

Adfreeze Forces on Lightly Loaded Pile Foundations of Solar PV Farms in Cold Regions

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Abstract Renewable energy generation through utility scale ground mounted solar photo-voltaic systems has gained steady popularity with increasing number of such facilities being constructed in various regions worldwide. Solar PV systems are very popular in the province of Ontario in Canada and strong growth in this sector is led by the popular initiatives of the Government of Ontario which offers extremely attractive rates for generation of renewable energy through Ontario Hydro's popular Feed-In Tariff (FIT) Program. Many other countries offer incentives on such generation of renewable energy while many governments aim at increasing the percentages of renewable energy in their systems tremendously. Most ambitious plan has recently been launched by the state of Hawaii to deploy 100% of renewable energy in their grid by 2045. Solar PV systems are a cheap source of renewable energy as the energy released by the sun is harnessed as electricity by the solar photo-voltaic panels which is fed to the main transmission systems after raising its voltage. The costs of solar photo-voltaic panels meanwhile have also kept downward trends while the manufacture of various types of solar panels has multiplied rapidly. These renewable energy generation facilities are fully sustainable being completely recyclable on completion of their design/ contract period. Typical utility scale ground mounted solar PV facilities usually comprise of solar PV panels mounted on series of racking tables supported on foundations mostly comprising of partially embedded steel pipes. The governing loads for the foundations of these lightly loaded solar PV structures are usually frost loads in areas facing extremely cold winters. In fine grained soils like silty/ clayey soils, large adfreeze stresses develop due to penetrating frost deep into the soil resulting into uplift of foundation piles. Typical winter conditions in Ontario are harsh with extreme frost conditions in most areas which poses unique issues for design and construction of such foundations. Being a relatively newer technology, codes and standards for design and testing of such lightly loaded solar PV structures are still in the formulation stages. Frost heaving and its effects often create adverse conditions for these structures thereby affecting the production and continuous supply of renewable energy. Due to larger depths of frost penetration in extreme winter conditions, understanding the action of frost and related development of adfreeze stresses on these lightly loaded pile foundations is extremely important. Calculating reasonable frost depths and thereby the design loads is an important part of pile design for such facilities while the contractors tend to save on pile lengths to save on costs and compromising the structural design. Many such Solar PV facilities have experienced frost uplift of foundation piles either during the construction phase or during its lifetime. Since frost heave is more of a serviceability related issue, unfactored adfreeze loads without any factor of safety is a usual tendency by the EPC contractors. This paper investigates the frost depths and adfreeze stress related issues with the foundation piles of solar PV facilities hence the governing design forces on these piles and suggests appropriate frost related design stresses for the foundation piles. The authors have been heavily involved in design/ design reviews, pile selection/ design and pile load testing in the majority of the solar PV farms in Canada and US along with rehabilitation of piles affected by frost [1,2,3].

Keywords: *adfreeze stresses, solar PV panels, renewable energy, racking table foundations, foundation piles, pile rehabilitation, frost effects*

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1. Introduction

Solar PV systems are a cheap source of renewable energy as the energy released by the sun is harnessed as

electricity by the solar photo-voltaic panels which is fed to the main transmission systems after raising its voltage. The costs of solar photo-voltaic panels meanwhile have also kept downward trends while the manufacture of various types of solar panels has multiplied rapidly. These renewable energy generation facilities are fully sustainable

being completely recyclable on completion of their design/ contract period.

Typical construction of the utility scale Solar PV facilities comprises of rows of solar PV panels mounted on racking tables connected in series and supported on foundations usually comprising of partially embedded steel pipes. Rows of solar panels are mounted on the racking and are connected through electric wires which take the DC generated by the panels through combiner boxes to inverter houses where inverters convert DC to AC. This AC is passed through step up transformers to raise the voltages suitable to be fed to the main utility lines to which the output is fed through a switching control and metering system. Suitable panel types with varying capacities from 77watts to 350watts are oriented in portrait or landscape orientations in various combinations of 2 to 4 panel heights in rows of racking supported on racking foundations. Fixed racking is common in Ontario with very few farms with sun trackers installed to move racking to face sun during the day.

The partially embedded foundation piles typically used for ground mounted systems may be fully driven into soil or installed in pre-drilled holes in hard soils and/or areas with boulders/cobbles and rock. Under reamed piles with concreted base are solutions for areas where sufficient resistance to uplift cannot be provided by straight piles but are slightly expensive as compared to straight pile options and are difficult to be installed in sandy soils without additional measures. Helical piles are also an option for cohesive and sandy soils however the helixes are likely to be damaged in soils containing cobbles/ boulders. Due to the large amount of piles, typically around 5000 piles for a 10MW solar PV farm, EPC contractors prefer steel piles, whether plain, screws or helical, since they can be installed fairly quickly as usual duration to complete a 10MW (usual size of farms being built in Ontario) is around 18 to 24 weeks including commissioning. In most cases, 2.75m to 4m embedment of 114mm to 125mm diameter steel pipes in dense granular and clayey soils usually produce the desired uplift resistance with or without 200mm diameter concrete jacketing usually carried out around the embedment depth. In case bedrock is available in near depth, the piles are anchored in bedrock through rock sockets which provide sufficient resistance against uplift. Most helical and screw piles with similar shaft sizes of around 114mm to 125mm diameters are commonly used in solar industry.

