Practical aspects of construction decisions for large wind turbine foundations

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Keywords: wind turbine, greywacke, foundation stiffness, Clegg hammer

ABSTRACT

The Stage 3 expansion of the Tararua wind farm involved construction of 31 new turbines. Cyclical rocking under wind loading requires a strong foundation material and particularly high stiffness. Greywacke rock was the preferred founding material. This paper concentrates on the practical aspects of construction decisions which must be made by the supervising engineer. This aspect does not figure highly relative to other aspects in geotechnical engineering literature, but is an important part of engineering practice.

1 INTRODUCTION

In 2007 TrustPower Ltd (TrustPower), a private power generation company commissioned the Stage 3 expansion of the Tararua wind farm. The civil works, involving construction of the access roads, hardstand platforms and turbine foundations, was undertaken through 2006 and continued through the winter. The existing wind farm, comprising the original two stages of construction has 103 turbines, each with a capacity of 0.66MW. The Stage 3 expansion included 31 new 3.0MW capacity turbines. The new machines are thus significantly larger than the first two stages, and are supported on a mass concrete foundation. The pads are octagonal in shape, 15m diameter and approximately 2m thick. Figure 1 shows the hardstand and foundation excavation stage and then the mass concrete pad at a later stage.

Figure 1: Stages of foundation construction

2 SITE DESCRIPTION

The existing wind farm spans a generally broad ridge which steeply rises above the flat Manawatu plains to the west and the Woodville valley to the east. The wind farm is located on a relative low point on the Ranges (a saddle) immediately south of the Manawatu Gorge, where the Manawatu River flows east to west through the Ranges. At this low point two wind farms have been located either side of the Gorge. The site extends 5.3km along the Tararua Ranges and was selected because of high annual mean wind speeds. The Tararua wind farm is recognized as one of the best generation sites in the world. The earlier smaller turbines typically occupy flat to gentle terrain at the crest of the Ranges. Subsequently the sites for the newer and larger turbines are often on smaller, local ridge spurs flanked by steep slopes. The elevation of the new turbine bases is typically 340 – 580m above sea level.

3 SITE GEOLOGY

The predominant material forming the Tararua Ranges is Mesozoic age greywacke sandstone and argillite. Overlying this is localised Tertiary sedimentary deposits and later Pleistocene/Holocene alluvial material forming terraces and filling gullies in older deposits.
The Tararua Ranges are bordered to the immediate east by the Wellington Fault which divides into the Ruahine and Mohaka Faults to the north. These faults are considered geologically active and have in recent times uplifted and tilted the Tararua Ranges. During the initial period of uplift it would appear the Manawatu River meandered across the saddle area of the Ranges (where the existing wind farm is sited) until settling and eroding a gorge in its present position. Though no active faults are publicly mapped directly crossing the wind farm site, many lineaments crossing the site (lineations in the ground surface) of varying length (hundreds to thousands of metres) have been observed from site walkovers and study of aerial photos (Lee & Begg, 2002).

The sandstone and argillite beds are generally referred to as 'greywacke,' which more correctly refers to the sandstones. Localised bodies of chert are also found within the greywacke. Argillite is occasionally present, generally exhibiting lower strengths than greywacke which is typically moderately to very closely fractured and has tested unconfined compressive strengths (UCS) near surface of 3MPa to 25MPa. Over significant areas of the wind farm the rock was more weathered and weaker, often completely to highly weathered to significant depths. Equivalent UCS were 1 to 5MPa and often lower. It is common for greywacke to be crossed by steeply dipping clay filled defects extending 10m+ in horizontal extent.

The Pleistocene age materials consist of complex layering of silts, sands and gravels exhibiting varying densities from loose to very dense. These deposits cover approximately half of the existing wind farm site becoming thicker to the north (exceeding 20m depth adjacent to the Manawatu Gorge). Though probably laid down relatively flat these deposits on the western side of the Ranges have now been tilted westward by 4º to 9º due to uplift. The Holocene deposits comprise clays, silts and occasional fine sands typically constrained to filling of old gullies or at the base of modern streams. Surficial loess (wind blown) deposits were also encountered sporadically mantling the surface across the wind farm, varying from 0.5 to 3.0m thick.

