# DESIGN, CONSTRUCTION AND INITIAL PERFORMANCE OF WIND TURBINE FOUNDATIONS IN ANTARCTICA

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ABSTRACT
Three wind turbines for electrical generation were constructed to lessen the need for imported hydrocarbons at two Antarctic research stations. The subsurface soils consisted of weathered volcanic rock with small to large interbedded ice bodies. The design of the foundations required a strict tolerance on differential settlement, namely 3 mm/m across the foundation element. This paper describes the foundation design and primary design issues.

The most important aspect of the foundation design was the estimation of creep settlement over the life of the project. The service loads on the foundation were grouped by load duration, and the corresponding creep settlement estimated. The foundation performance over the initial year after installation is described.

RÉSUMÉ
Trois éoliennes pour la production d'électricité ont été construites afin de réduire les besoins en hydrocarbures importés pour deux stations de recherche en Antarctique. Les terres subsurfaces sont constituées de roches volcaniques altérées renfermant de petites à grandes quantités de glace interstratifiées. La conception des fondations a nécessité une tolérance stricte pour les tassements différentiels de 3 mm/m en travers des fondations. Cet article décrit la conception des fondations et des principaux problèmes de conception.

L'aspect le plus important de la conception des fondations a été l'estimation du fluage pour la durée de vie du projet. Les charges sur les fondations ont été regroupés par durée de charge, et le fluage correspondant estimé. Le comportement de la fondation une année après l'installation est décrit.

## 1 INTRODUCTION

To reduce the dependence on hydrocarbon fuel generating electrical power at the McMurdo Station and Scott Base research facilities in Antarctica the construction of three wind turbines was proposed. The generation of electricity by wind power would reduce the combined consumption of hydrocarbon fuels by approximately 470,000 litres per year. Since these types of structures were unique to the Antarctic landscape and geological conditions the foundation design was proposed as a “proof of concept” approach.

The foundation for the towers was proposed as a multi-leg arrangement that were to be buried at a relatively shallow depth within the continuous permafrost. The allowable differential settlements of the towers required consideration of the creep behaviour of the soils, estimates of the long-term settlement, and development of contingency and mitigation measures to address potential non-compliant foundation behaviour.

This paper describes the subsurface conditions on which the tower foundations were designed, the foundation system and the initial performance data after one thaw season.

## 2 LOCATION AND SITE CONDITIONS

### 2.1 Location of Ross Island, Antarctica

Ross Island is located 1300 km from the South Pole, at approximately 77˚ 50.7’ S latitude. See Figure 1. The island is approximately 70 km by 70 km and is dominated by Mount Erebus, a 3800 m high active volcano that constantly emits steam. The geology of the island is dominated by its volcanic activity. The rocks are igneous of the Tertiary age.

### 2.2 Geotechnical Conditions

A detailed assessment of the subsurface conditions was hampered by the lack of drilling equipment at the research facilities. The subsurface conditions were explored using a top hammer hydraulic blast hole drill rig with the capacity to drill to at least 15 m, and return cuttings to the surface by compressed air. The lack of suitable tools for conducting geotechnical investigations in remote permafrost regions is a common problem experienced in the Northern Hemisphere also.

The native soils consist of weathered volcanic materials, having the characteristic of coarse gravel to cobbles, inter-filled with sand sized particles and ice.

