

STATIC-DYNAMIC TESTS OF BEARING CAPACITY OF WIND TURBINE PILES

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Abstract

The paper presents the static load tests (SLT) and dynamic load tests (DLT) of the piles and numerical analyses of piles in interaction with the soil of wind turbines. Pile tests were conducted using the equipment with counter-weights for SLT and an autonomous system for the control of DLT of the piles. Numerical DLT analyses were performed by the signal matching method. Tests proved that the design resistance of piles of SLT and mobilized static resistance of DLT are higher than the design forces obtained from the design of the wind turbine foundations. Also, the need to develop a plan for testing the bearing capacity of piles, concerning large and significant buildings was emphasized.

Key words: pile, testing, bearing capacity

Introduction. In the last twenty years, the production of green energy (solar energy, wind energy, geothermal energy, biomass energy, etc.) has seen a considerable expansion in the world. One of the systems, enabling the production of green – renewable energy is the wind turbine. In order for wind turbines to function properly, it is necessary to satisfy a significant number of criteria defined by laws, technical regulations and standards in the pre-design, designing, construction, testing and operation phases. A special segment of wind turbine design

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is the design of wind turbine foundations. In addition to designing, the testing of wind turbine foundations is also important. The design of the foundations of wind turbines on land, in most cases, is realized with a raft and piles. The general mechanism of interaction between the raft-piles-soil, for wind turbine foundation, can be decomposed into several smaller interaction mechanisms: pile-soil, pile-pile, raft-soil and raft-pile.

In [1], calculations of wind turbine foundations (piles and rafts) are presented using three different aspects of modelling: completely immovable piles (the effect of soil-structure interaction is minimized), the Winkler model (elastic springs were applied both for piles and for the raft) and a combined model in which the Winkler model is applied, with springs for the raft and piles along the shaft while the base displacement is prevented. The genetic algorithm and methods of Monte Carlo simulations were used to consider the performances of the wind turbine foundations [2]. In comparison to the previous design models of the raft, piles and soil, in [3] the aspects of 3D modelling with 3D brick finite elements were considered and the results were compared with the analytical solutions. The problem of modelling and analysis of the foundation of wind turbine with the shell and solid finite elements was discussed in [4]. The review of the state of affairs in the field of analysis of the piles for founding of wind turbines is presented in [5], where there was a special consideration of the piles exposed to axial tension. The problem of raft-piles-soil interaction to the seismic response of wind turbines was discussed in [6], while [7] showed analytical, numerical and experimental research of piles behaviour under the monotonous and cyclical load action. In comparison to the previously presented research related to the calculations and designs of the raft and piles of a wind turbine, papers [8,9] presented the bearing capacity tests of piles for founding of wind turbines. A more detailed review of the state of affairs in the field of testing integrity and bearing capacity of piles was provided in [10,11], while in [12,13] the aspects of testing and calculation of design resistance of real piles for the purpose of constructing foundations of wind turbines were presented. A probabilistic pile bearing capacity analysis based on in-situ soil testing and bearing capacity tests was presented in [14,15].

The research presented in this paper is based on numerical analysis and testing of wind turbine foundations by Static Load Test (SLT) and Dynamic Load Test (DLT). On the basis of the research presented in this way it is possible to perform a quality analysis of the wind turbine foundations for the operating conditions and verify the design solution obtained by the numerical analysis.

Design of raft and wind turbine piles. The calculation of the bearing capacity of the piles is carried out according to the mechanical parameters of the soil obtained from laboratory tests of samples from the field. Also, the calculation of the bearing capacity of piles is carried out by implementing in-situ soil tests, such as the Cone Penetration Test (CPT). For the purposes of this research, the bearing capacities of the piles were taken from the wind turbine foundation design,

and they were determined by applying three CPTs for the foundations of two wind turbines. The soil is composed of sandy loess (density $\gamma = 17.5 \text{ kN/m}^3$, angle of internal friction $\phi = 28^\circ$, cohesion $c = 8 \text{ kN/m}^2$, modulus of compressibility $M_v = 4\text{--}7 \text{ MPa}$, mean resistance of the cone tip $q_{c,m} = 1.5\text{--}2.5 \text{ MPa}$) and silty sand at a depth of 12 m (density $\gamma = 20 \text{ kN/m}^3$, angle of internal friction $\phi = 32^\circ$, cohesion $c = 0 \text{ kN/m}^2$, modulus of compressibility $M_v = 14\text{--}35 \text{ MPa}$, mean resistance of the cone tip $q_{c,m} = 3.5\text{--}7 \text{ MPa}$).

