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Performance of Diamond Pier® Foundations in Frost Zone Soils – 2009-2019 Frost Study

Introduction

First introduced into the Minnesota market in 2009, Diamond Pier foundations (models DP-50 and DP-75) have demonstrated the ability to resist the negative effects of frost heave in mild, moderate, and severe frost prone soils. Over a 10-year period, Diamond Pier foundations have resisted the effects of frost heave in 99.7% of footing installations in the study area discussed in this document, which covers Minnesota and portions of neighboring states in the Northern Midwest.

Even though performance has been validated through thousands of actual installations, the marketplace remains concerned regarding the use of Diamond Pier foundations in frost prone areas. Absent any ASTM testing methodology for foundation systems in freezing conditions, the building code industry depends upon observational evidence as the basis for deriving a reasonable standard of performance for a given frost zone depth. Diamond Pier footings are designed with wide-spread bearing pins that provide equivalent or better uplift resistance compared to traditional footings without requiring as much depth to accommodate for frost heave.

Pin Foundations, Inc. (PFI) developed the bearing pin concept in 1984 and introduced the Diamond Pier product into the marketplace in 1993. PFI created the engineering knowhow and acceptance criteria protocols to establish bearing capacities for ICC-ES AC336, "Acceptance Criteria for Bearing Pin Piers." In 2005, PFI submitted observational evidence of performance in accordance with AC336 to the ICC-ES, which published evaluation report ESR-1895. This report states, in paragraph 2.0, "The bearing pin piers are permitted for use in any of the weathering classifications defined in 2018 IRC Figure R301.2(4) or 2015, 21012, 2009 and 2006 IRC Figure R301.2(3)."

Over the years, PFI has submitted the following reports supporting the observational evidence of equivalent or better performance regarding frost heave resistance:

- 2005 – National Performance Affidavits
- 2010 – Final Frost Performance
- 2011 – Observational Report

These reports are available on our website: www.diamondpiers.com. Although the IRC cannot address uplift and lateral capacities for a foundation assembly, PFI has taken additional steps to publish third-party accredited testing to demonstrate the effectiveness/equivalency of our product to prescriptive methods regarding bearing, uplift, and lateral loads (see EEI, 2017).

PFI used the USDA Web Soil Survey to assess a large area of soil conditions around Minneapolis, Minnesota – the highest concentration of Diamond Pier Installations. We found 29 percent of soil in this area described as having Severe Frost Susceptibility. However, the performance of the Diamond Pier to resist the effects of frost heave are reflected in the statistics described herein.
(see Figure 4)

This study document adds considerably to our observational evidence by providing performance data for DP-50 and DP-75 installations over a decade in the frost prone Minnesota and surrounding areas. We first describe the mechanics of frost heave, before discussing the performance data, and concluding with incidence rates.

Understanding the Mechanics of Frost Heave

The study of frost heave and freezing soils is complex. To date there is no accepted methodology for determining the severity of frost force or for quantifying that force acting on a foundation. Therefore, no engineering calculation exists to determine "frost force," nor is there any established testing methodology regarding frost protection for any foundation system or type.

In a comprehensive study, Edwin J. Chamberlain, a research engineer for the US Army Cold Regions Research and Engineering Laboratory, evaluated methods available for testing the frost susceptibility of soil. It is evident from his introduction that no repeatable testing method had been developed:

> "The search for a reliable method to evaluate the frost susceptibility of soils has gone on for at least the past 50 years. More than 100 methods have been proposed since Taber's treatise (1929) on the mechanism of ice segregation in soils and Casagrande's conclusions (1931) that 'under natural freezing conditions and with sufficient water supply one should expect considerable ice segregation in non-uniform soils containing more than three percent of grains smaller than 0.02 mm, and in very uniform soils containing more than 10 percent smaller than 0.02 mm.' Even though there has been almost continuous research on frost heave since then, Casagrande's criteria are still the most successful for predicting the frost susceptibility of soils, in spite of the probability that he never intended that they be universally applied.
>
> The abundance of methods for determining the frost susceptibility of soils is evidence of the lack of success in developing a comprehensive method. Obviously, each has been developed because others have proven to be unsatisfactory. In many cases the new criteria have been successful for specific but limited purposes. In most cases, however, there is little evidence as to the degree of success, i.e. most new criteria receive little scientific field validation."
>
> (Chamberlain, 1981)

