https://dx.doi.org/10.22161/ijaers.6.2.3 ISSN: 2349-6495(P) | 2456-1908(O)

Critical Review of Three Selected Papers on the Design of Wind Turbine Foundations

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***Abstract*— *Research on wind energy, as a potential substitute for fossil fuels, has gained popularity worldwide with the arising global warming, environmental issues and scarcity of fossil fuel reserves. Wind turbine is known to be a device that harnesses wind energy to produce electricity cleanly. The foundation is the main structural element needed to carry the turbine and transit static and dynamic loads into the soil. When designing wind turbine foundations, several aspects are investigated to ensure safe and economical design details such as total site investigations, different loads on the foundation, as well as creep settlement. Furthermore, factors such as strength, stiffness, stability, differential settlement, durability and economy are also considered in the foundation design process. This work aims to review different designs of wind turbine foundations installed in South Africa, Turkey and Antarctica.*

Keywords—Gravity foundation; Wind turbine; Wind energy; Settlement.

I. INTRODUCTION

The foundation of turbine anchors the tower and offers stability and stiffness to the entire structure. Loubser and Jacobs (2016)utilized concrete gravity foundation, normally with a circular shape to endure multidirectional design loads.Diameter of foundation was determined depending on the type of soil underneath the base of turbine.They suggested to use rock or soil anchors to enhance stability but would result in increasing the overall cost of constructing the foundation.

Construction of wind turbines requires extensive geotechnical and geological site investigations as the soil carries the wind turbine. The significance of site investigations lies in the data they provide regarding soil conditions for designing wind turbine foundation. Cabalar *et al.* (2016) conducted field exploration to secure data on subsurface conditions in the Hasanbeyli area in Turkey. Soil specimens obtained from site were examined in the laboratory to identify physical and engineering soil properties. Their work elaborates recommendations and conclusions for constructing the turbine in Hasanbeyli and provides general methodology for designing wind turbine foundation according to engineering analysis.

Figure 1: illustrates the various components of a wind turbine system.

Fig.1: Components of a Wind Turbine System (Malhotraet al., 2007)

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Use of wind turbines is favoured to minimize reliance on fossil fuels to produce electricity. Oswell*et al*.(2010) studied the construction of three wind turbines at the McMurdo Station and Scott Base research facilities in Antarctica. Assuming total fossil fuel consumption couldbe decreased by 470,000 litres per year through electricity production by wind power (Oswell*et al*., 2010). Due to the different nature of the Antarctic terrain and subsurface formations, their foundation design was made to prove the possibility of building wind turbines in such areas. The foundation of the turbine was determined as multi-leg configuration placed within the permafrost at a shallow depth. Different aspects were investigated such as differential settlement of the turbines, creep of soil, long-term settlement, and emergency procedures to reduce the effect of undesirable behaviour of foundations. Their work illustrated underground conditions above which the turbines were constructed, the foundation design and performance information after a period.

Table (1) demonstrates the names and sources of the three research papers used for conducting the review.

Table.1: The three research papers used for critical review.

	Research Paper
1	Cabalar A, Uyan R and Akbulut N (2016), A Study of Foundation Design for Wind Turbines in Hasanbeyli, Turkey, Soil Mechanics and Foundation Engineering, 53(5), Available from: https://link.springer.com/article/10.1007/s11204-016-9402-8 [Accessed 5 November 2018].
2	Loubser P and Jacobs A (2016), Optimised design of wind turbine gravity foundations, Insights and Innovations in Structural Engineering, Mechanics and Computation, Available from: https://www.abt.eu/bestanden/Afbeeldingen/Actueel/Publicaties/5109-1/Wind_turbine_foundations_Axel_Jacobs_Peter_Loubser.pdf [Accessed 5 November 2018].
3	Oswell J, Mitchell M, Chalmers G and Mackinven H (2010), Design, Construction and Initial Performance of Wind Turbine Foundations in Antarctica, GEO 2010, Available from: http://pubs.aina.ucalgary.ca/cpc/CPC6-997.pdf [Accessed 5 November 2018].

1.2 Research Aims and Objectives

1.2.1 The Aim

The main aim of this work is to investigate and review the various structural designs of wind turbine foundations constructed in three locations which are Turkey, South Africa and Antarctica.

1.2.2 The Objectives

The objective of this study is to discuss and evaluate the different designs of wind turbine foundations while making direct and indirect comparisons. SWOT analysis is conducted to discuss the strengths, weaknesses, opportunities and threats of each design approach and a conclusion is drawn accordingly.

II. DISCUSSION

Cabalar *et al*.(2016)made geotechnical field investigations in Hasanbeyli area. A total of 20 boreholes with a depth of 20 meters were drilled to determine soil characteristics before constructing the turbine. After that, laboratory tests were conducted to determine soil properties which were later used as input for designing the foundation. The foundation design was mainly based on the geotechnical field conditions in the area. Analysis of foundations was conducted using SAP200 software. It involved calculation of self-weight, wind loads, and structural loads then modelling the structure with loads and conditions. Simplified approach for designing the wind turbine foundation was adopted in their study by assuming spread footing. The advantage of using this foundation type is that it depends on soil surcharge load as well as own weight to overcome overturning effect of high winds. Moreover, the upsides of using concrete in gravity foundations are its durability, strength, and ability to be casted in any shape.

The limitation of this paper is that it followed generalized approach for designing the foundation by making certain assumptions to simplify calculations. While this method can be suitable and economical for the specified area and conditions, it can be expensive especially when constructing larger wind turbines as it will require larger foundation sections. This will lead to an increase in the material cost of the foundation. Thus, efficient use of steel reinforcement as well as non-linear structural and soil modelling can enhance the economy of design.