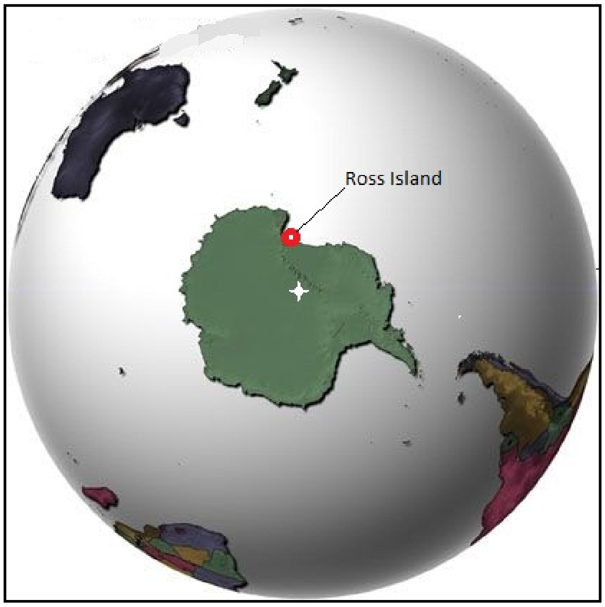


Figure 1. Location map showing Ross Island relative to the South Pole.

Partly weathered and unweathered bedrock exists at depth.

Drilling at each of the wind turbine sites revealed variable conditions in terms of ice content. For example, at site WT2, during drilling it was reported that a 1 m thick ice lens was encountered at a depth of approximately 6 m below ground surface. In numerous other cases, discrete ice lenses between 200 mm and 500 mm thickness were encountered. In at least one borehole, a discrete ice body about 1000 mm thick was indentified. Generally, the presence of ice lenses diminished with depth and only occasional ice lenses were encountered below a depth of about 8 m to 9 m. It is concluded from this information that the upper stratum of the subsurface soil conditions may be considered to be ice-rich.

The active layer is typically only 0.2 m to 0.3 m deep. No information was available with respect to pore water salinity.

## 2.3 Climate and Permafrost

The climate of Ross Island is severe in the extreme. The warmest recorded air temperature is +6 C and lowest recorded temperature is -57 C. The mean annual air temperature is about -20˚C. Figure 2 shows the mean monthly air temperature.

Ground temperature data are provided for one location. Eight temperature sensors were used to measure ground temperatures to a depth of 11.7 m below the top of one footing pad. The available data, recorded over a period of about four months prior to construction, indicate a mean annual ground temperature of about -17 °C with a depth of zero annual amplitude of approximately 8.5 m below the ground surface. At the base of the foundation, the annual soil temperature measured last season ranged from about - 7 °C to colder than -26 °C. See Figure 3.

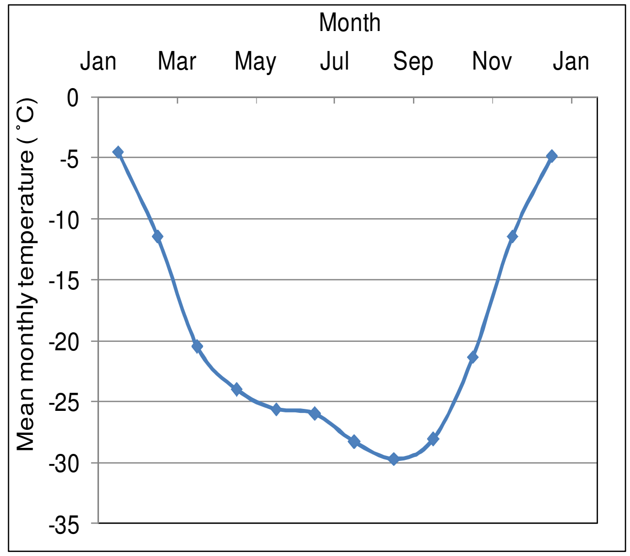


Figure 2. Mean monthly air temperature data from Scott Base, Antarctica.

