Foundation Design of Wind Turbines in Southwestern Alaska, a Case Study

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Alaska Village Electric Cooperative (AVEC), an electric utility cooperative providing power to 51 Alaska villages, has made a concerted effort to install wind turbines in their villages in an effort to mitigate the growing costs of electrical power generation. The subsurface for the turbines in several of these villages consists of sands and silts with ground temperatures of between 30 and 32 ^{0}F. The presence of warm, degrading permafrost has required innovative foundation designs, including the use of helical piers to support a steel and concrete foundation. The community of Kasigluk is a case study where three wind turbines have been installed. Uplift forces imposed on the foundations were approximately 100 kips. The design piers were 20 inches in diameter and installed 36 to 40 feet deep with two 36-inch diameter helices. The piers were installed in Kasigluk in April 2006 by STG, Inc. An uplift pile load test was conducted on the installed piers in order to determine the actual working load that each pier can sustain. The wind turbines in Kasigluk are currently operational. Refinement of the design continues for other villages that are slated to have wind turbines installed.

***Index Terms* — foundations, helical pier, permafrost, wind turbines**

I. Introduction

Alaska Village Electric Cooperative (AVEC), an electric utility cooperative serving 51 rural Alaska villages, is working to install and operate wind turbines in several of their villages in an effort to mitigate the overall rising costs of electrical power generation. With support from the U.S. Department of Energy and the Denali Commission, 13 wind turbines have been installed in four western Alaska villages in the last 6 years as part of a larger program to upgrade bulk fuel farms, power plants, and other components of electrical generation in these villages. Seventeen to 21 more turbines are slated for installation in seven more villages in the next 3 to 5 years. Kasigluk was one of the first villages to have wind turbines installed.

Kasigluk is a rural Alaskan village with a population of about 550. It is located approximately 26 miles northwest of Bethel along the Johnson River in the Kuskokwim River Delta. The village lies at approximately 60^0 52' N. Latitude, 162^0 32' W.Longitude (Sections 1, 2, 11, 12, 13, and 14; T009N; R075W; Seward Meridian). Figure 1 presents a location map. Kasigluk is reached by daily air service from Bethel year-round or by barge in the summer months. Air traffic to the 3,500-foot long runway is the most common way to access the village. Barges generally stop service in late August and can get stranded due to low water at various times in the summer months. There is no road access to Kasigluk.

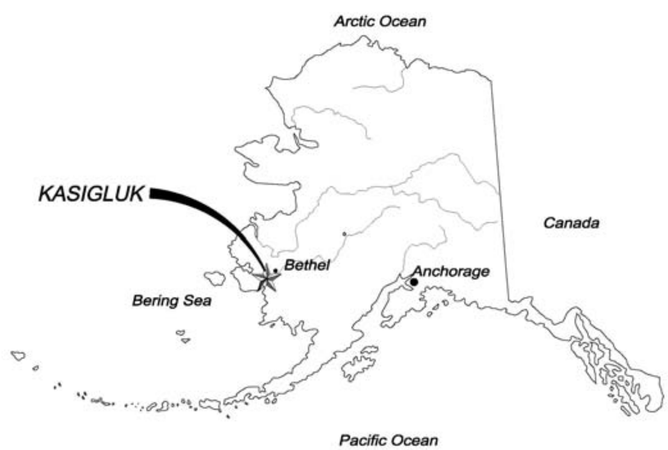

Fig. 1. Kasigluk is located in southwestern Alaska.

Most electrical power in Kasigluk and other western Alaska villages is acquired from diesel generators. A new power plant and tank farm were installed at Kasigluk in 2006. The tank farm capacity for the new power plant is 300,000 gallons of diesel fuel. Current usage is approximately 200,000 gallons each year and rising. The village has received several power-consuming capital improvements in recent years including piped water and sewer systems, and a number of new houses. It is estimated from these improvements and an increase in population that the village will need approximately 300,000 to 325,000 gallons in the next 10 years. The cost of delivering diesel fuel to this village has increased from $1.29 per gallon in 2002 to $2.27 per gallon in 2006. AVEC currently sells residential power in the village for $0.4536 per kWh. The AVEC system-wide average residential power cost is $0.51 per kWh. The wind turbines installed in Kasligluk are 100 kW machines supplied by Northern Power Systems (now known as Distributed Energy Systems, Inc.). The three new wind turbines are expected to provide approximately 20 to 25 percent of the overall electrical generation need for the village, creating an estimated net wind energy production of 415,500 kWh of power per year that would otherwise be generated by diesel fuel.

Construction conditions in rural Alaska are very challenging. All equipment must be shipped in by seasonal barges, roads are few, and tundra soils are soft. In Kasigluk, lack of adequate access for heavy equipment in summer resulted in winter construction for the wind turbine foundations. In winter, equipment can walk across frozen tundra without disturbance, but the winter weather is harsh on personnel and equipment, reducing efficiency. The turbine towers and nacelles were installed in the summer.

