terrasmart™

White paper

Drilling down on frost heave in utility-scale PV

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Executive summary

As more photovoltaic projects are developed in areas subject to deep freezes, there is growing concern about potential damage caused by frost heave and the subsequent frost jacking of embedded foundation structures.

Over time, repeated heaves and thaws can warp racking systems, cause connection failures, break PV module glass, disrupt electrical terminations, and severely shorten a solar plant's lifespan. Such damage severely impacts O&M budgets and erodes the long-term Levelized Cost of Energy (LCOE) performance of an asset.

Proper design from the outset to counter the stresses of frost heave, however, can mitigate and even prevent such damage in the first place. In addition to explaining the types of soils and conditions most likely to experience frost heave, this paper outlines how to determine the recommended design parameters for a given site and how to calculate potential loads for various frost depths.

While potential strategies and mitigation measures for using traditional driven piles are discussed, it becomes clear that ground screws are the preferred solution for counteracting significant cases of frost heave.

Terrasmart's proprietary technology — developed over the course of a decade of in-field experience embedding over 1.2 million ground screws — provides reliable, efficient installation that remains rock steady in the world's deepest frost zones.

2

Introduction

As the demand for renewable energy grows across North America, an increasing number of utility-scale photovoltaic (PV) projects are being deployed in regions that experience severe winter conditions, including deep ground freezes. With that freezing comes frost heave and subsequent frost jacking of foundations, which can wreak havoc on installations not properly designed to compensate for those stresses. To contend with the potentially catastrophic consequences of this geotechnical phenomenon, solar EPCs, developers, and asset owners need to understand the forces at play so that they can protect themselves from risks of overextended schedules, budget overruns, equipment damage, and system downtime.

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Frost heave

a. Definition and causes

Frost heave is the upward ground movement that occurs as soil freezes. Originally thought to occur as soil volume increased when water became ice, frost heave now is understood to occur because of ice lenses, which form parallel to the surface from water diffused within the soil. As frost penetrates the ground, water is drawn up into the freezing zone, forming layers that force soil particles apart and cause the soil surface to heave, as depicted in
Figure 1. Three factors need to be present for frost heave to occur:

1. Frost susceptible soil with pore sizes that promote capillary flow of water
2. Freezing temperatures that penetrate the ground
3. Presence of groundwater

Depending on the degree of these three factors, soil can heave at rates ranging from 1/64th of an inch to three-quarters of an inch each day.[1]

For PV plants with driven piles, the foundation also can be subject to adfreeze, in which the frozen soil adheres to the steel surface of the piles. This adfreeze, combined with frost heaving of the soil adjacent to the piles, results in an uplift force known as frost jacking, which lifts the foundation.

Figure 1 shows how permanent vertical deformation of the foundation can occur if it has not been designed to resist the frost jacking force through sufficient embedment below the frost zone. Later, when the ice melts and water dissipates back into the soil, the foundation and structure drop into the resulting void.

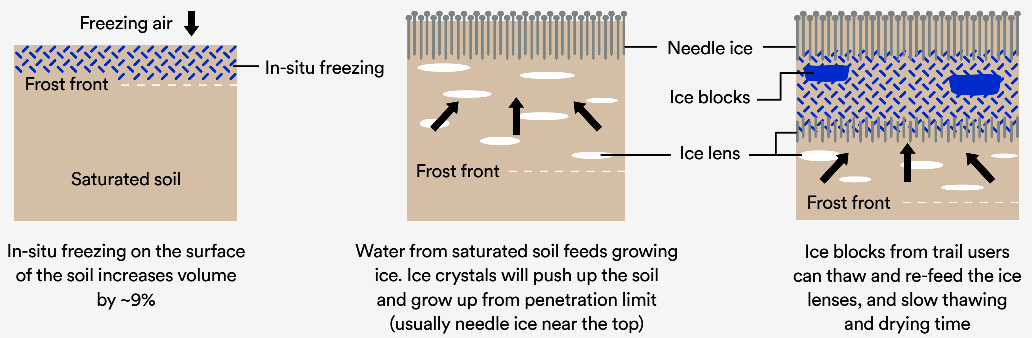

Figure 1: Effect of frost on soil

Such damage severely impacts O&M budgets, erodes the long-term levelized cost of energy (LCOE), and impacts the performance of the assets.