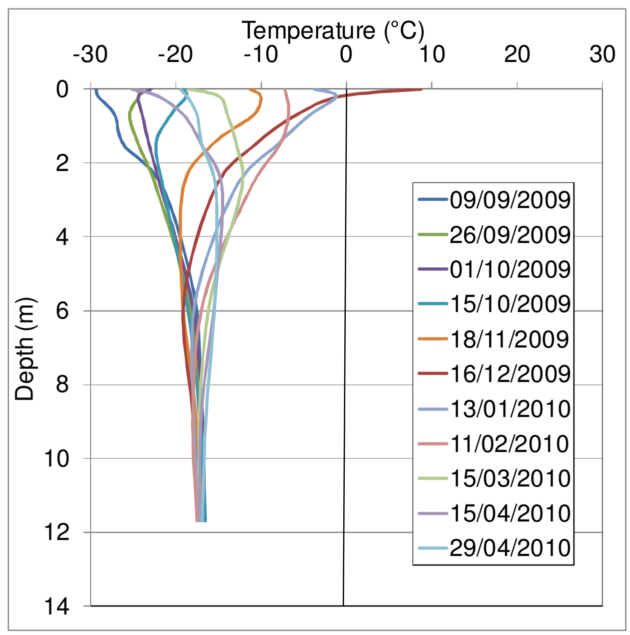


Figure 3. Ground temperature data collected at site WT-2.

## 3 FOUNDATION DETAILS AND DESIGN ISSUES

The foundation system for wind turbines may take many forms. What is common for all the systems is the need for very low tolerances for differential settlements. The presence of permafrost complicates the entire design and construction process. For a wind turbine project in southwest Alaska, large diameter (0.75 m) helix piers being 10 m to 13 m long were chosen as the foundation system. In the southwest Alaska case, the permafrost

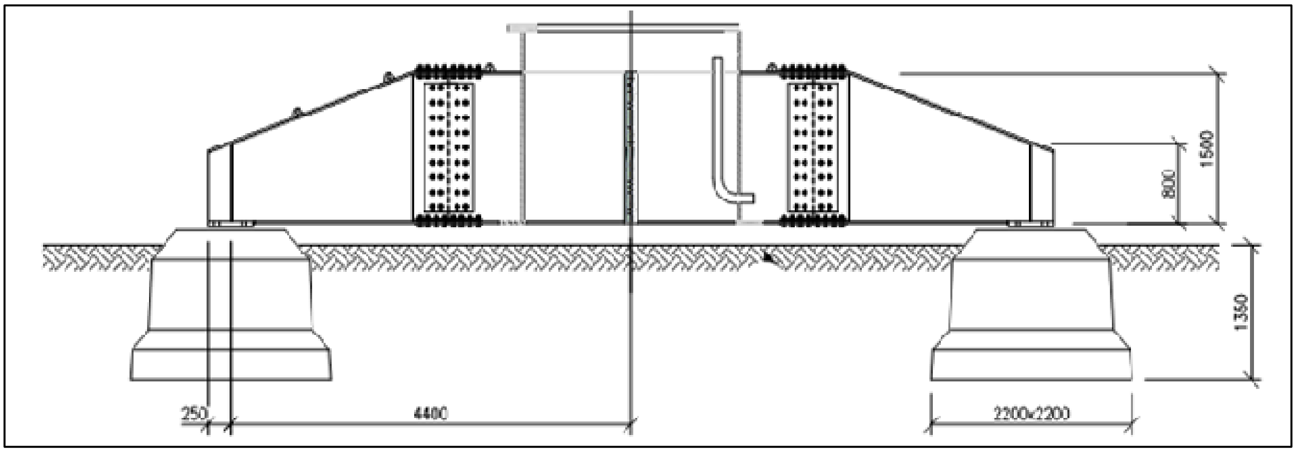


Figure 4. Cross section of wind turbine foundation system (all dimensions in mm).

was very warm and to enhance the load capacity, thermosyphons were installed adjacent to each helix pier (Dilley and Hulse, 2007). In another case, the 100 kW, 32 m high wind turbine in Hooper Bay, Alaska was supported on a set of six steel piles driven into the warm, fragile permafrost (Petrie, 2009).