While the development of codes and standards for design and testing of these lightly loaded solar PV structures still need to be formulated, severe winters and extreme frost conditions in certain areas in Ontario poses unique issues with design and installation of these pile foundations. Frost uplift is usually the governing load in almost every case for these pile foundations in Ontario, Canada. Mechanics of adfreeze forces and their extent/magnitude is not very well understood by the developers, which usually creates issues with the design and testing of pile foundations for solar panels. In the absence of specific design codes/ regulations governing the design/ testing of such solar PV facilities, differences usually erupt between EPC contractors and designers/ owners/ buyers on design and testing of these foundation pile structures. Due to larger depths of frost penetration in extreme winter conditions and thereby resulting frost

heaving and its effects may create adverse conditions for these structures thereby affecting the production and hence the continuous supply of renewable energy to the cities and towns which purchase this energy.

2. Development of Adfreeze Stresses on Frost Penetration

Frost penetration in ground due to seasonal freezing in cold weather is a common phenomenon in cold regions. As the frost penetrates into deeper layers of soil and ground swells due to freezing, the surface of ground may rise due to "frost heaving." This upward displacement of the ground upon freezing is due to the freezing of water contained in the soil voids along with formation of clear-ice segregations in the soil. This ice segregations grows as more water is drawn in continually from adjacent unfrozen ground due to lowering temperature gradients leading to further growth of ice segregations.

As the freezing isotherm descends through the ground, water is converted from liquid state to solid state. The magnitude of frost heaving depends upon three factors which are the air temperature at the site, the texture and moisture content of the soil in the area. The most favorable condition for growth of ice segregations and frost heaving is slow freezing of moist nonhomogeneous organic silts or silty clays. The freezing soils grip the foundations and exert an upward force on them due to the adfreeze stresses developing around the periphery of the foundations. These upward forces exerted on structures/ foundations during seasonal freezing force the structures to move upwards if the forces acting upward are greater than the forces pushing the structure downward. With piles, the amount of the upward force depends upon:-

- The depth of clear-ice segregations formed in the seasonally frozen ground,
- The tangential adfreezing strength, or bond, between the surface of the pile and the seasonally frozen ground,
- The surface area of the pile in the seasonally frozen ground.

The main factor opposing the upward frost heaving force is the grip of the ground on that part of the pile which lies below the seasonal frost. This grip is usually the "skin friction" of unfrozen ground. The tangential adfreezing strength of frozen ground varies with the texture and moisture content of the soil, temperature of the ground, and nature of the pile surface. It is strongest in ice-saturated fine sand and silt. The colder the ground, the greater the adfreezing strength. Differential movement of piles is of paramount problem; since such action produces extensive damage to many engineering structures.

Effects of frost heaving can be devastating. Frost heaving has displaced wood piling upward as much as 14 inches in a single winter season on an Alaska railroad bridge near Fairbanks, Alaska. About 24 inches of frost heaving of piles has been recorded in a single year in Russia. About 8" of uplift has been recorded for a bridge piles at Norman Wells, Northwest Territory, Canada. The maximum recorded cumulative heaving of a pile in a Russian bridge is about 6½ feet. Piling of a bridge 8 miles southeast of Big Delta, Alaska, has been frost heaved by 11 feet. Frost heaving combined with wind uplift can

overturn communication towers as shown in Figure 2.1 below.



Figure 2.1. Tower foundation failing under effects of uplift and frost

Because of skin friction, and because unfrozen ground below the piles squeezes into the void left as the pile rises, the base of the pile does not return to its original position in summer [4].

3. Establishing Frost Depth and Adfreeze Stresses

Establishing frost depth in the area requires data from environmental monitoring agencies and codes of practice.

In addition to physical monitoring, there are various methods of calculating frost depth too from the data on site air temperatures and degree-days usually monitored by environmental agencies however the data used must be for the worst case over the number of years, usually 50 years suggested by all codes, otherwise the design can get into trouble in case of worst case weather conditions. Frost depth calculated based on number of degree-days may not provide the worst case frost penetration depths unless the data includes the worst case weather conditions over the 50 year period and is supported by ground monitoring for confirmation of actual frost depth penetration.