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[1] Michael A. Reed, Frost Heaving Rate of Silty Soils as a Function of Pore Size Distribution, (Indiana, Purdue University, 1977), 12.

b. Soil types and frost heave

Most soils can heave if there is a sufficient freezing rate and water supply. But the rate at which soil can heave is dictated by its grain size structure and subsequent permeability and capillary flow. Generally speaking, soil can be classified into three groups: sand, silt, and clay. Sand and gravel, with their large grain sizes, are most permeable to water, which can help to move moisture away from the surface before it freezes. Clay soils have the smallest grain size, which means low permeability that impedes the rate at which water can feed a growing ice lens.

With grains that are smaller than sand but larger than clay, silt is the most susceptible to frost heave because its fine grain structure holds water within the frost depth zone. Silt also promotes capillaries that allow more moisture to feed into ice lenses, which can grow to be up to four inches thick.

c. Where frost heave occurs

Geographically, frost heave can occur anywhere that experiences freezing temperatures, but it becomes a more significant issue in northern climates where temperatures remain below freezing for prolonged periods of time. A shallow, brief freeze does not allow enough time for ice lenses to form and deepen. In general, the deeper the average frost depth, the greater the likelihood of frost heave and the more significant damage can be.

As previously discussed, frost heave requires freezing temperatures, fine-grained soils, and the presence of groundwater. Fine-grained soils are common in the Northeast and Midwest, where glacial till is widespread, as shown in Figure 2.

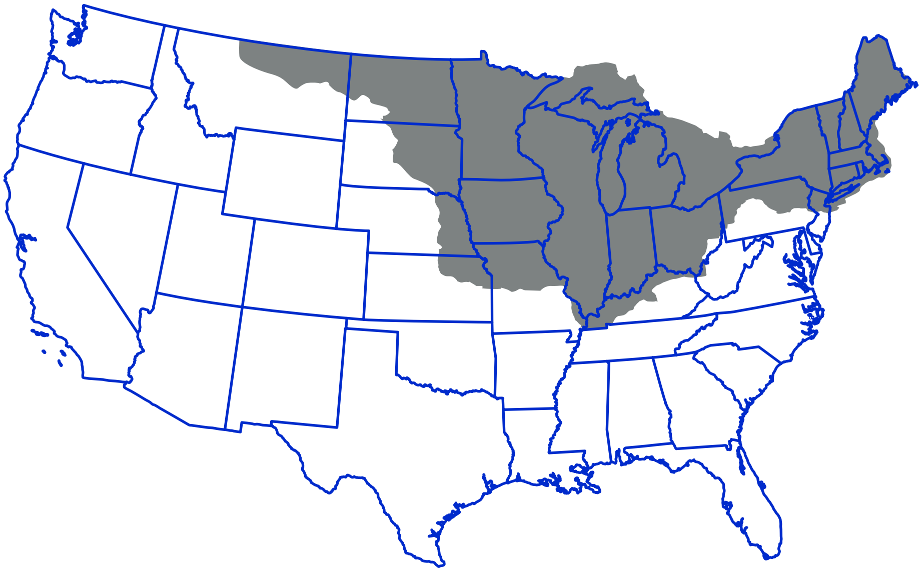


Figure 2: Map of glacial till occurrence in the U.S.

Northern regions in the United States typically have soils based on glacial till, the fine-grained silt sediment deposited by receding glaciers. Figure 2 shows where glacial till is most commonly found. The Northeast also experiences the country's longest, deepest freeze conditions. Nonetheless, the region's PV market is one of the fastest growing in the country, making frost heave considerations all the more critical there.

The U.S. Army Corp of Engineers conducted extensive research to classify the frost susceptibility of soils based on percentage of fine grain particles, soil type, and results from laboratory freezing tests. Results of this classification show the soils with higher percentages of fine grain material are classified as the most frost susceptible and which show the highest rates of frost heave.