For the Ross Island project where limited construction equipment was available, the foundation design required innovation and the recognition of the limited resources for construction. The wind turbine foundations were to consist of eight pre-cast concrete pads, with plan dimensions of 2.2 m by 2.2 m, and a thickness of 1.5 m. The base of each footing is placed at a depth of about 1.35 m below final grade, and rest on a layer of screened compacted native fill material of about 0.6 m thickness (below each footing pad). See Figure 4.

The normal bearing pressure on each footing is in the order of 40 kPa to 50 kPa with very short-term transient pressures of about 220 kPa, which may occur during an emergency shutdown event.

Each footing block was restrained against uplift loads by two soil adfreeze anchors, which are 40 mm in diameter and 12 m long. The adfreeze bond was provided by a hot water – bentonite slurry.

The governing geotechnical design issue was the creep settlement that the foundations could experience over the service life of the structure. The wind turbine manufacturer specified that the maximum allowable differential rotational settlement was 3 mm/m across the footing structure. The resulting differential settlement over the 20 years service life is therefore about 27 mm. The design temperature at the base of each footing was -4 °C. If ground temperatures exceeded this threshold mitigation would need to be applied.

For ice-rich soil at a uniform temperature, the settlement rate, $\varepsilon^{\bullet}$ (Nixon, 1978), is:

$$\varepsilon^{\bullet} = I\, a\, B\, (\Delta\sigma)^n \qquad [1]$$

where B and n are creep parameters, which vary with temperature and soil type

I = influence factor (depending on n), assuming Boussinesq stress distribution

a = half width of footing

$\Delta\sigma$ = footing contact pressure

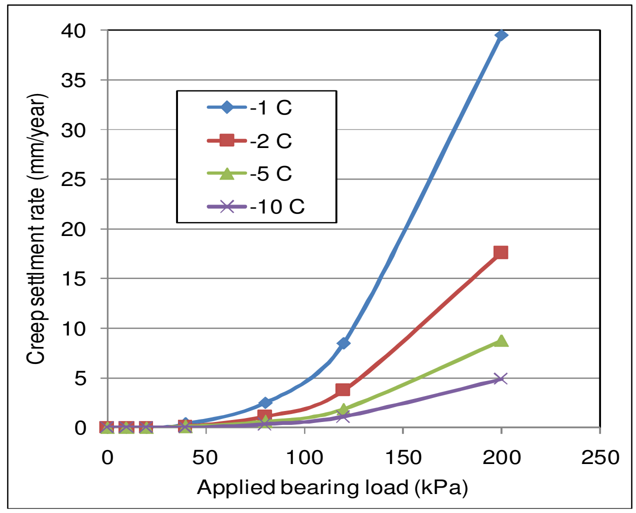


Figure 5. Creep settlement rate as a function of bearing load for various ground temperatures.

Table 1 lists the input parameters used in equation 1.

Table 1. Input parameter to estimate creep settlement.

| Design Parameters | Design Value |
|---|---|
| Footing influence factor (I) | 0.1 |
| Footing half width (a) | 1.1 m |
| Creep parameter (B) at -1˚C | $4.5\text{x}10^{-8}$ $kPa^{-3}yr^{-1}$ |
| Creep parameter (B) at -2˚C | 2.0 $\text{x}10^{-8}$ $kPa^{-3}yr^{-1}$ |
| Creep parameter (B) at -5˚C | 1.0 $\text{x}10^{-8}$ $kPa^{-3}yr^{-1}$ |
| Creep parameter (B) at -10˚C | 0.56 $\text{x}10^{-8}$ $kPa^{-3}yr^{-1}$ |
| Stress exponent (n) | 3 |

Figure 5 presents the estimated settlement rate as a function of the sustained foundation bearing load. At sustained bearing pressures less than about 100 kPa the settlement rate was less than 5 mm/year, even at very warm ground temperatures.

The foundation load scenarios were provided by the wind turbine manufacturer. Table 2 presents the various loading periods and corresponding foundation loads. For approximately 96% of the service life of the structure, the applied foundation load will be less than 50 kPa.