The key points from Chamberlain's observations for the severity of heave in frost zone soils seem to revolve around some common criteria and/or the interrelationship of several possible factors. These include, but are not limited to, soil type, rate of heat removal from the soil, moisture content, overburden stress, and repeated freeze-thaw cycling.

Soil Type

The Unified Soil Classification System (USCS) is used professionally to define and classify the texture and size of soil particles. Soil is typically a mix of silts, clays, sands, and aggregate.

The United States Department of Agriculture (USDA) uses a soil classification system that is relatively simple (see Figure 1), whereas the USCS classification is more complex (Figure 2). There is no direct relationship between these soil classification systems.

The USCS classification is represented by two letter symbols. Each letter is described in the symbol chart shown in Figure 2, with the exception of Pt (highly organic soils), which is located at the bottom.

The soil texture and particle size have an influence on the severity of frost heave. Sands and gravel sands (GW, GP, SW, SP) have low susceptibility to frost heave, whereas silty soils (ML, MH) have the highest susceptibility to frost heave. Clay soils (CH, OH, CL, OL) fall into a medium to high susceptibility to frost heave.

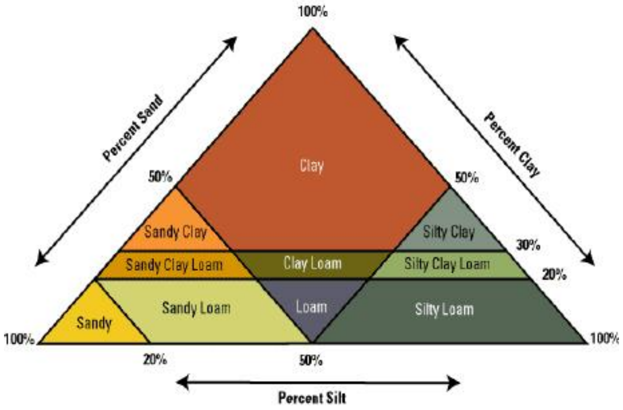
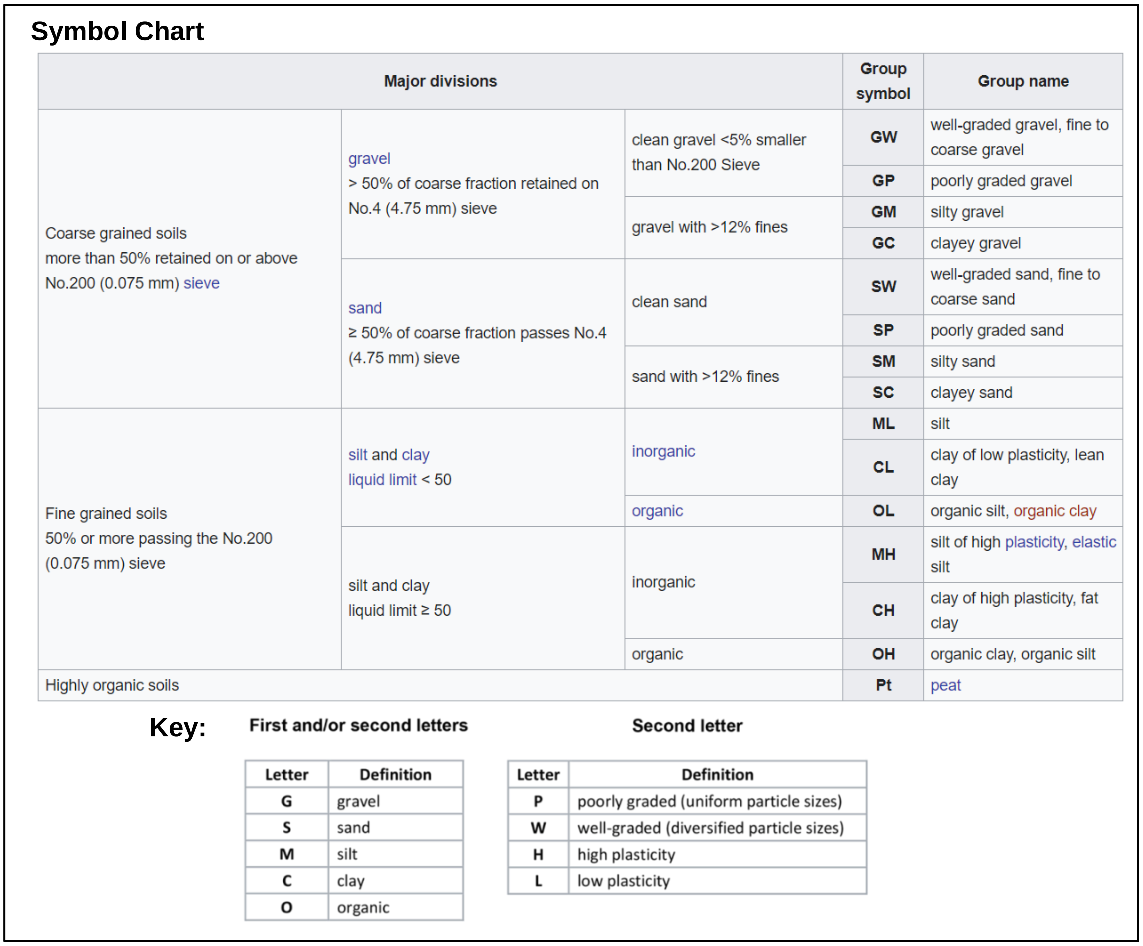


