

# Foundation Design for Wind Turbines in Warming Permafrost

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**Toksook Bay, Alaska**



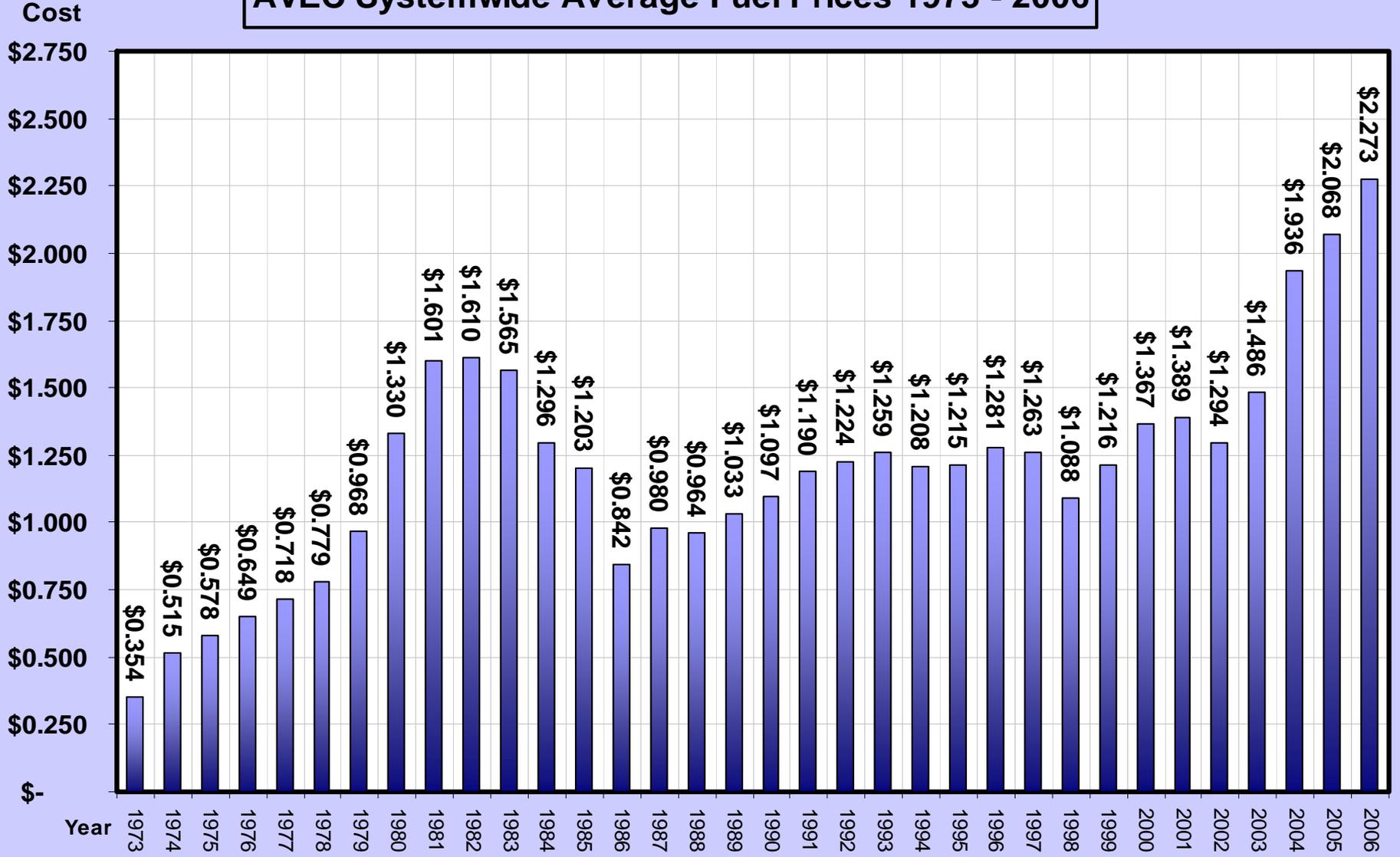
July 2007

This project received financial support from the Alaska Village Electric Cooperative, Denali Commission, Coastal Villages Region Fund, U.S. Department of Energy, and the Alaska Energy Authority.

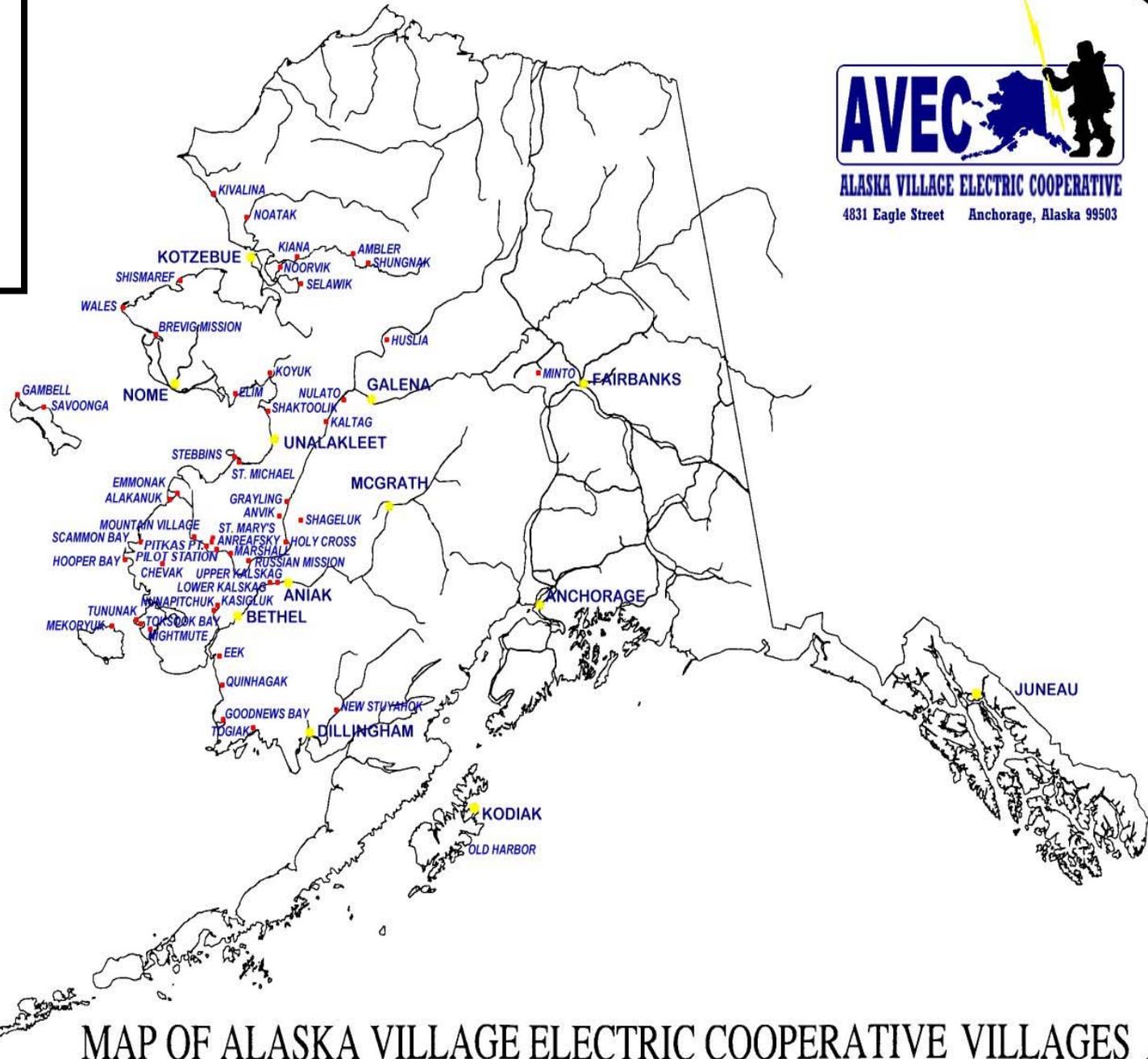
# Background Information

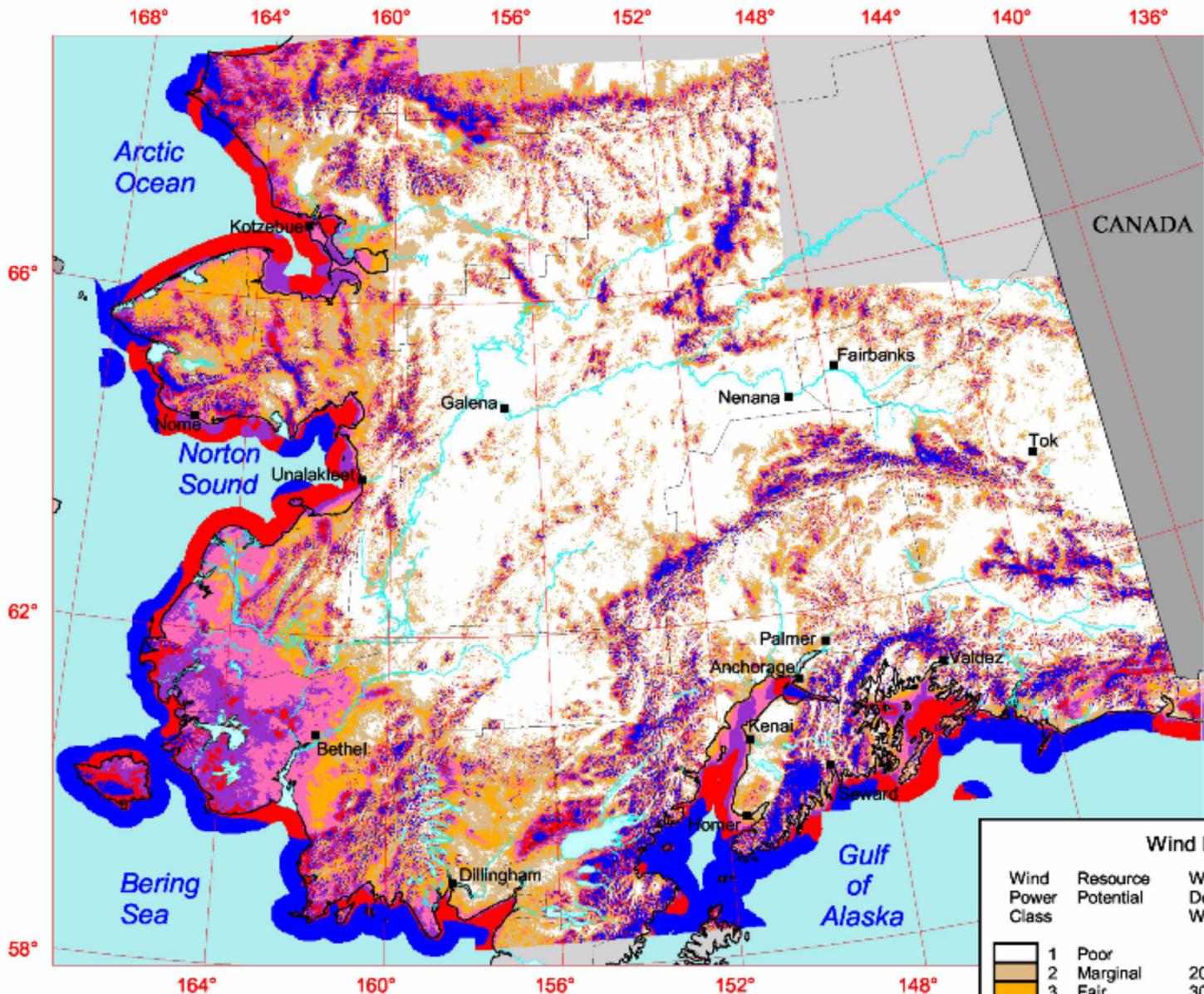
- 27 of AVEC's 52 villages are in wind regimes of class 4 or better.
- Given the characteristics of an NW/100, this means that one machine should be able to produce about 250,000 kWh per year.
- Given a diesel efficiency of 14 kWh/gallon generated by our new diesel sets, this means that one 100-kW wind turbine might displace about 17,800 gallons per year of diesel fuel use for power generation. A mini-wind farm of three units would displace about 53,400 gallons per year.

