ITG

Innovative Technologies Group

Technologically, Ecologically & Economically Sound Foundation & Anchorage Systems for Uses in all Industries

Eco-Tech Foundations

Report of Testing

The Moment & Bearing Foundation Systems, including the Anchorage & Hydraulics Systems used in Thier installation

Methods & Apparatus contained within this Report have Patents issued &/or Pending in the USA, Canada, Australia & select EPO Countries

Report of Testing

conducted & prepared by

The National Wind Technology Center
at
The National Renewable Energy Laboratory
in
Golden, Colorado

Letter Report of Results for Testing the ITG Moment and Bearing Foundations

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Executive Summary

Foundation cost is a substantial component of the overall cost of a wind turbine. The objectives of this CRADA are to determine the viability of a new, hydraulically installed, metal foundation technology for use with both large and small wind turbine installations, 2) demonstrate the installation and load carrying abilities of the foundations, and 3) verify the load carrying capacity models for the foundations. The novel foundation system offers many features including time savings, economic savings, and environmental friendliness. The technology may be especially beneficial for reducing the cost of energy in mountain regions, remote locations, poor soil conditions, and offshore installations.

The scope of this test includes monitoring the difficulty of installation and removal of the foundations and testing the foundation strengths in dry conditions. Two types of foundation systems were tested. A moment foundation system designed to primarily withstand overturning moments and bearing loads and a bearing foundation system designed to withstand uplift and bearing loads.

The moment foundation system was designed to withstand the overturning moment from a 50 kW wind turbine. The foundation system withstood 100% of the design load. The first installation attempt was terminated when rock was encountered by the nose of the foundation and the ultimate strength of the installing anchors was exceeded. The “nose” of the foundation was damaged and the lower 16 inches of the foundation removed. Upon drilling new holes adjacent to the first holes, the moment foundation was installed without any significant movement of the anchors.

The bearing foundation system met and surpassed its design requirements. The bearing requirements were exceeded by 22%. The developed final bearing capacity was 3.4 times greater than the unconfined compressive strength at a depth of 20 ft as determined by a soils report. The system proved its ability to greatly increase the natural bearing capacity of the soils using a controlled installation method. It also demonstrated the ability of the ITG anchor to be constructed and installed.

Introduction

Overview

Foundation cost is a substantial component of the overall cost of a wind turbine. The objectives of this CRADA are to determine the viability of a new, hydraulically installed, metal foundation technology for use with both large and small wind turbine installations, 2) demonstrate the installation and load carrying abilities of the foundations, and 3) verify the load carrying capacity models for the foundations. The novel foundation system offers many features including time savings, economic savings, and environmental friendliness. The technology may be especially beneficial for reducing the cost of energy in mountain regions, remote locations, poor soil conditions, and offshore installations.

The scope of this test includes monitoring the difficulty of installation and removal of the foundations and testing the foundation strengths in dry conditions. Two types of foundation systems were tested. A moment foundation system designed to primarily withstand overturning moments and bearing loads and a bearing foundation system designed to withstand uplift and bearing loads. The installing anchors may be removed after installation or remain permanently attached to the system if uplift load resistance is required. In practice the bearing foundation system is likely to be used at the base of guyed towers and truss towers and the moment foundation system will be used with stand-alone tubular towers and as guy anchors.

The moment foundation was tested using a surplus 250 kW wind turbine tower and the 600 kW Advance Research Wind Turbine (ART) as shown in Figure 1. This arrangement was chosen rather than attaching a guy from the top of the tower to a ground anchor because this arrangement results in a constant compressive force at the foundation. This prevents variable downwards forces from complicating the test and helps makes the cause of failure more evident.

The sizes of the foundations were selected in part to support a turbine as large as possible but still use equipment of a manageable size and cost. Both truss towers and tubular towers were considered. Manufacturers' plans for future tower designs were also considered. Wind turbine models considered include a Bergey 50kW prototype, a Bergey 10 kW turbine, and an Atlantic Orient Corporation 50 kW turbine. The moment foundation was ultimately sized to accommodate the Bergey 50 kW prototype turbine placed upon a 37m tubular steel tower.

The bearing foundation was installed and tested separately. The scope of the bearing foundation system consisted of monitoring the installation force required for its installation. The final installing force would indicate the installed system's bearing and uplift load handling capacities.

