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OSNOVNI ASPEKTI FUNDIRANJA VETROGENERATORA U NAŠIM USLOVIMA

THE BASIC ASPECTS OF WIND TURBINE FOUNDATIONS IN OUR CONDITIONS

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Prateći svetske trendove i u saglasnosti sa energetskim uslovima, u Srbiji se uspešno izvode vetrogeneratori, što dovodi do povećanja fonda znanja na ovom polju. U okviru rada, na bazi opštih geotehničkih uslova na teritoriji Srbije, biće prikazani najčešći tipovi fundiranja vetrogeneratora. Ukratko će biti predstavljena problematika analize opterećenja ovih objekata, a zatim i konceptualni zahtevi pri njihovom projektovanju. Takođe veza između konstrukcije i temelja će biti ukratko opisana. Uprkos globalnoj težnji da se ovaj aspekt konstrukcije vetrogeneratora uopšti i tipizuje, u konkretnim slučajevima ostaje veliki broj pitanja, koja se tiču komponentnih materijala, primene standarda i kriterijuma za dimenzionisanje, koji najčešće nisu prilagođeni projektovanju temelja vetrogeneratora.

Ključne reči: *vetrogeneratori, fundiranje, analiza opterećenja, projektovanje, primena*

Following the global trends and accordingly to the energy conditions, wind turbines are being succesfully built in Serbia, which leads to an increase in the fund of knowledge in this field. In the paper, on the basis of general geotechnical conditions in Serbia, the most common types of wind turbine foundations will be presented. Problems of the load analysis of these structures will be presented in brief, and also the conceptual requirements in their design. Connection between the tower and the foundation will be briefly described as well. Despite the global aspiration to generalize and industrialize this aspect of the construction of wind turbines, in specific cases remains a number of issues, regarding component materials, the application of standards and design codes, which are usually not adjusted to the design of wind turbine foundations.

Keywords: *wind turbines, foundations, load analysis, design, application*

INTRODUCTION

A wind power turbine (shorter wind turbine) can be defined as a machine which converts the kinetic energy of the wind into electricity [1]. The most frequently used wind turbines are of the order of 10 kW or less in terms on electricity production. In terms of total generating capacity, the turbines that make up the majority of the capacity are quite larger, ranging 1,5 to 8 MW [2]. Naturally, the larger turbines are used primarily in large utility grids, at first mostly in Europe and the United States, and more recently in China and India. In Serbia, according to the public information from the press, the first wind park was made in November of 2015, in Štolc-Kula, with three installed Vestas V-117 3.3 MW wind turbines.

Wind energy converters can be classified firstly in accordance with their aerodynamic function and, secondly, according to their constructional design [3]. Classification according to constructional design aspects is more practical and thus more common. The characteristic which most obviously meets the eye is the position of the axis of rotation of the wind rotor. Thus, it is important to make a distinction between rotors which have a vertical axis of rotation (e.g. Savonius-, Darrieus- and H- rotor types), and those with a horizontal axis of rotation. The most prominent turbine type is the one with horizontal axis of rotation.

The load bearing structures of a wind power turbine can be roughly divided into six groups: rotor blades, machinery structures, nacelle covers and spinners, bolted connections, tower and foundation [4]. It should be noted that a wind turbine can be divided into finer groups (e.g. structures which connect the foundation to the tower and the structures which connect the concrete part of a hybrid tower to the conical steel tube part of the tower, so called adapter). The tower can be made of several materials following different design concepts: concrete tower, free-standing steel tubulad towers, lattice towers, hybrid towers. At the moment, the most comonly used type of the tower is free-standing steel tubular tower.

Also, owing to the location of the wind turbine, wind turbines can be divided in two groups: offshore and onshore. Since, this paper deals with the foundations in our conditions, in Serbia, and considering that tubular towes are the most comonly used, the onshore wind power turbines foundations for free-standing tubular towers will be discussed.

OVERVIEW OF THE BASIC WIND POWER TURBINES FOUNDATIONS TYPES

Wind turbine foundations onshore rely on several competencies such as structural design, material design, production, etc [5]. The type and the size of the foundations used for the wind turbines are governed by the geotechnical conditions of the site, the maximum power of the turbine and the type of the tower. There are two general foundation groups, based on the geotechnical conditions: shallow and deep foundations. Both shallow and deep foundations are usually made of reinforced concrete in our conditions, but steel is also applicable in certain cases.

