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Design of Piles for Utility Scale Ground Mounted Solar Systems in Ontario, Canada.

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Abstract: Wind and solar farms have come up to be popular sources of renewable energy in many parts of the world, in addition to other renewable energy sources. The province of Ontario in Canada has turned out to be one of the most popular locations for setting up renewable energy facilities because of its strong initiatives for sustainable policies and development along with attractive rates offered for renewable energy through Ontario Hydro's popular Feed-In Tariff (FIT) Program. In addition to wind, numerous Solar PV Farms have been completed; many are under construction while still more are in planning and permitting stage in this province, varying from 3MW to up to 260MW located in the suburbs of cities and towns which are being benefited from these renewable energy sources.

Winter conditions and extreme frost in certain areas in Ontario poses unique issues with construction of such utility scale farms. Typical ground mounted construction comprises of solar PV panels mounted on racking tables supported on foundations usually comprising of partially embedded steel pipes while foundations for inverter houses, control houses, transformer foundations and substation structures are either concrete pads or piles. While the substation structures, I-House and E-House foundations have well defined design procedures regulated by different codes and standards, the procedures, codes and standards for design and testing of lightly loaded solar PV structures still need to be formulated. In the absence of any specific codes and standards regulating the design aspects of these lightly loaded solar PV structures with frost uplift being the governing load in almost every case for Ontario, Canada, frost heaving and its effects are not very well understood and often create adverse conditions for these structures thereby affecting the production and continuous supply of renewable energy to the cities and towns in vicinity who purchase this energy.

This study investigates these unique issues related with renewable energy farms which are presented in this paper. The authors have been involved in design reviews, pile selection/ design and pile load testing in the majority of the solar PV farms either operational or under construction in Ontario along with being involved with the rehabilitation of farms affected by pile heaving issues [1].This paper carries out a critical study on the available design and installation procedures for lightly loaded pile foundations in the Canadian codes, regulations and engineering practices along with a review on the associated research on such foundations. Possible design, installation and testing procedures are also suggested to cater for such harsh conditions.

Keywords: Renewable Energy, Solar PV Farms, Solar Racking, Racking Foundation, Panel Tables, Solar Panels

I. INTRODUCTION

Generation of renewable energy is an important aspect of sustainability since the traditional methods of energy generation are a major source of pollution in this world. Solar Photovoltaic (PV) farms have come up to be very popular sources of renewable energy in many parts of the world along with other renewable energy sources. The best part for these generation systems are zero pollutants throughout their lifecycles, if appropriately designed, since everything involved in these solar PV generation facilities is recyclable at the end of their design lives. The province of Ontario in Canada has come up as a very popular location for setting up renewable energy farms because of the strong sustainability initiatives along with sustainable policies adopted by the government of Ontario. This province of Canada offers extremely attractive rates for purchase of all such renewable energy generated by such solar PV farms established in Ontario through Ontario Hydro's popular Feed-In Tariff (FIT) Programme for a usual period of 25 years. Due to this popular initiative, numerous Solar PV Farms have been completed and generating renewable energy while a number of solar PV farms are under construction with yet more are in planning and permitting stage in this province. Usual sizes of these farms vary from 3MW to 10MW with very few larger than these, up to 260MW have also been built and are in service. The present trend is to encourage large scale solar PV farms in the range of 200 to 300 MW. These solar PV farms are usually commissioned/ contracted for 25 years and are fully recycled at the close of contract with almost every component of these farms being recyclable.