# AVEC Systemwide Average Fuel Prices 1973 - 2006



Many of AVEC's villages are in Western Alaska have Class 4 or better wind regimes.





# Alaska Mainland Regions

## 66° 50 m Wind Power

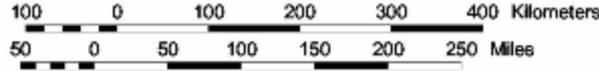
The annual wind power estimates for this map were produced by AWS Truewind using their Mesomap system and historical weather data. It has been validated with available surface data by NREL and wind energy meteorological consultants.

Wind Power Classification				
Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m <sup>2</sup>	Wind Speed <sup>a</sup> at 50 m m/s	Wind Speed <sup>a</sup> at 50 m mph
1	Poor	0 - 200	0.0 - 5.3	0.0 - 11.9
2	Marginal	200 - 300	5.3 - 6.1	11.9 - 13.7
3	Fair	300 - 400	6.1 - 6.7	13.7 - 15.0
4	Good	400 - 500	6.7 - 7.3	15.0 - 16.4
5	Excellent	500 - 600	7.3 - 7.7	16.4 - 17.2
6	Outstanding	600 - 800	7.7 - 8.5	17.2 - 19.0
7	Superb	> 800	> 8.5	> 19.0

<sup>a</sup> Wind speeds are based on a Weibull k of 1.8. Weibull k values in Alaska vary from 1.4 to 2.0.



U.S. Department of Energy  
National Renewable Energy Laboratory



# Consider that in 2006 AVEC:

- Purchased 5.2 million gallons of diesel fuel
- Actively used nearly 550 fuel tanks for storage
- Took on fuel in 170 separate deliveries (including 44 by air)
- Has only one village – Minto – that can be supplied by a fuel truck
- Continued to experience electric load growth driven by new water and sewer systems, airports, schools and housing in the villages
  - This load growth increases fuel use and fuel storage needs



# Therefore, successful integration of wind generation could mean the following to AVEC:

- A hedge against increasing fuel costs
- A hedge against the increasing costs of marine deliveries
- Extension of on-hand fuel supplies which may translate to favorable delivery scheduling by marine transporters
- A reduction of the need to build expensive, additional storage on hard-to-acquire or difficult-to-construct sites.



**To do such efforts cost effectively, we need to do good planning and coordinate efforts with other construction projects underway in the village.**

- The recent bulk fuel tank farm and power plant priorities of the Denali Commission provide some opportunity to coordinate logistics and use specialty equipment such as pile drivers or cranes that may be on-site.



**Access for specialty equipment required to place foundations and erect turbines is a challenge.**





**Poor roads, water and sewer lines, boardwalks and existing overhead power and phone lines present obstacles and challenges.**



**Above ground water and sewer lines are often crossed with timber bridges that will only support an ATV or snowmachine.**



**Boardwalks can be easily damaged by heavy equipment or melting permafrost.**

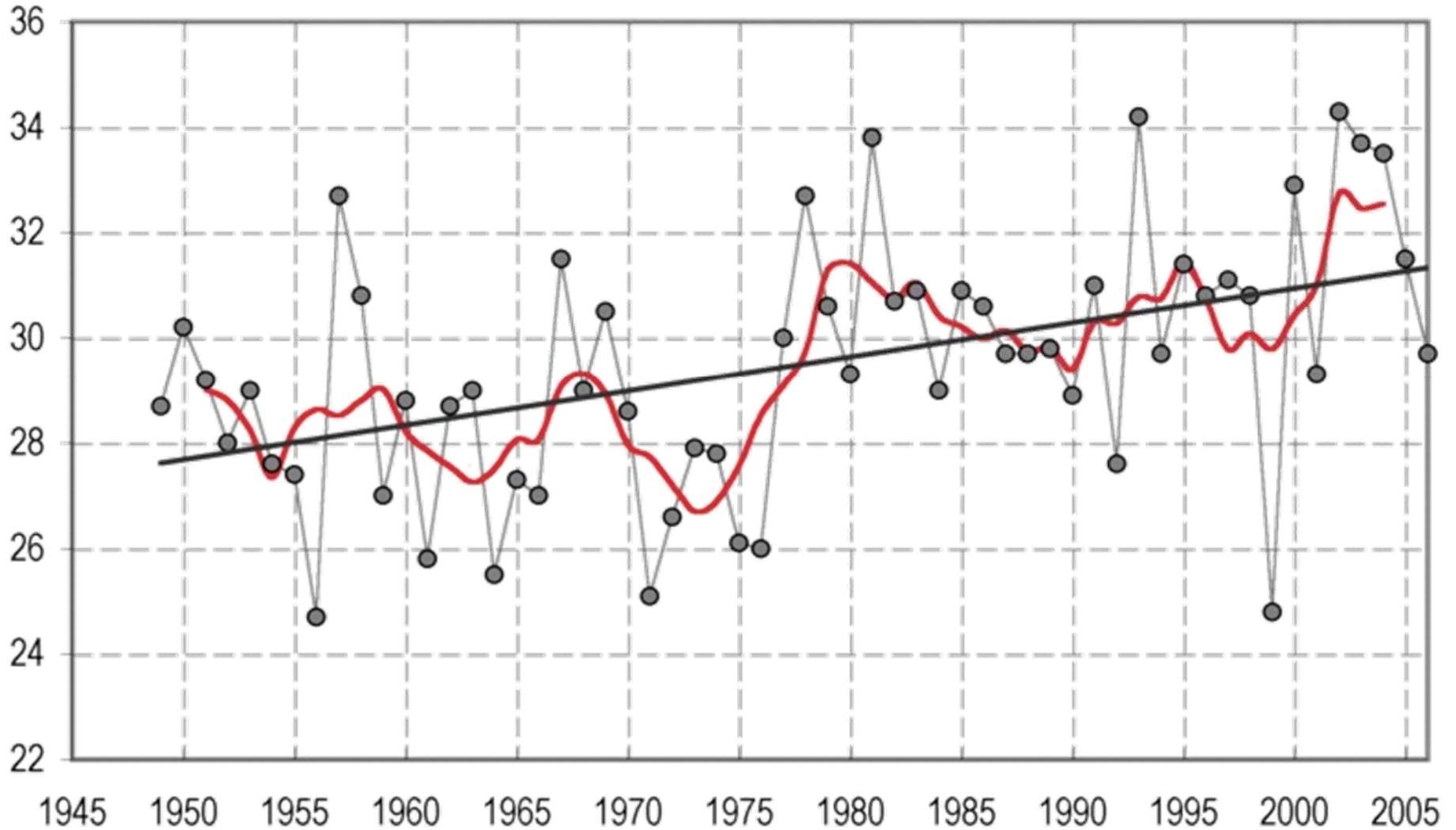
# Foundations in permafrost are a challenge

- They must not settle, tilt or be uplifted
- Pile foundations (six to eight piles) may extend  $\frac{1}{3}$  to  $\frac{2}{3}$  the height of the tower into the ground



- Due to the significant capital expense of installing deep foundations in permafrost conditions, the turbine owner wants to make sure that the investment will consistently produce power over the – year life of the equipment.
- Warming trends are affecting the expanse and depth of permafrost.
- For example, the next slide shows that the mean annual temperature in Bethel has increased from less than 28° F to over 31° F in the 55 years from 1950 to 2005

# Bethel Mean Annual Temperature (°F)



University of Alaska Geophysical Institute Climate Trends

- Increasing mean temperatures may contribute to diminished snow cover, increased surface water, and other conditions that may lead to thawing in the underlying permafrost.
- One manifestation of warming permafrost is the disappearance of lakes, which is thought to be caused when the permafrost under the lake thaws through its entire thickness and allows the lake to drain into the material below. (Science Magazine; June 03, 2005)
  - The following slide illustrates the process.

# Disappearing Lakes

In summer, ice melts across much of the Arctic, forming thousands of lakes. Under each lake is a layer of permanently frozen ground, or permafrost. When the permafrost melts, the water seeps into the ground.

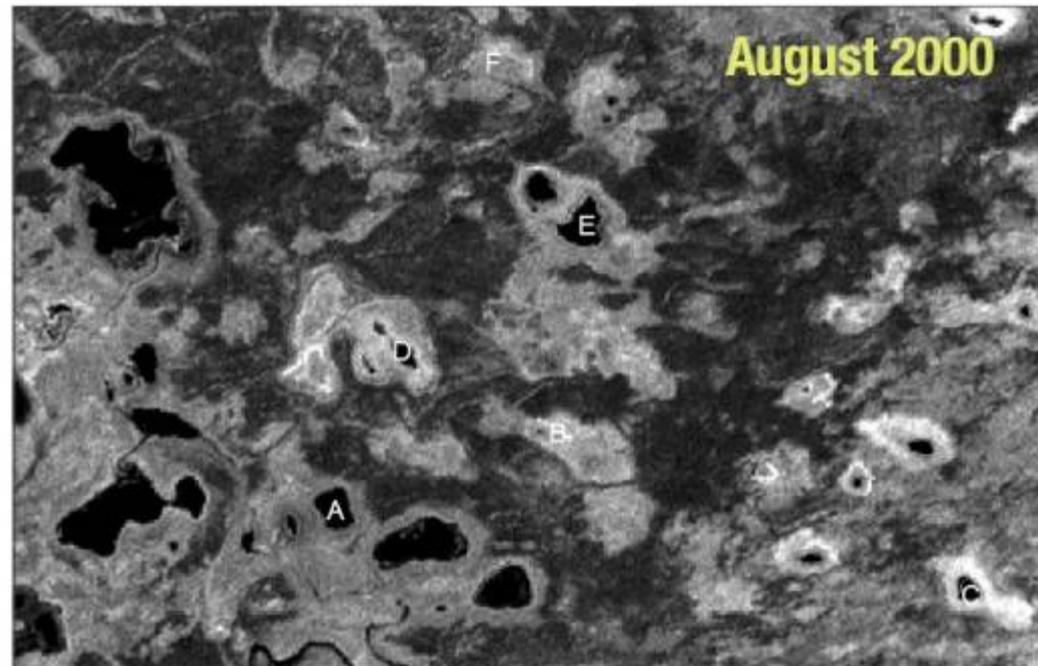
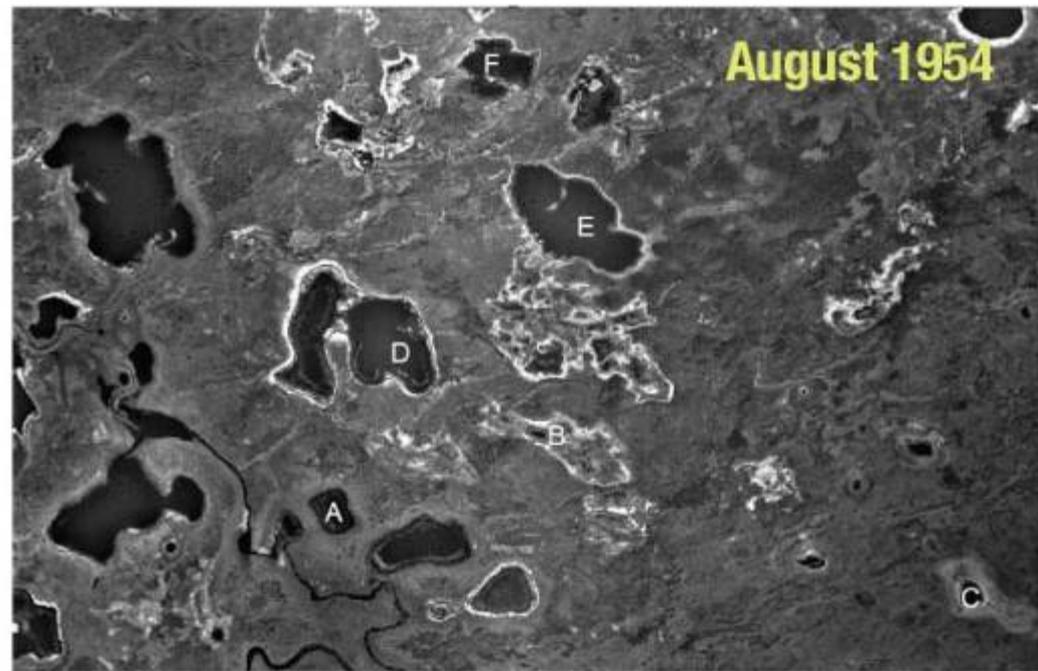