Frost Group	Degree of Frost Susceptibility	Type of Soil	Percentage Finer than 0.075 mm (# 200) by wt.	Typical Soil Classification
F1	Negligible to low	Gravelly soils	3-10	GC, GP, GC-GM, GP-GM
F2	Low to medium	Gravelly soils	10-20	GM, GC-GM, GP-GM
		Sands	3-15	SW, SP, SM, SW-SM, SP-SM
F3	High	Gravelly Soils	Greater than 20	GM-GC
		Sands, except very fine silty sands	Greater than 15	SM, SC
		Clays PI > 12	-	CL, CH
F4	Very high	All Silts	-	ML-MH
		Very Fine Silty Sands	Greater than 15	SM
		Clays PI < 12	-	CL, CL-ML
		Varied clays and other fine grained, banded sediments	-	CL, ML, SM, CH

Table 1: Frost susceptibility classification of soils (NCHRP 1-37a)

The degree to which frost heave will impact a site is directly related to the depth the ground fully freezes.

This is typically referred to as depth of frost penetration or, more simply, frost depth.

When designing a foundation, estimating frost depth becomes the critical design parameter to determine frost heave's potential effects.

Figure 3 shows the frost heave forces acting over the frost depth on a driven pile.

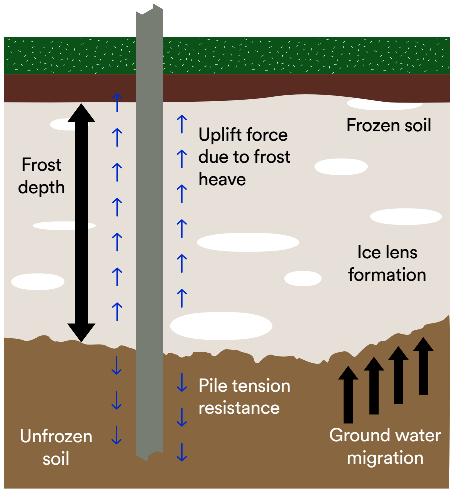


Figure 3: Frost heave forces on a driven pile

d. Methods for determining frost depth

Frost depth is related directly to how long the ground surface is exposed to below-freezing temperatures. Annual temperature data collected from weather stations quantifies historical exposure. This data is then used to calculate an air freezing index, or AFI, a metric that quantifies the annual below-freezing temperatures. An example of this metric is shown in Figure 4, which is a generalization of the temperature fluctuation for the site of interest. The AFI is represented by the portion of the curve — units of degree-days — that is below freezing temperatures.

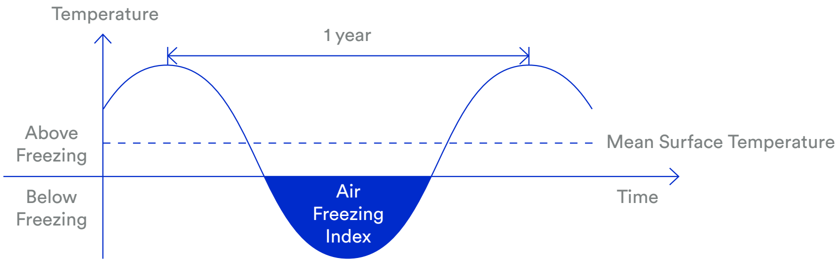


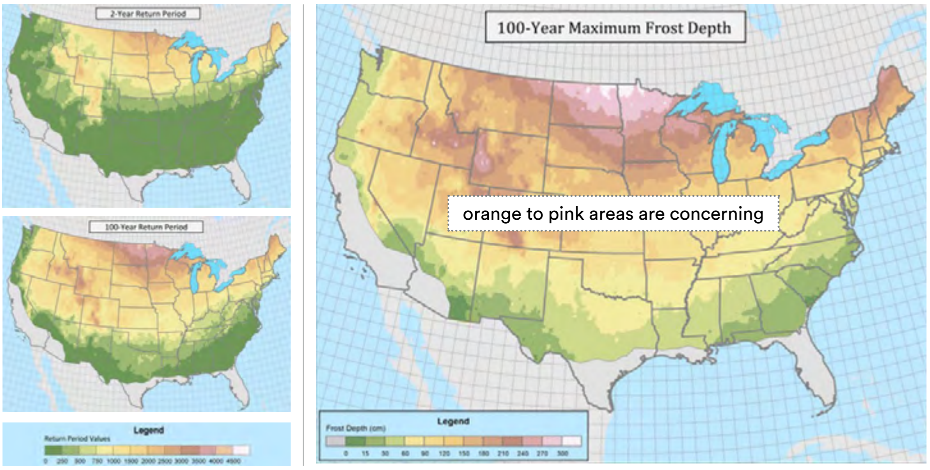
Figure 4: Air freezing index (AFI) curve

AFI values can be collected over multiple years and statistically analyzed as a generalized extreme value probability distribution, which is useful for assessing any return period. AFI values can be used to estimate a frost penetration depth. As shown in Figure 5: AFI and Frost Depth Maps (100-year AFI map), northern regions of the United States are more prone to longer periods of below-freezing temperatures, which result in relatively deeper frost penetration.