4 INVESTIGATION AND DESIGN PHASE

Riley Consultants Ltd (RILEY) was engaged by TrustPower to investigate geotechnical conditions for 31 turbine sites, and to undertake civil design. Investigations at each site typically comprised a site walkover by an engineering geologist, followed by subsurface investigation consisting of a series of test pits and either machine boreholes or hand auger boreholes. At many sites depth to rock was highly variable and additional relatively inexpensive percussion boreholes were sunk.

The maximum bearing pressure to the foundation, derived by the structural designer, Opus Consultants Ltd, was about 750kPa in an extreme wind load case. Rocking stiffness was also an important parameter stipulated by the turbine suppliers; and was a more critical parameter than the bearing capacity. The equivalent Youngs modulus required was about 200MPa; this was beyond the strength of a hard soil and necessitated a rock foundation. Laboratory testing and use of various correlations pointed to an equivalent unconfined compressive strength (UCS) of about 1MPa being required, ie a rock at the lower end of the very weak category. The general design requirement for the foundations were also to have an acceptably low risk of being detrimentally affected by slope instability, liquefaction, or other loss of support over the design life, and to be unaffected by active faulting beneath the footprint.

The general expectations were that some sites had uniform sound rock close to the ground surface but more variability and poorer conditions were expected for quite a few sites. Of the 31 sites, 29 were expected to be on greywacke rock; with undercutting likely on a significant proportion. The remaining two sites were located on dense Pleistocene sands and gravels.

5 CONSTRUCTION ASPECTS

5.1 General

The general methodology at each site involved excavation to the general hardstand level. This was followed by a further 2m deep excavation for the turbine foundation. Foundation verification inspections were carried out at several stages and, where considered necessary, detailed geological mapping of defects and geological structure was carried out. The ground conditions were the responsibility of RILEY, with the structural designers inspecting the steelwork. Some of the key issues encountered are discussed in the following sections.

5.2 Safety of personnel

The safety of short term unsupported excavations is an aspect of geotechnical engineering not particularly amenable to rational analysis in many cases. However, where excavations are deep, with heavy machinery and personnel working at the bottom, it is an important consideration. One site reached an undercut depth of 3 to 4m, ie an overall excavation depth of about 6m. It was agreed by all parties this depth of excavation at a steep slope presented an unacceptable risk; hence benching to improve safety was carried out. At this site the undercutting required was far greater than envisaged, precluding an “engineered” initial batter excavation.

5.3 Further investigations in construction phase

Wind farms allow some flexibility in locating the final turbine site. This can be used to advantage in optimising the location, especially where ground conditions are variable over short distances. This results in significant savings in time and money. The considerable initial excavations for the hardstands allowed a visual appraisal of the ground conditions; and test pits provided further information. This approach requires commitment and cooperation in the construction phase from both the designers and the contractors. Targeted additional drillholes were also carried out at several locations during construction. As the project proceeded, the backfilling of undercuts was extended into winter and were initially proving to be time consuming and difficult. Further confirmation on the likely undercut volumes was considered prudent at that stage for remaining sites. Also, further drillhole investigations beyond test pit range indicated savings for alternative locations over the original site on several occasions, with considerably less undercut required.

5.4 Verification methods for foundations and acceptability criterion

The initially envisaged site verification methods involved a combination of visual inspection, probing and numerical methods. These methods included penetrometer and Schmidt hammer (SH), or Clegg hammer (CH). After initially trialling the SH, the CH proved to be far more reliable, quicker, and gave reasonable results for both various grades of weathered rock and sands/gravels. The CH was also able to quickly identify potential undercut areas by using a grid system over the large foundation footprint. Correlations were developed between CH value and the key criterion of modulus with an appropriate degree of conservatism adopted. The target CH values were 20 averaged over each foundation sector, and preferably 25. Penetrometer results (virtual refusal) and visual appraisal together, also formed part of the foundation acceptability. The SH results were found to be heavily influenced by defects, which were common. The CH does have some limitations; in particular, readings may be influenced by surface disturbance and moisture.