*Rising Temperature*



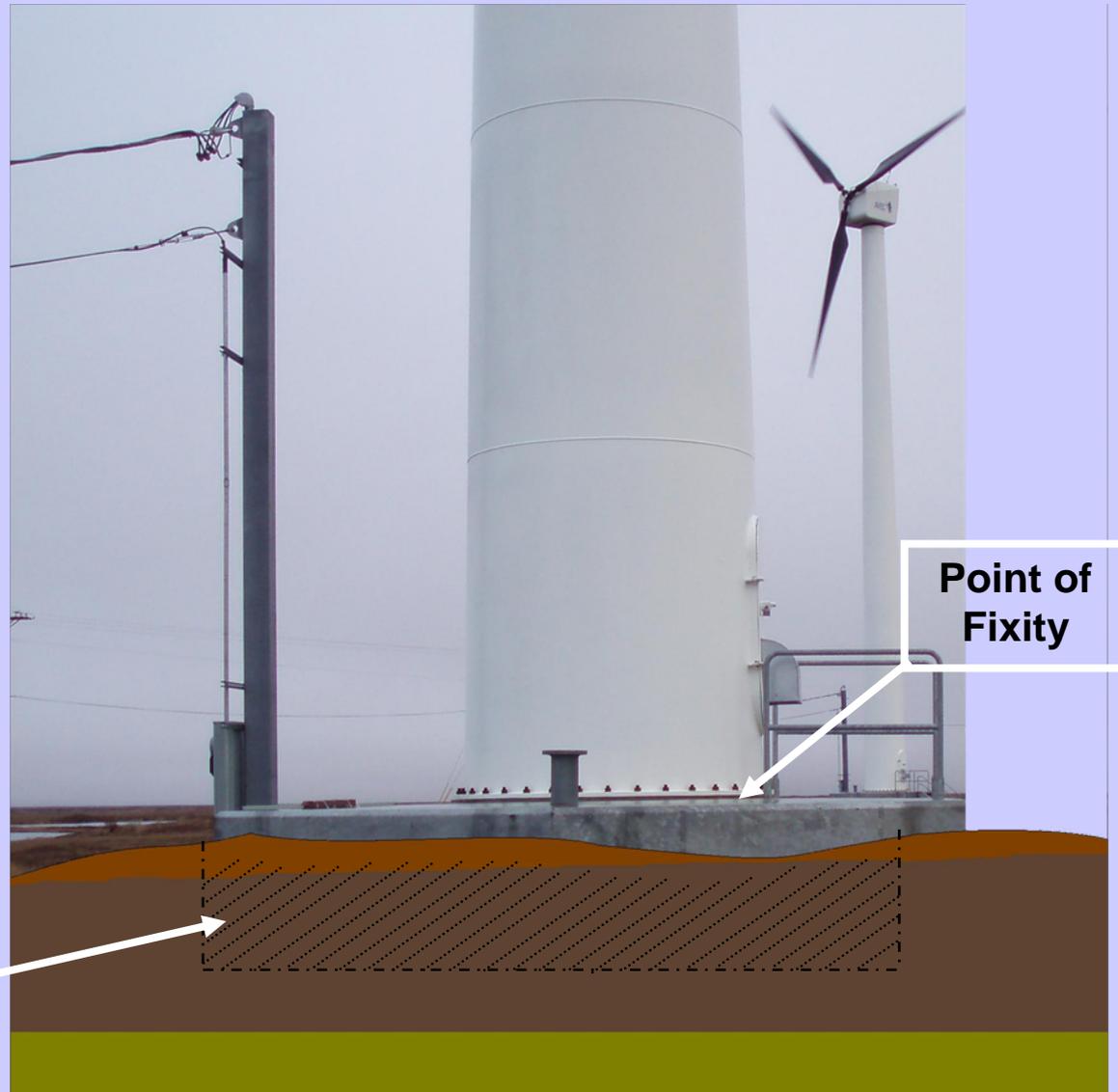
Such processes can be noted today when one flies over the tundra and lake expanses of Western Alaska.

Diminished lake sizes on Alaska's Yukon Flats are evident between 1954 (top: aerial photograph) and the 2000 (bottom: Landsat ETM+ image). Image credit: Institute of Arctic Biology, University of Alaska Fairbanks.



- In 2004, after two years of planning, AVEC and its construction manager, STG Inc., began mobilization of materials and equipment to the Toksook Bay wind project construction site.
- The site was underlain by frozen soils extending 5 to 15 feet deep over a tilted bedrock base.
- During the course of shipping the towers and piling, the turbine vendor alerted participants to a concern about the deep point of fixity and possible adverse harmonic conditions that might result.

**Wind towers on land in most of the world are built with a 'point of fixity' at the base of the tower where it typically rests on a massive concrete foundation.**



**Point of Fixity**

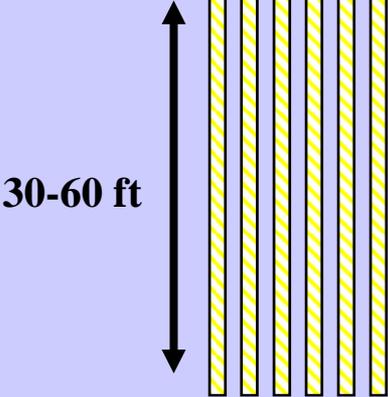
**Reinforced Concrete Pad**

**The tower foundation is elevated to allow cold air to pass over the ground to keep it frozen and to avoid heaving of the tower base.**



**100  
ft**

**In order to be properly secured in permafrost, wind turbines may require pilings in the ground which are 1/3 to 2/3 of the height of the tower.**



**30-60 ft**



One problem with Alaska permafrost conditions is that the point of fixity may be below the ground surface and may vary throughout the year as the frost line of the active layer migrates.

Frozen ground at surface in March

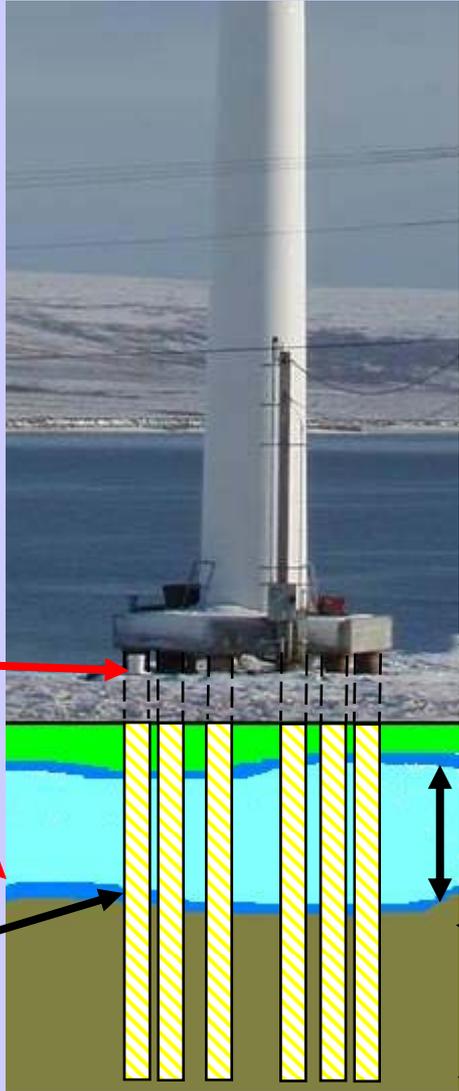


2 to 14 ft



Frost line in September/October after seasonal thaw





When the active layer is thawed, there is minimal to no lateral support to the piling near the base of the tower.