Multiple methods exist to estimate frost penetration depth that accounts for soil type and ground coverage. An example of this calculation is shown in the equation below developed by Brown (1964)[2] which estimates the frost penetration depth, FD, for a bare ground surface (i.e., no snow or sod coverage) for an AFI return period of 100 years. The results of this estimation, based on National Oceanic and Atmospheric Administration (NOAA) reports, are shown in Figure 5.

$$FD = 0.0174\ (AFI100yr)0.67$$

Brown (1964)



orange to pink areas are concerning

Figure 5: AFI and frost depth maps

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[2] Brown, W. G., 1964: Difficulties associated with predicting depth of freeze or thaw. Can. Geotechnol. J., 1, 215–226.

e. The impact of poor frost heave planning

Although frost heave impacts can be avoided if mitigations are accounted for from the start, even projects where designers believed they had taken appropriate measures have been damaged.

Poor execution and costly assumptions

In 2015, researchers investigating frost heave at PV farms in Ontario, Canada, found that none of the piles installed at damaged sites had been anchored as they should have been, which is below the actual maximum frost depth. Instead, designers had used lower frost penetration depths because they assumed that snow accumulation would provide some ground cover, reducing frost penetration.

Unfamiliarity with calculating frost depths and adfreeze stress values

According to a paper published in the American Journal of Civil Engineering and Architecture[3], investigators discovered that modules installed atop piles deflected snow away from the ground, which meant that there was in fact little to no snow accumulation — and therefore, no cover to mediate frost penetration. Researchers also found that system designers did not understand that average adfreeze stress values listed in the Canadian Foundation Engineering Manual were low and not as damaging as actual stress values observed in the field. Actual frost depths and adfreeze stress values, they found, often were much greater than those outlined in the manual, prompting them to call for establishing a new factor of safety to be incorporated into future designs.

Ill-equipped local building codes

Standards are still being developed in emerging markets, which means that local building codes frequently are older and ill-equipped to accommodate solar. For example, the original pile contract for a 10-megawatt solar farm was set at $1.6 million for materials and installation over the course of six to eight weeks. To stay within budget, the contractor sank pilings only to the minimum depth required by local codes. By the time spring rolled around, frost heave had displaced nearly every piling.

Remediation costs climbed to nearly $8 million — more than four times the cost of the original contract — and stalled the facility’s operational date for six months.

Not accounting for varied soil condition on site

In a paper presented to the GEOQuebec 2015 conference[4], researchers described two private utility-scale PV sites in southwestern Ontario that had been damaged by frost heave during the first winter after they were built.

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[3] Kibriya T, Adfreeze Forces on Lightly Loaded Pile Foundations of Solar PV Farms in Cold Regions, (Delaware, American Journal of Civil Engineering and Architecture, 2015), 109-117.

[4] Pierre-Philippe Levasseur, A Case Study of Frost Action on Lightly Loaded Piles at Ontario Solar Farms, (Quebec City, GEOQuebec 2015, 2015), 2-6.

More than 25,000 steel H-piles were driven to support the two facilities. The 15-foot piles were embedded 11 feet into the ground, leaving four feet of exposure to mount the solar panels above expected snow accumulation levels. Both sites had varying soils considered among the most susceptible to frost — silt and silty sand, with some silty clay and fine sand reported. Estimated frost depth levels were expected to be between 43 inches and 55 inches.

By the end of the first winter after construction:

- Up to 9 percent of Site A's piles had moved 1.4 inches — beyond the project's structural tolerance
- Up to 17 percent of the site A's piles had moved between 0.8 inches and 1.4 inches
- Site B fared somewhat better, with less than 2 percent of its piles shifting more than 1.4 inches and 9 percent moving between 0.8 inches and 1.4 inches

Researchers noted that Site A's piles shifted most in areas where its groundwater levels were highest, permitting more ice lenses to form closer to the surface.