To establish the frost depths, Ministry of Transport, Ontario, Canada carried a 7 year in-depth study at various locations in Ontario where actual frost depths were physically measured over few years period. Later frost depths were also calculated through various analytical methods. Having considered the frost depths obtained from the analytical methods as well as with the frost depths physically measured on ground, the study concluded at suggesting maximum frost penetration depth contour plans for northern and southern Ontario as shown in Figure 3.1 and Figure 3.2 below. It was however observed that physical frost depths were general higher than the calculated values for most locations. This seven year research did not have the most severe winters during the study.

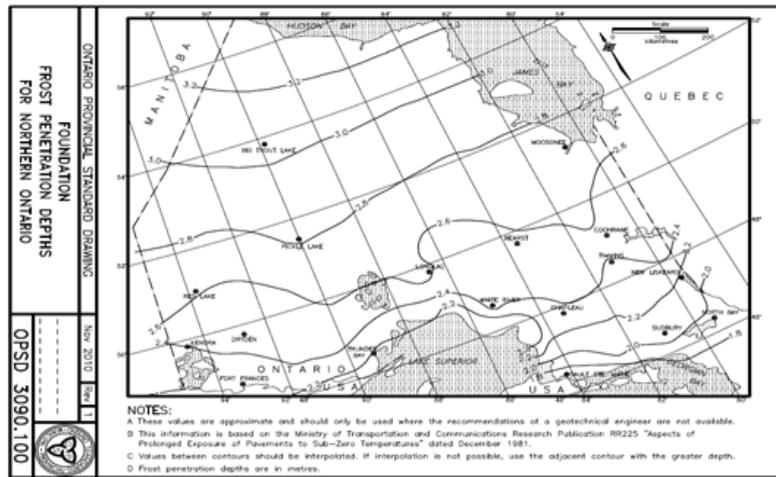


Figure 3.1. Typical frost penetration depths in Northern Ontario

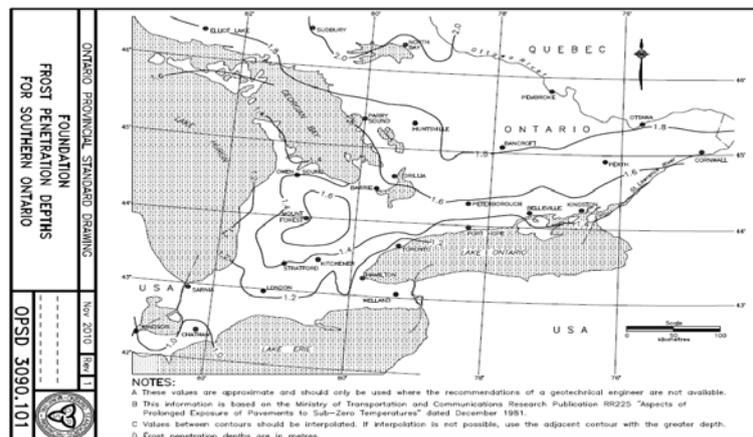


Figure 3.2. Typical frost penetration depths in Southern Ontario

13.5.1 Adfreezing

Soil in contact with shallow foundations can freeze to the foundation, developing a substantial adfreeze bond. Backfill soil that is frost susceptible can heave and transmit uplift forces to the foundation. Spread footings normally have sufficient uplift resistance from their expanded base to resist heave, but the structural design of the wall-footing connection must be sufficient to transmit any load applied through adfreeze. Average adfreeze bond stresses, determined from field experiments, typically range from 65 kPa for fine-grained soils frozen to wood or concrete to 100 kPa for fine-grained soils frozen to steel (Penner, 1974). Design adfreeze bonds for saturated gravel frozen to steel piles can be estimated at 150 kPa (Penner and Goodrich, 1983). The most severe uplift conditions can occur where frost penetrates through frost stable gravel fill into highly frost susceptible soils surrounding a foundation. These conditions result in a heaving situation with maximum adfreeze bond stress and have been known to jack H-piles driven to depths in the order of 13 m (Hayley, 1988).

Figure 3.3. Average values of adfreeze bond stresses between concrete and steel with fine grained and saturated gravelly soils. (Taken from Canadian Foundation Engineering Manual [5])

Guiding design values for adfreeze pressures on piles are taken from Canadian Foundation Engineering Manual [5] gives average adfreeze bond stress values for fine grained soils adhering to concrete and steel along with adfreeze stresses developed between saturated gravel with steel as shown in Figure 3.5. The adfreeze stress values of 65KPa given for concrete and 100KPa given for steel in fine grained soils are basically meant for clayey silts (70% clay & 30% silt) whereas the piles in silty soils experience larger adfreeze forces due to easier movement of water within the silty soils to the freezing isotherm from the surroundings and faster/massive growth of ice lenses. Hence a careful selection of adfreeze stress for silty soils is required.