Testing of bearing capacity of wind turbine piles. The bearing capacity test of wind turbine piles was performed using SLT and DLT. SLT of the pile is the most reliable high-strain test for determining the static bearing capacity of a pile using a counterweight. The pressure acts on the pile head as the press is braced against the own weight of the counterweight. The expression bearing capacity test of the pile comprises determining the intensity of reactive forces of the pile in the cumulative (total) form (of both the shaft and base of the pile). The pile is tested for the load that should be used to prove the factored value of the design force. The equipment for SLT of piles consists of the following [12]: hydraulic presses, hydraulic system (pump), power generator, steel calottes, plates, spacers, reference system, digital comparators, hardware system for conversion and acquisition of data, software system for processing and visualization of data and the surveying system (levelling and bar code staves) for pile deformation monitoring. Figure 1 shows formed counterweights for conducting of in-situ SLT of piles of wind turbines WT 1 and WT 2. The counterweight is built up of concrete blocks and steel sections. The measured settlement of the tested pile was monitored via four digital comparators which were connected to the reference beams at an angle of



Fig. 1. Created counterweights for conducting in-situ SLT of piles of wind turbines: a) WT 1, b) WT 2

90°. The system of reference beams was the frame of mutually interconnected steel tubes rested on the soil via four support points. Simultaneously with monitoring of the settlement of tested piles using comparators, geodetic surveys of settlement of tested piles were conducted. The programme of applying loading and unloading increments was conducted in agreement with the standard ASTM 1143 [16]. The ground level of the rafts of wind turbines WT 1 and WT 2, examined by SLT, are different, so in this sense somewhat different results were obtained. The ultimate resistance of wind turbines WT 1 and WT 2 were determined by extrapolating solutions from SLT using the Chin–Kondner method. The Chin–Kondner method extrapolates the load-settlement curve according to [17]:

$$(1) \quad P = \frac{s}{C_1 s + C_2},$$

where P is the force, s is the settlement, C_1 and C_2 are the curve coefficients. Additional bearing capacity analyses were conducted according to the standard EN 1997-1:2004 [18], whereby the ultimate settlement of the pile equal to one tenth of the pile diameter $s_u = D/10 = 520/10 = 52$ mm holds. Based on the value of ultimate settlement obtained in this way, the corresponding mean and minimal resistances of the pile $R_{c,m,SLT}$ were determined:

$$(2) \quad (R_{c,m,SLT})_{\text{mean}} = \frac{1}{n} \sum_{i=1}^n R_{c,m,SLT,i},$$

$$(3) \quad (R_{c,m,SLT})_{\text{min}} = \min(R_{c,m,SLT,1}, \dots, R_{c,m,SLT,i}, \dots, R_{c,m,SLT,n}),$$

and subsequently, the characteristic ultimate compressive resistance of the pile $R_{c,k,SLT}$ was calculated:

$$(4) \quad R_{c,k,SLT} = \min \left\{ \frac{(R_{c,m,SLT})_{\text{mean}}}{\xi_1}, \frac{(R_{c,m,SLT})_{\text{min}}}{\xi_2} \right\},$$

and the design compressive resistance of the pile $R_{c,d,SLT}$:

$$(5) \quad R_{c,d,SLT} = \frac{R_{c,k,SLT}}{\gamma_t},$$

where ξ_1 and ξ_2 are correlation factors defined in the function of the number of piles examined by SLT, and γ_t is the partial compressive resistance factor.

DLT belongs to the high-strain test group and it is based on determining the mobilized static resistance of the pile during the dynamic external excitation. DLT is performed by the own testing system consisting of: modular steel supporting structure, modular weight, hydraulic system for lifting of drop weights to a specific height, braking system of the drop weight, power generator, surveying system for monitoring pile settlements, accelerometers and strain gauges for

data acquisition, hardware system for monitoring and data processing, PDA/DLT and DLT/WAVE software [13]. During testing the instrumented pile is monitored, whereby the *Profound* PDA/DLT system directly displays and saves the measurement data. The drop weight is released to free fall from a specific height, whereby, due to the impact of the drop weight on the pile head, a dynamic excitation in the pile is caused. The pile is tested to the load which should prove the design force and the behaviour of the pile at the design force level, considering that such a test is conducted on the service piles which are used as the primary foundation elements of a structure. Sensors fitted to the pile head extension register strains and accelerations of the pile over time. Based on the measured strains $\varepsilon(t)$, modulus of elasticity of concrete E and the area of the cross-section of the pile A , the force $F(t)$ is calculated according to [19]:

$$(6) \quad F(t) = \varepsilon(t)EA.$$

On the other hand, based on the measured accelerations, using the first numerical integration, the velocities $v(t)$ are obtained and the force $F(t)$ is calculated according to:

$$(7) \quad F(t) = v(t)Z = v(t)\frac{EA}{c},$$

where Z is the pile impedance (depends on the material characteristics and geometry of the pile cross-section), and c is the velocity of wave propagation in concrete. Force diagrams obtained measuring strains and accelerations over time represent a basis for interpretation of the results of DLT. The total value of the static R_{sta} and dynamic R_{dyn} resistance is determined from the sum of downward travelling waves $F^\downarrow$ and upward travelling waves $F^\uparrow$:

$$(8) \quad R_{\text{tot}} = F^\downarrow(t_{\text{max}}) + F^\uparrow\left(t_{\text{max}} + \frac{2L}{c}\right),$$

where L is the length of the pile, while in the general case, forces obtained from the waves are calculated according to:

$$(9) \quad F(t)^\downarrow = 0.5 \left(F(t) + Zv(t)^\downarrow \right), \quad F(t)^\uparrow = 0.5 \left(F(t) - Zv(t)^\uparrow \right).$$

The bearing capacity is determined from the in-situ DLT results by using the indirect method. In the indirect way, the bearing capacity is determined using the signal matching procedure, which is an iterative procedure of finding the static and dynamic soil parameters with the goal to obtain a calculated signal which is the best match for the measured signal. More accurately, the signal of the nonlinear numerical model of pile-soil interaction is matched with the signal measured from an in-situ DLT. Figure 2 shows in-situ tests and equipment for DLT of WT 1



Fig. 2. In-situ tests and equipment for DLTs of wind turbine WT 1 and WT 2 piles

and WT 2 wind turbine piles. The tests were performed in agreement with the standard ASTM 4945 [20]. For each wind turbine, three service piles were tested. Diagrams of variation of forces over time, obtained by in-situ DLT, by measuring strains and accelerations and subsequent calculation, for the drop weight impacts which mobilized the highest static resistance of the soil are presented in Fig. 3 for the wind turbine WT 1 and WT 2 piles, respectively. By analyzing the diagram, it can be concluded that the pile basis resistance is considerably higher than the shaft resistance. Figure 4 presents the load-settlement diagrams obtained by SLT,

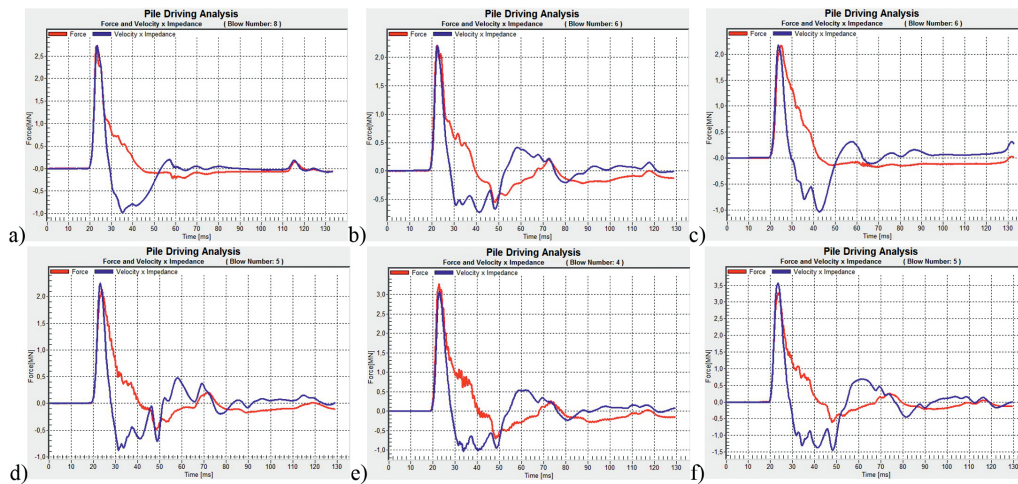


Fig. 3. Diagrams of force variation over time obtained by in-situ DLT, by measuring strains and accelerations and subsequent calculation: a) WT 1 pile 1, b) WT 1 pile 2, c) WT 1 pile 3, d) WT 2 pile 1, e) WT 2 pile 2, f) WT 2 pile 3