Shallow foundations are generally applied on rock or competent soil. In this case the most usual and the simplest foundation is spread footing (Fig. 1), which is essentially a gravity foundation, that relies upon soil overburden and concrete to provide sufficient stability and reliability in different conditions (e.g. weight to resist overturning of the foundation at extreme wind loads).

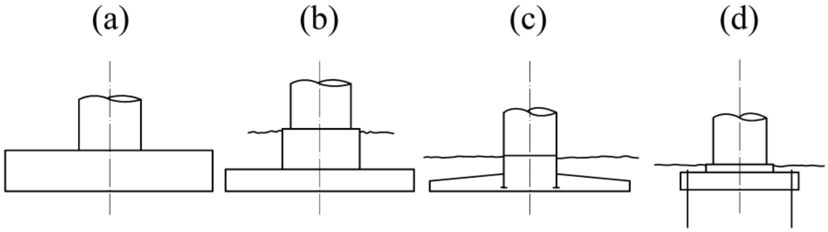

Figure 1. (a) Plain Slab; (b) Stub and Pedestal; (c) Stub Tower Embedded in Tapered Slab; (d) Slab Held Down by Rock Anchors

This type of foundation is applicable in a broad range of sub grade strengths, from soils to rock. Spread footings on the beadrock can be achored to the bedrock in order to eliminate the need for soil cover. On weaker or softer soils, where bearing capacity or stiffness is too low, and expected settlements are too high, rammed aggregate piers or vibro-piers under footings or mats can be applied. More expensive options include soil improvement such as: deep soil mixing, compaction, over-excavation & replacement with compacted lifts of aggregate.

Deep foundations are used in the case where the soils are weaker. This type of foundations include piles, drilled shafts, and concrete-filled corrugated pipes with post-tensioned anchor bolts (Figure 2). Foundation in low substrate entails higher costs in field research, load analysis, dimensioning and construction.

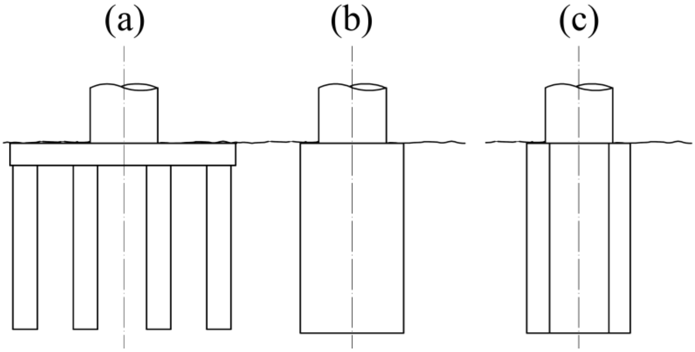

Figure 2. (a) Pile Group and Cap; (b) Solid Mono-pile; (c) Hollow Mono-pile

LOAD ANALYSIS AND DESIGN REQUIREMENTS FOR WIND TURBINES FOUNDATIONS

A commitment to electricity from renewable resources, such as wind, along with the trend of manufacturing bigger wind turbines, makes obtaining the most efficient and safe designs of the structures that support them ever more important. In order to reduce the manufacturing costs, the current trends tend not to site-optimise wind turbines, but rather to produce a selection of standard wind turbines. Therefore, standard wind turbine is chosen from this selection and verified as a suitable one for given location. The foundation design must always be site-specific, because it needs to be designed for the local soil conditions [6]. Soil investigations should provide all necessary soil data for detailed design of specific foundation structure at specific location [6]. Soil investigations and data may be divided into several groups: survay, geological, seismic, hydro-geological and geomechanical [7].

Design requrements for the most comon foundations in our conditions, shallow onshore foundations, include addressing the following problems [8]: minimum embedment below frost depth, bearing capacity, settlements (elastic, consolidation and differential), safety factors against sliding and overturning, drainage, foundation stiffness accounting for modulus degradation due to cyclic loading and dynamic analysis for avoiding resonance of soil-foundation-structure system.

The frost depth of the soil depends on local climate conditions. Foundations must be set to 10-20 cm deeper than the frost depth. Otherwise, the water contained in the pores of the soil changes volume due to freezing. Therefore, foundation conditions and interaction of the foundation and the ground are changing, leading to the destruction of the soil itself. In our climate it is recommended that the building is founded at a depth of at least 80-100cm [7].