No lateral support when thawed

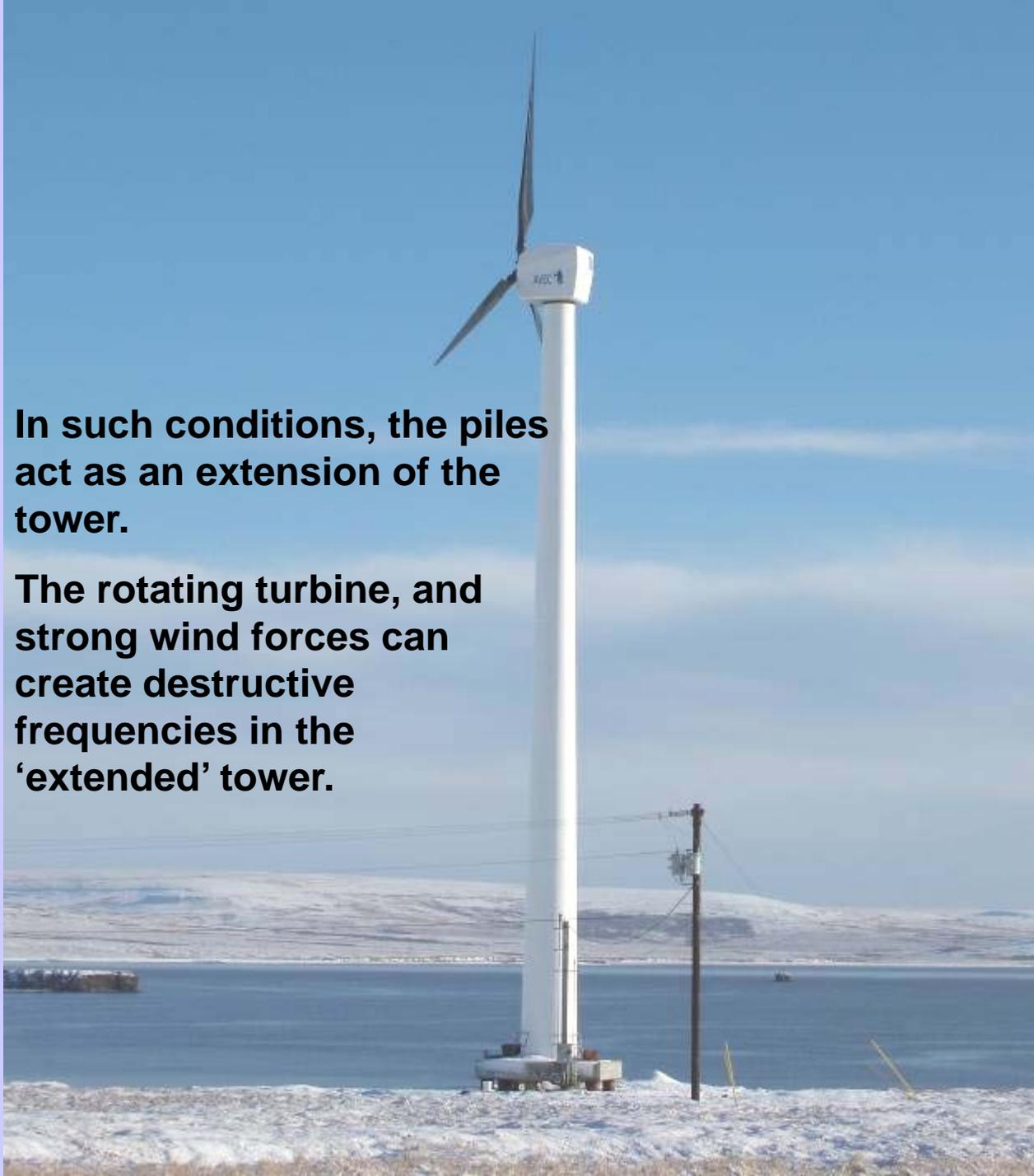
2 - 14 ft

New 'point of fixity'

Frozen/Solid Ground

**In such conditions, the piles act as an extension of the tower.**

**The rotating turbine, and strong wind forces can create destructive frequencies in the 'extended' tower.**



**This could be addressed by slowing down the turbine and losing valuable energy, especially in the late part of the year when the ground is thawed to its deepest, and when wind speeds are excellent for power production.**

**This approach loses energy and requires complex monitoring of the system operation.**

# Alternative Solution

An alternative solution is to stiffen the foundation and damper the structure by adding mass.

In the case of two projects involving six towers in permafrost environments at Toksook Bay and Kasigluk, Alaska, pile foundations were modified by adding a 130,000 pound, concrete and steel mass between the tower base, and the piles.

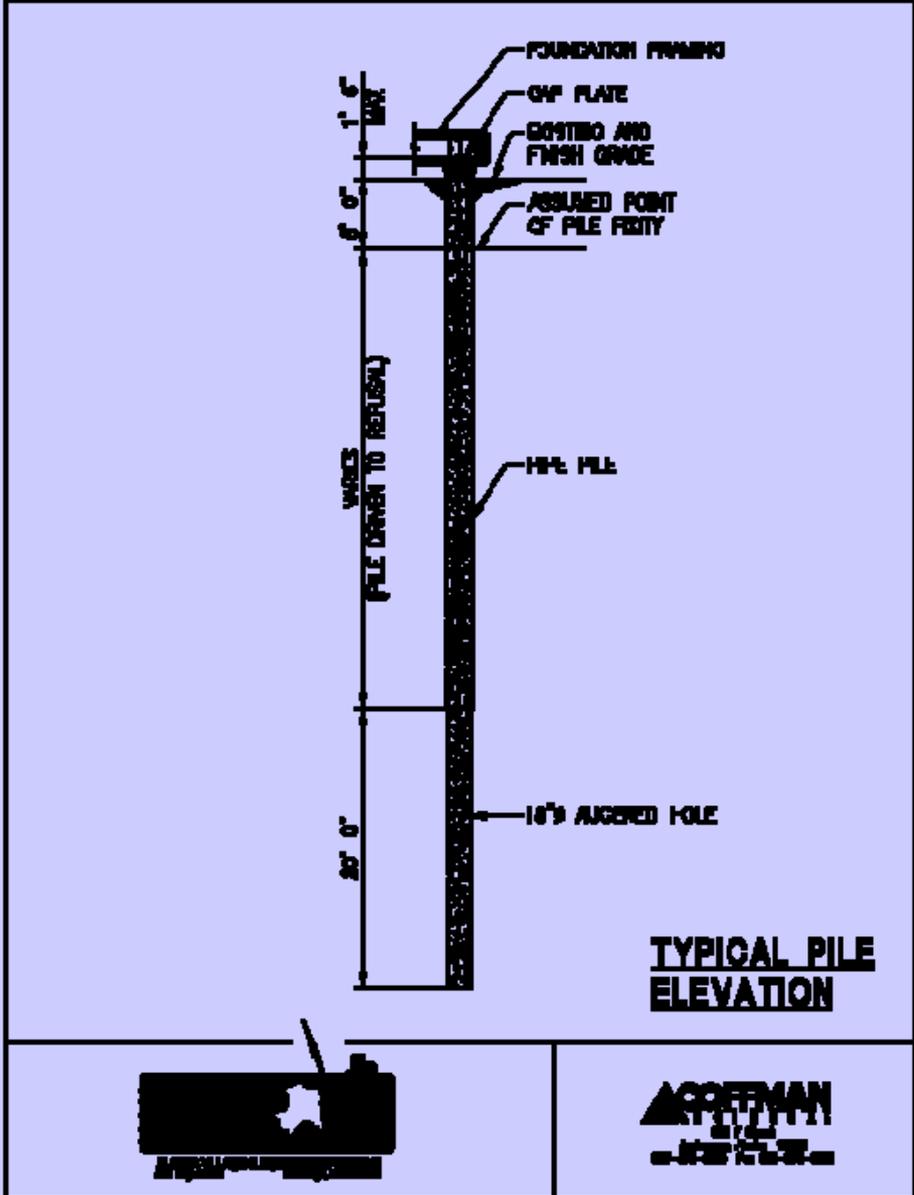
In Kasigluk, foundation piles were used with 24 inch helices to resist uplift and with thermal siphons to keep the ground frozen. The objective was to reduce the thickness of the active frost layer, and bring the point of fixity closer to the tower base. Temperature Acquisition Cables (TAC) have been installed at each tower in Kasigluk to monitor changes in ground temperature and to detect thawing below each tower.

# Overview – Toksook Bay



## Wind site

5-15 feet of frozen silts lie over tilted bedrock at the site.



- Holes pre-drilled
- Piles driven to refusal
- Piles later cut



# Drilling out center of piles to 20' below end of pile

Rock bolts would be placed into the rock and tensioned to the pile cap.

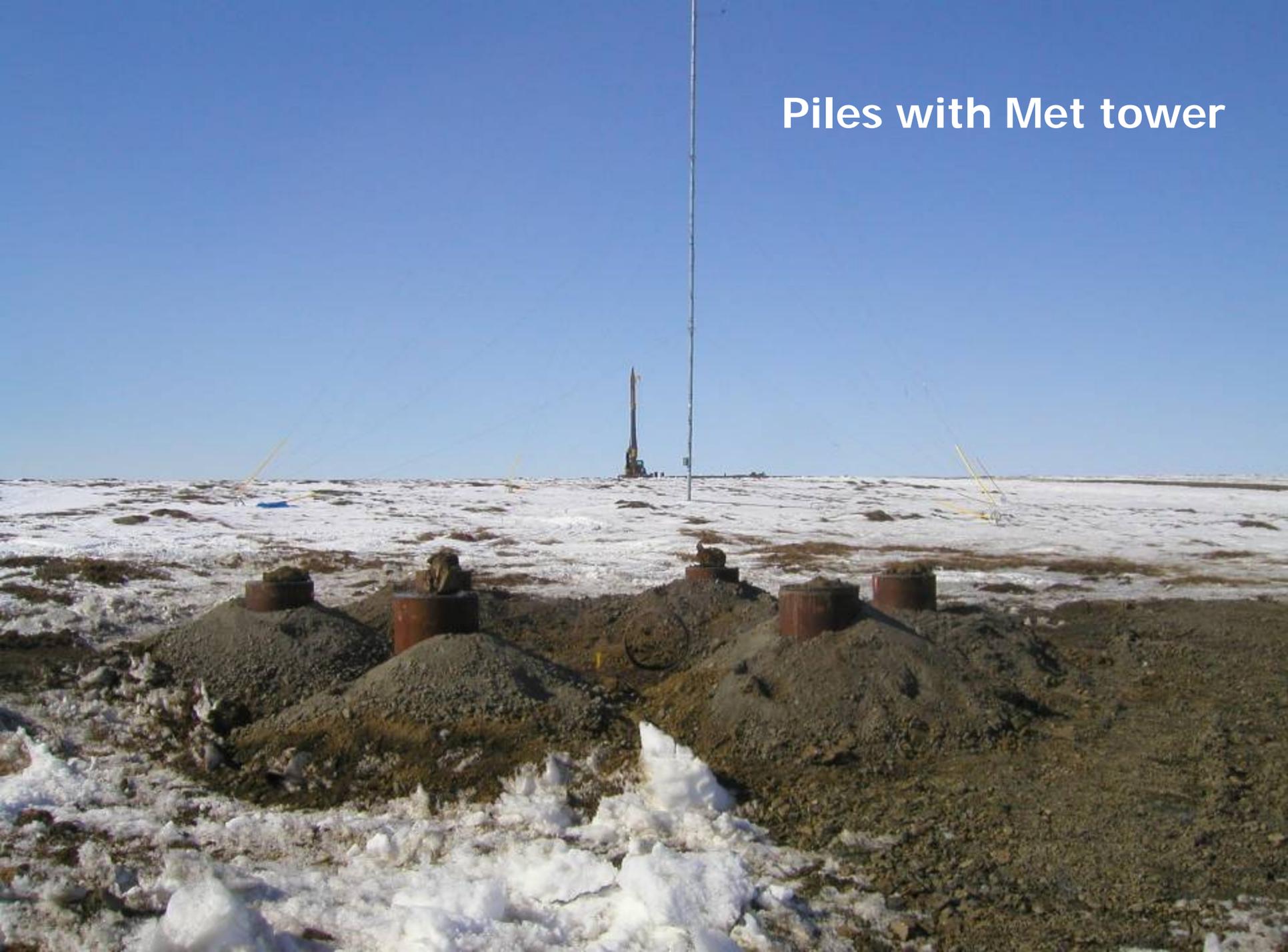
Additional Mass was added by placing a rebar cage and concrete in the pile.