Due to the considerable size of the excavation and inherent variability in ground conditions, decisions on foundation acceptability and required treatment were often not straightforward. For example, 15 of the 31 sites required undercutting, some to considerable depth. The ground conditions were broadly in line with expectations from the site investigations, but variability even over short distances was often encountered and, at some sites, complex geology.

The most challenging ground conditions comprised several categories:

- a steeply dipping competent rock surface with unsuitable (soil strength) material above;
- marginal strength over the entire footprint; and
- weak zones in bands within a more competent rock mass (sometimes several areas).

These scenarios are shown in Figure 2. In addition to considerations of foundation stiffness and uniformity of support, a focus of geological mapping was identifying potential wedge-type ground movement mechanisms daylighting on adjacent steep slopes. Stability analyses were carried out where considered necessary to confirm acceptable margins on slope stability.

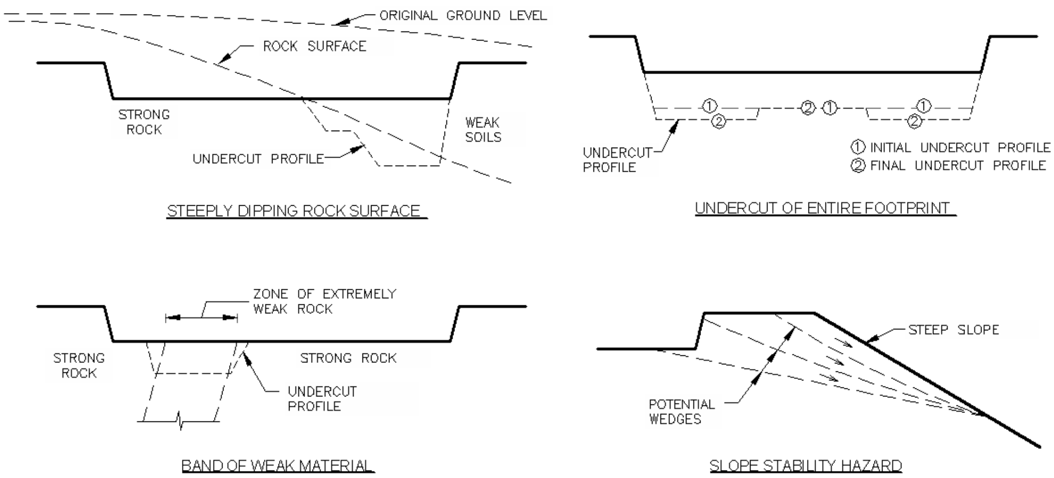

Figure 2: Foundation scenarios

5.5 Decisions on undercutting

Where marginal foundation materials existed the material was undercut to a more suitable level, and backfilled with an imported high quality hardfill. Due to the size of the foundation pad extensive excavation and backfilling volumes were undesirable, from both timing and cost considerations. Table 1 below shows how each of the various scenarios were addressed during construction.

For undercutting decisions it was found useful to supplement qualitative judgement with an analytical approach. Where the foundation at undercut level met the acceptance criteria this approach was not necessary. However, the situation where the undercut level was marginal or less than the acceptance criteria was commonly encountered. As the thoroughly compacted hardfill layer had a stiffness of approximately twice that required, the layer provided a “rafting” effect over the underlying materials, and foundation demands were reduced.

Table 1: Foundation scenarios and adopted solutions

<table>
<tr><th colspan="2">Scenario</th><th>Solution</th></tr>
<tr><td rowspan="2">1. Steeply dipping rock surface</td><td>Material meets acceptance criteria at undercut level</td><td>Acceptable</td></tr>
<tr><td>Material does not meet criteria at undercut level</td><td>Consider rafting effect of hardfill</td></tr>
<tr><td rowspan="2">2. Unsuitable over entire footprint or weak material in a band</td><td>Material meets acceptance criteria at undercut level</td><td>Acceptable without further analysis</td></tr>
<tr><td>Material does not meet criteria at undercut level</td><td>Consider rafting effect of hardfill</td></tr>
</table>

The extreme wind loads were applied over a 5m width of the foundation perimeter, and Westergard Charts were used to quantify stress reduction with depth. A “weighted average modulus” (WAM) was derived for the non-uniform foundation profile, taking account of the variation of assessed modulus with depth and the corresponding stress level. This value could be compared to the design criteria of 200MPa uniform profile. The logic was that if the WAM was similar to 200MPa, foundation performance should be similar and meet expectations. Conventional settlement calculations were also used to compare the “non-uniform” profile to the uniform profile.