Severe winters and extreme frost in Ontario pose unique issues with construction of such solar PV farms. Typically, solar PV panels are mounted on various shapes and forms of racking tables which are supported on foundation posts. These foundation posts are usually partially embedded steel pipes which carry the loads to the soil below. The foundations for inverter houses, control houses, transformers and other substation and transmission structures are concrete pads or piles which have well defined design procedures regulated by different codes and standards, however the procedures, codes and standards for design and testing of these lightly loaded solar PV structures still need to be formulated. Due to larger depths of frost penetration in extreme winter conditions, understanding the action of frost and related development of adfreeze on these lightly loaded pile foundations is extremely important. In the absence of any specific codes and standards regulating the design aspects of the solar PV structures and frost uplift being the major governing load in almost every case for Ontario, Canada, frost heaving and its effects may create adverse conditions for these structures thereby affecting the production and continuous supply of renewable energy to the cities and towns in the vicinity which purchase this energy. Being a newer industry and in the absence of specific codes and standards regulating the design aspects of the solar PV structures, differences usually erupt between EPC contractors and designers on design and testing of these foundation piles. This study investigates the unique issues related with the design and construction/ installation of foundations for solar PV ground mounted systems for extreme weather conditions in Ontario, Canada where deeper frost penetration presents major challenges to designer's and builders. These aspects are presented in details in this paper.

II. PLANNING/ DESIGN OF TYPICAL SOLAR PV FARMS

Typically lands selected for establishing Solar PV farms are barren/ semi barren lands with rare usage for regular farming. Such tracts of land which are in the vicinity of small towns and villages with the regular utility power lines existing nearby are selected for building solar PV farms. Usually the existing lay of the ground is maintained as far as possible so as not to affect the existing storm water flow patterns, keeping economy in construction in view.

Solar PV farms comprise mainly of rows of solar PV panels fixed on pre-engineered racking systems assembled in the field. 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. As the solar PV panels are exposed to the sun, DC current is generated in these panels. All the solar panels in each row are connected through wires which carry this DC generated by each panel to the combiner boxes. Usually each row of solar panels is connected to a combiner box towards its end. The wiring connects a set of combiner boxes with an inverter located in an inverter house. These inverters convert DC to AC. AC generated by a set of inverters is then fed to a step-up transformer which raises the voltages to higher levels suitable to be fed to the main utility lines to which the output is to be fed through a switching control and metering system. Suitable smart monitoring and control systems are usually installed to monitor the performance and control the functioning of these solar PV farms.

III. DESIGN OF RACKING AND FOUNDATIONS FOR SOLAR PV FARMS

A. Racking

A variety of pre-engineered racking systems are available in the market for various layouts of solar PV panels and quick installation. Most racking manufacturers provide racking designed to site specific conditions along with installation crews trained in installing these rackings at a swift pace. Most racking systems comprise of elements manufactured from either structural steel or a combination of structural steel and structural aluminium components. Most of the racking manufacturing companies get the racking design through wind tunnel tests. Most racking components have performed satisfactorily except for few racking types which caused damage to the solar panels due to fluttering/ vibrations in high winds due which they had to be strengthened/ replaced with stronger components with reduced vibrations

B.Racking Foundations

Typical foundations for the solar racking / panel tables comprise of various types of steel piles like steel pipes, screw piles, helical piles, steel piles jacketed in concrete through the embedment depths though ballast supported racking is also used in areas with very soft soils/ landfill sites. These piles are usually partially driven into usual soils but may be installed in pre-drilled holes in hard soils, soils containing large 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 is slightly expensive as compared to straight pile options. Such under-reamed piles are difficult to be installed in sandy soils without additional measures due to problems with retaining the soil along the pre-drilled holes.

Since a large number of such pile foundations are to be installed over a relatively shorter duration of time to maintain speed of construction and economy in construction too, foundations which pose least problems to ease of installation are usually selected. Usually around 5000 to 6000 such piles are required to be installed for a 10MW solar PV farm which is the usual size of Solar PV farms being installed in Ontario. Most EPC contractors prefer steel piles, whether plain, screws or helical, which can be installed relatively quickly since usual duration to complete a 10MW Solar PV farm is around 18 to 24 weeks including commissioning. In most cases, 2.75m to 5m 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 around 1m in solid bedrock forming rock sockets which provide sufficient resistance against uplift. Most helical and screw piles with similar shaft sizes of around 114mm to 125mm diameters and thicknesses around 6mm to 9mm are commonly used in solar industry.