As foundations of wind turbines usually have relatively small areas, bearing capacity formulas for idealised conditions will normally suffice and be acceptable for design. All forces (Fig. 3) acting on the foundation, including forces transferred from the wind turbine, are transferred to the foundation base and combined into resultant forces H and V in the horizontal and vertical direction, respectively, at the foundation-soil interface [6]. The eccentricity is calculated as: e = M / V, where *M* denotes the resulting design overturning moment about the foundation-soil interface.

The following general formula can be applied for the bearing capacity of foundation with a horizontal base, resting on the soil surface, for fully drained (long-term) conditions [9]:

$$q_{ult} = c' \cdot N_c + q' \cdot N_q + \frac{1}{2} \gamma' \cdot b_{eff} \cdot N_\gamma$$

where: b_{eff} and l_{eff} – effective foundation dimensions; c' – cohesion; N_c, N_γ, N_q – bearing capacity factors, dimensionless; q' – effective overburden pressure at the level of the foundation-soil interface (kN/m^2), γ' –effective (submerged) unit weight of soil (kN/m^3).

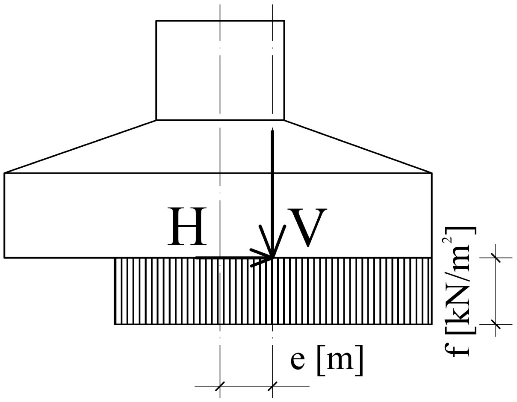

Figure 3. Loading under idealised conditions

Settlement is usually a sum of three parts: s_e – elastic settlement (immediate), which is most important for sands, s_c – consolidation settlement (due to evacuation of water and air from pore space), which is most important for clays, and s_s – secondary settlement (long term rearrangement of soil structure under constant effective stress), whose magnitude depends on mineral types present in soil. Safety factor against sliding is defined as the sum of resisting forces devided by sum of driving forces. Safety factor against overturning is defined as the sum of restoring moments devided by sum of overturning moments. Both factors have to be at least 1,5 in order for the foundation to be stable.

In order for the design bearing capacity to be maintained, water drainage has to be provided (for instance by using drainage tiles, draining backfills or sloping the finished grade in a manner to prevent pooling). Excessive wetting of clay soil can cause expansion and therefore differential settlements, while excessive drying of clay soils can cause shrinking, leading to settlements.

A complete natural frequency analysis has to be performed for the combined structure consisting of turbine, tower, tripod and piles, where the non-linear soil must be linearized. The lowest frequencies have to differ at least ±10% from the rotor frequencies at nominal power. Dynamic soil response affects response of structure and vice-versa. There should be conducted analysis regarding the stiffness of the components and the whole soil-structure-foundation system.

For design of piles, it is common to disregard a possible interaction between the axial pile resistance and the lateral pile resistance locally at any point along the pile and to treat these two forms of resistance as being independent of each other. The argument for this is that the soil near the surface principally determines the lateral resistance without contributing much to the axial resistance, while the soil further down along the pile toward the pile tip principally determines the axial resistance without contributing much to the lateral capacity. For foundations consisting of pile groups, i.e. clusters of two or more piles spaced closely together, pile group effects need to be considered when the axial and lateral resistance of the piles is to be evaluated.

Generally, seismic factors, shape factors and inclination of the forces also have to be included in the design of wind turbines.