Figure 1. USDA Soil Classification System



Symbol Chart

Major divisions			Group symbol	Group name
Coarse grained soils more than 50% retained on or above No.200 (0.075 mm) sieve	gravel > 50% of coarse fraction retained on No.4 (4.75 mm) sieve	clean gravel <5% smaller than No.200 Sieve	GW	well-graded gravel, fine to coarse gravel
			GP	poorly graded gravel
		gravel with >12% fines	GM	silty gravel
			GC	clayey gravel
	sand ≥ 50% of coarse fraction passes No.4 (4.75 mm) sieve	clean sand	SW	well-graded sand, fine to coarse sand
			SP	poorly graded sand
		sand with >12% fines	SM	silty sand
			SC	clayey sand
Fine grained soils 50% or more passing the No.200 (0.075 mm) sieve	silt and clay liquid limit < 50	inorganic	ML	silt
			CL	clay of low plasticity, lean clay
		organic	OL	organic silt, organic clay
	silt and clay liquid limit ≥ 50	inorganic	MH	silt of high plasticity, elastic silt
			CH	clay of high plasticity, fat clay
		organic	OH	organic clay, organic silt
Highly organic soils			Pt	peat

Key:

First and/or second letters

Letter	Definition
G	gravel
S	sand
M	silt
C	clay
O	organic

Second letter

Letter	Definition
P	poorly graded (uniform particle sizes)
W	well-graded (diversified particle sizes)
H	high plasticity
L	low plasticity

Figure 2. USCS Classification of Soils Symbol Chart (ASTM, 2018)

Chamberlain references a soil type classification table (Figure 3), which is also reproduced in IRC Table R405.1 under Section R405, Foundation Drainage. As stated earlier, however, soil type alone cannot be assumed to solely cause heave in frozen ground and other influencing environmental factors need to be considered.