The advantages of this approach included:

- a more rational basis for undercutting extent than a purely qualitative judgement;
- excessive undercut was avoided, with cost benefits to the Principal and Contractor; and
- this information could be relayed rapidly from the Site Engineer to minimise the time required to make a decision.

The geometry of the undercut was also an important consideration. In general terms sound practice for major engineering structures is to have uniform support (primarily due to concerns on differential settlement). This is less important for a wind turbine foundation because the major loading is applied to only a segment of the overall foundation; and foundation pressure due to weight alone is relatively small. Where possible, undercuts were carried out to a near horizontal profile, but in several instances a non-uniform profile was accepted. This is because in these instances removal of sound rock would have been necessary and the additional cost involved was considerable. Some other practical considerations included:

- adequate width for practical compaction is vitally important, as often difficult shaped wedges were involved; and
- in winter conditions the logistics of access in a deep hole is difficult, particularly where groundwater creates additional problems.

In order to ensure a uniformly high standard of compaction in these conditions each layer was tested by densometer. The compaction requirement was an average dry density exceeding 95% of the vibrating hammer laboratory density. Undercutting was carried out on 15 of the 31 sites. By the methods described above, additional investigations and optimisation of the turbine locations the undercut volume was 58% of the initially scheduled volume.

5.6 Control of groundwater

Groundwater was not an issue at most sites, as the turbines are typically located on elevated ridges or spurs. However, one site encountered groundwater inflows in an undercut section despite being located on a broad ridge. Large inflow when backfilling in a deep hole was difficult to deal with as pumping or drainage was not always effective. This is because in a deep wet hole the moisture from the foundation is inevitably drawn up into the lower layers, saturating the hardfill and effective compaction is impossible. In this case, local site concrete plus drainage enabled the water to be isolated from the backfill and much drier conditions enabled good compaction.

5.7 Role of Contractor and Principal

The role of these two parties is vital to a successful outcome of a civil project. At Tararua the main contractor Higgins Contractors, and the three earthworks sub-contractors, had to deal with a wide range of material types. This included working in difficult winter conditions. Quality assurance of the foundation preparation stages and backfilling was a significant component involving both the Engineer and the Contractor; giving confidence to the Principal TrustPower that the project requirements were being met. At times the Engineers deliberations in resolving foundation issues conflict with the Contractors' desire to progress the job. The Engineer should be mindful of this in a project of this type.

CONCLUSIONS

- The scope and expense involved in site investigations is subject to considerable judgement, and is site and project specific. For a wind farm type development there is some flexibility in final siting, and a cost-effective methodology can be used to advantage.
- For the Tararua Stage 3 project many sites had variable ground conditions. Simple supplementary investigations during construction and observation of initial excavations could be used to advantage to minimise costs.
- Safety aspects should always be considered particularly where deep temporary excavations are involved.
- A sound understanding of the geological setting and sites that may be problematic assist the Engineers tasked with the ultimate foundation decisions.
- It is helpful, where possible, for the Engineer to have some numerical backing to what are essentially judgement based decisions during construction.
- The Clegg hammer was found to be the most useful testing tool during construction to identify weak spots in a variety of rock conditions. The limitations of this tool must, however, always be recognised and not form the sole basis for decision making.
- Practical considerations related to construction decisions do not figure highly relative to other aspects in geotechnical engineering literature. This aspect is, however, a key part of engineering practice.
- The Contractors' and Principal's roles are important during construction. A team approach to the foundation construction should minimise the effect of any difficulties that arise. The Engineer should always be mindful of the necessity for prompt decision making, as this may directly affect the Contractors' workflow; whilst ensuring the decisions are soundly based in terms of the project requirements.

ACKNOWLEDGEMENTS

The permission of TrustPower Ltd to publish this paper is gratefully acknowledged.

REFERENCES

Lee, J.M. & Begg, J.G. (2002) *Geology of the Waiarapa Area.* Institute of Geological and Nuclear Sciences.