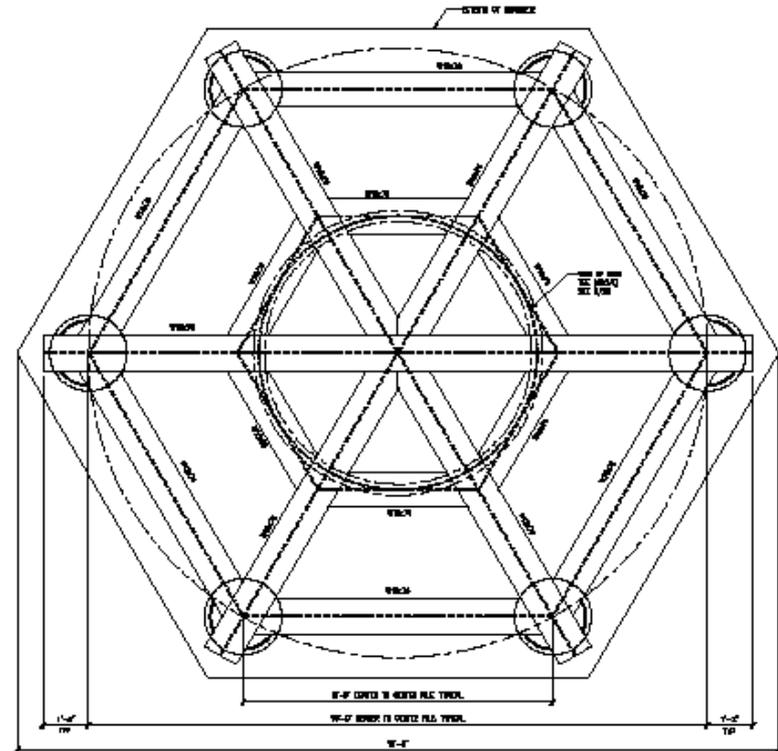
# Six piles for a single tower foundation



Piles with Met tower



The steel foundation cap contains I-Beams to connect the piles and a ring to make the tower base.

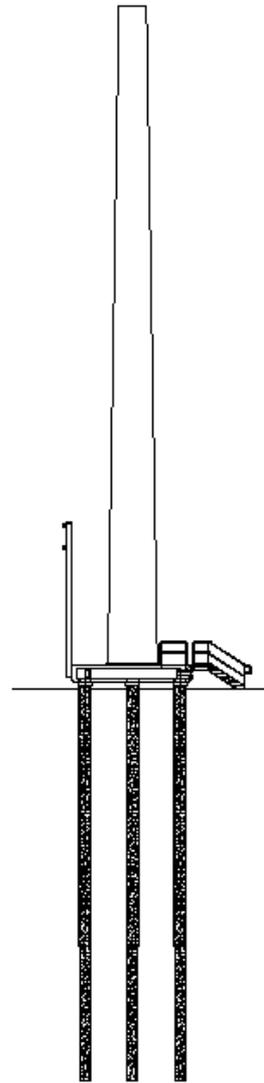


**FOUNDATION PLAN**





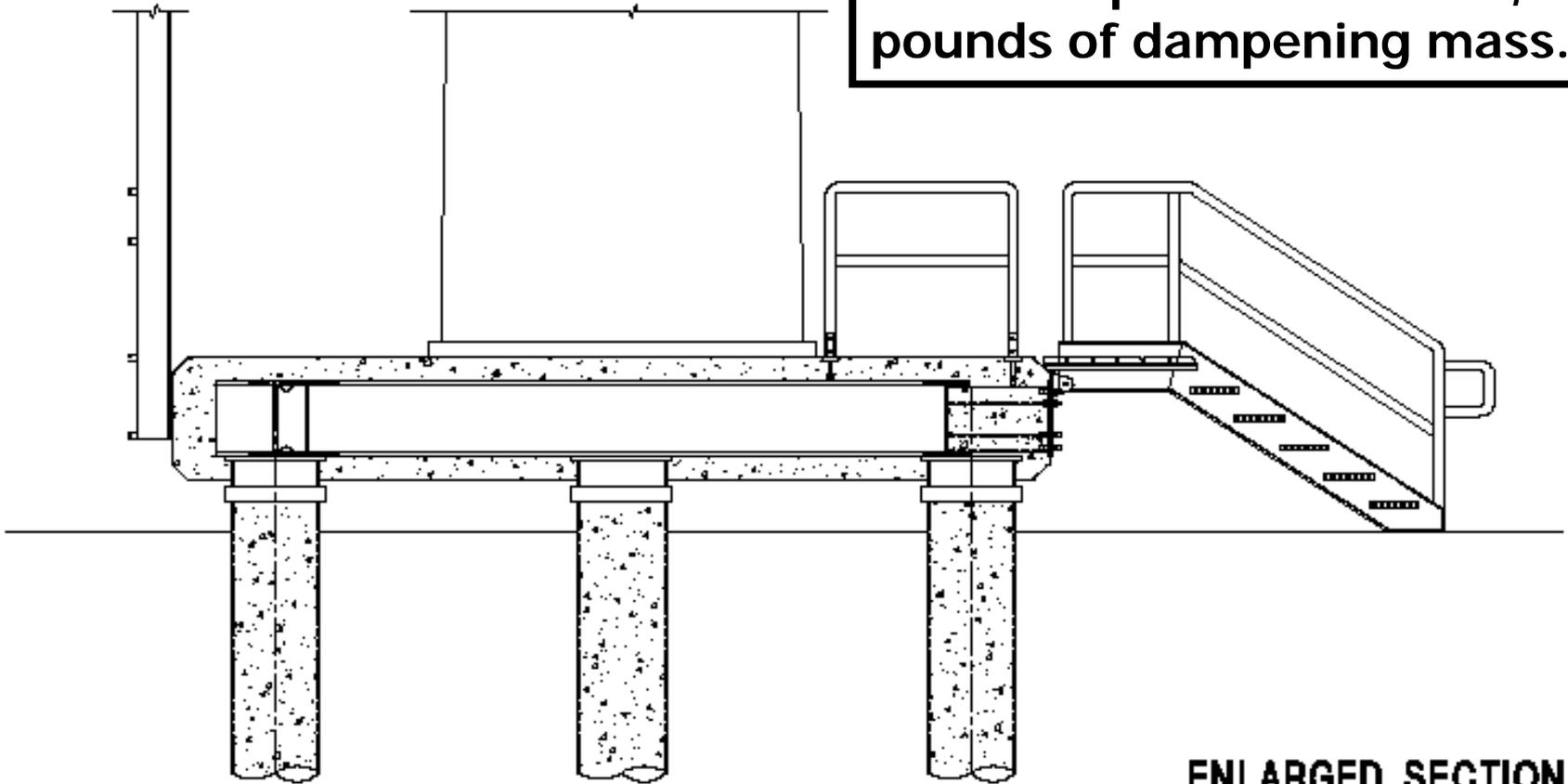
**Steel Foundation Star  
(Typical of 3)**



**TOWER &  
FOUNDATION  
SECTION**



Concrete and rebar was incorporated into the tower base and piles to add 130,000 pounds of dampening mass.



**ENLARGED SECTION**



**COFFMAN**  
ENGINEERS  
800 F Street  
Anchorage, Alaska 99501  
907-278-4884 Fax: 907-278-5042

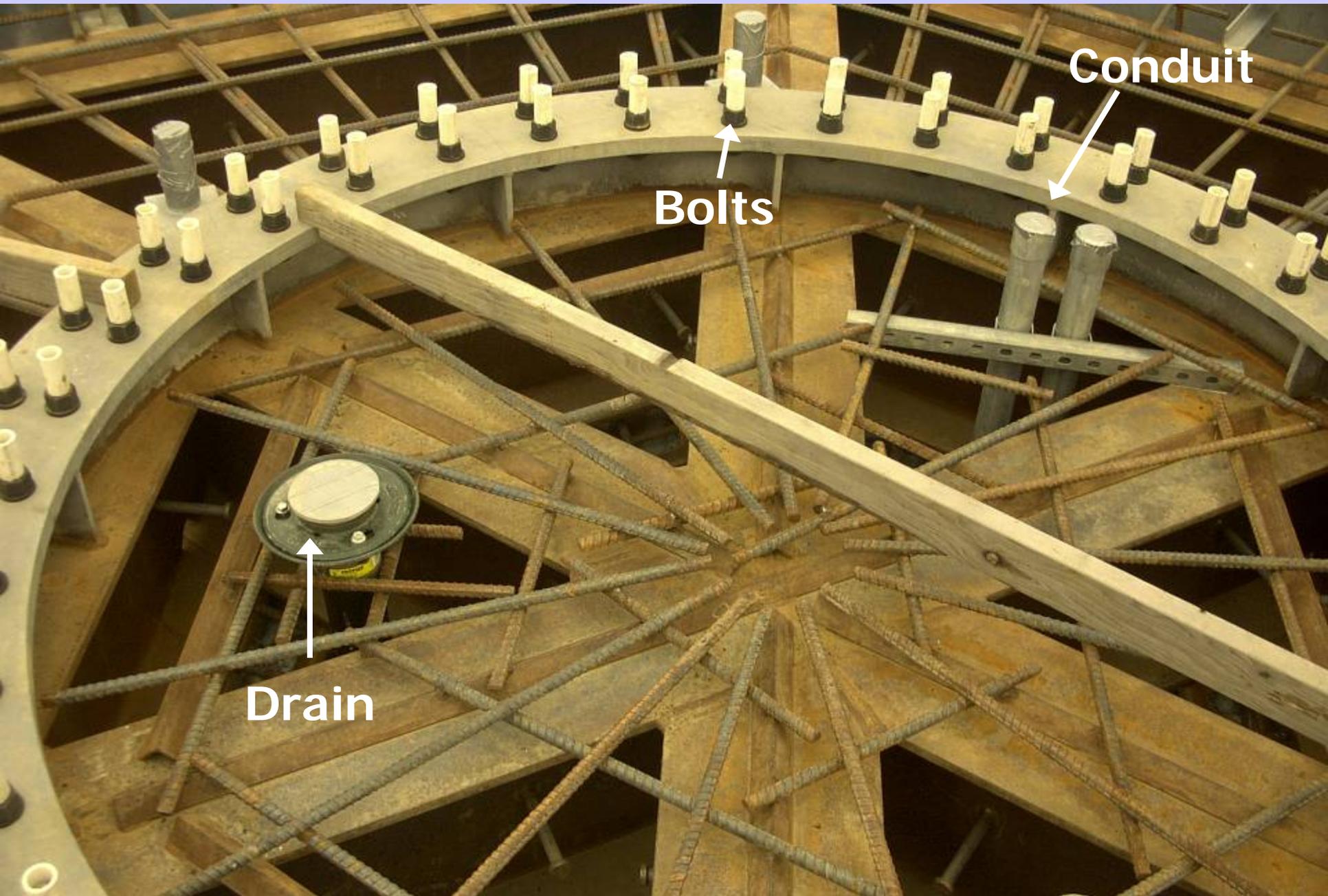
Rebar Cage to go into a pile.