While the adfreeze stress values given in the Canadian Foundation Engineering Manual may be good for medium to high imposed loads, they are on the somewhat lower sides for the foundation piles for solar PV facilities which experience low gravity loads and the governing loads are

usually uplift due to frost penetration. TM5-852-4 of the US Army and Air Force [8] indicates that the adfreeze stresses may be as high as 276KPa before the initial break in bond between frozen silty soil and steel pipe in tests carried out on an 8” pipe. Similarly, adfreeze stress developed on steel piles in saturated gravel can develop up to 150 KPa for steel piles as given in the Canadian Foundation Engineering Manual, while no adfreeze stresses are specified for concrete piles in saturated frozen gravel. The research by Penner, E. and Goodrich, L.E. on steel piles in saturated frozen gravel on smaller sized pipe i.e. 86mm diameter piles was observed up to 380KPa. The adfreeze stresses also vary with the size of the piles with maximum stresses on the smaller sizes like 3” to 6” diameter pipes experiencing maximum adfreeze stresses as compared to larger diameter piles. The piles used in the solar PV industry are usually 4” to 6” in diameter or depth hence experience maximum adfreeze stresses as is shown in research by many researchers.

Uplift Forces on Foundations in Frost Heaving Soils - E. Penner 1974

	December			January			February			March			Season average		
<i>Steel columns 1971-72 freezing index 1920 degree-days</i>															
	S-3	S-6	S-12	S-3	S-6	S-12	S-3	S-6	S-12	S-3	S-6	S-12	S-3	S-6	S-12
Peak adfreeze (p.s.i.) ¹	37.0	29.4	25.0	25.6	19.7	13.9	16.0	15.4	11.1	14.8	13.6	11.4	15.3	13.6	11.1
Avg. adfreeze (p.s.i.)	25.3	20.0	15.3	12.7	11.0	9.4	12.9	12.8	9.1	10.2	10.6	10.5			
Peak force (kips) ²	8.7	13.6	23.0	7.5	12.3	18.5	8.2	15.6	28.0	8.2	17.7	31.0			
<i>Concrete columns 1970-71 freezing index 2029 degree-days</i>															
	C-3	C-6	C-12	C-3	C-6	C-12	C-3	C-6	C-12	C-3	C-6	C-12	C-3	C-6	C-12
Peak adfreeze (p.s.i.)	16.3	21.8	17.3	16.2	21.5	16.6	14.7	16.0	14.1	7.5	10.0	9.0	10.1	13.9	11.6
Avg. adfreeze (p.s.i.)	13.1	18.9	14.8	11.5	15.5	13.4	10.0	13.8	12.0	5.6	7.4	6.1			
Peak force (kips)	3.9	9.3	14.4	6.0	11.6	20.6	6.6	12.4	23.0	3.5	8.0	13.3			
<i>Concrete columns 1971-72 freezing index 1920 degree-days</i>															
Peak adfreeze (p.s.i.)	27.9	36.1	20.4	12.8	16.3	12.0	10.9	13.2	9.1	7.5	8.9	7.0	8.2	11.9	9.3
Avg. adfreeze (p.s.i.)	12.3	19.7	14.3	7.7	11.5	8.1	7.4	9.7	8.3	5.5	6.6	6.6			
Peak force (kips)	3.6	8.1	12.8	3.4	7.5	10.1	3.9	8.0	11.9	3.4	6.7	11.8			
<i>Wood columns 1970-71 freezing index 2029 degree-days</i>															
	W-3	W-6	W-12	W-3	W-6	W-12	W-3	W-6	W-12	W-3	W-6	W-12	W-3	W-6	W-12
Peak adfreeze (p.s.i.)	16.8	25.7	20.2	14.0	16.4	13.3	10.8	12.7	10.4	4.0	7.6	7.1	8.1	11.0	9.7
Avg. adfreeze (p.s.i.)	12.0	16.9	14.4	10.0	12.1	10.0	7.5	9.8	8.6	2.7	5.0	5.8			
Peak force (kips)	3.1	7.3	10.0	4.9	9.3	12.3	5.0	9.7	13.9	2.0	6.2	10.1			
<i>Wood columns 1971-72 freezing index 1920 degree-days</i>															
Peak adfreeze (p.s.i.)	19.0	32.8	35.3	11.1	15.2	12.3	10.7	12.0	10.2	7.5	8.9	7.9	7.5	10.5	9.4
Avg. adfreeze (p.s.i.)	11.0	17.0	15.3	7.1	10.0	8.4	6.9	8.8	7.4	4.8	6.3	8.3			
Peak force (kips)	2.4	7.3	14.1	2.8	6.6	9.8	3.7	7.3	11.5	3.2	6.7	11.3			
<i>Block concrete wall 1969-70 freezing index 2029 degree-days</i>															
Peak adfreeze (p.s.i.)	11.4			7.3			6.5			6.5			6.0		
Avg. adfreeze (p.s.i.)	6.8			6.5			6.3			4.2					
Peak force (kips)	16.0			27.0			30.8			31.0					
<i>Block concrete wall 1970-71 freezing index 2029 degree-days</i>															
Peak adfreeze (p.s.i.)	3.0			3.9			3.7			3.7			3.1		
Avg. adfreeze (p.s.i.)	2.6			3.1			3.4			3.2					
Peak force (kips)	7.3			15.0			18.0			17.2					

¹ p.s.i. = 0.07 kg/cm².
² kip = 454 kg.