CONSTRUCTION REQUIREMENTS

In the most cases, in our conditions, foundations are reinforced shallow slabs (made in square, circular or octogonal shape), like the one which is presented in the Fig. 4. Proper design of reinforced concrete has to be practiced, followed by proper execution on field. Regarding the used materials, it must be ensured that the following minimum requirements are fulfilled: water/cement ratio for the concrete is determined in consideration of the environmental class, typically less than 0,55 at all times, maximum aggregate size has to be less than 32mm and the minimum distance between reinforcement bars, minimum distance between non-restressed reinforcement bars has to be 150-200 mm, reinforcement diametars should be 12-20 mm. High strength cementitious and epoxy grouts can be used more in 2+ MW turbines, and higher strength concrete in the pedestals, enhanced reinforcing details at the bearing area in 3+ MW turbines. Important details include higher flange bearing stresses and fatigue requirements of the anchor bolts and the grout / concrete. Additionally, designers may begin to evaluate the plastic capacity for the bearing area.

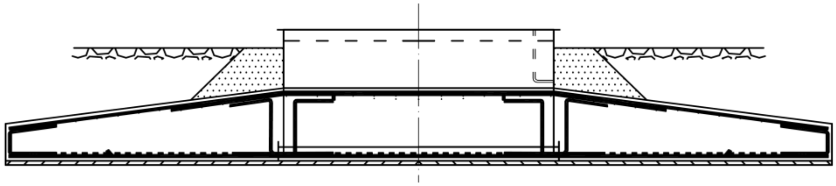

Figure 4. The usual foundation for onshore turbines in good soil and bedrock

Approaches taken by foundation designers vary but some codes used are: ACI Chapter 10 – simple column bearing; ACI Chapter 18 – post-tensioned anchorage; AASHTO 5.7.5, 5.10.9 – bearing / post-tension / reinforcement; PTI anchorage zone design; Eurocode 2 – 5.10, 6.5, 8.10.x, Eurocode 7 - geotechnical design, Eurocode 8 – geotechnical design under seismic loading; DNV Offshore Standards – J101, C502 – concrete fatigue and others. The choice of code is driven by the assumed behavior. For example, if simple column bearing behavior is assumed then meeting the basic compression stress limits of ACI Chapter 10 may be sufficient. However, if the simple Chapter 10 rule can't be applied due to very high stresses, analysis of the location as a post-tensioned anchorage under some other set of provisions (ACI or another code), with all requirements for bursting reinforcing and service level stress maxima, may be required.

CONNECTION BETWEEN THE TOWER AND THE FOUNDATION

One of the important parts of the wind power turbine is the connection of the tubular steel tower to the foundation. There are two different principal arrangements to connect the tower to the foundation, namely insert ring cast in the foundation and steel adapter fixed by stud bolts, Fig. 5 [4].

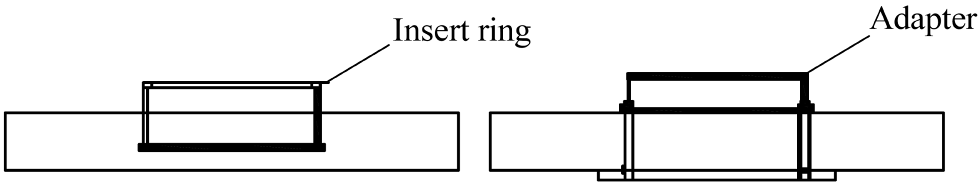

Figure 5. Two types of connection of the tower to the foundation [4]

With the development of larger wind turbines, the stresses in the connection of the tower to the foundation by means of insert ring have increased. The report shows that this may lead to cracking of the concrete and formation of gaps between the concrete and the insert ring.

CONCLUSIONS

Building wind turbines with higher rated power requires bigger structure and foundation. Hence, bigger footings with more concrete and reinforcement are expected [5]. Naturally, cost efficient design solutions should be applied. Structural failures are linked to definable causes that have been experienced before and can be prevented [10].

Foundations must be designed for the site conditions of each project [9]. The conduction of proper geotechnical investigation and foundation design are of high importance, in order to prevent problems [8].

Particular attention has to be paid to the on-site activities that can lead to reduced service life of wind turbines [11].The most important ones are: good concrete cover, proper installation of reinforcement, adequate concrete curing (including conditions of ambient high and low temperatures), concrete mix (including control of water content in the concrete mix), casting joints.

Generally, the recommendations of wind turbine foundations design in our conditions are in accordance with international, including following contents: development of guidelines for planning and production of wind power, turbine foundations, production and quality control, inspection, and damage assessment. Nevertheless, guidelines and handbooks for repair of damaged foundations, as well as more numerical modeling results of the structural behavior of the wind power turbines and their parts should be developed.

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