# Verification of pile testing



- 18' driven pile
- Drilled out 20' below pile end
- Installed rebar cage and poured concrete (3,000 PSI)
- Design load 63 KIPS
- Tested up to 2 times load 127 KIPS (0.019 in movement)
- Tested up to 210 KIPS – less than 1/4" movement



Conduit

Bolts

Drain

Rebar placement





**Meter base and riser to  
connect to overhead  
distribution system**

**Forms were placed  
underneath the  
foundation star to  
hold the concrete in  
place until it cured.**

## Foundation Design Criteria

- Design Wind Speed = 130 mph (50 year)
- Overturning moment = 1,830,000 ft lb
- Total tower/turbine weight = 42,000 lb

## Frequency Analysis

- Tower only natural frequency (supported on infinitely rigid base) = 1.15 Hz
- Minimum natural frequency for tower and foundation = 1.07 Hz

Based upon 5% over maximum rotor frequency plus 5% factor of safety

- Operating frequency of rotor – 0.97 Hz (58 rpm)



The Wind Turbine Controller is placed before the tower is set.

# Danwin Tower Midway Platform



# Danwin Tower Inside Flange/Bolt Holes



## Tower/Turbine Specifications

- 108 feet from ground level to center of rotor
- Rotor diameter (3 blades) = 61 feet



**View from the top!**

13,950 lb nacelle  
being prepared for  
its lift to the top of  
a 32 meter tower.



Cleaning the yaw gear teeth prior to setting it on top of the tower.



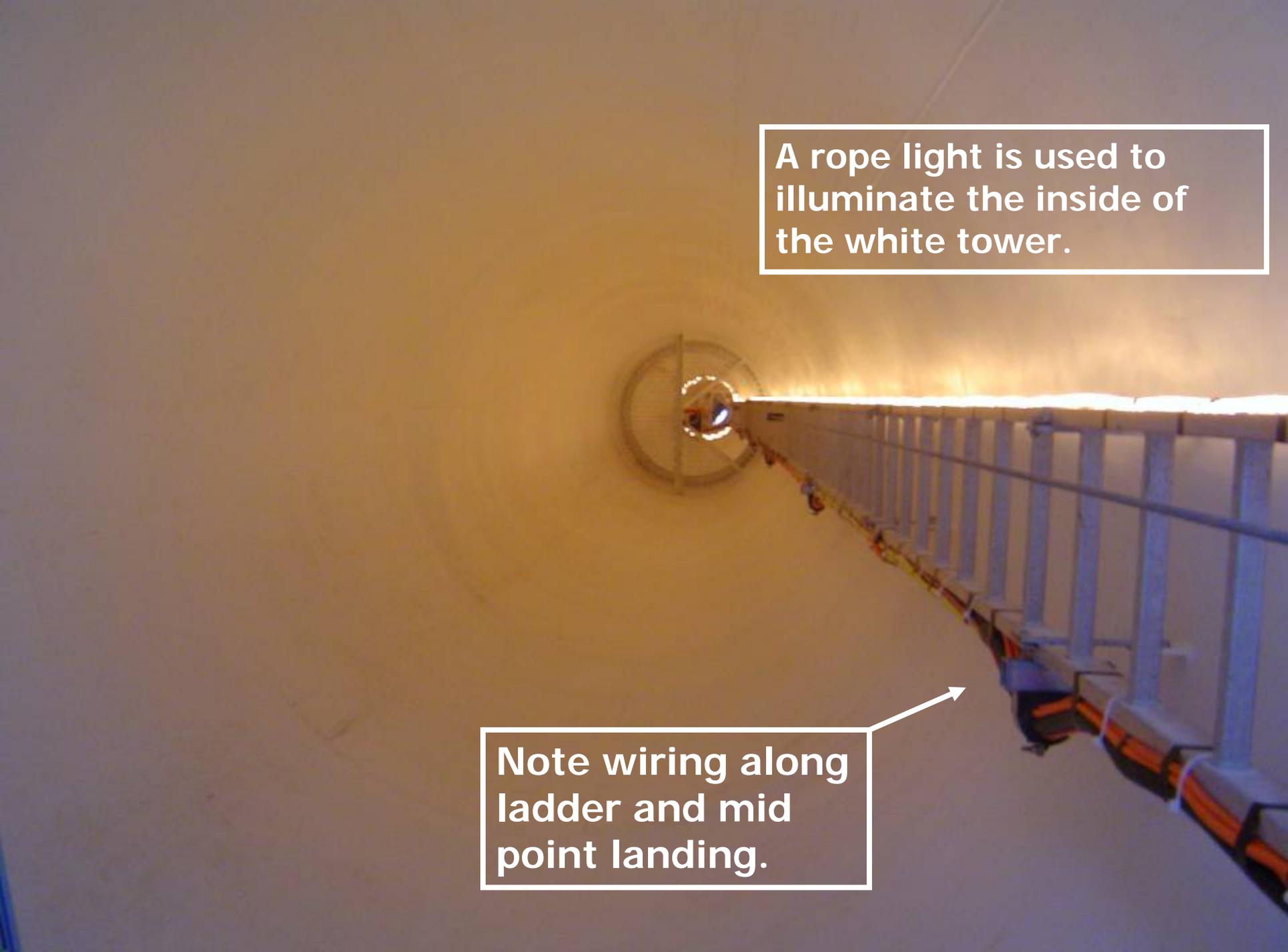
**A Nacelle and tower are placed on a cured foundation.**

**A foundation awaiting concrete is in the foreground.**



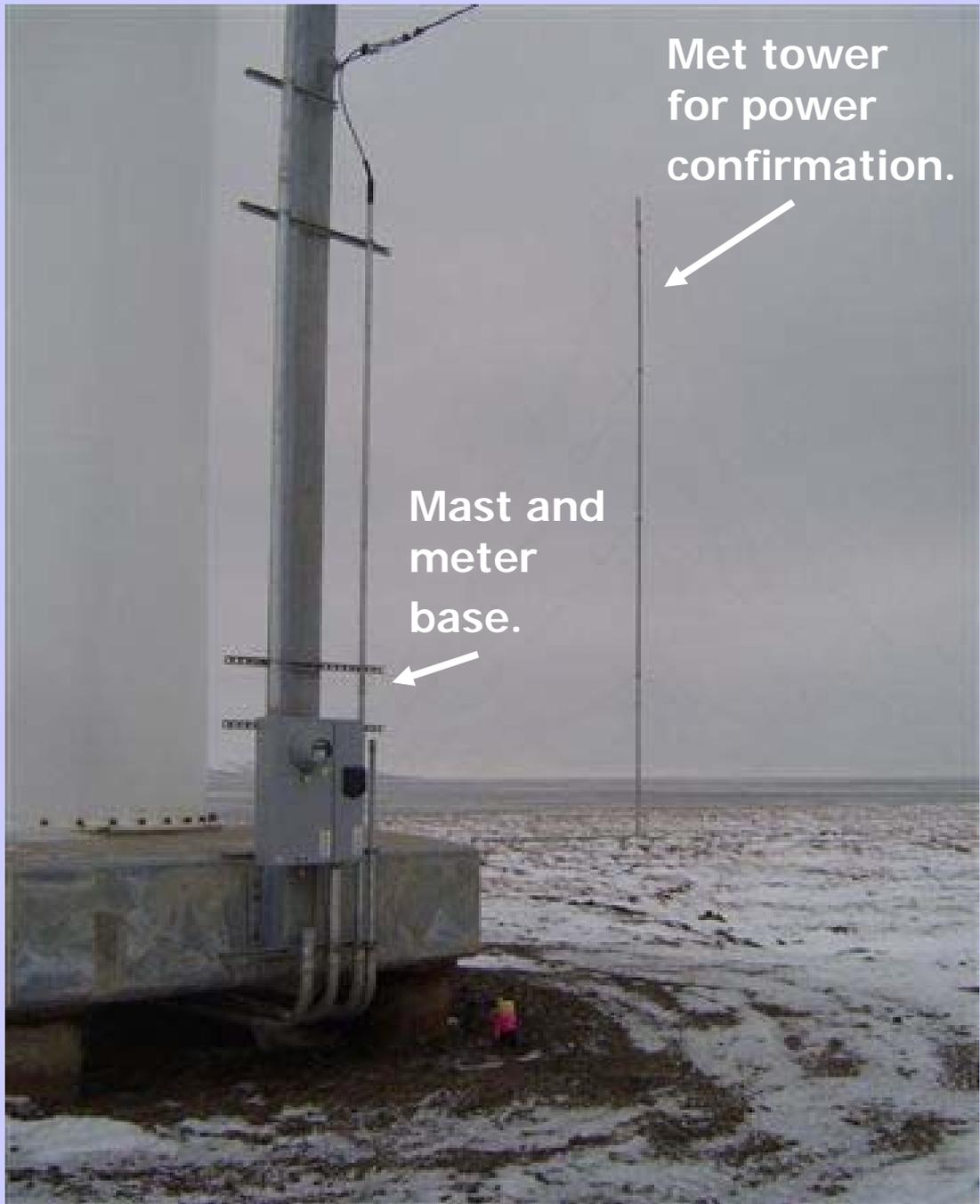
**Second tower section  
being put in place**



The image shows the interior of a white tower. A rope light is mounted along the top edge of the tower, providing illumination. A ladder is visible on the right side, with wiring running along it. A circular vent or light fixture is visible on the left wall. The overall lighting is warm and yellowish.

A rope light is used to illuminate the inside of the white tower.

Note wiring along ladder and mid point landing.



Met tower  
for power  
confirmation.



Mast and  
meter  
base.