Oswell *et al*.(2010) made an innovative design of the wind turbine foundation based on the presence of permafrost and lack of resources in Ross Island. It was designed to serve up to 20 years. The foundation system consisted of eight pre-cast concrete pads having specified dimensions. These pads are placed on a compacted fill material below ground level and then buried to increase resistance to overturning. Then, each pad was fixed to the ground by two soil ad freeze anchors. Geotechnical aspect focused on creep settlement as it was the main issue in the design process.

Limitations of this paper lies in the design which relies on the loading scenarios given by the turbine producer instead of calculating wind, structural and own weight loads sustained by the foundation. Calculation of loads provides accurate and economical design output. In contrast, generalized loading conditions result in maximized cost as they utilize extreme loading scenarios and factor of safety values. Moreover, analysis method of the foundation was not elaborated in the paper to show the basis behind choosing the dimensions of footings. It has been proven that using advanced structural modelling and three-dimensional soils decrease material used by 30 – 40 % compared with simplified design methods (Loubser and Jacobs, 2016).

Loubser and Jacobs (2016) carried out an optimized design of the foundation using non-linear analysis and modelling which provided 7.1 % and 34.3 % savings in concrete volume and rebar, respectively compared with the simplified linear elastic design. Their design considered several factors such as bearing capacity of soil, stiffness, settlements, Factor of Safety against overturning. In addition, Euro codes 2 and 7 were used as references for concrete and geotechnical designs, respectively. The advantage of this paper is that it compared the design by non-linear approach to the linear elastic approach and summarized the results of both methods in a table showing the amount of savings in concrete and steel reinforcement. Moreover, diagrams showing models of rebar and variation of concrete stresses were clearly illustrated.

The disadvantage of this paper is that although it clearly states that non-linear approach optimizes the design of foundation, the operator refused the outcomes of this approach and requested to re-design the foundation according to the linear elastic system.

Figure (2) demonstrates the dimensions, top view and cross section of a typical foundation slab.

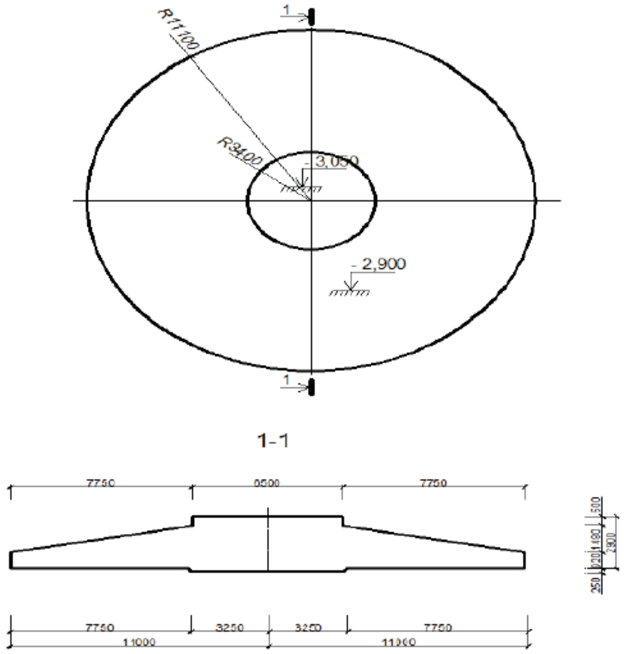

Fig.2: Dimensions and cross-section of typical foundation slab. (Zhussupbekovet al., 2016)

2.1 SWOT Analysis

Table.2: SWOT Analysis

Strengths	Weaknesses
Cabalar *et al.* (2016)– Economic and safe design for the specified conditions. **Cabalar *et al.* (2016)**– Foundation analysis conducted by SAP2000 modelling and analysis software. **Oswell*et al.*(2010)**–Innovation in design due to scarcity of construction resources. **Loubser and Jacobs (2016)**– Optimized foundation design by non-linear approach. **Loubser and Jacobs (2016)** – Modelling of concrete foundation and soil by 3D structural and soil modelling software.	**Cabalar *et al.*(2016)**–Simplifieddesign leads to uneconomic foundation. **Cabalar *et al.*(2016)**– Absence of justification for assumptions made. **Oswell*et al.*(2010)** -Shortage of equipment to carry out geotechnical investigations in permafrost areas. **Oswell*et al.*(2010)** –Unclear elaboration of calculation assumptions and process. **Loubser and Jacobs (2016)**– Inability to apply non-linear analysis results due to operator resistance.
Opportunities	**Threats**
Cabalar *et al.*(2016)–Generalized design for all the foundations built in the area. **Oswell*et al.*(2010)**–Revolution of foundation design under extreme weather conditions. **Loubser and Jacobs (2016)**– Foundation optimization by non-linear approach leading to substantial cost and time reductions.	**Cabalar *et al.*(2016)**– Expensive approach when constructing larger turbines. **Oswell*et al.*(2010)**– Permafrost presence complicates the design and construction procedure. **Loubser and Jacobs (2016)**–Operator refusal to adopt non-linear method results to increase in the overall schedule and budget.

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III. RESULTS AND DISCUSSION

3.1.1 Conclusion

In conclusion, designinga wind turbine foundation can either be simple or sophisticated. The high cost of construction as well as the recurrence of many turbine foundations built on similar ground conditions encourage the use of non-linear analysis and 3D modelling software to minimize time and cost of design. It is therefore the responsibility of construction firms to start utilizing the latest 3D modelling software for soil and concrete structure and assume non-linear behaviour to obtain optimized design results.

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