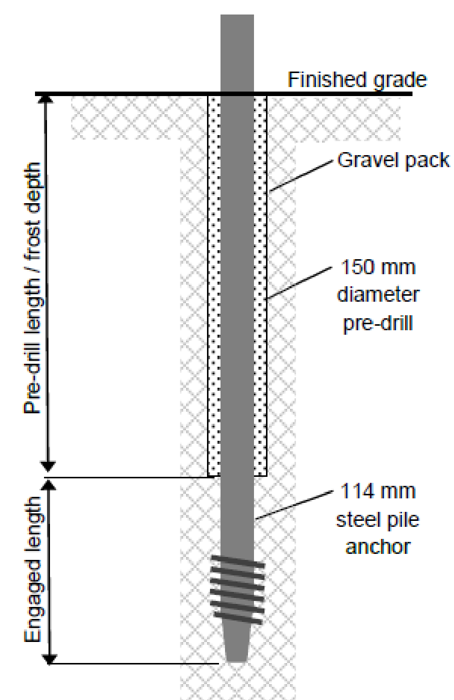


Figure 6. Illustration of earth screw design with pre-drill and gravel pack within frost penetration depth.

Figure 7. Typical as-constructed earth screw with pre-drill and gravel pack over the full pile length. Note helix wear compared to the original pile condition (insert).

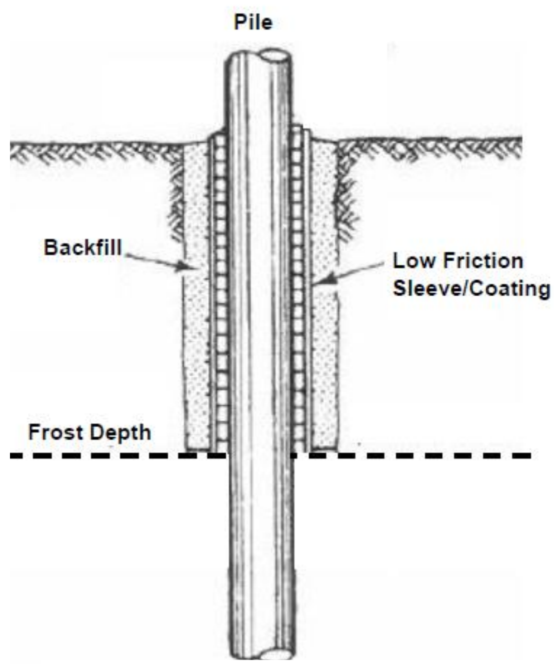
5 REMEDIAL MEASURES

Poor foundation performance due to frost action at Ontario solar farms has triggered the need for remedial measures in many instances. The remedial work is hampered by the fact that the panels cannot be taken out of service and so the works must be undertaken under the panels. A wide range of remedial measures have been used at Ontario solar farms, including:

- re-setting of piles with hydraulic pressure (temporary measure);
- over-excavation and poured concrete base (below the frost depth) to increase the dead weight (and uplift resistance) of the pile foundations;
- bond breakers (i.e. low friction sleeves/coatings) around the piles within the frost depth to minimize soil adherence and adfreeze bond stresses (Figure 8); and,
- insulation to prevent ground frost penetration around the piles (Figure 9).

The implementation of remedial measures has had significant cost implications on many solar farm projects, sometimes largely exceeding the initial construction costs.

(a)



Adapted from Andersland and Ladanyi (2004)

(b)

Figure 8. Remedial measure – bond breaker, photograph (a) and schematic (b).

Figure 9. Remedial measure – insulation.

6 CONCLUSION

A study of poor foundation performance due to frost action at solar farm developments in Ontario has been presented in this paper. Minimum adfreeze values back-calculated from the observed pile heave at one of the sites suggest that the adfreeze bond stresses that acted on the piles did not exceed values published in the literature and local design guidelines.

Solar energy developments are relatively new in the Ontario energy landscape and many instances of poor foundation performance were reported over recent years. While frost action appears to be the main contributor to the poor foundation performance, other factors have contributed such as the lack of local experience, the lack of geotechnical oversight during construction, and difficult piling conditions/unsuitable choice of piles in some of the hard glacial till materials which are prevalent in many regions of southern Ontario. The poor foundation performance has triggered the need for the implementation of a wide range of retrofit measures at Ontario solar farms to remediate heaved piles.

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