CAN. GEOTECHNICAL J. VOL. 11, 1974

Figure 3.4. Taken from Paper “Uplift Forces on foundations in frost heaving soils”, by Penner, E., Canadian Geotechnical Journal, Volume 11, No.3, 1974 [6] based on which CFEM values of Average Adfreeze bond of 65kPa for concrete and 100kPa for steel have been suggested in fine grained soils

Calculated Adfreeze Stresses *(kPa) on Steel Pipe Piles	
Thompson, Manitoba	
(A) 1972/73, F1 2599°C-days, Maximum stress before release--surface gravel layer adfrozen to piles	
S6 (dia. 169 mm)	- 380**
S12 (dia. 323 mm)	- 179**
S18 (dia. 458 mm)	- 124**

Figure 3.5. Taken from Paper “Adfreezing Stresses on Steel Piles, Thompson, Manitoba” by Penner, E. & Goodrich, L.E., Proceeding of Fourth International Conference – Permafrost, Fairbanks, Alaska, July 17-22, 1983 [7]. Average design adfreeze bond values for saturated gravel frozen to steel piles of 150kPa given by CFEM based on these test results

While most engineers design the piles based on these average values suggested in the Canadian Foundation Engineering Manual, it is not generally well understood that these are mere guideline values and tend to be towards the lower bound only. Actual adfreeze stresses developed between freezing soils in contact with piles may actually be much larger. Typical values given for steel and concrete are 100KPa for contact with steel and 65KPa for contact with concrete. Understanding the magnitude of adfreeze stresses is generally lacking. While

the Canadian Foundation Engineering Manual clearly indicates that the adfreeze pressure values suggested are average values, EPC contractors and some consultants generally argue these pressures to be the ultimate. TM5-852-4 of the US Army and Air Force [8] indicates that the adfreeze stresses may be as high as 276KPa before the initial break in bond between frozen soil and steel pipe in tests carried out on an 8” pipe tested in frozen silty soils as is shown in Figure 3.6 below.

If the pile can experience loading in tension from the structure the equation must be adjusted accordingly. The nature and mechanism of the heave phenomenon and values of frost uplift pressures which can act at the plane of freezing are discussed in paragraphs 2-2 and 2-4. The effects of frost heave on engineering structures and methods of controlling these effects are discussed in paragraph 4-3. Because a pile in tension contracts in the transverse direction, there is a tendency for skin friction under high tensile load to be less than in compression. As shown in figures 4-44 and 4-45, peak frost heave forces have been measured of 55,800 lb or 2220 lb per perimeter-inch for an 8 inch steel pipe pile and 35,60 lb or 809 lb per perimeter-inch for a creosoted timber pile, both in frozen silt slurry. For steel piles in silt with ample moisture available, an average value of f_h of 40 psi should be assumed to act over the full depth of seasonal freezing; in the coldest upper strata of seasonally frozen

4-139

Figure 3.6. Taken from TM5-852- 4 Arctic and Subarctic Construction - Foundations for Structures, US Army & Air Force [8]

Sailors Engineering Associates [9] carried out laboratory testing on samples of small diameter pipes with and without application of Slick-coat - friction reduction Epoxy. These tests also measured adfreeze pressures of up to 296KPa on steel pipes. The SEA Report states that the adfreeze pressures of up to 296KPa exist just before the initial bond break between the frozen soil and steel pipe and hence it is assumed that the adfreeze pressures given

by Canadian Foundation Engineering Manual are average residual pressures after the initial bond break between the frozen soil and the steel pipe. This clearly indicates that peak adfreeze forces acting on the piles can be much higher than the average values given by the Canadian Foundation Engineering Manual as is shown in Figure 3.7 below.

Conclusions

It is our understanding that design criteria for shallow piles supporting lightly loaded structures which have undergone frost heave include an adfreeze bond stress of 100 kPa for uplift calculations. While this is an accepted value for design and is mentioned in the Canadian Foundation Engineering Manual, it is our opinion, based on the results of our testing and the review of research by others, that this is not an adequate bond stress for design of steel piles for very lightly loaded structures. The peak adfreeze stress values initially experienced by the piles prior to breaking of the initial bond are much higher than 100 kPa. Utilizing the 100 kPa value requires assuming that the initial bond is broken and residual adfreeze stress values are being experienced. This might be a good assumption for structures supported by piles which have medium to high dead loads. It is our opinion, however, that significant movement of the piles could occur during frost heave prior to breaking of the peak adfreeze bond values for lightly loaded piles. TM 5 of the US Department of the Army and the Air Force, Section 4-8.f.3 “Pile Safety Against Frost Heave” (page 4-139) recommends assuming 40 psi (276 kPa) as an average value for the full depth of the seasonal freezing.