Several remedial measures have been tried at the Ontario solar farms — including resetting piles with hydraulic pressure, insulating around the piles, and over-excavating to pour concrete bases below the frost depth — but researchers did not spell out costs for such measures. Nonetheless, researchers noted that remediation has been costly: "The implementation of remedial measures has had significant cost implications on many solar farm projects, sometimes largely exceeding the initial construction costs." Industry averages would indicate that remediation likely cost up to four times the original material and installation cost for the foundations.

Impact of frost heave on pile foundations

Figure 6 illustrates frost heave's effect on pile foundations found in the Midwest. These photos show two examples of piles that were uplifted twice during frost heave. During the first event, the pile jacked about three inches above surface level, and then the second event jacked the pile three to four inches, for a total uplift of almost eight inches above surface level.

Figure 6: Frost heave effect on piles

4

Frost heave and foundation design

a. Designing foundations with frost heave in mind

Of course, frost heave is not unique to the solar industry. Local jurisdictions long ago began developing regulations intended to mitigate it in all types of construction. Typical building codes in the Northeast, for example, require engineers to consider a frost depth averaging around 48 inches in their load calculations, although the northern part of Maine has depths up to 90 inches.

Because building codes are not granular about specific sites within a region, developers should seek out more detailed data about their unique location. Frost depth maps are available from several government agencies, including the NOAA — which synthesizes such data because frozen soil generates problems for a variety of industries, from building construction, transportation to farming.

Developers also can hire a geotechnical engineering firm, which can provide a detailed report about the unique aspects of a development site. Geotechnical engineers can help determine if frost susceptible soils are present.

b. Calculating loads for frost depth

Once the frost depth value is known, engineers can estimate adhesion forces on piles to determine how strongly the soil will grip to a foundation as it freezes. Because all foundations exist to some degree within the frost zone, measures must be taken to prevent adfreezing and upward movement through frost jacking. It is generally accepted that the adfreezing bond stress of 100 kPa (14.5 psi), as outlined in the 4th Edition of the Canadian Foundation Engineering Manual (CFEM),[5] can be used to calculate estimated uplift force caused by adfreezing. Uplift force is calculated using the formula below. In this calculation, we assumed an **ABS of 14.5 psi, a W6X9 pile with a perimeter of 27.22", and a frost depth of 48".**

UF (uplift force) = ABS (adfreezing bond stress) x FD (frost depth) x P (perimeter of the pile)

$$UF = 14.5 \text{ psi} \times 48 \text{ in} \times 27.22 \text{ in}$$

$$UF = 18{,}945 \text{ lbs}$$

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[5] Canadian Geotechnical Society, Canadian foundation engineering manual. (Vancouver, BC, 2006), Ch. 13.

After an uplift force from frost heave has been estimated, the resisting tension capacity of the foundation must be determined. Tension capacity for embedded foundations — piles — are generated through side friction between the pile surface and soil. There are various design methods to determine soil/pile skin friction which can be based on soil type and in situ testing. For the solar industry, pile capacity typically is estimated through project-specific load testing because it provides the most accurate and cost-effective means of determining the tension capacity. Typically in PV design for northern regions, frost heave forces will apply the largest tension loads to the foundations.

Because the frost heave uplift force will act over the frost depth, that portion of the pile side friction is disregarded. This results in a need for longer piles to ensure adequate tension resistance for the portion of the pile below the frost depth. Figure 7 shows the frost heave forces which need to be estimated in the frost depth zone. This figure also shows the portion of the foundation below the frost depth line that can be used to resist the frost heave force. Additional cost and specialized equipment are required for piles longer than 17 feet.

