Foundations of wind power plants - challenges in designing and execution of construction work

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Abstract. The paper is focused on foundations of wind turbines and challenges in design, execution and long-term maintenance. Some typical solutions are listed: footings (round plates) on natural soil, footings on modified soil (DSM, stone columns, CMC) and deep foundations (piles). The author juxtaposed basic problems that appear in design phase: data acquisition for various kinds of foundations, appropriate calculation model and possibility of on-site verification and possible changes. Problems appearing during execution of works are illustrated with examples of service roads arrangement, earth works (excavations) and soil improvement or piling. The author emphasized the role of quality control including: monitoring of soil conditions and groundwater level at execution stage and impact of earth works – re-profiling of ground level. In final remarks, some recommendations are given for current control of quality (ground parameters, soil improvement, piling) and long-time maintenance – possible problems in foundations related to: time, cyclic loading and changes in the soil related to previous earthworks.

1. Introduction – the scope of the study
The paper presents some selected aspects of decision-making process while selecting the technology and also author’s experience from control tests of foundation piles run at construction site of wind farms. The issues of founding the structures for wind power generation have been widely talked-about and referenced in bibliography. Publications appear from both academic environment, like [1-4], and also from contracting companies [5]. It probably results from favourable outlook for geotechnical work market in this economy sector of dynamic development. The interest of research units results from nontrivial nature of subsoil examinations and foundation analyses due to long-term cyclic loads, high operational requirements for wind turbines and their costs. A relatively high level of analyses is required at each successive stage of implementation – from decision on the type of foundations, through the scope and way of analysing the soil subbase and design stage, to the method of executing and controlling geotechnical work and unto the later long-term monitoring.

2. Selecting the foundation method
Environmental [6], social [7] and technical issues [8-10] related to the construction of the towers (figure 1) can be found in numerous papers. Technical literature provides valuable information about standardized requirements. The only non-standardized field is the foundation that has to be designed according to local conditions at the chosen localization of the wind turbine. Starting from access roads, working platform for giant assembling crane and underground electrical infrastructure, a large number of geotechnical works and technologies are involved in the construction of the towers and assembling of turbine and wings. Some problems are dependent on the size of the tower [8] and other factors [10].
If we skip financial aspects (the non-technical ones) and cases where preliminary geotechnical investigations for potential location indicate that deep foundation is necessary, the following conditions are used to determine the method of foundation for wind turbine:

- favorable soil conditions enabling spread foundation;
- possibility of subbase modifications within active zone beneath spread foundation level (to increase stiffness and to reduce settlements);
- possibility of reinforcing the subbase with columns (piles) which, when joined with top plate (cap), transfer the pulling forces and reduce edge overloads;
- limiting the size of top plate size by using deep foundation – transferring all forces to foundation piles connected with top plate and acting both to push in and pull out.

Available publications show that sophisticated numerical models (e.g. finite element methods [2]) are commonly used to analyse various variants of tower structure and foundations. In-depth analyses, especially refer to displacement forecasts, as wind turbines fall under stringent requirements [11] for foundation stiffness (limited settlements, and especially the tilt). Depending on the foundation type selected, modelling is performed for the subbase or for subbase with vertical reinforcing elements.

3. Preparing data for design stage

Formal basis for performing the geotechnical investigation of subbase for wind power plant to be designed is [12]. It should be emphasized that in case of foundations for wind turbines, two-stage data acquisition is virtually always required.

The first stage – being run in line with searching for optimum placement (on account of wind) – usually include just preliminary recognition of the type and condition of soils in subbase in order to select the type of foundation. And only then it can be made a dedicated investigation for assumed calculation model. In Poland, such procedure is generally consistent with the Ordinance of the Minister of Transport, Construction and Maritime Economy of 25 April 2012 on establishing geotechnical conditions for foundations of civil structures (Journal of Laws, No. 463/12). Idea of this solution comes down to enforcing interaction between a geologist (geotechnical engineer), design engineer and contractor so as the data gained enable to design and safely execute the foundation and – what is of importance - to forecast the behaviour of the structure over a long time period.

Standards and ordinances provide no detailed recommendations and guidelines for ground survey for specific needs of wind power plants. Most often, subbase examinations are made on the basis of recommendations of turbine manufacturers or experienced design engineers. One can also make use of German guidelines “Richtline für Windenergieanlagen. Einwirkungen und Standsicherheitsnachweise für Turm und Gründung, BIBT, Berlin 2012“ or Norwegian ones „Det Norske Veritas (DNV) (2002). Guidelines for Design of Wind Turbines“.

**Figure 1.** Rural landscape with wind turbines

**Figure 2.** Preparing building embankment for access roads (COWI)
Independently of standards and guidelines, it seems that the best ground investigation is to make deep foundation in technology which enables current control of bearing capacity. Optimum solutions are then the is placement pile technologies (RC prefabricated driven piles, Franki-type piles) which allow for current assessment of each one pile as concerns its capacity and stiffness. For other piling technologies and for ground reinforcing columns, the best control of foundation stiffness is the in-situ testing (e.g. test load – not necessary up to the ultimate bearing capacity).