II. Climate

Kasigluk is located in a transitional climate zone and is influenced by the coastal climate of the Bering Sea and the Gulf of Alaska. The village has cool summers and relatively warm winters. Humidity and precipitation are high, but lower than that of the maritime climate. Specific climate data is unavailable for the village; however, the following information recorded for Bethel should be representative of the conditions experienced in the area. The record high temperature of 86° F was set in 1951 and the record low temperature of -46° F was set in 1973.

Mean Annual Temperature	29° F
Mean Annual Precipitation	17 inches
Mean Annual Snowfall	51 inches
Thawing Index	2,500 degree days
Design Thawing Index	3,200 degree days
Freezing Index	3,450 degree days
Design Freezing Index	4,400 degree days
Heating Index	13,100 degree days

Although the above data is used for design near Bethel, temperature data from Alaska Climate Summaries for the past 20 years indicates a warming climate. From 1977 through 1996, only three years have been colder than 29°F. The average annual air temperature at Bethel for the 18 years from 1977 to 1994 was 31°F. The average freezing and thawing indices for the same period at Bethel were 3,300° F-days and 2,800° F-days, respectively. Anecdotal evidence from village elders in this region substantiates the warming trend. This warming as part of climate change is affecting the foundation design for virtually every structure that is being installed in this region.

III. Soil Conditions

The Yukon-Kuskokwim Coastal Plain lies within the discontinuous permafrost region of Alaska. Many areas are underlain by fine-grained ice-rich soils varying in thickness from tens to hundreds of feet. Permafrost may be locally absent near bodies of water. Kasigluk sits atop ice-rich permafrost. The active layer (material that undergoes seasonal freeze/thaw cycles) in the vicinity of Bethel varies from 2 to 7 feet in thickness. Permafrost in this region is considered warm, with a temperature from 30° to just under 32°F, and is sensitive to disturbances to the thermal regime. During the thaw cycle, the active layer is usually saturated with water. Upon reaching the freeze cycle, the saturated soil will heave (frost heave) as the active layer freezes. Frost heave adds uplift forces that must be considered in foundation designs.

Two borings were advanced at the wind generation site in Kasigluk in January 2005. The borings were advanced using a Geoprobe 6610DT drill rig mounted on tracks. This is a direct- push machine that utilizes static weight and percussion to advance a soil-coring rod. Continuous undisturbed core samples were collected in five-foot runs for the depth of each borehole. One boring was advanced in a lowland area with several drainage paths in the near vicinity. A second boring was advanced in an area that was higher and drier. The first boring encountered silt with organics to a depth of 11.5 feet. Silt and organics were encountered in second boring to a depth of 6 feet. Underlying the silt and organics was an approximately 10 foot thick layer of silty sand in both borings. Below the sand layer were layers of silt with variable amounts of sand ranging from about 45 percent sand to trace amounts. In the second boring, silty sands occurred from depths of 30 feet to the bottom of the boring (43 feet). Fines content ranged from 18 to 40 percent for this layer. Moisture contents ranged from 21 to 45 percent with an average of 28 percent. The soils in the borings were frozen from the surface to the depth of the borings. A 1.5 foot thick ice lens occurred in the first boring from 11.5 to 13 feet. Ground temperatures measured over the next several months showed that the permafrost in these borings is between 30.8 and 31.5°F.

These conditions are typical of the entire western Alaska region. Minor variations in the silt and sand content occur, but soils are typically silts that are highly moisture-sensitive and near thawing.

IV. Wind Regime and Turbine Description

Kasigluk is located in western Alaska where the wind power class is rated at 5 out of 7 according to the Department of Energy Wind Maps. A Wind Power Class of 5 would have a wind speed at a height of 33 feet of between 13.4 to 14.3 mph and a wind power density of between 250 and 300 W/m^2. The prevailing wind direction is 6 degrees east of due north, similar to the orientation of the runway.

The Northwind 100 wind turbine is a rugged machine specifically designed for cold-weather conditions. The wind turbine site is located on high ground approximately 150 meters from the new power plant site (Figure 2), and has a 32-meter hub height. The turbine units are 100 kW wind turbine generators with a total height of approximately 43 meters and a swept area of 300 square meters. Each turbine is mounted on a single-shaft tower. The 2.3-meter diameter tower base is bolted to the foundation structure.

Fig. 2. The wind turbines are located to the south of the village on an area of higher ground.