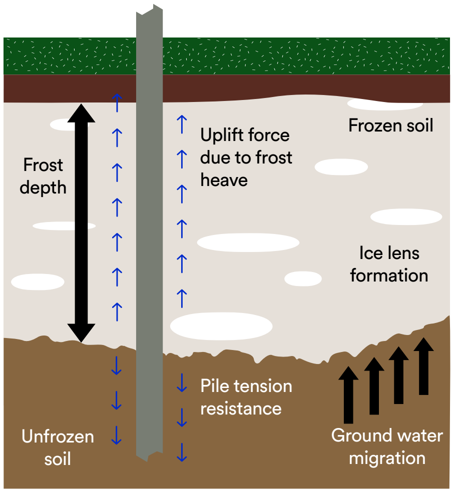

Figure 7: Frost heave forces on a driven pile

5

Foundation strategies

a. Potential mitigation measures

Once engineers know the load that any given foundation might face, different mitigations and foundation strategies could be put in place to offset potential damage:

- **Longer pile:** Embedding piles at three times the frost depth could mitigate against frost heave but driving 18- to 30-foot piles (standard piles are ten feet) is unwieldy, requires specialized equipment, and increases the likelihood of refusal upon striking bedrock, boulders, or cobbles.
- **Slick coat:** Reducing adfreeze with special coatings can keep piles in the ground, but requires another phase of highly specialized manufacturing that drives up costs and lead times.

- **Gravel sleeve:** Encasing piles in a PVC sleeve or a combination of a sleeve and gravel can prevent frost heave, but the cost and time involved in doing that for thousands of piles on a project is prohibitive. Additional costs could include importing the fill, allowing additional install time to drill the required holes, and removing the spoils afterward.
- **Ballast:** Digging below the frost line and pouring a concrete base for each pile may prevent heaving, but requires costly excavations and a significant amount of concrete to withstand wind uplift loads.
- **Ground screws:** Hollow tube that has multiple threads that lead to a pinpoint. This type of foundation provides the greatest counterforce against pullout.
- **Helical:** Cylindrical post with a helix attached near the bottom. These are often cost prohibitive due to the increased drilling required if you hit refusal.

b. Analyzing costs for different strategies

None of the options for mitigating frost heave using standard piles is ideal because each measure results in additional costs. Depending on the option selected, the project's timeline must be extended to allow for special installation requirements. And each potential frost mitigation measure adds to foundation costs; comparisons of the various options are shown below in Figure 8. Because the ballast option has been proven to be excessively expensive, it is rarely used. Pile options are more cost effective, but carry some additional cost uncertainty because of the difficulty involved in installing them. This additional cost is represented by the green portion of the chart. As seen in the chart, ground screws offer a cost-effective solution while negating any unforeseen additional cost, which will be explored further in the next section.

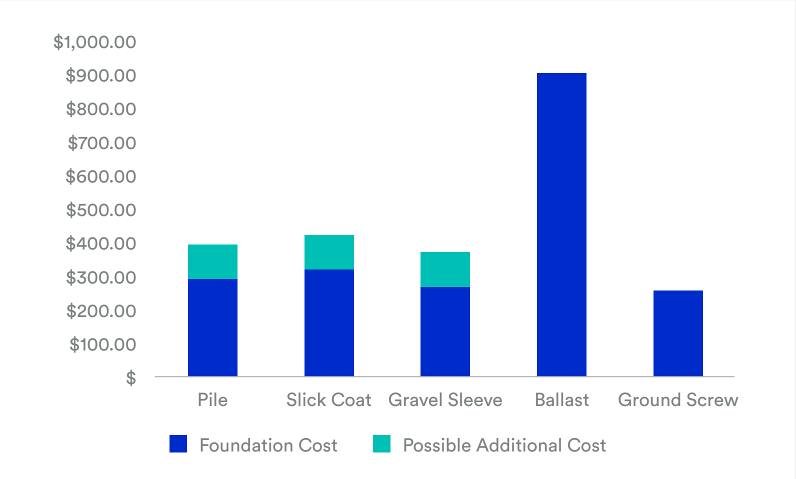

Figure 8: Cost comparison between foundation types*

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*Costs based on pricing from 2019

6

Mitigating frost heave with ground screws

a. Advantages in resisting frost heave

In addition to enabling development of previously inaccessible rocky, steeply sloped sites, ground screws have proven uniquely suited to deep-freezing regions. Because its 34-inch threaded section is embedded below the frost line, a ground screw can resist the upward force of ice lenses while its tip creates a cone of firmly embedded soil that resists frost heave. In addition, the three-inch diameter screw provides less surface area against which frost heave forces can work versus standard driven piles such as W6X9, as shown in Figure 9.