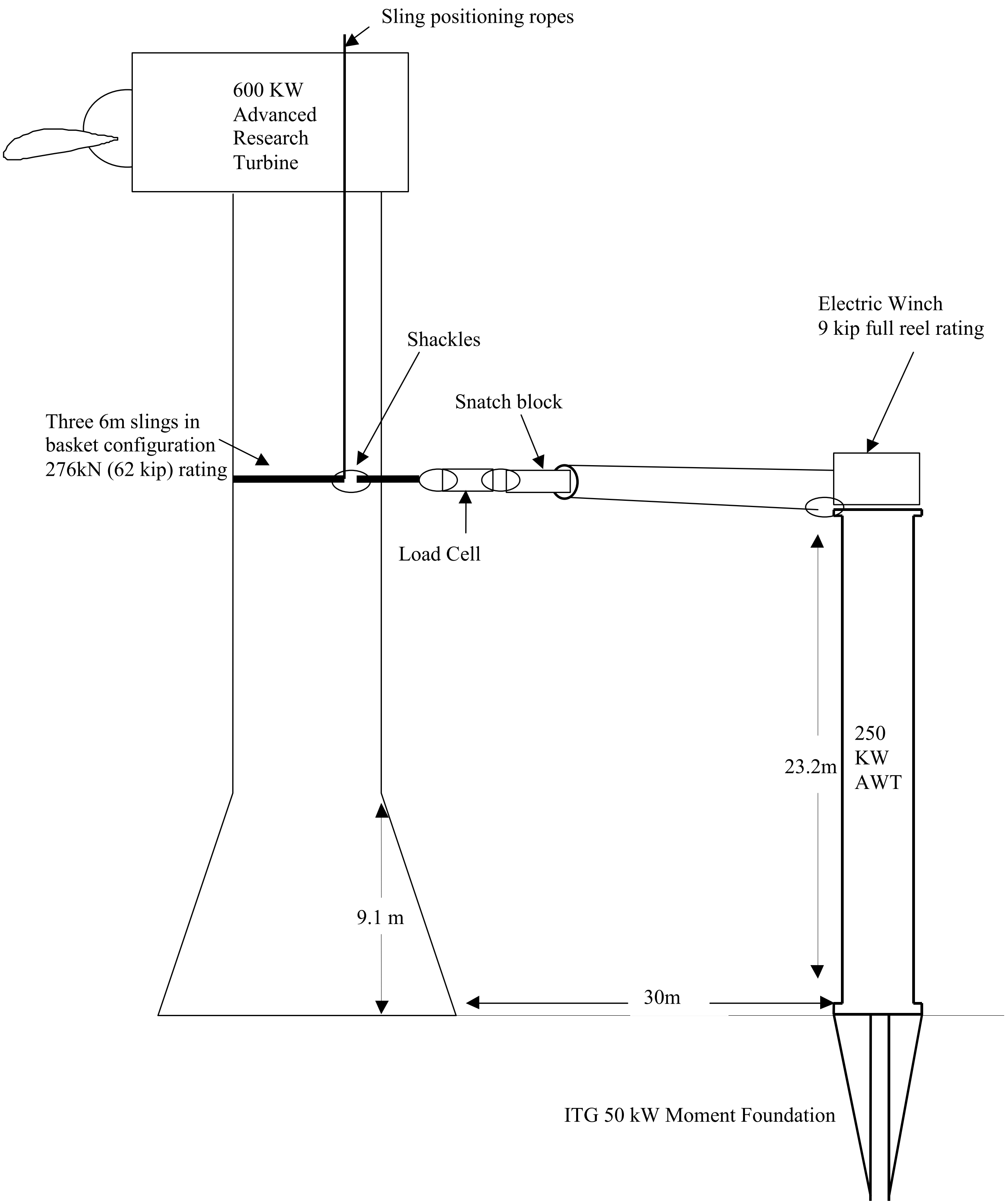


Figure 1: Moment Test Arrangement.

Theory of operation

Unlike many structures, wind turbines are characterized by large variation in loads that often change direction. These fatigue loads are best withstood by essentially preloading the soil. For example, a traditional wind turbine foundation design such as a slab foundation compresses the soil before the slab is pored by using compactors or other means. This compression effectively acts as a preload similar to how bolt preload functions. As the overturning moment on the tower is increased, the compressive forces on one side of the foundation are reduced. In order to keep the foundation edges from lifting, some compressive force must be maintained.

In all soil, there exists pressure beneath the surface in the lateral and horizontal directions. During installation of the ITG foundation, the friction along the wall of the foundation and the compressive forces generated by the anchors compacts and consolidates a zone of adjacent soil laterally and vertically thereby increasing the lateral passive pressure and the vertical passive pressure. The lateral passive pressure then reacts against foundation to provide resistance to overturning forces, shear forces, and torsional forces; the vertical passive pressure reacts the bearing forces.

The bearing capacity is determined directly by measuring the installation forces. The moment load capacity of the ITG foundation can be predicted using established earth pressure theory. Wedge theory (originally due to Coulomb in 1776), which is commonly used to predict the earth pressure on retaining walls, can be adapted for the ITG foundation. In wedge theory, it is assumed that the pressure on a retaining wall is due to a wedge of earth, which tends to slip down an inclined plane (see Figure 2) [1]. The passive pressure acting on a vertical retaining wall (or the foundation in this case) depends on the angle of friction for the wall δ and the angle of friction for the soil ϕ.

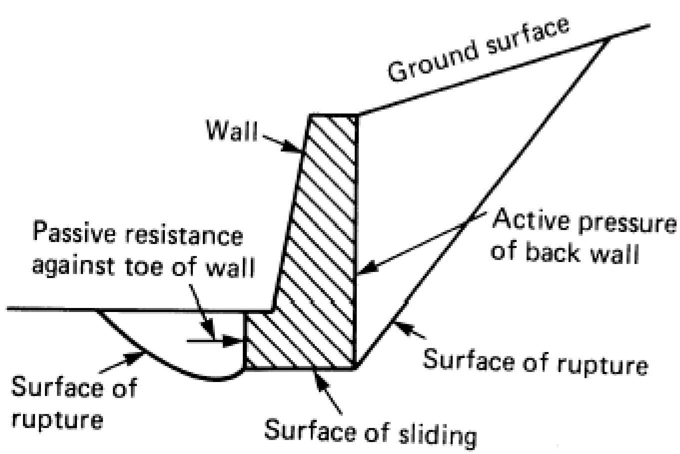


Figure 2: Diagram of active and passive resistance used in wedge theory.

Figure 3 is a diagram of the installation forces acting on the foundation. The passive pressure can be related to the installation force using Equation 1.

Equation 1 $\quad Q = \text{Friction} = Pp / (\cos\delta) * \sin\delta * \text{Perimeter} = Pp * \tan\delta * \text{Perimeter}$

The overturning capacity can be estimated using Equation 2.

[1] Civil Engineer's Reference Book. 4th Edition. 1994.