V. Foundation Structural Design

One of the driving factors in the design of the wind turbine foundation was normalization to make it a prototype for future installations at other villages. AVEC previously commissioned design of a steel ring foundation structure for Toksook Bay, where it was supported by piles embedded in bedrock. The goal was to use this structure, with minimal modifications, at Kasigluk. The soft silty soils, although frozen, were very different from the bedrock encountered at Toksook Bay. During the design process for Kasigluk, it was determined that the structural steel foundation members needed to be encased in concrete in order to dampen oscillations in the tower. The foundation structure provides the connection from the turbine tower to six subsurface anchors in the ground, in this case a helical pier foundation. Figure 3 illustrates the steel ring structure that was fabricated off-site. The steel structure was shipped to Kasigluk as one unit and the concrete encasement was poured on-site, resulting in a 130,000-lb dampening mass between the turbine tower and the subsurface foundation.

Fig. 3. Steel foundation ring structure connection between turbine tower and pile foundation.

The design uplift load for the wind turbine foundation piles was approximately 60,000 lbs. The 60,000-lb uplift load is the per-pile reaction to a 50-year wind event (130-mph winds). This loading scenario would be exerted over a short duration during peak wind events. Other design criteria include the overturning moment (1,830,000 ft-lb), the total weight of the tower/turbine (42,000 lb), and the 130,000-lb concrete/steel foundation structure.

VI. Helical Piers

It was understood that lack of equipment and expertise in the village would make maintenance of the structure extremely expensive, so the goal was a relatively maintenance-free foundation. It was also understood that during the design life of the structure, soil conditions could change due to a warming climate from a permafrost condition to a thawed condition, greatly affecting the soil's bearing and uplift resistance capacity. The critical condition was a thawed soft silty saturated soil.

Several types of pile foundations were considered including slurried piles, refrigerated piles and driven piles. Due to the thermal analysis and the permafrost temperatures that were near thawing, slurried or refrigerated piles were considered a less feasible option for the foundation. Slurried and refrigerated piles require a freezeback period to maintain long-term frozen soil temperatures. The concern was that this freezeback may not occur or be difficult to achieve and maintain due to the current soil temperatures and the assumed increase in temperature over the life of the facility.

The turbine structure experiences an active lateral load from the wind pressure, with small vibrations that are dampened by the structural foundation mass. The lateral load is transferred to the subsurface set of piles as moment with a resulting uplift force. The lateral loads were such that the piles could not develop sufficient skin friction resistive forces to counteract the uplift forces with transferred through the structural foundation ring. Deflection tolerances were very low for the 100-foot high towers. The addition of 36-inch diameter helices on the 20-inch pipe pile provided enough additional uplift resistance to meet the design criteria. These piers were decided upon as the best foundation support.

The large-diameter helical piers were manufactured by Almita Manufacturing Limited, in Alberta, Canada. Almita manufactures helical shafts range in size from 2-7/8 inch to 36-inch with helice diameters ranging from 6 inches to 48 inches.

There were no models or design equations available to model uplift of helical piers in fine-grained saturated soils at near thawed condition. The design team approached the design of the helical pier in the warm permafrost in a similar manner to a pile analysis. Since the permafrost was at thawing temperatures, the equations for piles in permafrost do not adequately estimate the capacity of a pile. The adhesion factor and creep parameters are difficult to determine at 31.5^0F. Therefore a two-step approach was made where (1) the pile capacities were calculated in a permafrost condition using slightly higher creep parameters and adhesion factors in the design process and then (2) the pile capacities were also calculated for a non-frozen condition. The lesser capacity was then chosen. Factors of safety ranged from 2.5 to 3.

Standard equations for thawed conditions and permafrost conditions indicated that a 16-inch diameter pier with two 36-inch diameter helices embedded to a depth of 35 feet would be adequate.

As the project continued, 20-inch diameter piers became available to the client at a reduced cost and therefore were used instead of the 16-inch diameter design piers. Another change in the design evolved when the structural design of the foundation ring changed, reducing the uplift load. Both these factors reduced the required embedment depth to 25 feet.

Since this was a critical energy facility, the owners and designers wanted to be conservative in the approach to the foundation. In addition to the two-step approach described above, the helical pier design accommodates the potential for warming in future years by ignoring soil resistance contributions from the top 10 to 15 feet of the soil, the active layer. In a soft, thawed soil, the pier would have little resistance in the upper 10 to 15 feet. This created an additional lateral load on the pier by effectively increasing the tower height by 10 to 15 feet. The resulting total embedded depth in the design was 35 to 40 feet. The design equations do not accommodate the range in soil temperatures from 31.5 to 32^0F, lending uncertainty to the uplift and bearing capacity of the soil in that temperature range. Vertical thermosyphons were designed and installed at each turbine to assist in maintaining ground temperatures below 32 ^{0}F.