The reactions on the foundation piles are obtained through the wind tunnel tests. The un-factored pile loads for these foundation piles range typically from 45kN to 60kN of compression, 8kN to 14kN of lateral, 15kN to 24kN of wind (up/down) and 5kN to 9kN of dead loads in Ontario.

The frost loads vary from 45kN to 76kN for 114mm outer diameter of the shaft of piles being used at most of the sites in Ontario, based on correct interpretation of frost depths. Ministry of Transport carried a 7 year in-depth study at various locations in Ontario where actual frost depths were measured over few years after which frost depths were calculated through various analytical methods too and the study concluded at suggesting maximum frost penetration depth contour plans for northern and southern Ontario as shown in Figures 1 and 2. Few EPC contractors tend to get lower frost depths calculated through their consultants to save on pipe, but usually such sites are the ones which are affected by frost in the first severe winter season.

Typical design values for adfreeze pressures on piles are taken from Canadian Foundation Engineering Manual [2] for steel and concrete which gives average adfreeze bond stress values for fine grained soils adhering to concrete and steel along with adfreeze stresses developed between saturated coarse granular with steel as shown in Figure 3.

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 [3] 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. Sailors Engineering Associates [4] carried out laboratory testing on samples of small diameter pipes with and without application of Slickcoat - 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.

1) *A study carried out by Parmesvaran [5] on adfreeze stresses on piles in ice shows following values:-*
   a) Concrete varying from 0.624 to 1.1 MPa
   b) Steel varying from 0.175 to 0.580 MPa
   c) Wood varying from 0.435 to 1.8 MPa
2) *Another study carried out by Hiroshi Saeki [6] on mechanical properties between ice and various materials indicated following results for adfreeze stresses: -*
   a) Concrete with 0.05 to 0.25 MPa
   b) Steel with 0.04 to 0.26 MPa
   c) LDPE with 0.01 to 0.03 MPa

Yet another study by L. Domaschuk [7], 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 5. Keeping in view such large adfreeze stresses actually developing, it is imperative to use higher factors of safety in design of these piles to avoid any issues at a later stage and a continuous generation of electricity is ensured from the solar panels.

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. 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. 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 a Factor of Safety added to the governing load case or a reduction factor 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 that it 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 and 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 [8]. Such piles with low factors of safety will remain prone to uplift in extreme weather conditions.

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.

IV. 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, 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 as shown in Figures 6 to 10. 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.

V. TYPICAL PILES AND THEIR PERFORMANCE IN VARIOUS SOIL CONDITIONS

To save on costs and time, typically the piles to be installed in the solar farms are tested by the EPC contractors mainly for uplift since the design is governed by adfreeze forces which are usually somewhat higher than the compressive loads, in addition to limited lateral testing. EPC contractors are reluctant to carry out compressive testing on piles and a usual argument given is that if the tensile resistance of the piles is larger than the compressive loads, the pile is good for the compressive loads too. This argument comes from the fact that soil resistance in tension is usually lower than in compression and has been tested to be right in most cases. In the presence of bedrock, piles anchored in solid rock forming rock sockets, at least 1m deep, are usual and provide sufficient uplift resistance. Helical piles have shown good resistance to uplift in soils depending upon the helix size and thickness but are difficult to install in the presence of boulders and cobbles in the subgrade while screw piles performance in dense soils requires slightly larger embedment depths for required uplift resistance.

One of the techniques followed by screw pile companies for installing screw piles in areas with bedrock and soil with gravel/cobbles/boulders is to pre-drill a hole slightly larger than the diameter of the screw (150mm for a 122mm diameter screw), backfill the hole partially with gravel in the bottom portion of the pile embedment, below the frost zone, and install the screw pile with the design torque. This technique did not perform very well in providing the required uplift resistance in many cases and many such screws failed in the field in Ontario. Few of such failing screw piles, when retrieved after load tests were seen to have their screws sheared off from the shafts. Larger lengths of such screws did provide better uplift resistances. However, when the same screw piles were installed in pre-drilled holes slightly smaller than the screw sizes (89mm for 122mm diameter of screw) without any gravel backfill, the screws were observed to perform better.