Figure 3.7. Taken from Sailors Engineering Associates Adfreeze Test Report [9]

A study carried out by Parmeswaran [10] on adfreeze stresses on piles in ice shows following values as shown in Figure 3.8 below:-

- Concrete varying from 0.525 to 1.6 MPa
- Steel varying from 0.527 to 1.36 MPa
- Wood varying from 0.40 to 1.2 MPa (Creosoted Fir)

PARAMESWARAN							
Values of the peak adfreeze bond strength measured under constant rates of displacement for various piles							
Cross-Head speed (l)* (mm·min ⁻¹)	Adfreeze strength (τ _i), MPa†						
	B.C. fir	Concrete	Painted steel	Creosoted B.C. fir	Spruce	Unpainted steel	Steel H-section
0.0005	1.140	0.525	0.497	0.403	0.960	0.527	0.640
0.001	1.175	0.553	0.496	0.487	0.863	0.760	0.513
	1.290					0.609	
0.002	1.113	0.671	0.648	0.690	1.122	0.680	0.648
	1.247			0.505			
0.005	1.610	0.733	0.677	0.720	1.196	0.806	0.691
0.01	1.560	0.866	0.679	0.813	1.167	0.734	0.695
		0.940				0.745	
0.02	1.936	1.160	0.973	0.920	1.461	0.868	0.854
0.05	2.231	1.293	1.026	0.875	1.290	1.181	0.852
					1.506		
0.10	2.420	1.611	1.146	1.220	1.542	1.364	0.983
						0.704	

*The actual pile displacement rate could be an order of magnitude smaller than this.
†1 MPa = 10.2 kg·cm⁻² = 145.06 psi.

Figure 3.8. Taken from Table 1, Adfreeze strength of piles in ice with varying loading rates, Adfreeze strength of model piles in ice. Canadian Geotech. J. Vol. 18. [10], 1981.

Another study carried out by Hiroshi Saeki [11] on mechanical properties between ice and various materials indicated following results for adfreeze stresses for temperature variations from 0°C to - 25°C:-

- Concrete with 0.05 to 0.25 MPa
- Steel with 0.04 to 0.26 MPa
- LDPE with 0.01 to 0.03 MPa

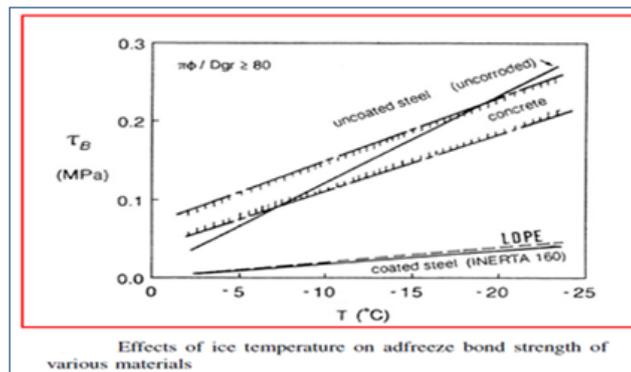


Figure 3.9. Adfreeze stresses due to ice on various materials [11]

Yet another study by L. Domaschuk [12], carried out in University of Manitoba in Winnipeg, Canada for evaluating adfreeze stresses on various materials indicated much higher values of adfreeze stresses on concrete and

steel as compared to the average values given by the Canadian Foundation Engineering Manual as shown in Figure 3.10.

Maximum measured adfreeze stresses			
Soil type	Investigators	Method of test	Max. adfreeze stress (kPa)
silty clay loam	Kinosita & Ono (1963)	field test, members, restrained, iron pipe	210
		vinyl pipe	165
		concrete pipe	116
clay	Penner and Gold (1971)	field tests: concrete block wall	45-62
		steel column	96-114
		concrete column	90-134
		wood column	62-90
varved clay (permafrost)	Johnston & Ladanyi (1972)	field test, rod anchors extracted: Thompson, Man.	147-231
		Gillam, Man.	118-249
clay	Tsytoich (1975)	lab tests, breaking bond between wood stakes and frozen soil by loading the stakes	286-1834
silt	Crory and Reed (1965)	field test, piles restrained	275
silt	Domaschuk (1980)	large model studies, steel members restrained	234
Ottawa sand	Parmeswaran (Pers. commun. 1979)	small model, piles extracted, wood	1220-2420
		steel	1146
		concrete	1611
sand	Tsytoich (1975)	lab tests, breaking bond between wood stakes and frozen soil by loading the stakes	128-2702
	Trow (1955)	lab tests, breaking bond between frozen soil and concrete container	2756

Figure 3.10. Adfreeze stresses between various soils and piles of different materials [12]

Adfreeze stresses of up to 1.2MPa at -120C were observed in field tests on steel piles by Volokhov [13] for soil samples comprising clay and sandy loam, both of which developed similar adfreeze stresses.