VII. Helical Pier Installation

Equipment and structures were barged to Kasigluk in autumn 2005. STG, Inc. installed the piers during frozen conditions (April 2006) to minimize tundra disturbance and also to prevent thawed soils and water in the active layer from sloughing into the predrilled pilot holes. The 18 piers (six per tubine) were installed in 14 days using a Lynx AF120 tracked rig equipped with a rotary head rated at 100,000 ft-lbs of torque. The piles were installed in one 18-foot and one 20-foot section that were spliced together with a field weld after the installation of the lead length. The lead length (the 18-foot section) included two 36-inch diameter helices spaced at approximately 9 feet with the first helice 3 feet from the pile tip.

The torque required in the field to install the piers exceeded the rating of the rotary head. The rotary head was dialed up to 110,000 ft-lbs, the highest level the machine could handle and greater than it's rated capacity and the piers went into the ground with little more difficulty.

Fig. 4. Kasigluk wind turbine foundation completed, including power drop and thermosyphons.

VIII. Pier Uplift Test

The pile uplift load test was conducted with two production piers that were installed for the foundation of Tower #2. The test pier was installed on April 3, 2006, and the uplift load test began on April 19th; allowing 16 days for the steel/soil adfreeze bond to develop before testing. The soil temperatures were measured from the inside of the test pile on April 12th and reconfirmed during the test. Soil temperatures ranged from 30.5ºF to 31.8ºF; any heat generated during the installation process dissipated to below freezing by April 12th, allowing for the adfreeze bond to develop.

The production piers were installed to a depth of 37.5 feet. A reaction beam (header beam) was attached to the reaction pile with a pin connection and attached to the test pile with a fabricated plate pin connection. The reaction pile was subjected to a downward force of half the test load using a hydraulic ram to apply the force.

Six uplift loads were applied to the test pile; an initial alignment load of 10 percent of the design load (6.4 kips) followed by loadings of 50 percent of the design load (30 kips), 100 percent of the design load (60 kips), 150 percent of the design load (90 kips), 175 percent of the design load (105 kips), and 200 percent of the design load (120 kips). Each loading was applied for a period of 24 hours with the exception of the 10 percent and 50 percent loadings, which were applied for 2 hours and 17 hours respectively. Each additional incremental loading was applied directly following the 24-hour monitoring period of the previous loading. For each loading, displacement was monitored and recorded until a stabilized displacement rate was achieved. ASTM Standard D5780-95 was followed in the performance of the load test with some deviation due to site conditions and schedule.

The test pier performed very well under all loadings. The pier reaction under each loading stabilized out to zero displacement, or creep, within 24 hours following each loading cycle. The measured pier displacement was minimal over the duration of the load test. Total pier displacement, in upward movement, accumulated to about 0.0093-inch (0.236 mm) through all loadings; 0.0072-inch (0.183 mm) when unloaded from the 200 percent load to zero load. When measuring such small increments of movement, the noise or error observed in the dial gages becomes significant. The overall test results indicate that the displacement was minimal or that pier capacity exceeds that of the test loads applied.

IX. Future Wind Turbine Foundation Designs

The results of the uplift tests were helpful in confirming that the design approach was appropriate for the conditions and loads. The test results gave the design team and owner confidence that a similar approach would be successful at other sites. AVEC intends to install wind turbines for the villages of Chevak, Hooper Bay, Savoonga, Gambell, Mekoryuk, Shaktoolik, and New Stuyahok in the next 3 to 5 years.

The future wind turbine foundation designs are being refined as the design team gains confidence in the design procedure. AVEC and its contractors experienced a learning curve with the helical piers at Kasigluk, both in design and installation. Future designs will be less conservative, given the success of the pier uplift test and other refinements. Better understanding of the turbine vibrations has resulted in the elimination of the concrete mass in the foundation structure for future installations. The steel ring structure has also been slightly modified. The field crews will become more efficient, reducing installation time by 30 percent or more. Equipment with a higher torque rating will be used.

Fig. 5. Operational Northwind 100 wind turbines at Kasigluk.

The foundation designs at Chevak and Hooper Bay are now based on piles instead of the helical piers. The soils in those villages are sandier and are slightly colder. Cost comparisons between the driven pile and helical pier foundation are highly influenced by shipping costs to the remote villages. A driven pile, dependent on skin friction for uplift resistance, would need to be longer than a helical pier, increasing shipping costs although material costs may be about equal. Installation effort for the helical pier is greater than for the driven pile, but not substantially so.

Adaptation of the foundation for each new site needs to occur depending upon the soil types and temperature of the soils. As the climate continues to change and affect the permafrost temperatures, new design approaches such as the one described here have to be developed to accommodate the new soil conditions that will be encountered. Large factors of safety without new design approaches will cost the client in terms of overly conservative designs. Increased design confidence in the helical piers in warm permafrost and uplift testing will refine design factors and optimize the turbine foundations for AVEC. As diesel prices remain high, the demand for wind turbines in this wind-rich and remote region can only grow. Climate changes affecting this permafrost landscape require that engineers develop new design strategies for these and other high-load structures.

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