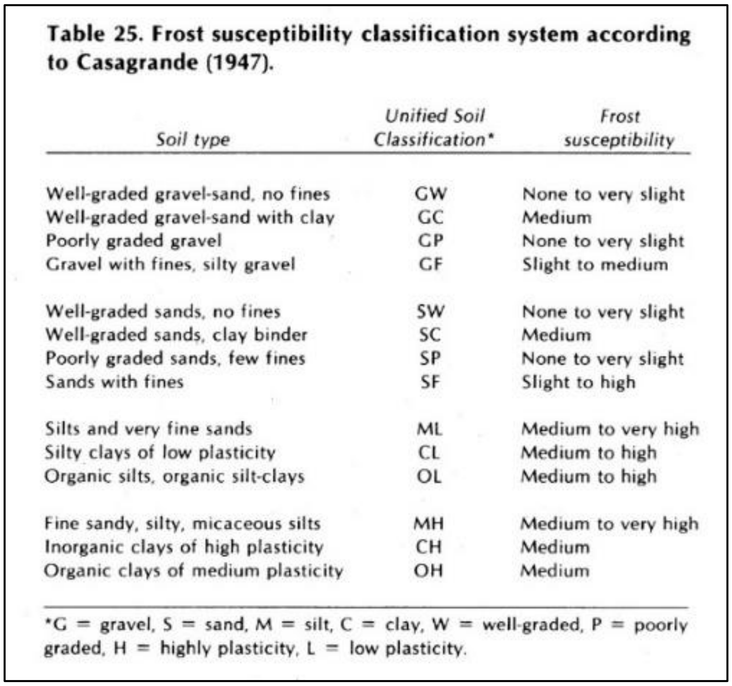


Table 25. Frost susceptibility classification system according to Casagrande (1947).

Soil type	*Unified Soil Classification**	*Frost susceptibility*
Well-graded gravel-sand, no fines	GW	None to very slight
Well-graded gravel-sand with clay	GC	Medium
Poorly graded gravel	GP	None to very slight
Gravel with fines, silty gravel	GF	Slight to medium
Well-graded sands, no fines	SW	None to very slight
Well-graded sands, clay binder	SC	Medium
Poorly graded sands, few fines	SP	None to very slight
Sands with fines	SF	Slight to high
Silts and very fine sands	ML	Medium to very high
Silty clays of low plasticity	CL	Medium to high
Organic silts, organic silt-clays	OL	Medium to high
Fine sandy, silty, micaceous silts	MH	Medium to very high
Inorganic clays of high plasticity	CH	Medium
Organic clays of medium plasticity	OH	Medium

*G = gravel, S = sand, M = silt, C = clay, W = well-graded, P = poorly graded, H = highly plasticity, L = low plasticity.

Figure 3. Frost Susceptibility Classification System (Chamberlain, 1981, p. 30)

To assess a large area of soil conditions, PFI used soil data provided by the USDA. The USDA classifies frost susceptible soils into three categories: Mild, Moderate, and Severe (see USDA, 2019). For an illustrative example, we compiled soil information from the USDA Web Soil Survey around the Twin Cities area of Minnesota and calculated the percentages of the three soil types in the area (see Figure 4).

In the area outlined in Figure 4, roughly 29% of the soils are defined by the USDA as Severe Frost Susceptible Soils (SFSS). Given the large number of Diamond Pier installations spread across the Twin Cities area, it can reasonably be assumed that a sizable portion of the Diamond Pier footings have been installed in SFSS