Equation 2 **M = Net Horizontal force * 2/3 H**

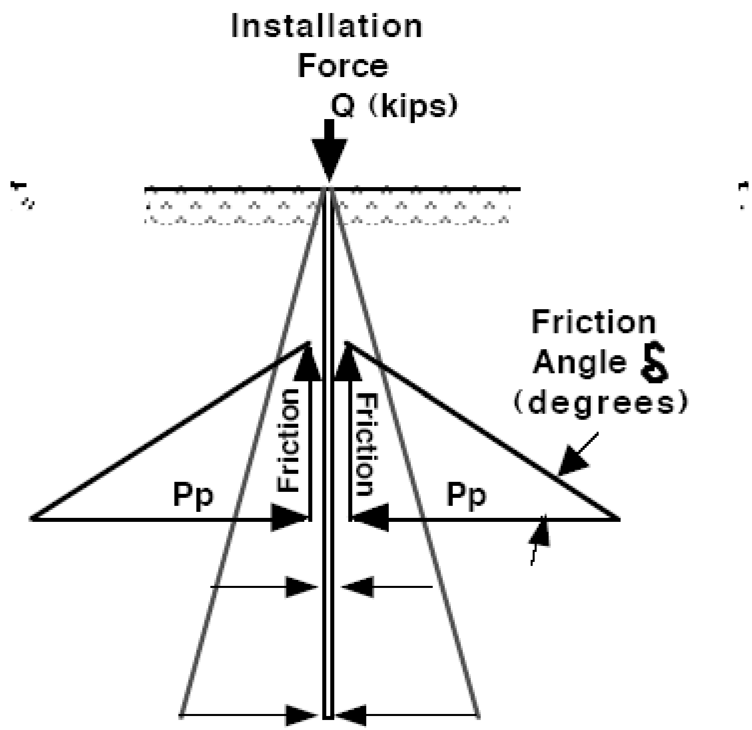


Figure 3: Resultant forces on the foundation during installation.

Fabrication, Installation, and Removal

Two foundations were installed, a bearing foundation and a moment foundation. ITG fabricated, delivered and installed both foundations. The installation procedures for these foundations are similar and are illustrated in Figure 4 and Figure 5.

5 holes were drilled for the moment foundation and 3 for the bearing foundation in order to install the anchor connections. The holes were 14" in diameter. The center hole was drilled 21 ft deep and the others 11 ft deep. The bearing foundation holes were all 11 ft deep. The soils report is included in Appendix E.

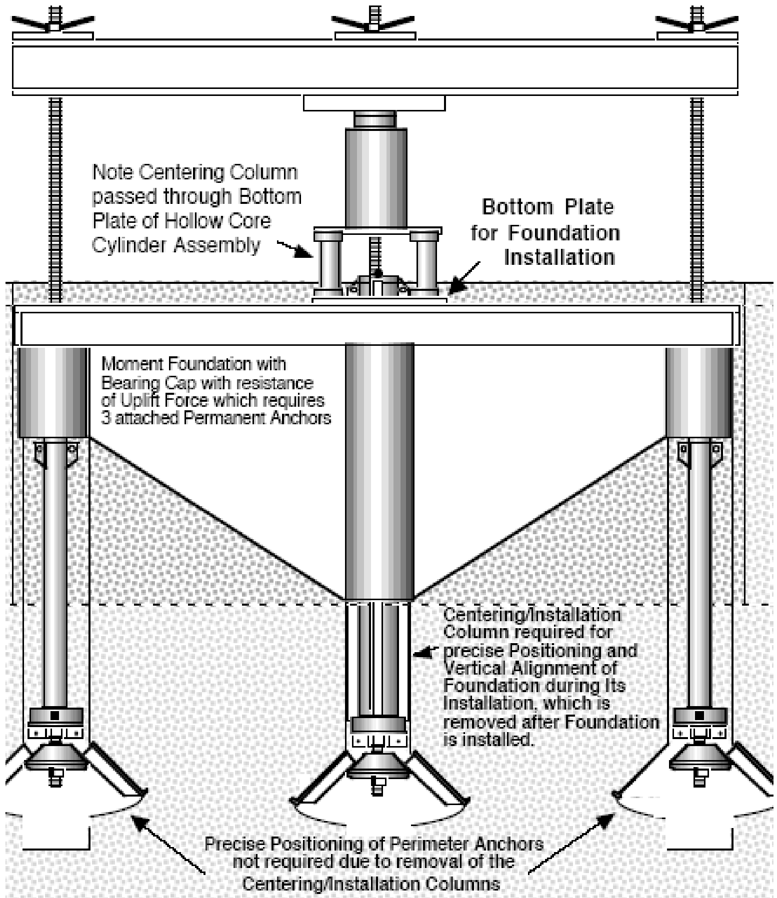


Figure 4: Installation Schematic for the Bearing & Moment Foundations.

Figure 5: Photograph of the Moment Foundation Installation.

Moment foundation

Test Description

The objective of the moment foundation test was to compare the predicted overturning capacity to the actual overturning capacity. A second objective of the test was to demonstrate the technology on a scale representative of a small wind turbine installation.

In order to apply loads on the moment foundation, which best represent those generated by a wind turbine, the loads applied to the foundation were obtained from the Bergey XL50 Final Design Review. Bergey used ADAMS simulations to determine the ultimate thrust (35.4 kN) and corresponding tower top bending load (58.1 kNm) on the tower. For the purposes of this test, these loads were assumed to act at the top of a 37m free standing tower. The 37m AWT tower was selected because it is of similar mass (12,800 kg) to the combined weight of a Bergey XL50 tower and turbine (13,500 kg) and because the NWTC had this tower available in surplus. From these numbers, a partial safety factor of 1.35 and a material partial safety factor of 1.1 were added to the load to produce a peak base moment of 2,100 kNm. A winch was installed on top of the tower and a load cell was used to measure the applied load.

A digital level accurate to 0.1 degree was attached to the base of the tower in order to measure the deflection of the foundation. The loads were applied in increments until the peak load was reached. Between load increments, the load was removed to check for any permanent set in the foundation. A significant permanent deflection is an indication of a failure of the foundation or soil. The load was applied up and back two times.

Installation Results

Hole drilling, anchor installation, and pressing of the moment foundation occurred twice. The first time the "nose" of the moment foundation encountered a formidable rock and a hole was formed in the nose that eventually required a new installation of the moment foundation. The rock was continually pushed against and the nose slowly eroded, and that caused the anchors to continually rise, as they could not apply enough force to continue to press the moment foundation through the rock. As a result, the moment foundation "nose" was bent and there was a hole in it that was smoothed out by using a welder on it. The nose of the moment foundation after the welding is shown in Figure 6. A picture of the stopping point of the first moment foundation is shown in Figure 7.

After re-drilling new holes, the second installation of the moment foundation went very smoothly. Several more rocks were encountered during drilling and the installation of the foundation. During installation, the force to install the foundation was increased by increasing the hydraulic pressure. The maximum compressive force applied during the installation of the foundation was 1,967 kN (442 kips). The minimum compressive force was 48.7 Kips. As calculated in Appendix C using Equation 1 and Equation 2, this installation force corresponds to a minimum of 804 Nm of overturning capacity for the foundation as installed.