4. Establishing Factor of Safety

Frost loads are not the governing loads for building structures, hence are not given to be factored in the present building codes. Frost loads are the governing loads for these lightly loaded panel support structures of the Solar PV facilities. Most EPC contractors are reluctant to add any Factor of Safety to design load i.e. the frost load for pile load testing and in most cases, the argument given is that frost is a serviceability load. Hence they tend to install the test piles and test them to 100% of frost loads only.

Design of piles for solar PV farms based on soil investigations is not usual. EPC contractors tend to select the piles based on load test results only. Keeping in view the variation in soil conditions and safety, Canadian Foundation Engineering Manual suggests geotechnical resistance factors of 0.6 in compression and 0.4 for tension for resistance based on pile load test results which results into factor of safety of 1.67 for compression and 2.5 for tension as shown in Figure 3.6. With such a wide split in the adfreeze stress values given by various researches, it is worthwhile to understand that to maintain quality and ensure that 100% of piles perform as designed on sites where large numbers of piles (say 5000 piles for a 10MW facility) are to be installed, there has to be an adequate Factor of Safety considered in the design. With the variation in soil conditions, an appropriate reduction factor has to be applied to the soil resistance, otherwise the mere variation in soil and other pile installation

inadequacies in the field may not provide the desirable quality of foundations. Most EPC contractors are extremely reluctant to this FOS of 2.5 based on uplift and submit argument like the frost loads are serviceability loads and that FOS of 2.5 is too un-conservative for the solar panel foundations. Occasionally they suggest an FOS of 1.5 based on considering frost loads to be live load to keeping the pile lengths smaller, while others tend to evade this high factor of safety by resorting to the 200% design load testing suggested by ASTM D3689-07, Testing of deep foundations under static axial tensile load [14]. Such piles with low factors of safety will remain prone to uplift in extreme weather conditions.

Keeping in view such uncertainty in the magnitude of adfreeze stresses actually developing, it is imperative to use factors of safety in design of these piles as suggested by Canadian Foundation Engineering Manual so as to avoid any issues at a later stage and maintain a continuous generation of electricity from the solar panels.

Most piles for the load tests are fully driven into undisturbed soil and load tested. The pull out capacity of these piles is then compared with the design frost loads. By doing this, the skin friction of the effective frost depth zone is thereby also included in the pile resistance. To accurately assess the capacity of the embedment of the pile below the frost zone, it is preferable to pre-drill to the frost depth of the pile, install the pile with design embedment depth below the frost zone and test these piles for their capacity to hold against the frost uplift forces. Alternately, skin friction of the pile surface through the frost depth needs to be estimated/ calculated and added to the frost loads for comparison with the pull out capacity of the piles, for an accurate capacity assessment of the test pile.

Geotechnical Resistance Factors for Shallow and Deep Foundations NBCC (2005)		
Description		Resistance Factor, Φ
1.	Shallow foundation	
(a)	Vertical bearing resistance from semi-empirical analysis using laboratory and in-situ test data	0.5
(b)	Sliding	
(i)	based on friction ($c = 0$)	0.8
(ii)	based on cohesion/adhesion ($\tan \phi = 0$)	0.6
2.	Deep foundation	
(a)	Resistance to axial load	
(i)	semi-empirical analysis using laboratory and in-situ test data	0.4
(ii)	analysis using static loading test results	0.6
(iii)	analysis using dynamic monitoring results	0.5
(iv)	uplift resistance by semi-empirical analysis	0.3
(v)	uplift resistance using loading test results	0.4
(b)	Horizontal load resistance	0.5

Figure 4.1. Geotechnical resistance factors given by Canadian Foundation Engineering Manual

5. Understanding Correct Frost Penetration Depth under Solar PV Panel Tables

In a number of sites experiencing frost uplift, it revealed that a lower frost penetration depth was considered for design of the foundation piles embedment

based on the assumption that snow accumulation in the area will provide a cover and thus would result into a lower frost penetration depth. The actual situation on site is totally different. Due to the inclined shape of panel table structure with panels usually mounted at an angle of 200 to 300 with the horizontal, practically there is almost zero to very little snow accumulation in the area around the pile. This was observed in severe winter snowfall conditions at various solar PV farms thereby implying greater frost

penetration depths around foundation piles. For the solar PV farms where pile foundations moved out under the effects of frost after first few winters, it revealed in investigations that all the piles installed at these sites did not anchor below the maximum depth of frost. 100% piles at few sites had therefore to be remediated. There were other farms too where frost effects had to be remediated since they were also built with the assumption of snow accumulation leading to reduced frost penetration. Correct interpretation of frost is an important factor in design of foundation piles since frost loads are the governing loads in this region.