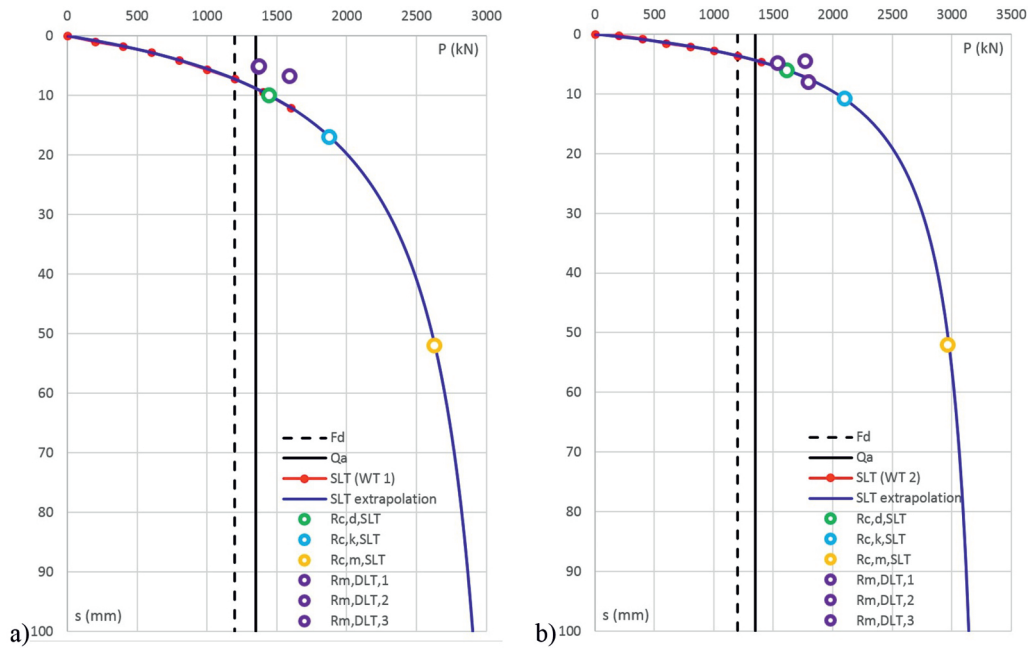


Fig. 4. Load-settlement diagrams obtained by SLT and discrete values from DLT: a) WT 1, b) WT 2

diagrams of mean value of extrapolation of the SLT solution of the Chin–Kondner method, diagrams of the design force F_d , diagrams of allowable resistance Q_a , discrete value of design resistance $R_{c,d,SLT}$, discrete value of the characteristic ultimate resistance $R_{c,k,SLT}$, discrete value of the ultimate resistance $R_{c,m,SLT}$, and mobilized static resistance $R_{m,DLT}$ from DLT.

Conclusions. Based on the research presented in this paper, through the design and testing of wind turbine foundations, the following conclusions can be drawn:

- DLTs of wind turbines WT 1 and WT 2, proved that the mobilized static resistances of the piles $R_{m,DLT}$ from DLT are higher than the design forces F_d , and they are also slightly higher than the allowable resistance Q_a , which was the objective of DLT:

$$(10) \quad R_{m,DLT} > Q_a > F_d.$$

- SLT and DLT of piles of wind turbines WT 1 and WT 2, and the calculation is in agreement with EN 1997-1:2004 [18] an order of the values can be demonstrated (which was the intention, because in this way the bearing capacity, stability and serviceability of wind turbines is provided):

$$(11) \quad R_{c,m,SLT} > R_{c,k,SLT} > R_{m,DLT} > R_{c,d,SLT} > Q_a > F_d.$$

- on the basis of conducted SLTs it can be concluded that the wind turbine WT 1 and WT 2 piles elastically settle to the level of permissible bearing capacity;
- on the basis of the conducted research and SLT, the safety factor for the wind turbine WT 1 piles is $F_{s,1} = R_{c,m,SLT}/F_d = 2.2$, while the safety factor for the wind turbine WT 2 piles is $F_{s,2} = R_{c,m,SLT}/F_d = 2.5$.

Given the cost of testing, DLT has recently been used to test the bearing capacity of piles. Also, to a large extent, tests are conducted on service piles, and less and less on trial piles. In addition to all this, the principle of minimizing the amount of testing is applied, which directly reduces the levels of reliability of bearing capacity, stability and serviceability of certain units, or a complete system of foundations of a structure. When it comes to a large number of building piles, it is more reliable to make a test plan before constructing piles. A quality test plan can predefine the test piles on which SLT and/or DLT will be performed, and thus correct the construction technology and/or disposition and/or the number of piles. Subsequently, certain service piles can be tested by DLT.

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