Below are estimates of the time required to install and remove the foundation the second time (The pressing of the moment foundation took approximately 12 hours the first time before the holes were aborted for a new set).
Hole drilling for the moment foundation— 3 hours
Assembly of the installation hardware— 4 hours
Pressing in the moment foundation—5.5 hours
Removing the foundation from the ground—1 hour

Figure 8 shows a picture of the successful installation of the moment foundation, and Figure 9 shows a picture of the tower attached to the moment foundation.

Figure 6: Photograph of the Moment Foundation Nose after Repair.

Figure 7: Photograph of the Stopping Point of the First Moment Foundation Installation Attempt.

Figure 8: Photograph of the Moment Foundation After Successful Installation.

Figure 9: Photograph of the Moment Foundation After Tower Installation.

Test Results

The complete data from the side pull test is presented in Appendix A. A maximum overturning moment of 1,549 kNm was achieved in the test, which was the design load.

Figure 10 summarizes the data collected during the side pull test. The tower angle changed by 1.3 degrees during the tower pull, and this angle returned to zero after the load was removed (not including the tare load). The load was applied twice, but the second time the angle was measured only after the pull, and it returned to the zero angle condition. During the tower pull the fins on the moment foundation moved in the dirt between 0.125 and 0.25 inches as measured at the top of the foundation.

Meteorological conditions during the test were adverse, with the test starting in a hard semi-vertical rain that later turned to a wet snow. Figure 11 shows a picture of the tower pull

When the anchors were pulled out at the end of the test, it was noticed that one plate of the center anchor was slightly bent. A picture of this anchor is shown in Figure 12.

Figure 10: Side Pull Test Results

Design Recommendations

One potential problem of the foundation is the ability of the nose of the foundation to slice through rocks. It may be possible to locally harden the end of the nose section to improve the ability to cut through rocks. It appears that the fins work well as they probably encountered rocks and no deformation took place.

Figure 11: Tower Pull during Snow and Rain Storm

Figure 12: Picture of Slightly Bent Center Anchor after Removal

Bearing Foundation

Test Description

The bearing foundation systems are applicable for several types of wind turbine structures. There are basically two types of systems. In one system, the anchors are removed after installation. This system handles axial bearing and ground line shear loading. This foundation could be used to support the base of a guyed tower.

In the other system, the anchors remain as a permanent part of the foundation. This system is capable of handling axial bearing, ground line shear, and uplift loading. This system could be used to support each leg of a 3 or 4 legged lattice tower or for spread around the base of large diameter tubular towers.

The ITG bearing foundation is unique among wind turbine foundations in that the foundation strength is proven during the installation process as the hydraulically applied installing load is the same as the uplift and bearing capacities. Another unique feature of the foundation is the ability to increase the natural bearing capacity of the soil. The installation test was designed to show the systems ability to greatly increase this bearing capacity within the load bearing zone of influence.

A further unique feature of the foundation system is the ability to “fail” gracefully. If the uplift capacity is exceeded, the anchors will move towards their surface but will maintain their load bearing capacity.

After the foundation was installed, an anchor pull test was executed. The anchor pull test consisted of increasing hydraulic cylinder force used to install the foundation until the anchors moved. The objective of the test was to demonstrate that the anchors would only move if the uplift capacity is exceeded but the anchors would maintain their load bearing capacity.

Installation Results

The following are estimates of the time to install and remove the foundation system.

Hole drilling for the bearing foundation system – 5 hours
Assembly of the installation hardware (anchors, jigs & associated hardware – 2 hours (Note that much of the equipment was already unloaded and assembled from the moment foundation system test.)
Installing the foundation system – 2 hours
Removing the foundation from the ground - .5 hour

The soils report is at boring B-2.

Test Results

Figure 13 is a plot of the installation force to install the bearing foundation. This is the force applied by the hydraulic cylinder. During installation, the peak compressive force was 683 kN (153 kips). This is also the bearing force the foundation can withstand without further deflecting the soil. The design was intended to provide 556 kN (125 kips) of bearing capacity assuming soil with 20 kip/sq. ft resistance. The margin of the design load against exceeding the actual bearing capacity is 22%.

The unconfined compressive strength was measured during the soil sampling at 7.2 kip/sq.ft. The compressive strength needed to achieve a compressive force of 153 kips is 153,000 lb / 6.25 sq.ft. = 24.5

kip/ sq.ft. Thus, the unconfined compressive strength of the soil was increased 3.4 times during installation of the foundation.

In the bearing foundation, the anchors are used to pull the foundation into the ground and are left in the ground to provide uplift capacity for the foundation. Although not tested directly, the uplift capacity in this case is expected to be slightly higher than the bearing capacity because of the weight of the foundation. The foundation weight is 3 kN (675 lb). Thus the expected uplift capacity at which no further anchor movement is anticipated is on the order of 690 kN.