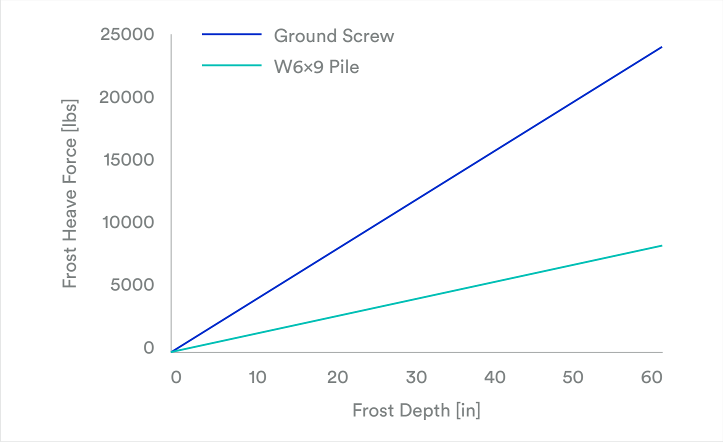

Figure 9: Estimated frost heave force vs frost depth for solar foundations

b. Leading the way with an in-field expert

To combat frost heave, Terrasmart combines site load testing with its extensive database to ensure each ground screw has an adequate tensile capacity. Terrasmart's data library, developed over the course of ten years of load testing, has resulted in the development of proprietary formulas to calculate the most reliable designs for ground screw installation.

Based on information gathered in the field, Terrasmart is able to establish site-specific ground screw capacity as determined by reliability-based design methodology. Uncertainties in the ground screw's capacity are quantified statistically using both the site's load test results and our historical ground screw database. Design capacities are then calculated based on a reliability index. This in turn allows us to specify an installation torque that ensures every ground screw installed meets the required reliability for each project. Figure 10 is a graphical representation of Terrasmart's ground screw database collected from over 1,600 ground screw load tests.

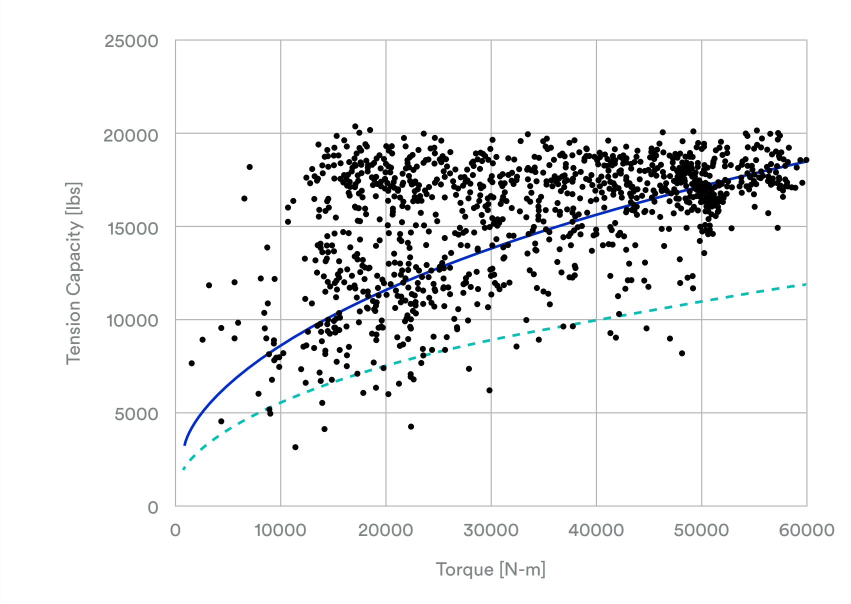

Figure 10: Terrasmart's proprietary ground screw database

7

Stories of success

a. Gardner, Massachusetts

Shortly after Terrasmart began working in frost-susceptible areas, the company received a report from Gardner, Massachusetts that several of the racks it had installed at a 7 MW site were sinking into the ground. When crews did an urgent new survey, they discovered that the developers had misinterpreted what they were seeing; the racks had not moved at all. The front edges of the rows were still in alignment and the top elevation of the ground screws had not changed.

Instead, because the ground screws supporting the racks were so firmly embedded, frost-heaving soil had swelled up several inches beneath the rack, burying the tops of the ground screws. When the spring thaw came, receding soil left streaks of dirt down the sides of the re-exposed ground screws, indicating the integrity of the foundation.