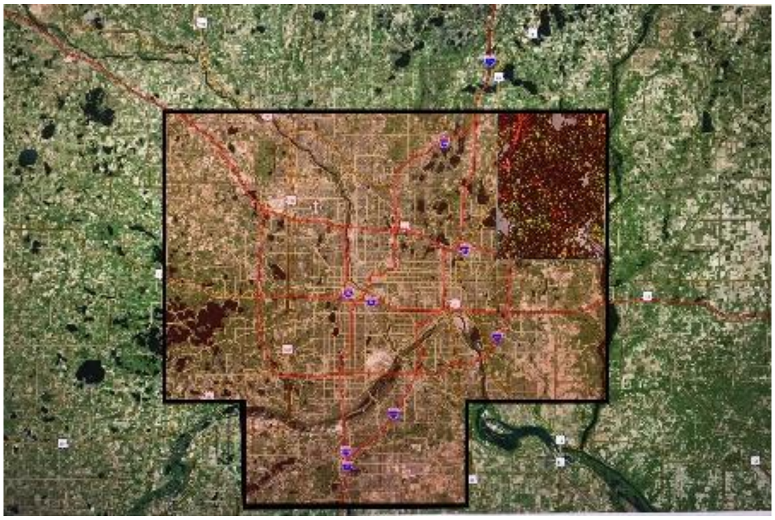


Figure 4. Area Showing Percentages of Frost Susceptible Soils in the Twin Cities Metro Area.
Outlined area shows Moderate soils (40.33%), Severe soils (29.37%),
and Mild soils (30.30%); methods of analysis are available from PFI upon request.

What is not reflected in the soil condition map are other environmental factors that can greatly affect the occurrence of frost heave such as:

Rate of Heat Removal from the Soil

The rate of soil temperature drop contributes to the severity of frost heave effects. The depth of snow cover or other insulators affect the freezing gradient; however, there seems to be confusion and debate on this topic as the soil type and temperature gradient has produced varying results (Chamberlain, 1981, pp. 8-9).

Moisture Content

High moisture content and high water tables increase the potential for frost heave.

Overburden Stress

Overburden stress is a factor in limiting the effects of frost heave. These loading types are as follows: point load, line load, uniformly loaded circular area, rectangular loaded area, and strip loading (see Chegg, 2019).

Repeated Freeze-Thaw Cycling (Thaw Weakening)

Repeated freeze-thaw cycles alter the soils to varying amounts, which tends to increase the effects of frost heave. According to Chamberlain, several unpublished studies have shown that freezing and thawing can greatly affect frost heave. For a clay soil, a second freeze was reported to have increased the amount of frost heave by a factor of 8 when the surcharge was 3.5 kPa (see Chamberlain, 1981, Figure 15). However, Sherif et al. (1977) reported that the amount of frost heave for a silty sand decreased with freeze-thaw cycling.

It is important to note that frost heave has more to do with soil type and contributing factors, than with the depth of the frozen ground, which varies year to year.

Code Compliance for Point Load Footings Based on Depth

The historical solution to mitigate negative structural impacts of frost heave on isolated point load footings for lightweight structures, such as decks, screen porches, gazebos, etc., has been to design a footing to be buried to an assigned depth. Problems with this method include:

- *The depth relies more on anecdotal observations and experience of what seems to perform to a reasonable standard.*

- *To our knowledge there is no testing standard that relates the depth of a footing and its ability to resist frost heave.*

PFI realizes the fundamental performance of an isolated point load footing in freezing soil is to counteract the upward heave forces by providing greater uplift resistance through a wide pin spread engaging a large soil overburden, while minimizing the footing area that frost can engage.

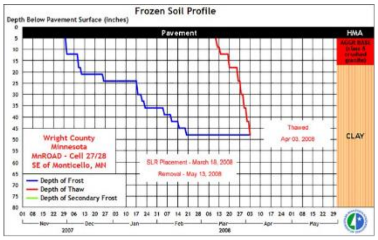
Without a reliable testing or engineering methodology to determine frost force, PFI has conducted uplift testing to quantify an uplift resistance value to compare to the method the industry has deemed an acceptable expectation of performance.

The standard practice, however, is based on trial and error. The current practice of installing an isolated point load footing in a frost zone soil is to start with setting the footing at an assigned depth based on frost history in the area. If the footing fails, then it is replaced with a deeper, bigger footing, with the belief that greater uplift resistance is achieved by making the foundation heavier. If that footing fails to resist frost heave, then best practice is to install an even bigger, deeper footing or to bell the base of the footing. This process of increasing uplift resistance continues until the effects of frost heave are overcome, without really understanding the mechanisms at work.