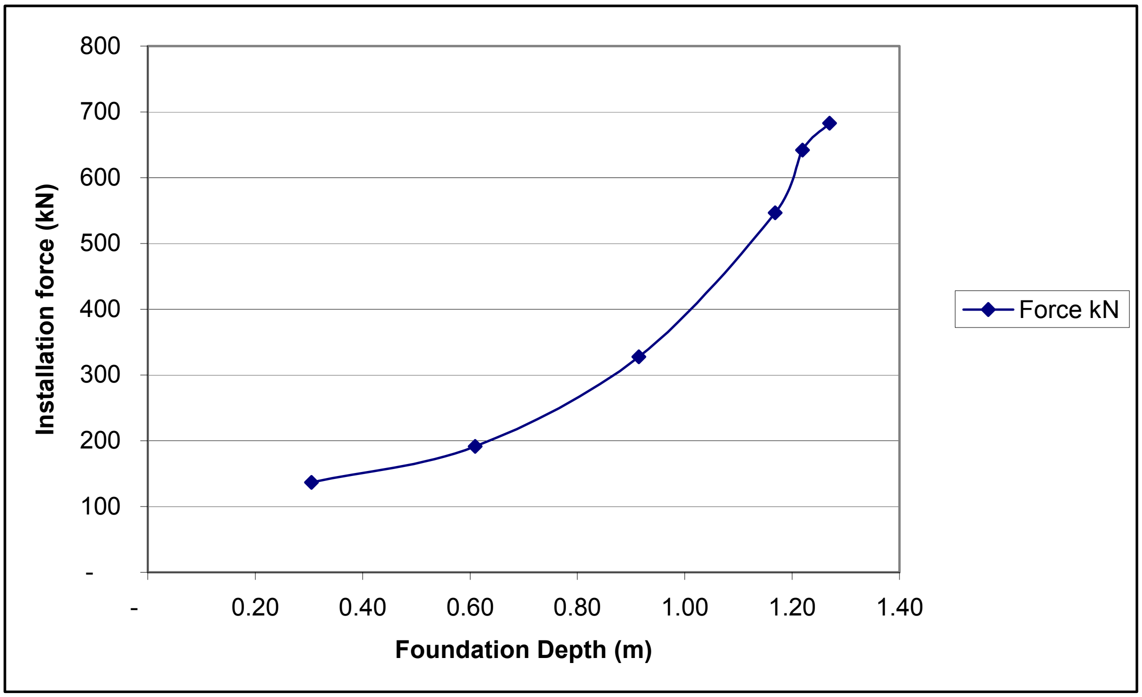


Figure 13: Installation force for the bearing foundation

The results of the anchor pull test are plotted in Figure 14. The results demonstrate that the anchors “fail” in a graceful manner. The anchors move if the uplift capacity is exceeded but their load bearing capacity actually increases.

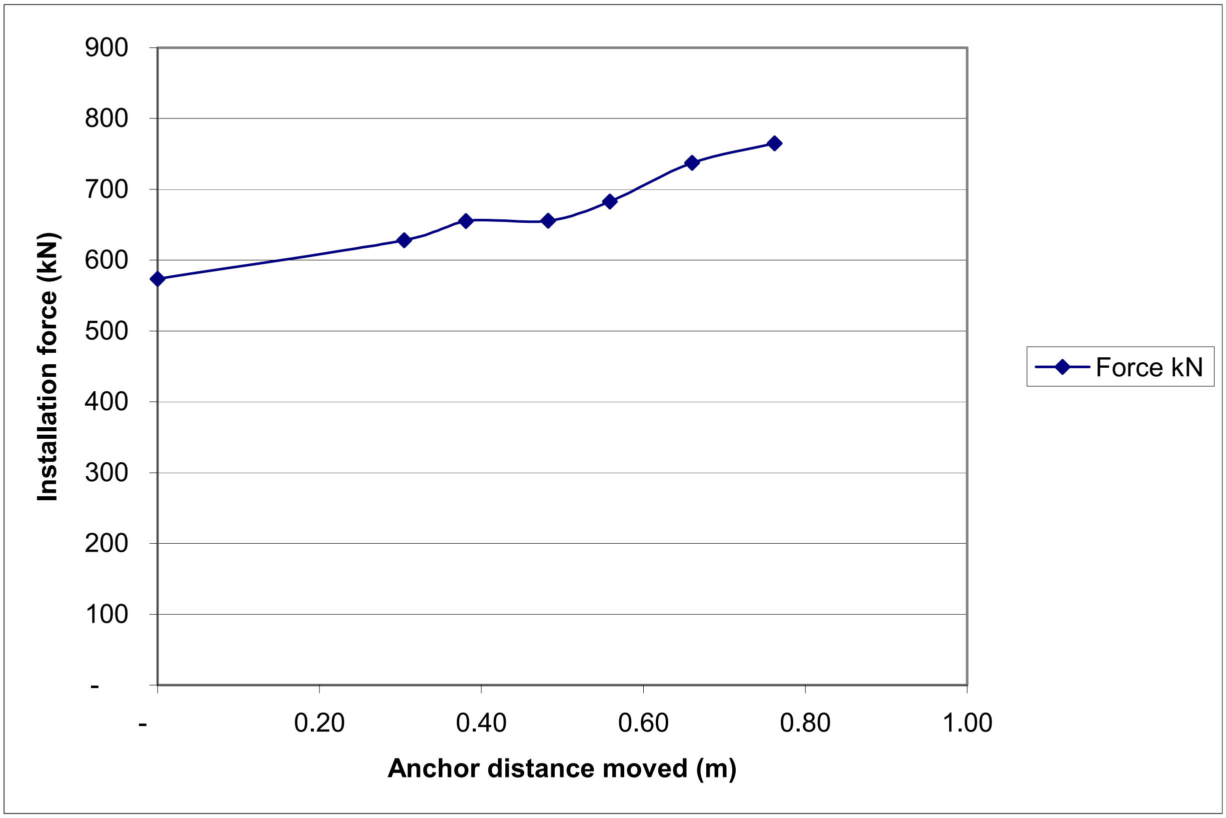


Figure 14: Anchor pull test results.

Future Testing

Future Testing would not be required, as the bearing foundation system exceeded all of the design requirements. It is recommended that the bearing foundation system be considered for use in appropriate wind turbine applications.