The foundation loading cycles described in Table 2 may be combined with Equation 1 to provide an estimate of the total foundation creep settlement that may occur over the project life of the foundation (20 years)

Table 3 presents the cumulative 20 year creep settlement as a function of soil temperature and duration for each loading condition. For a constant soil temperature of -5 ˚C and -10 ˚C, the total creep settlement is estimated to be in the order of 30 mm and 9.5 mm, respectively. Examination of Figure 2 shows that the ground temperatures below the footing level may be expected to be less than -5 ˚C during the summer months, and colder than -10 ˚C for much of the remaining part of the year. Hence, it is estimated that the actual 20 year creep settlement could be in the order of 10 mm to 15 mm.

Table 2. Foundation loading cycles and pressures over 20 year service life of wind turbine foundation considering the suite of loading scenarios that the foundation will experience.

| | Number of loading cycles | Relative frequency of loading event | Maximum foundation load (kPa) |
|---|---|---|---|
| | 1 | $3.214 \times 10^{-10}$ | 218 |
| | 1000 | $3.214 \times 10^{-7}$ | 114 |
| | 10,000 | $3.214 \times 10^{-6}$ | 104 |
| | 100,000 | $3.214 \times 10^{-5}$ | 93 |
| | 1,000,000 | 0.0003214 | 80 |
| | 10,000,000 | 0.003214 | 67 |
| | 100,000,000 | 0.03214 | 55 |
| | 1,000,000,000 | 0.3214 | 46 |
| | 2,000,000,000 | 0.6428 | 41 |
| Total | 3,111,111,001 | 1 | |

Table 3. Incremental creep settlement for each foundation loading period

| | Loading duration (years) | Incremental creep settlement (mm) for two ground temperatures | |
|---|---|---|---|
| | | -5 ˚C | -10 ˚C |
| | $6.43 \times 10^{-9}$ | $2.214 \times 10^{-7}$ | $1.032 \times 10^{-7}$ |
| | $6.43 \times 10^{-6}$ | $6.354 \times 10^{-5}$ | $2.523 \times 10^{-5}$ |
| | $6.43 \times 10^{-5}$ | 0.000528 | 0.0002 |
| | 0.000643 | 0.00422 | 0.0016 |
| | 0.00643 | 0.0316 | 0.0115 |
| | 0.0643 | 0.229 | 0.0798 |
| | 0.643 | 1.526 | 0.504 |
| | 6.429 | 10.76 | 3.399 |
| | 12.857 | 17.73 | 5.464 |
| Total | 20 | 30.28 | 9.46 |

## 4 CONSTRUCTION DETAILS

The foundation elements for the three wind turbines were constructed during summer of 2008-2009. The general construction sequence for the turbine footings was first to excavate the native soils to a depth of about 2.1 m, and then replace this material in lifts to a design grade of 1.35 m below final grade. The footings were then placed on the prepared surface, and the remaining excavation backfilled with screened native soil.

The excavated soils required blasting prior to excavation. Figure 6 shows a photograph of the native soils during excavation. The blasted material was screened over a 200 mm grating. The purpose of the over-excavation was to provide a relatively uniform bearing surface for the individual footings and to ensure that no massive ice bodies were present immediately below the footing elevation. Burial of the footings would also assist in managing potential overturning loads.

The screened soils were replaced in 250 mm lifts using a large bulldozer and large plate tamper for compaction. This work was, by necessity of the construction season, undertaken in freezing temperatures in the range of -18 °C to – 22 °C. Hence, the state of compaction of this fill material may be lower than desired and could be susceptible to settlement in the event of thawing; Haas (1988) has documented the reduction in the in situ density of sand of varying water content when compacted at -7 °C. For example, as the water content increased from 3% to 16%, the resulting dry density declined from 1600 $kg/m^3$ to about 1200 $kg/m^3$. Burwash and Clark (1981) and Brooker (1992) provide cases histories of poor fill or embankment performance as a result of compaction of soils in freezing conditions. However, given that the expectation that the foundation soils would remain frozen over the life of the structure the necessity to provide a high degree of compaction was balanced against the other construction imperatives.