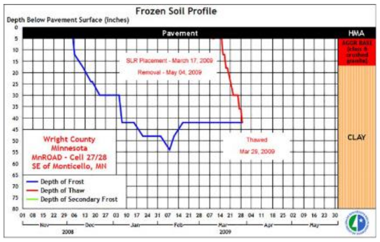
The ability of an isolated point load footing to resist frost is not merely the result of installing the footing below the depth of frozen ground. If it were, knowing that frost depths vary year to year and by locations, there should be ample evidence that depth of footing alone creates an acceptable foundation. But the general failure rate of all footings does not solve the frost heave question with historical frost depth measurements.

The Minnesota Department of Transportation published frost depth charts from 2007 to 2017 for Wright County, Minnesota, at the following web address:
http://dotapp7.dot.state.mn.us/research/seasonal_load_limits/thawindex/frost_thaw_graphs.asp
The graphs in Figure 5 show this 10-year history of frost depth. During 7 of the 11 years recorded, the ground froze below the 42" depth for footings required by the 2015 Minnesota Residential Code, yet the 42" deep footings performed successfully. Likewise, there are instances in which PFI has witnessed 42" concrete footings heaving when the frost depth was above the 42" designated depth.

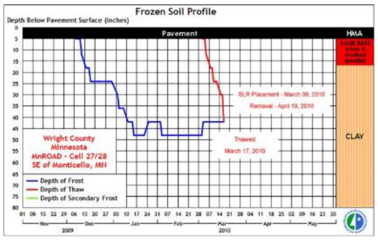
In conclusion, frost action is a phenomenon that is exceedingly difficult to predict or test. One can only define statistically reasonable performance criteria, <u>not an absolute solution.</u> The building standards industry has established that level of performance based on years of trial and error, and PFI seeks to establish equivalency to those standards with its own performance review.



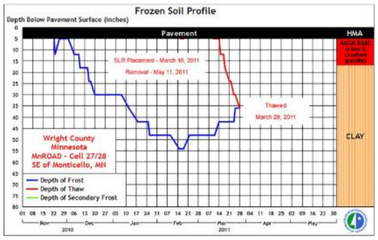
2007 – 2008 Winter
Max Frost Depth 48”



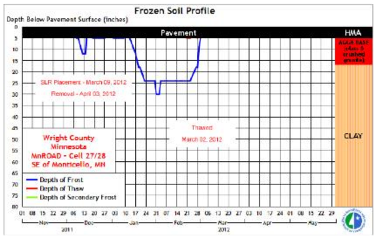
2008 – 2009 Winter
Max Frost Depth 53”



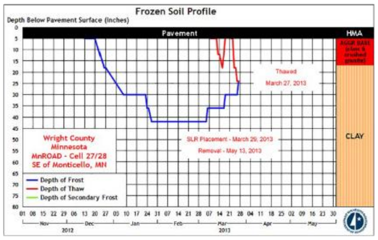
2009 – 2010 Winter
Max Frost Depth 48”



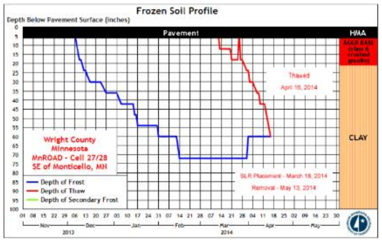
2010 – 2011 Winter
Max Frost Depth 53”



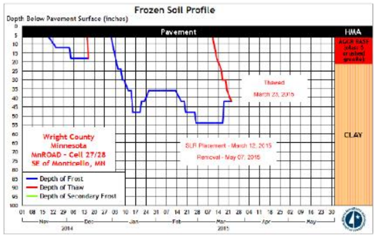
2011 – 2012 Winter
Max Frost Depth 30”