Appendix A: Side Pull Test Data

Tower Pull Test 04/09/2004

Force Applied (Newtons)	Applied Moment (kN-m)	Tower Angle (Degrees)
0	0	0
2225	52	0
4450	103	0.1
8900	206	0.1
13350	310	0.2
17800	413	0.2
22250	516	0.3
26700	619	0.4
31150	723	0.5
35600	826	0.6
40050	929	0.6
44500	1032	0.7
48950	1136	0.8
53400	1239	0.9
57850	1342	1
62300	1445	1.2
66750	1549	1.3

Appendix A: Side Pull Test

—X— Change in Tower Angle with Target Load Applied

—O— Change in Tower Angle When Unloaded (Tare Load)

—▲— Change in Foundation Angle When Loaded

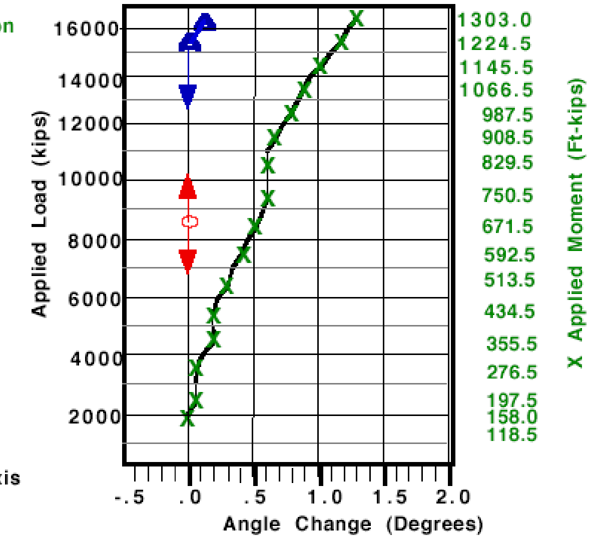
Vertical Axis
0 Degrees

Installation Log

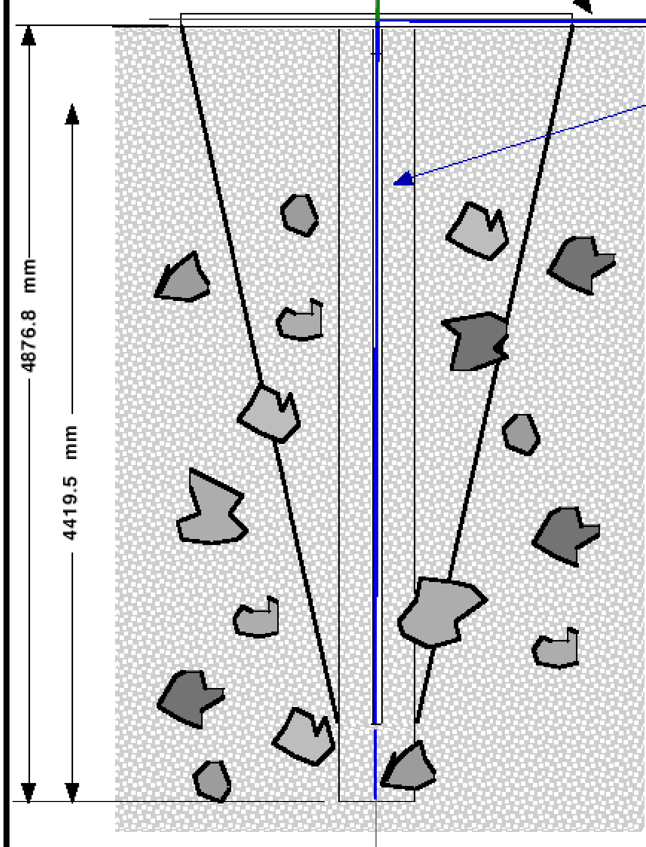
Force (kips)	Loaded Angle
1.5	0
2	0
2.5	0.1
3.5	0.1
4.5	0.2
5.5	0.2
6.5	0.3
7.5	0.4
8.5	0.5
9.5	0.6
10.5	0.6
11.5	0.7
12.5	0.8
13.5	0.9
14.5	1
15.5	1.2
16.5	1.3

Note: Applied Force includes 1.5 kips of Pre Tensioning Load

Tower Deflection Under 16.5 kip Load =1.3 Degrees from Vertical Axis



Horizontal Axis
0 Degrees



Foundation Deflection occurred during 1303 Ft-kips final Target Load was 0.085 Degrees from Horizontal & Vertical Axis'

<u>Conclusions from Test Results</u>:

- No permanent deflection, when Target Load was released, occurred during the entire test.
- The Final Target Load of 1303 Ft-kips exceeded the Design Requirements of 1103.3 Ft-kips, which included a 1.35 Safety Factor, by 18%.
- The Tower deflection of 1.3 degrees, during the application of the final Target Load, was well within allowable limits.
- Foundation Deflection occurred during the application of the final Target Loading. This was indicated by the spaces of 3/8" and 1/4" that appeared on the leading edges of the 2 fins, that were perpendicular to the line of Force application, upon release of the Target Load.
- In comparing the Tower Deflection to the Foundation Deflection it appears that the angle change in the tower occurred totally in the flexing of the Tower, in all but the final Target Load Application.
- The capacity of the Test Winch was reached, preventing further Load Applications.