Pile installation in loose silty soils with ground water seepage has been a difficult proposal. Larger embedment depths of screw piles and helical piles may work if the qualities of soil at greater depths are better. Concreting around the piles in such areas provides larger contact areas in addition to slight increase in the dead loads which can increase the resistance of the piles to bear the uplift loads, however larger depths of embedment have to be resorted to. Sloughing and caving of the sides in the case of pre-drilling in such areas are usual issues along with curing of concrete in the presence of ground water seepage. Ground water must be pumped out from the pre-drilled holes before concreting otherwise segregation of mortar and aggregates is likely in case the concrete is poured on seepage water inside the pile holes. Tremie method is advisable for concreting in the presence of water.

VI. LACK OF TESTING ON QUALITY AND LIFE CYCLE OF PILES

In the absence of any Canadian codes, Standards and Regulations on load testing of piles, testing of deep foundations is usually governed by ASTM 3689 [8] for axial tensile testing, ASTM 1143 [9] for axial compression testing and ASTM 3966 [10] for lateral testing of piles. The foundation piles for such facilities are not designed based on the soil geotechnical characteristics but are usually selected based on the limited pile load tests carried out in the area they are to be installed. When it comes to testing foundation piles for solar PV farms where a relatively large number of piles are to be installed, these standards do not provide definitive guidelines on numbers of piles to be tested for design testing or production testing although they do layout a very detailed procedure on methodology of carrying out the testing itself and its procedures and measurements to be taken along with failure criteria. The various testing methods given in these standards also do not differentiate between design testing and production testing. These aspects always pose a problem for the designer to specify an appropriate number of pile load tests which should be carried out on site to confirm the capacity of the piles. While most EPC contractors tend to go with as little as 2 to 4 pile load tests for design verification with few only willing to carry out 8 to 10 pile load tests for design verification for the entire farm, and around 1% of piles for production testing. It is worthwhile mentioning here that for the usual size of solar PV farm with 10MW capacity; usually around 5000 to 6000 piles are to be installed on an area of around 60 to 80 acres of land. The geotechnical investigations too for such large areas are investigated at 8 to 10 points only. Hence with limited geotechnical investigations and a very large number of piles to be installed, extensive testing is required. Most EPC contractors are reluctant to carryout extensive design testing and argue that they will carry out production testing on 1% of the piles. It must be understood that design testing is carried out for the design load with an appropriate factor of safety included to confirm the capacity of the piles while production testing is merely to confirm the correct installation of the piles and hence production testing is carried out at 100% of the design load. Production testing is not an alternate to design testing. Another reason of reluctance to design testing by the EPC contractors is also on the grounds that the solar panel support structures are not life-threatening structures and any movement is of little consequence if it occurs. However most EPC contractors did understood the consequences when they were explained the possible effects of moving out of piles uniformly/ differentially which could make electrical wires taut and break the connection between panel tables, combiner boxes can be damaged with damaged wires due to frost heave effects, additional stresses can be induced in racking beams to damage them while large movement can damage the panels too due to distortion , all of which can result into loss of production along with rehabilitation effort and the expenses involved.

To ensure that the piles will perform satisfactorily throughout the design life and to maintain the quality of construction, a reasonable number of piles should be installed at various locations throughout the site and subjected to design load (including the factor of safety given in the Canadian Foundation Engineering Manual) testing throughout the area with minimal failure rate. Since a large number of piles are to be installed on such sites, an appropriate number of piles usually suggested for design testing and pile selection should be 1% of the total piles installed although the percentage can be raised for trouble soils. Another way of controlling this issue is to specify a failure rate like < 0.5% to 1% for the entire site which is being adopted by few owners of such farms being built now. Production testing may be based on ANSI ASQ Z1.4 [11] which is a good reference since it provides sufficient guidelines and tables to interpret the sample size and failure rate of the piles over the entire site. Canadian Foundation Engineering Manual [2] guidelines are extremely useful in this context since it suggests that piles must be tested up to twice the design load and preferably up to failure for design stage load testing.