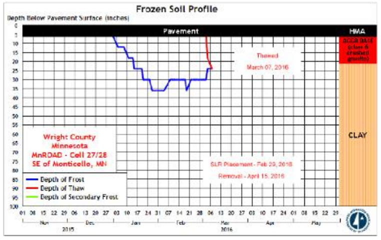
2012 – 2013 Winter
Max Frost Depth 42”



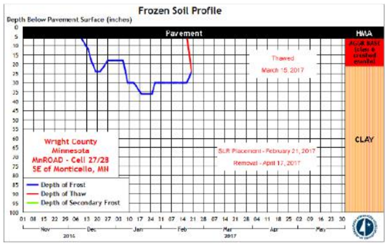
2013 – 2014 Winter
Max Frost Depth 72”



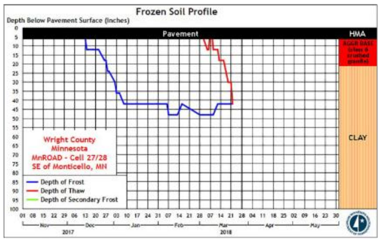
2014 – 2015 Winter
Max Frost Depth 54”



2015 – 2016 Winter
Max Frost Depth 36”



2016 – 2017 Winter
Max Frost Depth 36”



2017 – 2018 Winter
Max Frost Depth 48”

MnDOT
Maximum Frost Depth
Wright County, MN

2007	2008	48 inches
2008	2009	53 inches
2009	2010	48 inches
2010	2011	53 inches
2011	2012	30 inches
2012	2013	42 inches
2013	2014	72 inches
2014	2015	54 inches
2015	2016	36 inches
2016	2017	36 inches
2017	2018	48 inches

Figure 5. Ten-Year History of Frost Depth in Wright County, Minnesota

Diamond Pier Performance Data for 2009-2019

Evidence of Equivalent Frost Heave Protection

The study area for this discussion covers Minnesota extending into western Wisconsin, eastern North and South Dakota, northern Iowa, and Omaha, Nebraska. The total number of Diamond Pier model DP-50 and DP-75 footings installed in this area at the end 2019 is 95,000, or just over 14,200 projects that have been installed using Diamond Pier footings.

Over a 10-year period, PFI has been notified of unacceptable movement due to frost in 70 of the 14,200 projects, which represents 0.00493% of the projects installed. This represents ½ of 1% (0.005).

These sites were investigated and all were found to have severe frost heave potential according to the USDA Web Soil Survey and did not meet specific PFI conditions and uses guidelines found in the Diamond Pier Installation Manual (PFI, 2018; see first paragraph under “Supporting Soils,” page 5).

Even on these sites, most piers were unaffected, with 102 requiring intervention - 63 adjusted and 39 replaced. The piers replaced represent about 1/20 of 1% (0.00041) of Diamond Pier footings installed.

The incident rate is far lower than might be expected based on frost susceptibility soil conditions parameters as well as many environmental cycles and represents statistical evidence of wholly acceptable Diamond Pier performance in frost zone soils.

We have not received a single reported movement issue for DP-50 and DP-75 footings installed according to the guidelines in the Installation Manual.

Incidence Rates

Considering all installed Diamond Piers in the study area, both conforming and not conforming to the Diamond Pier Installation Manual instructions, the following statistics were recorded:

- Percentage of projects reporting some type of movement – 70 divided by 14,200 = 0.00493, or ½ of 1%.
- Number of footings requiring intervention – 102 divided by 95,000 = 0.00107, or 1/10 of 1%.
- Number of footings requiring replacement – 39 divided by 95,000 = 0.00041, or 1/20 of 1%.

Such low incidence rates provide a statistical measure of acceptable performance, considering the many and varied soil conditions encountered in the frost zone.

PFI feels this represents valid empirical evidence of equivalent or better performance when compared to anecdotal performance of traditional concrete footing.

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