Appendix B: Bearing Foundation Data

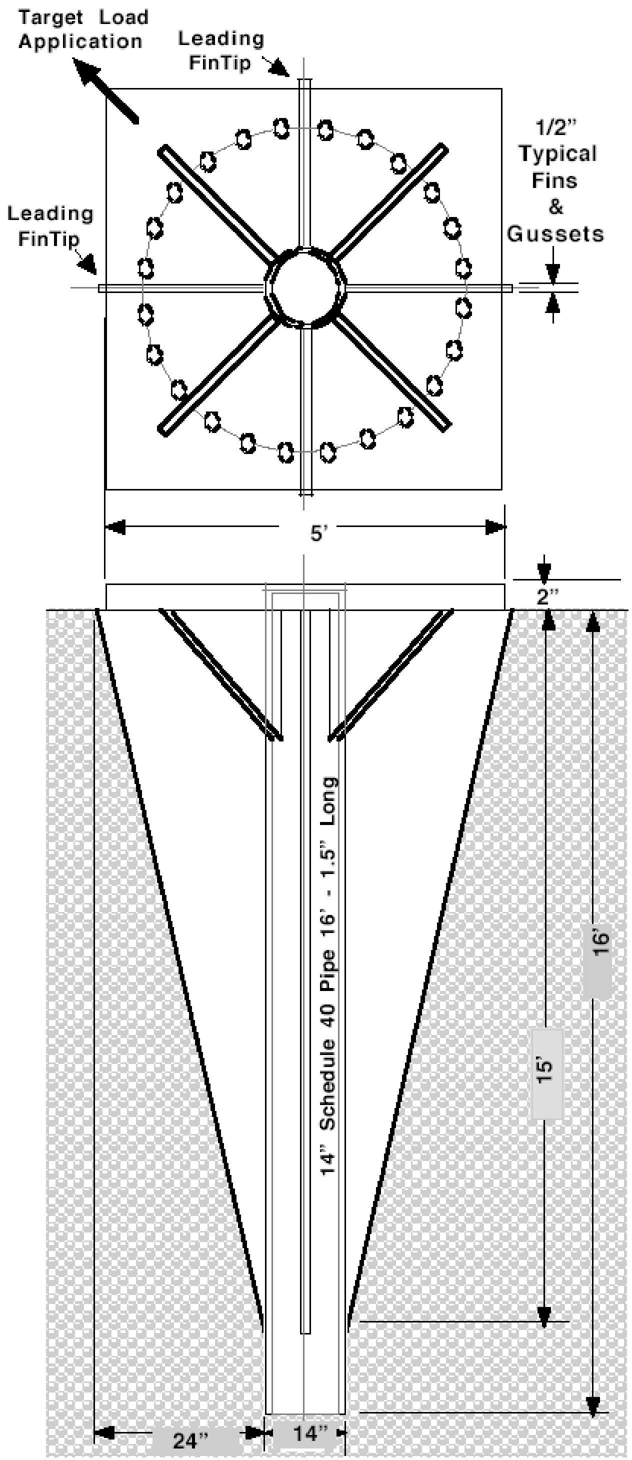
Installation data

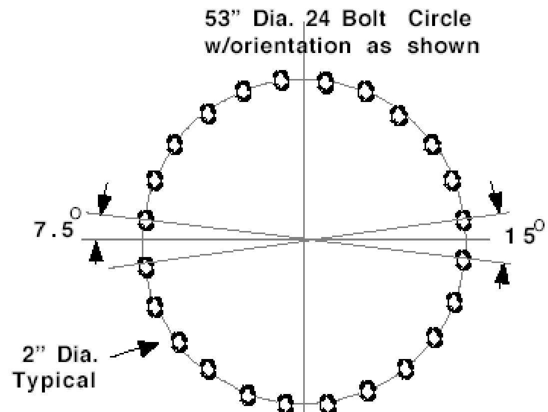
Depth of Foundation (in)	Depth of Foundation (m)	Force Kips	Force kN
12	0.30	31	137
24	0.61	43	191
36	0.91	74	328
46	1.17	123	546
48	1.22	144	642
50	1.27	154	683

Anchor pull data

Anchor distance moved (in)	Anchor distance moved (m)	Force lb	Force kN
-	-	128,982	574
12	0.30	141,266	628
15	0.38	147,337	655
19	0.48	147,408	656
22	0.56	153,550	683
26	0.66	165,834	738
30	1	171,976	765

Appendix C: Moment and Bearing Foundation Specifications





Attachment/Leveling Studs
14" L - 1 3/4" D Galvanized B-7 Rod
W/4 H.D. Nuts, 8 Washers & 2 Lock Washers

<u>Fabrication Details</u>

1. Material
   Fins, Gussets & Top Cap - T-1 Material
   ASTM A514
   Pipe ASTM A53 Schedule 40
2. Welds
   . <u>Fins to Column & Top Cap</u> - 1/2" Continuous along perimeter of contact
   . <u>Column to Top Cap</u> - 3/8" Continuous Top and Bottom
   . <u>Gussets to top Cap and Column</u> - 1/2" Continuous along perimeter of contact
3. Coating - Galvanized per ASTM A123

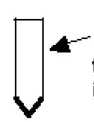
Note: All Material & Accessories will be made in USA

<u>Design Requirements w/ 1.35 S. F.</u>

- Mo/t = 1495.8 kNm = 1103.3 Ft-kips
- Turbine Mass = 5630 kg = 16.76 kips
- G/L Shear = 149.1 kN = 33.75 kips

<u>Foundation Design Data/Capacity</u>

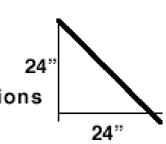
- Soils Density = 110#/Cu Ft
- Soils Shear Angle = 30 degrees
- Soils/Foundation Friction Factor = .2
- Foundation F1-14-15+1-<u>24</u>-<u>24</u>
- Passive Pressure = 37.125 kips/Ft
- G/L Shear = 117.69 kips (OK)
- Mo/t = 1176.86 Ft-kips (OK)
- Q (Min. Inst. Force) = 86.867 kips (OK)
- Foundation Weight = 4323 #