6. Design of Piles

Design of foundation piles for solar PV installation is usually carried out in following steps:-

- Establishment of maximum frost depth for the area.
- Calculation of factored design loads based on wind, dead and reasonable values for adfreeze loads according to soil type.
- Confirmation of pile resistance through pile load tests.
- Review of pile load testing and pile installation procedures to finalise design.

The estimate of adfreeze stresses has to be sensibly made between the average values given in the CFEM and the actual adfreeze stress values observed in field testing by Penner, 1974 [6] as given in Figure 3.3 for clayey silts (70:30 ratio) and Penner and Goodrich, 1983 [7] as given in Figure 3.4 for frozen gravels adhering to piles, based on which the average values are given by CFEM. Whilst selecting appropriate values of adfreeze stresses, it may be noted that the most favorable condition for growth of ice segregations and for frost heaving is slow freezing of moist nonhomogeneous organic silt or silty clay for which no values are given in CFEM, in addition to concrete piles in saturated gravel/sand. Hence appropriate values have to be obtained from literature.

$$F = \pi dl * \alpha \quad 6.1$$

Where F = Frost load, d = Outer diameter of pile, l = Frost depth and α = Adfreeze stress (KPa) for the appropriate soil type, taken from Canadian Foundation Engineering Manual [5].

The pile resistance is calculated based on pile load tests and/or the geotechnical investigations report for the depth of the pile embedded below the frost depth. An average value of soil resistance obtained from the pile load tests may be used to calculate the resisting capacity of the piles for the embedment length below the frost depth however, the safe pile resistance must be derived considering the geotechnical factors suggested in Canadian Foundation Engineering Manual as follows [3,5]:-

$$\text{Safe Pile Resistance} = \pi dL * \frac{\beta}{GF} \quad 6.2$$

Where d = Outer diameter of pile, L = the embedment length of pile below the frost depth, β = Average soil resistance (KPa) obtained from pile load tests and GF is the appropriate geotechnical resistance factor taken from Canadian Foundation Engineering Manual.

A review of the on-site pile load testing results carried out based on ASTM D3689, D1143, D3966 [14,15,16]

will indicate the soft spots in the area along with the performance of the piles during load testing including the pile installation procedures. A comparison of the factored design loads with pile load testing and pile installation procedures will indicate the suitability of the piles tested.

7. Conclusion

While the adfreeze stress values given in the Canadian Foundation Engineering Manual may be good for medium to high imposed loads, they are on the somewhat lower sides for the foundation piles for solar PV facilities which experience low gravity loads and the governing loads are usually uplift due to frost penetration. The adfreeze stress values of 65KPa given for concrete and 100KPa given for steel in fine grained soils are basically meant for clayey silts (70% clay & 30% silt) whereas the piles in silty soils experience larger adfreeze forces. Hence a careful selection of adfreeze stress for silty soils is required. TM5-852-4 of the US Army and Air Force indicates that the adfreeze stresses may be as high as 276KPa before the initial break in bond between frozen silty soil and steel pipe in tests carried out on an 8" pipe. Similarly, adfreeze stress developed on steel piles in saturated gravel can develop up to 150 KPa for steel piles as given in the Canadian Foundation Engineering Manual, while no adfreeze stresses are specified for concrete piles in saturated frozen gravel. The research by Penner, E. and Goodrich, L.E. on steel piles in saturated frozen gravel on smaller sized pipe i.e. 86mm diameter piles was observed up to 380KPa.

The adfreeze stresses also vary with the size of the piles with maximum stresses on the smaller sized pipes experiencing maximum adfreeze stresses as compared to larger diameter piles. The piles used in the solar PV industry are usually 4" to 6" in diameter or depth hence these smaller sized piles experience maximum adfreeze stresses as is shown in research by many researchers.

Solar PV Farms are a great source of renewable energy to the towns and suburbs in which they are located. By following the best engineering practices, these Solar PV Farms can be erected with minimal effort in short durations. Over the years, most EPC contractors have become more experienced having faced issues at some of the solar PV farms along with most designers and quality of construction is improving with the understanding of the issues involved. Rapid construction and commissioning of these farms along with associated advantages of minimal maintenance, low running costs and higher returns has increased the interest of large investment houses and financial companies in this sector due to which a large number of such renewable energy facilities have come up while many more are in the development stage in various regions of Ontario in Canada. Severe winters and extreme frost conditions pose unique issues with design and installation of pile foundations commonly used for solar PV racking structures and hence require careful design.

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