VII. CONCLUSION

To keep these Solar PV renewable energy generating facilities running continuously and to provide optimum renewable energy uninterruptedly, the foundations for such solar PV panel systems be conservatively designed against reasonable adfreeze loads and the appropriate geotechnical resistance factors / safety factors suggested in the Canadian Foundation Engineering Manual since it is understood that the suggested adfreeze stresses given by the Canadian Foundation Engineering manual are lower bounds only and are the average residual pressures after the initial bond break between the frozen soil and the pile whereas actual adfreeze pressures before bond break which are responsible for the upward movement of the piles could be much higher.

Solar PV Farms are a very efficient source of renewable energy with completely sustainable objectives. Solar PV Farms can be built in short period of time with minimal effort. These renewable energy farms have minimal maintenance through their service life comprising of change of major parts like inverters and transformers, on completion of their design life in addition to other smaller issues. Every component of these solar PV farms is recyclable at the end of their design life. Over the years, some designers and EPC contractors have become somewhat experienced in design and construction of such facilities, having faced issues mentioned in this paper at some of the earlier constructed solar PV farms with the quality of construction improving with the understanding of the issues involved however others still need to be careful with the issues mentioned in this paper. Rapid construction and commissioning of these solar PV farms along with minimal maintenance, low running costs and better rates offered by Ontario government under its FIT Programme has greatly 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 either already been built and many more are in the development stage in various regions of Ontario in Canada. This source of clean energy is greatly helping the universe in achieving sustainable objectives.

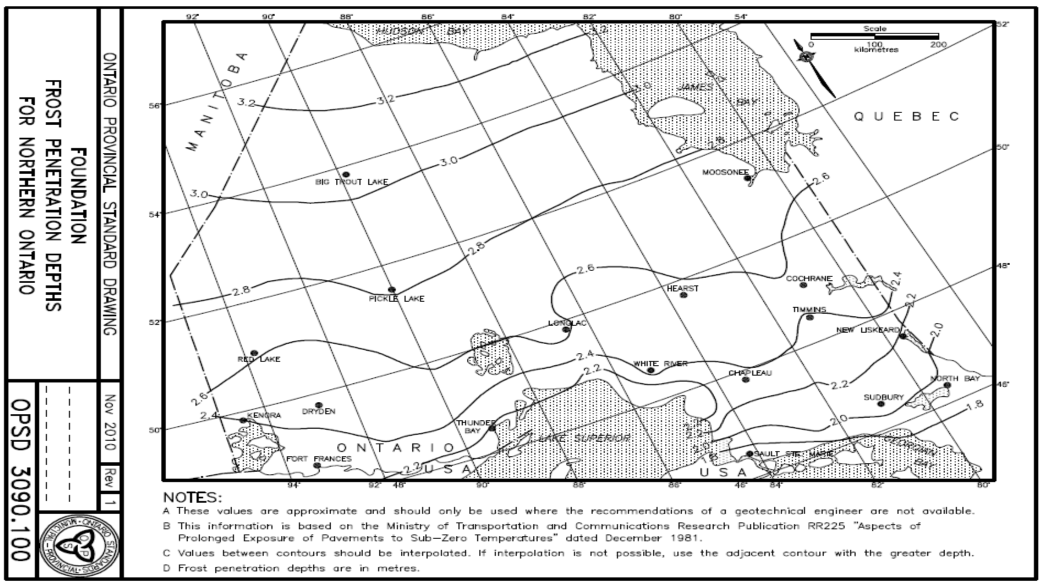

Figure 1. Typical frost penetration depths in Northern Ontario.