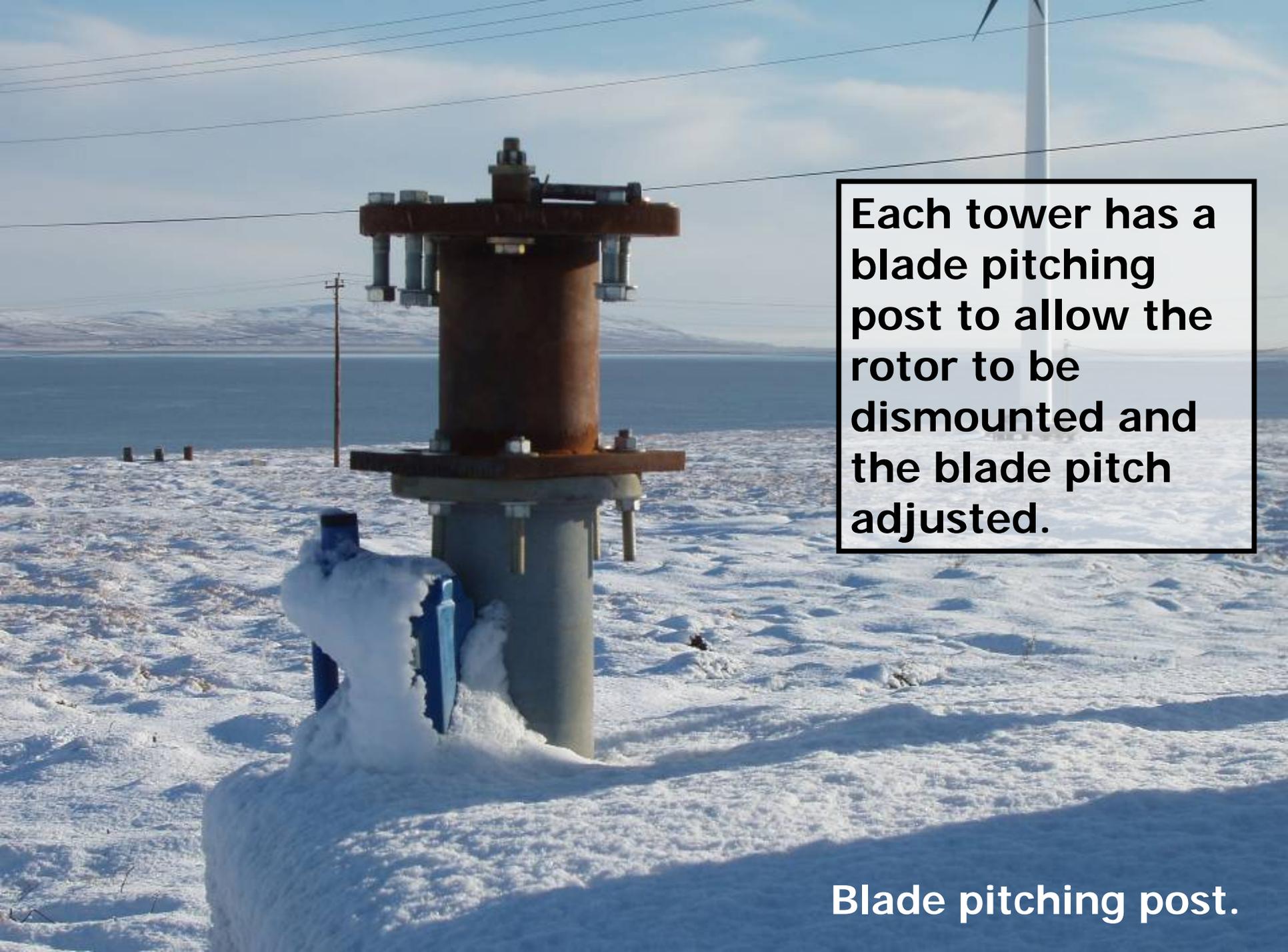


Concrete &  
Steel Mass

Meter Base

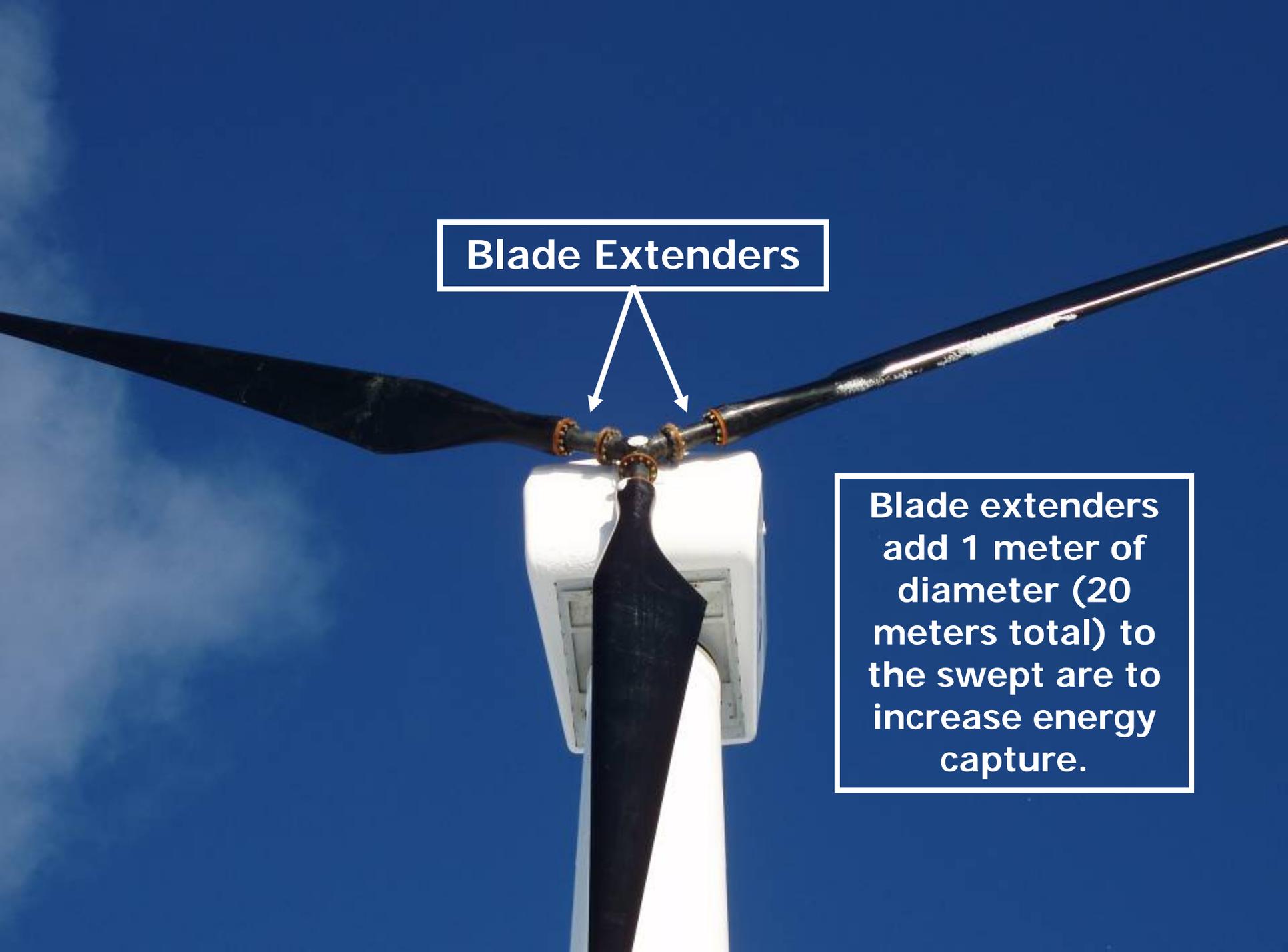
Three wind turbines completed at Toksook Bay.





**Each tower has a blade pitching post to allow the rotor to be dismounted and the blade pitch adjusted.**

**Blade pitching post.**



## Blade Extenders

Blade extenders add 1 meter of diameter (20 meters total) to the swept area to increase energy capture.

Tightening hub to turbine



# Blades with blade extenders



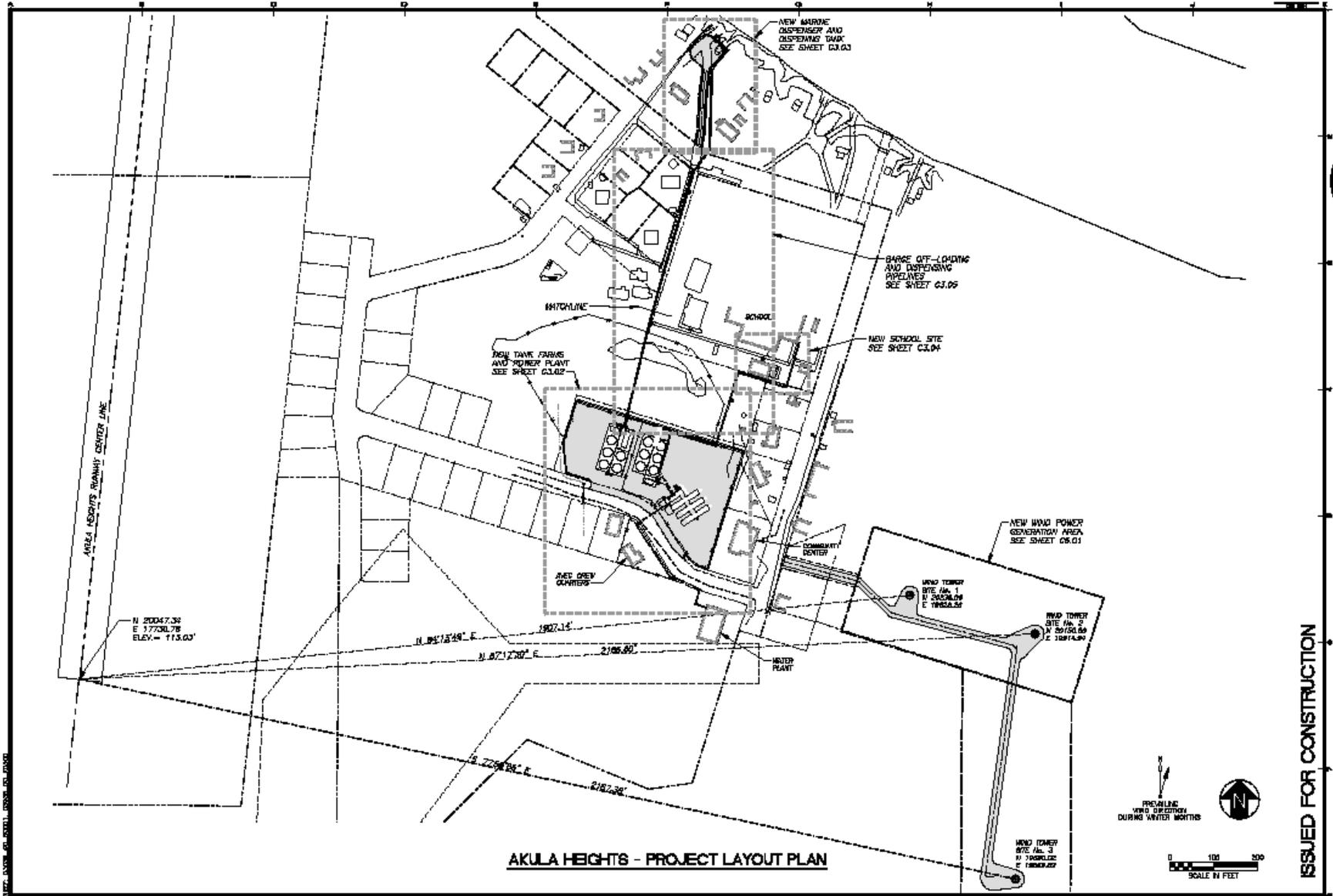
**At Akula Heights (also called Kasigluk) three NW 100 Turbines were installed east of the village on frozen sand and silt. No bedrock was encountered.**

- Mass was added by filling the steel foundation star with concrete, as in Toksook Bay.
- Because there was no bedrock, piles with 24 inch helices were screwed into pilot holes predrilled into the ground.
- Thermal siphons were added between, and outward of the piles to extract heat from the soil.