The photos in Figure 11 illustrate the impact of frost heave at this site. The first two images show the ground elevation near the top of the ground screw, where typically it would be six inches below. The second set of images show the same rack locations after the heave with the foundation's integrity maintained.

Figure 11: Real-life example of ground screw performance in a site pre and post frost heave

The ground rose to the top of Terrasmart's ground screws to about 6 or 7 inches high. The racking foundation never moved during the frost heave period.

Same site in Massachusetts post frost heave. Terrasmart's ground screws have a lifetime guarantee up to 20 years on a project site.

b. Milo, Maine

In 2020, Terrasmart worked on an 100-acre solar project in the town of Milo, Maine. Challenging site conditions included a deep frost line, high ground snow loads of 90 psf, and wind loads of 105 mph.

Our ground screw foundation and GLIDE Agile racking was selected for the site. Designed to work with tough soil conditions, the ground screws were able to penetrate the site's 59" frost depth, increasing installation efficiency and mitigating the risk of frost heave. The GLIDE Agile's install-friendly design also accommodated the modules' 25-degree tilt angle, adjusted to a front panel clearance of 36" to allow for snow shedding.

The site currently produces 27.5 MW of clean energy to power 10,000 homes in Milo, saving Maine taxpayers up to $25 million in a period of 20 years[6].

Figure 12: Utility solar project in Milo, Maine utilizing GLIDE Agile

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[6] https://www.newscentermaine.com/article/news/local/as-seen-on-tv/new-solar-farm-in-milo-set-to-power-more-than-10000-homes/97-4e0af4c2-4a0d-4338-838a-57bc72fc40a7

c. Bangor, New York

A 6.77 MW solar project in North Bangor, New York engaged Terrasmart for its foundation and racking solutions. Despite tough environmental conditions—with ground snow loads of 80 psf and wind loads of 99 mph—Terrasmart was able to ensure reliable performance using its TerraTrak single-axis tracker system.

A total of 1,890 ground screws were drilled to a frost depth of 52”, minimizing the risk of frost jacking. This was paired with TerraTrak’s A-frame design for added strength and stability, providing durable racking for 16,718 panels. Meanwhile, the tracker’s advanced monitoring and control enabled by PeakYield™ technology delivered maximized energy production. On-site weather stations and integrated weather API monitors wind and snow conditions and proactively stows the site before bad weather approaches.

Figure 13: North Bangor site installed with TerraTrak.

8

Conclusion

While the deep frost of northern climates may not seem hospitable to utility-scale PV installations, advance planning and proper design can help ensure success comparable to that found in milder climates.

Partnering with an expert that has in-field experience with frost heave ensures you set your project up for success from the onset. Mitigating the impact of frost heave can save you from unplanned expenditure and remedial costs, while ensuring the longevity of your solar projects.

Find the right solution for your projects and mitigate risk with the help of an expert partner.

Author

Michael Faraone
Ph.D., P.E. | Director of Engineering

Dr. Faraone joined Terrasmart in 2016 as a geotechnical engineer and has since become Director of Engineering, leading the engineering department to develop, analyze, and test the company's progressive solar-racking solutions. Dr. Faraone received his Ph.D. in Geotechnical Engineering from the University of Florida, where he was a research engineer working on the development of reliability-based designs for deep foundations for the Florida Department of Transportation. His experience in deep foundations and extended studies in geotechnical engineering has earned him the nickname "Dr. Dirt."

terrasmart™

About Terrasmart

Terrasmart's comprehensive portfolio of racking, eBOS, and project optimization software offers diverse solutions that power our customers to solar success. Backed by 13 years of experience installing over one million ground screws, and an 85-year track record building efficient structural systems, we know our way around complex sites.

With a combined installed capacity of over 19 GWs across 4,600 projects, we understand how to evaluate each project's unique profile. Whether it's rocky soils, slopes and terrain, time of year of construction, or risk tolerance — from the owner or the EPC contractor — our experts can help navigate the best path to project success.

Working closely with EPCs and developers to identify and source the most suitable options, we help to unlock the most value possible, delivering cost and schedule certainty on any site, anywhere, and under any conditions.