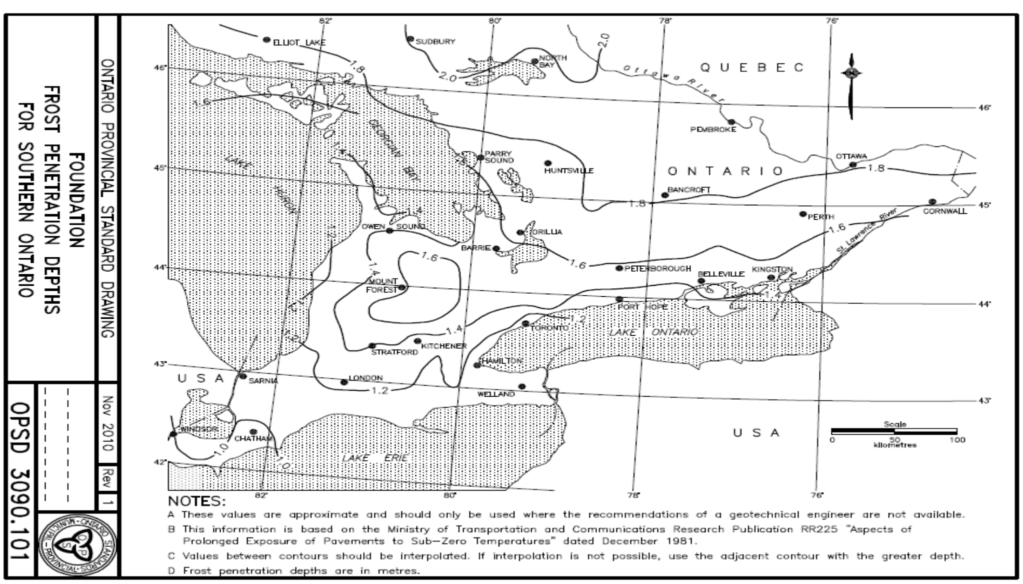

Figure 2. Typical frost penetration depths in Southern Ontario.

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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. Average values of adfreeze bond stresses between concrete and steel fine grained and saturated coarse-grained soils. (Taken from Canadian Foundation Engineering Manual [2].

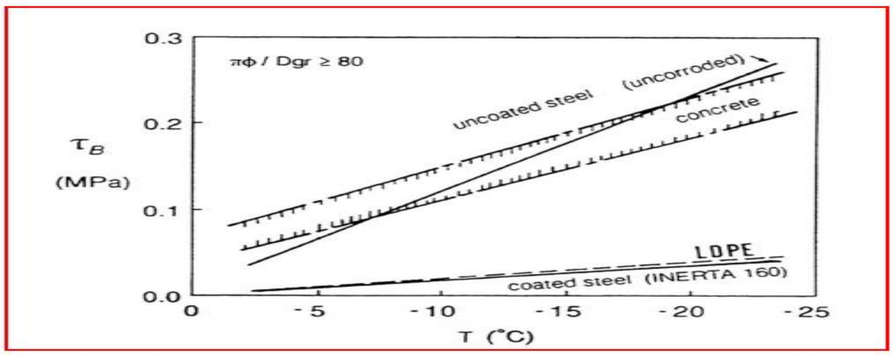

Fig. 11 Effects of ice temperature on adfreeze bond strength of various materials

Figure 4. Adfreeze stresses due to ice on various materials [6].

TABLE 2. 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	Tsytovich (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	Parameswaran (*Pers. commun.* 1979)	small model, piles extracted, wood	1220–2420
		steel	1146
		concrete	1611
sand	Tsytovich (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 5. Adfreeze stresses between various soils and piles of different materials [7]

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TABLE 8.1 *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 ϕ = 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 6. Geotechnical resistance factors given by Canadian Foundation Engineering Manual.

Figure 7. Typical row of solar panels in winter showing very little to no snow accumulation around foundation piles.