With the foundation elements in place by early 2009, the wind turbine towers and electric generating machinery were installed in late 2009. The turbines underwent compliance testing in early January 2010 and were commissioned at the end of January 2010. In April 2010 the turbines operational performance was higher than what had been initially expected.

## 5 INITIAL FOUNDATION PERMFORMANCE

The performance of the wind turbine foundations was monitored since installation in early 2009. Elevation surveys of the foundations were undertaken over several months and will continue on a seasonal basis for several years.

The periodic monitoring results indicate that over the initial year after construction maximum settlement of individual footings ranged between 3 mm and 8 mm, with differential settlement across the three foundation structures ranging between 3 mm and 4.5 mm.

Ground temperatures are being monitored at all three wind turbine sites. At wind turbine site 1 and 3 the ground temperatures are monitored to a depth of about 3.5 m, while at wind turbine site 2, ground temperatures are monitored to a depth of about 12 m (see Figure 3 and

Figure 6). In Figure 6, the temperature at the base of the footing is never warmer than about -7 °C during the summer months. The minimum ground temperature at the footing base has not exceeded the specified maximum value, and these data support the decision to estimate the total expected creep settlement based on ground temperatures between -5 °C and -10 °C, as listed in Table 3.

## 6 CONCLUSIONS

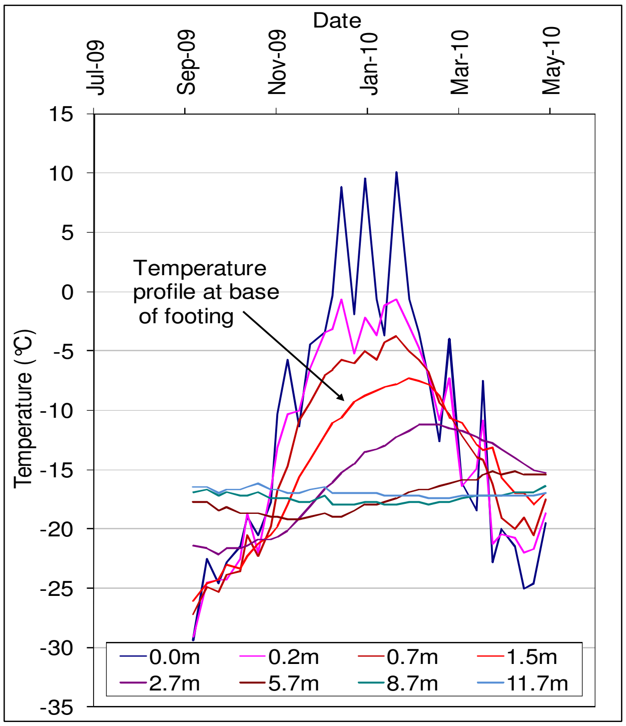


Figure 6. Ground temperature data under WT-2, footing 3 following footing installation.

The design and construction of shallow footings to support three wind turbines at the Scott Research Station in Antarctica has been documented. Performance monitoring over the first summer of operations has provided encouraging information on the ground temperatures at depth and on the settlement.

Additional monitoring will be conducted in future years to ensure the performance criteria are being met, or to initiate mitigation to enhance the performance.


## ACKNOWLEDGEMENTS

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Figure 7.  View of excavation of foundation soils, November 2008.

Figure 8. Wind turbine #1 foundation; material near base of excavation.

Figure 9.  Wind turbine #1; recompaction of excavated fill with large hydraulic plate compactor.

Figure  10. Wind turbine #1; foundation steelwork in place.