Apart from investigations for foundation of the turbine itself, geotechnical survey should also include the ground (subbase) for access roads (figure 2), cable subways (figure 3) and working platforms (e.g. for erecting cranes). For such cases, the site acceptance tests for embankment shaping should be kept in mind.

4. Executing the foundation and control procedures

4.1. Spread foundation

A series of non-obvious threats result when we select the theoretically simplest way of foundation. For the sake of large horizontal size (diameter) and great thickness of foundation plate, the excavation must be appropriately deep. When the foundation level is deeper, the foundation can be additionally “ballasted” with ground over the plate. However, we need to remember that lowered ordinate of foundation increases the arm of horizontal forces acting on the rotor, thus increasing the moments.

Independently of the problems with ground water inflow during foundation work (figure 4), the ground water upthrust during wind turbine operation (presumable at larger depths) considerably reduces the ballast function of the plate and forces its larger dimensions. Backfills of foundations, always made in practice from qualified structural fills of non-cohesive soils often lead to essential change in foundation conditions. Water stagnation in the backfill changes considerably the long-term conditions of spread foundation or foundation on a reinforced subbase. To a lesser extent it also refers to piled foundations (deep – interconnected with top plate) as assumption is made that loads are transferred to the layers which are not disturbed (in negative meaning) by foundation work.

The issues related to acceptance of grounds in excavation for spread foundation in a form of large plate of diameter often exceeding 20 m are to be the subject for a separate paper because the size of active zone under such foundation exceeds the diameter of this plate. The range of control testing (test boring or sounding) is usually not larger than several meters and not uncommon are also “ground inspections in excavation” which are reduced to establishing that grounds at excavation bottom are consistent with earlier documentation, or local testing with VSS plate or with dynamic plate, which enable to assess ground stiffness and condition in a layer several dozen centimetres below excavation bottom. Disputable is also adequacy of testing made during temporary lowering the ground water table for final conditions when dewatering systems no more exist. Extensive review of issues related to ground testing for the needs of wind turbine foundations is given in the paper of [1].

Figure 3. Excavations for cable subways (COWI)  
Figure 4. Excavation for spread foundation – dewatering for earthworks time (COWI)
Extremely interesting and extensive program of subbase testing in relation to legal requirements and possible qualifying the wind turbines to critical infrastructural elements is also given in reference [13]. However, we may have reasonable doubts whether such non-standard (though very valuable) program of subbase testing using examination of dynamic shear modulus with seismic dilatometer or using spectroscopic analysis have a chance for widespread use. According to author’s observations, it seems that rather reverse phenomenon takes place. Relatively (seemingly) the least complicated way of founding provokes to order the work at lower and lower levels of contractors of limited competences and experience. Then, the quality of work is difficult to enforce – especially for temporary work like excavation and foundation ones.

Figure 5. Wind farm in Pęgów – Deep Soil Mixing columns DSM 1600 mm (KELLER)

Figure 6. Load test for area reinforced with columns (MENARD)

Figure 7. Integrity testing with PIT method

4.2. Foundation on reinforced subbase

The subbase for foundation plate is most often strengthened by the following means:
- stone, gravel or concrete columns (with load transfer platform);
- wet DSM columns (freshly sheared) to plate base ordinate;
- DSM columns or displacement columns (e.g. CMC type) interconnected by reinforcement with cap structure (numerous examples of such foundations are available in promotional materials of Keller and Menard companies).

Figure 5 shows DSM column diameter and the bottom of excavation after “cutting” the wet DSM column heads. It needs to be highlighted that improvement of subbase with columns causes that the requirements on proper foundation stiffness are much easier attainable. However, it helps to a small extent only to meet the conditions on the position of the resultant of actions at the foundation level in various load schemes. Also, the field verification of such improvement effectiveness is questionable. In case of large-diameter DSM columns, which by definition are carrying most of loads from the plate, it is quite common to apply static test load to them within the range allowing to assess the stiffness of...
a single column and further on – by numerical modelling – to forecast the behaviour of the whole plate.

It is much more difficult to confirm in field test the usefulness of stone columns or concrete displacement columns (CMC), which are designed to carry just some part of loads from the plate. Loading a large area is required to get a full control of calculation model for foundation on a strengthened subbase. Reliable examination would then require that loading is applied to a large surface testing area improved with such columns. During engineering negotiations for one wind farm in Wielkopolska Region, the requirement was to test the strengthened subbase with load of 270 kPa. It should be realized that the load of 270 kPa is equivalent to 11 m of concrete. The cost of control test would be then probably higher than the cost of the work itself, however such experiments were made over the world so far (Figure 6). In the case of concrete displacement columns, integrity testing is highly recommended [14,15].