Figure 8. A pile moving out due to frost

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Figure 8. Piles affected by frost showing deformation of the racking

Figure 9. Pile moved into soft soil before concreting

Figure 10. Pile failure in uplift in load testing in soft soils

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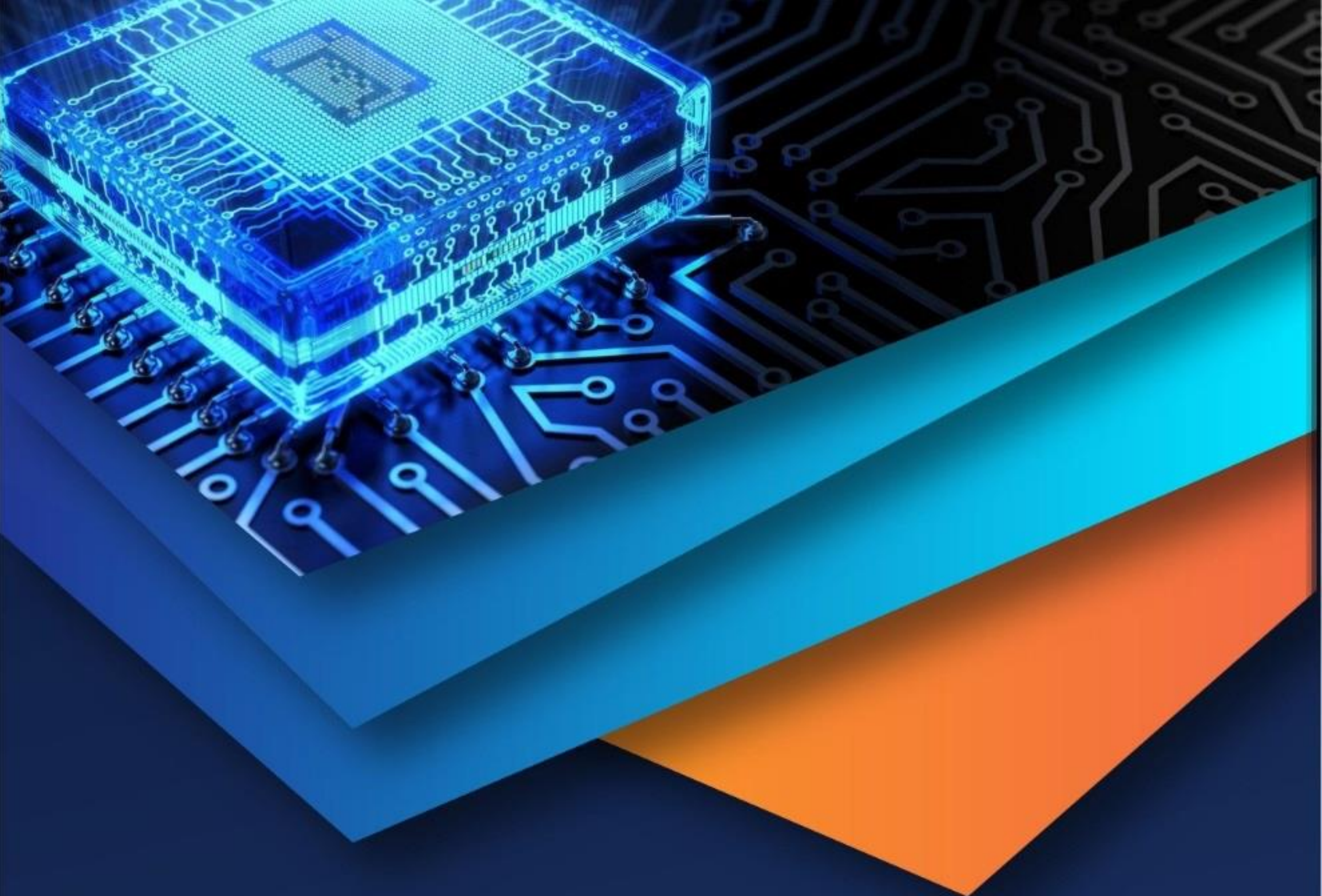

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