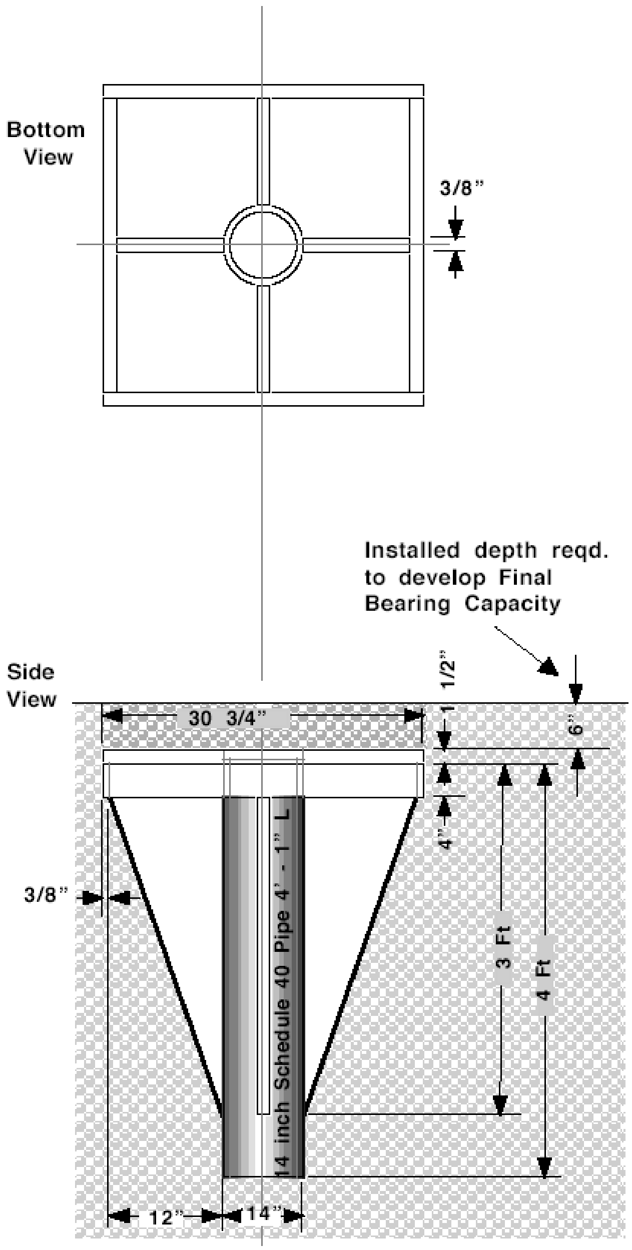


The lower 5 ft of the leading edge of the fins will be ground, as shown, to increase thier rock cutting ability.

Steel Grade	Tensile - ksi	Yield - ksi	BHN
ASTM A36	58-80	36	137
T-1 ASTM514	110-130	100 min.	235/293

Gusset Dimensions





<u>Foundation Design Data/Capacity</u>

- o Soils Density = 110 #/cu. Ft
- o Soils Shear Angle = 30 degrees
- o Soils/Foundation Friction Factor = .20
- o Fin Thickness = 3/8 inch
- o Foundation BF2-30x30-14- 3+1-<u>12</u>-<u>12</u> (as shown)
- o Foundation Depth = 4 Ft
- o Foundation Effective Width = 2.2 Ft
- o Foundation avg. perimeter = 7.66 Ft
- o Passive Pressure = 2.64 kips/Ft
- o G/L Shear = <u>5.8 kips</u>
- o Q (Fins) = Min. Inst. Force = 4.04 kips
- o Bearing Area = 6.25 sq. Ft
- o Q (Brg. Capacity) @ 20 kips /sq. Ft = <u>125+ kips</u>
- o Foundation Weight = 675#
- o 3 - 14" Anchors used for installation & resistance to uplift Forces. Ultimate Strength per anchor = 120 kips. Design Strength = 60 kips.
- o Uplift Capacity = <u>180+ kips</u>

<u>Installation/Test Data</u>

- o Installation was stopped @ position shown due to Movement of 1 of the installing anchors
- o The installing force was 153.55 kips

<u>Conclusions</u>

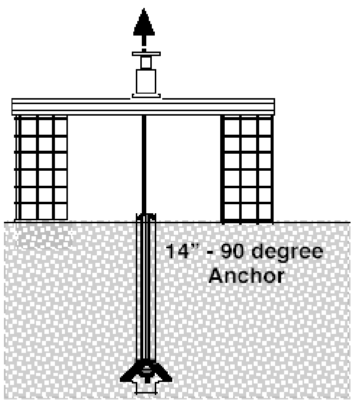
- o The developed Final Bearing Pressure/Capacity was 24.6 kips/sq. Ft, Which exceeded the Design Bearing Capacity by 23%
- o At a depth of 20 Ft, the tested Unconfined Compressive Strength of the soils @ that location was 7.2 kips/sq. Ft (Taken from the Soils Report)
- o The Developed Final Bearing Pressure/Capacity was 3.42 times greater than the tested Unconfined Compressive Strength of the soils
- o The Uplift Capacity is153.55 kips+

Appendix D: Anchor Testing Data

(Note: The Anchor Test Data was recorded by ITG as part of the moment foundation installation process and was not part of the NREL test plan.)

Tested Anchor Strength - Test #1
Center Anchor of Bearing Foundation Installation

- 1 - 14 inch Anchor.
- 2 - 150 Ton Cylinders provided the Uplift Force.
- Final Test Force applied to Anchor = 171.976 kips or 764.949 kN.
- The Anchor, at the Final Uplift Force, was Tested to 143% of its Ultimate Strength or 286% of its Design Strength



Cumulative Movement		Applied Force	
Inches	meters	kips	kN
0.000	0.000	128.982	537.712
12.000	0.304	141.266	628.351
15.000	0.381	147.337	655.355
19.000	0.483	147.408	655.670
22.000	0.559	153.550	682.990
26.000	0.660	165.834	737.630
30.000	0.762	171.976	764.949

Tested Anchor Strength - Test #2
Required for Moment Foundation Installation

- 5 - 14 inch Anchors used for providing uplift resistance for Installation Force.
- 2 - 150 Ton Cylinders provided the Installation Force.
- Total Force required to install Foundation was 552.78 kips or 110.56 kips/Anchor.
- The Anchors, at the Final Setting Force, were Tested to 90% of their Ultimate Strength or 180% of their Design Strength

Standard Anchor Sizes & Capacities

Anchor Size	Design Strength		Ultimate Strength	
4 inch	5 kips	22.240 kN	10 kips	44.480 kN
6 inch	15 kips	66.720 kN	30 kips	133.440 kN
10 inch	30 kips	133.440 kN	60 kips	266.880 kN
*14 inch	60 kips	266.880 kN	120 kips	533.760 kN
16 inch	100 kips	444.800 kN	200 kips	889.600 kN
18 inch	150 kips	667.200 kN	300 kips	1324.000 kN
24 Inch	300 kips	1334.400 kN	600 kips	2268.800 kN

Design Strength - Poor Soils Maximum Strength
Ultimate Strength - Highly compacted rocklike Soils Maximum Strength

Appendix E: Soils Report

Overview

The following soils report would indicate that the test site is an area of glacial till, which normally indicates an extreme variance of soils consistencies throughout the site. This is shown in comparing the two test borings. It is highly possible that design and installation of any structure, on this type of site, will encounter a variety of problems if borings are not taken at the precise location of each installation.

The moment foundation installations were not at the precise location of a boring. An installing problem occurred in the first attempt in installing the moment foundation when the foundation encountered rock. When moved several feet away the installation was performed without any significant problems.

The bearing foundation installation was installed at Boring B-2 and no problems were encountered during the installation.