**Special Equipment  
was required to  
twist the helical  
piles into the ground**



AKLA-18-000001-000001-000001-000001



### AKULA HEIGHTS - PROJECT LAYOUT PLAN

NO.	1	2	3	4	5	6
DATE						
BY						
CHECKED						
APPROVED						



**HDR** HATHORN DALEY ANSELL  
 ENGINEERS ARCHITECTS  
 1000 W. 10TH AVENUE  
 ANCHORAGE, ALASKA 99501  
 (907) 571-4100  
 FAX (907) 571-4100

PROJECT: AKULA HEIGHTS  
 SHEET: C3.01  
 DATE: 01/20/2018

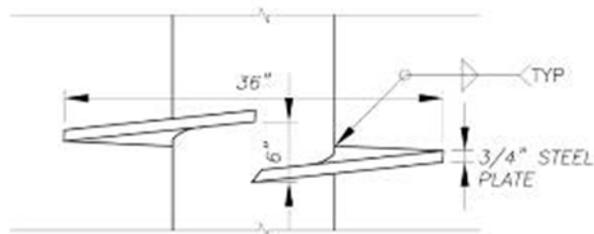


AKSILGIK/NUMARPITCIK ENERGY PROJECT  
**ALASKA VILLAGE ELECTRIC COOPERATIVE**  
 AKULA HEIGHTS, UNAPPTONAK AND OLD KASLUK, ALASKA

PROJECT	AKULA HEIGHTS PROJECT LAYOUT PLAN
SHEET NO.	C3.01
DATE	01/20/2018
SCALE	AS SHOWN
DESIGNER	HEATHER DALEY ANSELL
CHECKED	
APPROVED	

ISSUED FOR CONSTRUCTION

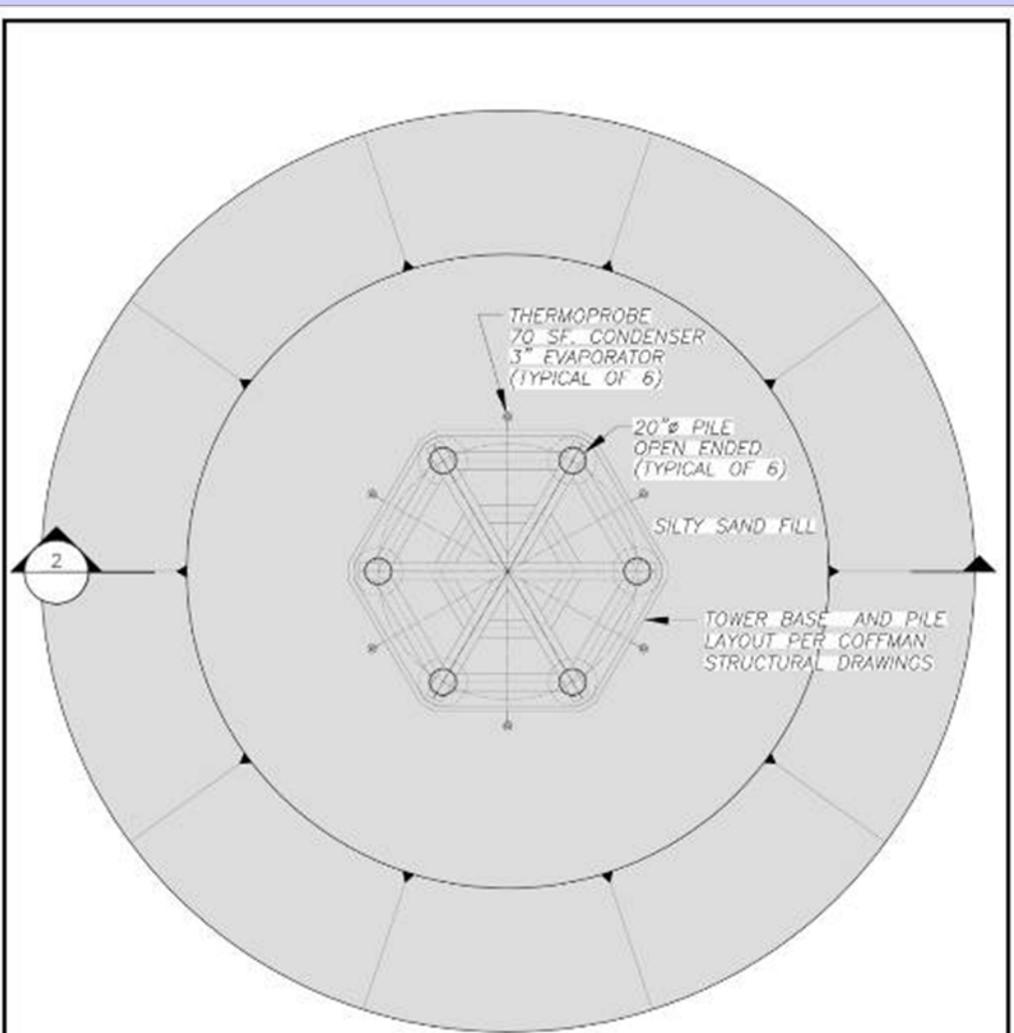




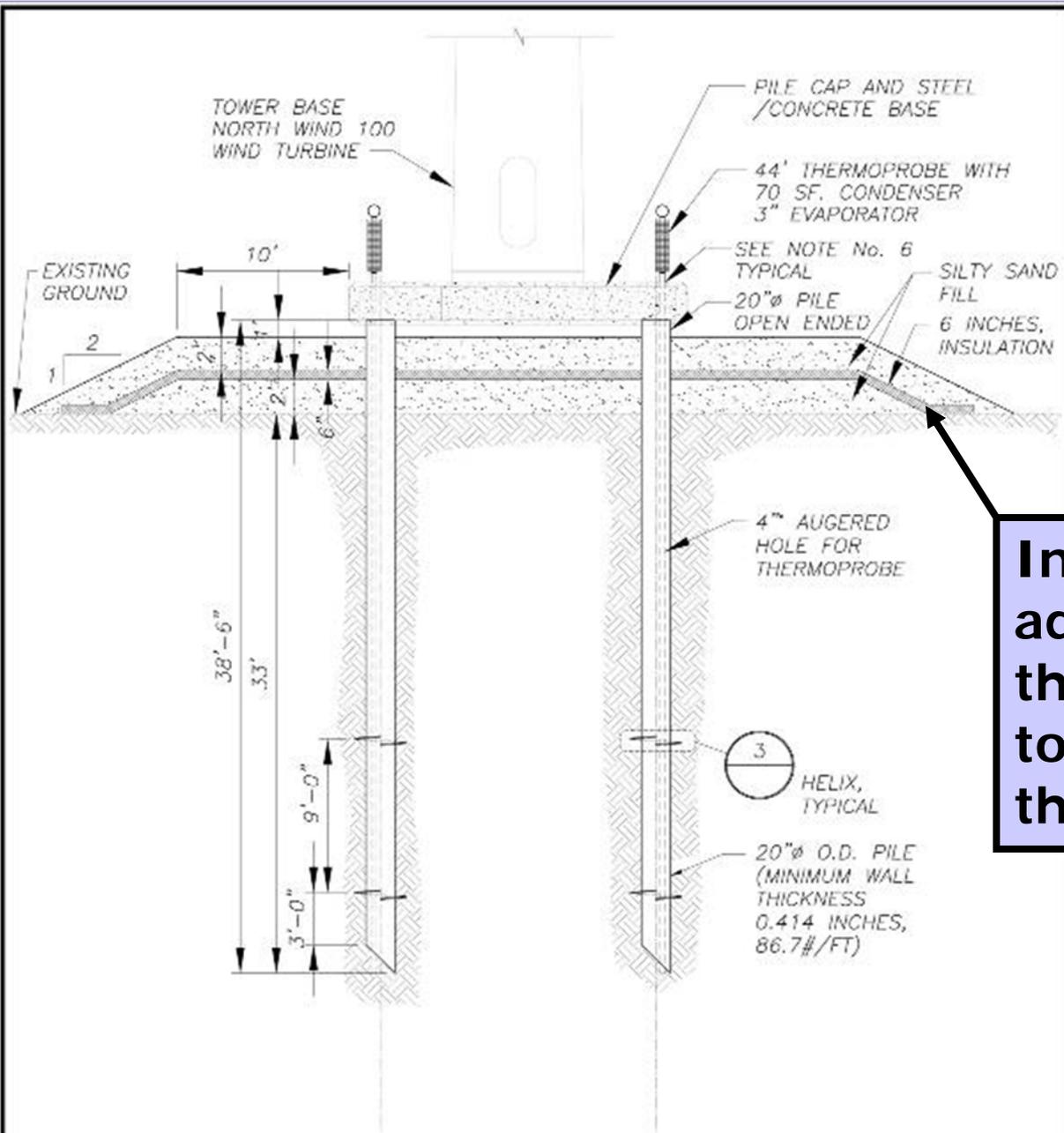
3 SECTION - TYPICAL HELIX  
SCALE: NONE

NOTES

1. ALL PILES SHALL BE INSTALLED OPEN ENDED WITH ENDS CUT AT 45 DEGREES.
2. THE CONTRACTOR SHALL SUPPLY THE ENGINEER WITH THE INSTALLATION TORQUE OF EACH PILE. THE TORQUE VALUE SHALL BE AVERAGED OVER 24-INCHES DURING INSTALLATION OF EACH PILE WITHIN 5 FEET OF THE FINAL PILE INSTALLATION DEPTH.
3. ALL PIPE SPICING SHALL BE FULL PENETRATION BUTT WELDS.
4. ALL WELDING, WELD PROCEDURES, PROCEDURES SPECIFICATIONS, AND WELDER QUALIFICATIONS SHALL BE IN ACCORDANCE WITH AWS D1.1. WELD ELECTRODES SHALL BE E70XX MINIMUM.
5. ALL WELD SIZES SHALL BE THE THINNER OF THE TWO METALS JOINED, UNLESS NOTED OTHERWISE.
6. FIELD WELD 1/2"x12" LONG, STEEL PLATE TO TOWER BASE AND CLAMP TO THERMOPROBE ADJUST WIDTH OF STEEL PLATE AS NECESSARY. DO NOT WELD TO THERMOPROBE.



1 **WIND GENERATION TOWER BASE PILE LAYOUT PLAN**  
 SCALE: NONE



**Insulation was added below the tower base to resist thawing.**



**Installing thermopiles during the Spring at Kasigluk**



**Installed thermopiles at Kasigluk**

**Temperature sensor strings, similar to the following, have been installed at Kasigluk to monitor seasonal and long term changes in permafrost temperatures.**



**TAC Images courtesy of Beaded Stream**

TOP LEFT: Temperature Acquisition Cable (TAC) and Reader

BOTTOM LEFT: All TACs are permanently labeled with their serial number which ties in with owner information, last calibration date, number and spacing of sensors, & sensor identifications.

RIGHT: An artists image of what an installed TAC looks like.



# Lessons Learned

- Geotechnical information is critical
  - In areas of complex geology or a highly varied active layer, it is useful to have information from the actual turbine site in order to recognize local variances.
  - When acquiring geotechnical information, also acquire the permafrost temperature and, if possible, install a temperature acquisition cable to monitor temperatures up to the time of construction.
  - Continue thermal monitoring of the turbine site after construction.

- Materials

- The lack of appropriate local aggregate for concrete can increase costs. Appropriate aggregate may have to be imported in addition to importing cement and mixing equipment.
- Waiting for the concrete to cure and then testing it can consume valuable time and may require a demobilization and remobilization of the crew.
- An all steel foundation would require larger components to provide desired stiffness, but may reduce construction complexity by eliminating tasks involving concrete. Portions of such a foundation could be prefabricated and shipped to the site.

- Frequency Modeling should include the pile foundation.
  - In a permafrost environment the point of fixity will rise and fall along the pile during the seasonal change.
  - Under such conditions the piles may behave as an extension of the tower and the turbine, tower and foundation systems may interact to develop a frequency that could be damaging.

- Mitigation

- Adverse harmonics could be mitigated through:
  - Adjusting turbine rpm, but slowing the turbine would reduce valuable energy output.
  - Addition of mass to dampen system response at known frequencies.
  - Stiffening the piles, pile caps, or tower.

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