4.3. Deep foundation with piles

The idea of indirect foundation assumes that piles will carry both pressing in and pulling out forces. As the highest stresses, caused by moments transferred to foundations, appear at its edges (figure 8), supporting with piles is usually made on the circumference of the cap plate. Often, the piles are made inclined. Such solution has two favourable features. Firstly: slanted piles have distant bases and cooperate with larger volume of ground. Secondly: tilt of piles reduces the risk of their damage during executing the successive ones. It is of special importance in case of displacement piles (prefabricated driven-in piles, Franki NG piles). An example of spatial model of pile supported foundation (Franki NG piles) was worked out by Król (figure 9). Exemplary arrangements of piles made with various technologies on the circumference of foundation plate are shown in figure 10 (FRANKI) and figure 11 (RC driven piles).
Investigations of deep foundations are of two-sided nature. Assessment of bearing capacity and stiffness of pile supports is run on the basis of test loads. The results may reveal both: favourable (figure 12) and unfavourable test results (figure 13). Construction of static load test stand is usually quite complicated and requires additional anchoring piles. Hence, preferred are technologies which allow to assess bearing capacity of each pile on the basis of resistances while it is driven-in (RC prefabricated driven-in piles, Franki NG piles). At the same time, these are the technologies featuring the smallest settlement of piles. It is also possible to use dynamic testing which allow to get comparable information at lesser cost and in shorter time. The advantage of dynamic testing (figure 14) consists also in that piles can be randomly taken for testing (provided the head is properly prepared) and that we can find information about ground reaction distribution over pile length, which – as a consequence – enable to draw conclusions about pull out resistances [16].

The second control procedure, quite commonly implemented for wind turbine foundations, refers to testing for continuity run with PIT or SIT low-stress method (figure 7). Author’s experience indicates that reliability of such testing is limited by constraints of testing technology related to the maximum slenderness of element under testing. For example, when testing the piles about 0.5 m in diameter, reliable information can be get for a distance of about 25 diameters, i.e. about 12.5 m and for such depth we can possibly confirm that no defects are to such depth. When piles are longer – and in case of wind turbine foundations, the length of Franki-type piles exceed not infrequently 20 m – or when piles have connections (joined prefabricates), the signal can be hardly interpreted reliably [17].

While commenting the use of piles to wind turbine foundations, it is hard to resist reflection related to recent informal campaign for improving safety in geotechnical work. Most of pile technologies requires execution of access roads and appropriate working platforms.
In many locations, such preparations are additional item in cost estimate. In case of wind power plants, all these elements are necessary due to operation of construction cranes, so they can be used so to speak “for free” for transporting and operation of piling machine.

5. Summary and final remarks
Spread foundation or on strengthened subbase are most often designed with Finite Element Method – the tool both good and sensitive to quality of data. Thus, designing is largely wishful as the testing results for modules (if it was made at all) are taken either from correlation relationships or from specimens of several centimetre long while the model is 60 m wide and 30 m deep. For deep foundation (using piles), recognition (both for bearing capacity and displacements) usually corresponds to the size of pile, hence is more “fitted”.

Checks on site are encumbered with the same problem – acceptance inspections of natural soil or strengthened subbase are of “local” character, both in spatial and time aspects. Most often, there are no chances to check the whole or it is very expensive.

In deep foundation – especially for displacement technologies, control of the pile foundation process includes all its elements. However, special attention should be paid to the connection of piles with the top plate (figure 15) – it is of key importance when piles cyclically subject to pull out loads. At this point, special importance is assigned to the construction site inspector who should force appropriate cleaning the heads!

Earth work and backfilling around the foundations often cause essential change in foundation conditions with respect to description from geotechnical documentation. Even cursory observations show that spread foundation can lead to disturbances of water conditions in the immediate vicinity resulting in inestimable consequence further on. Water stagnation in the backfilling changes significantly long-term conditions for spread foundation or that on strengthened subbase. It does not refer to the pile foundations (deep ones, connected with a cap) as the loads are assumed to be transferred to intact layers.

Independently of the selection made for the way of wind turbine foundation, special attention should be paid to the following:

- subbase testing program should be compatible with the calculating models in use, so as to determine (as far as possible) those ground parameters which are directly used in the model (to omit the correlation relationships);
- to perform earth and foundation work so as not to cause essential change in soil/water conditions within the foundation with respect to the data specified in earlier testing, which created the basis for design documentation;
- forecast of change in soil parameters in the subbase caused by earth work performed and long-term cyclic load.
The last issue itself seems to be a challenge for design engineers. Forecasting over a longer time horizon is not easy when available are the results of point tests only. Available are already publication dealing with tests for individual piles subjected to cyclic loads. However, the issue of direct foundation stiffness varying over time, for subbase strengthened with columns or group of piles under diversified soil conditions, would probably be evaluable not until experiences gained and long-time observations of real objects.

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